Bombing Bombay?

Effects of Nuclear Weapons and a Case Study of a Hypothetical Explosion

IPPNW Global Health Watch
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About the Author

M. V. Ramana obtained his Ph.D. in Physics from Boston University. Since then, he has held research appointments at the University of Toronto, Massachusetts Institute of Technology, and Princeton University. In 1996, the Social Sciences Research Council (SSRC) awarded him an SSRC-MacArthur post-doctoral Fellowship on International Peace and Security. This report is based on work done during this fellowship period. More recently, he was awarded an SSRC-MacArthur Fellowship for International Collaborative Research.

He is actively involved with the peace movements in India and the US.

About IPPNW

International Physicians for the Prevention of Nuclear War is a federation of national medical organizations in more than 60 countries dedicated to safeguarding public health through the prevention of war.

During the Cold War, IPPNW educated the medical profession, the general public, and political leaders about the medical consequences of nuclear warfare. For this effort, IPPNW won the 1985 Nobel Peace Prize.

Today, IPPNW's mission includes research, education, and advocacy to minimize the effects of war and preparation for war on health and health services.

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* References are indicated throughout the text by Roman numerals.

Overview

The nuclear tests by India and Pakistan in May 1998 signaled the beginning of a dangerous new era in South Asia. Nuclear war in this part of the world that is home to well over a billion people would be catastrophic. Nor would the effects of such a war be limited to just the region. Long-lasting radioactive fallout respects neither spatial nor temporal boundaries.

This report describes the effects of nuclear explosions and the possible consequences of a hypothetical nuclear detonation over the Indian city of Bombay (or Mumbai). The precise effects of such a detonation depend on a variety of variables, such as the exact location, the weather and wind conditions, the yield of the weapon, and so on. Many of these cannot be known in advance. Nevertheless, it is possible to make educated estimates. Using a range of physical models that describe nuclear explosion effects, we make conservative (i.e., assuming that the effects would be as low as reasonably possible) evaluations of the short-term consequences of a hypothetical explosion for some assumed parameters. The methodology has been described in sufficient detail so that an interested reader can extend the analysis to other sets of parameters.

The leading causes of casualties following a nuclear explosion are:

- thermal (heat) radiation and resulting large-scale firestorms that could cause burns and other severe injuries;
- shock waves and accompanying high-speed winds that could crush people or throw them around;
- prompt radiation and radioactive fallout that could cause radiation sickness.

Based on the data from Hiroshima, this report estimates the number of casualties from these different sources of injuries. Depending on the population density in the part of the city that is targeted, the numberod deaths would range between 160,000 to 866,000 for a 15 kiloton explosion — approximately the same destructive power as the weapon dropped on Hiroshima in 1945. A 150 kiloton weapon — typical of more modern hydrogen bombs — could cause somewhere between 736,000 and 8,660,000 deaths. These estimates do not include the long-term effects like cancers that would afflict thousands of people in the following years, or genetic mutations that could affect future generations.

Citizens in New Delhi protesting after India conducted five nuclear test explosions in May 1998.

Chapter 1

The Effects of Nuclear Weapons

The series of nuclear tests conducted by India and Pakistan in May 1998 give particular relevance to an examination of what nuclear weapons mean in a South Asian context. The purpose of this report is to describe the physical effects of a nuclear explosion, thereby informing people of the real dangers posed by nuclear weapons. These effects are so different from any other physical process that most people experience that it is useful to consider, as a case study, these effects on a hypothetical "target" that is familiar. Therefore, as an example, we consider the Indian city of Bombay[2] as a target and describe the effects of a 15 kiloton explosion, the same size as the bomb used on Hiroshima. The consequences of such an explosion over any other large, densely populated South Asian city, such as Lahore or Dhaka, would be similar.

The bomb dropped on Hiroshima by the United States on 6 August 1945 destroyed a considerable portion of the city and caused about 150,000 deaths. Among the survivors, thousands have been suffering from various illnesses caused by exposure to radiation. The consequences of even a small nuclear explosion are so horrendous that it should be clear to anyone that nuclear weapons are genocidal in their very nature and should have no place in civilized society.

The other goal of this report is to describe how an interested reader can use the necessary methodology to do similar calculations for other towns or cities (or other targets) after obtaining all the required information like area, population densities, etc. This work is drawn, in part, on lectures and textbooks, especially References I and II, on the general effects of nuclear weapons. Some earlier studies on the effects of a hypothetical nuclear explosion or nuclear war in South Asia are described in [III], [IV] and [V].

The first part of the report is a technical description of the effects of a general nuclear explosion. Despite a few mathematical equations, this part should be comprehensible to a lay reader. Section 1.1 contains a brief description of nuclear weapons. In Section 1.2, we describe the different prompt effects following a nuclear explosion and in Section 1.3 we describe the delayed effects. The second part of the report is the case study of Bombay. In Sections 2.1 to 2.4, we describe the effects of blast, firestorms, prompt radiation and radioactive fallout resulting from a hypothetical 15 kiloton explosion over Bombay. Population data for Bombay is summarized in Section 2.5. We describe three models of calculating casualties in Section 2.6 and the casualty estimates resulting from each model.

[2] Recently, the city's official name was changed from Bombay to Mumbai, the original name in the local language. We will,however, use Bombay for familiarity and ease of recognition.

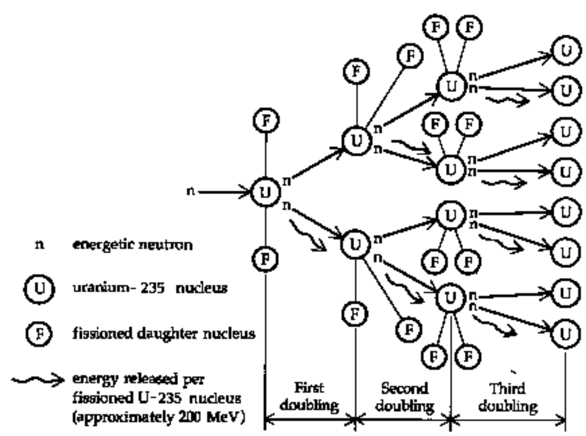
1.1 DESCRIPTION OF NUCLEAR WEAPONS

Any explosion involves the release of a large amount of energy in a very short interval of time. In chemical explosions, the energy arises from chemical reactions; these involve rearrangements of the constituent atoms, which in the case of modern explosives are usually carbon, hydrogen and nitrogen. The energies released in a chemical reaction, therefore, are proportional to the chemical binding energies of the atoms. In a nuclear explosion, on the other hand, the energy is produced by redistribution of protons and neutrons among the interacting nuclei. Thus, the energy released in a nuclear reaction is proportional to nuclear binding energies, which are much larger than chemical binding energies. This difference in energy released is why nuclear weapons are so immensely destructive relative to chemical explosives.

The redistribution of nuclei is observed to happen in one of two ways: a heavy nucleus can split into two lighter nuclei or two light nuclei can combine to form a heavier nucleus. The former is called fission, and the latter, fusion. These different processes form the basis of the fission weapon and the fusion weapon, also known as the atom bomb and the hydrogen bomb, respectively.

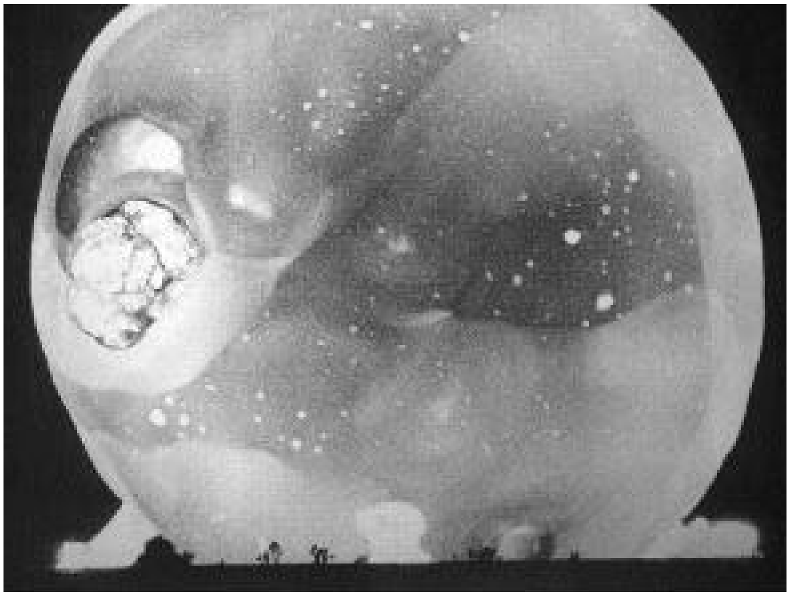
Fission of a heavy nucleus can be spontaneous or induced by the absorption of a neutron. During fission, when the heavy nucleus splits into two lighter nuclei, extra neutrons are released. Under some circumstances, these neutrons could be absorbed by other heavy nuclei, in turn causing these nuclei to split and so on, thus leading to a chain reaction. Very few materials can undergo a chain reaction; among these are the isotopes uranium-235 and plutonium-239. The minimum mass of fissile material that is needed for a chain reaction to proceed is called the critical mass.

Fusion can happen only at very high temperatures; for this reason, all fusion weapons designed so far start with a "primary fission trigger.” The elements used in fusion weapons are isotopes of hydrogen — deuterium and tritium. It is the fusion reaction between deuterium and tritium that provides the main source of fusion energy in such weapons. Since these two elements are gases at ordinary temperatures, they are inconvenient to use in weapons. Fusion weapons typically use lithium-6 deuteride, a solid compound, which undergoes a series of reactions with neutrons from the primary fission reaction to release energy.



The chain reaction principle.

The details of the design and construction of nuclear weapons are beyond the scope of this report. It is sufficient to note that an important purpose of these designs is to bring together a larger-than-critical mass of fissile material and to ensure that this mass stays together for a sufficiently long period so that a large number of nuclei undergo fission. The interested reader can learn more about designs of nuclear weapons from [VI], [VII] and [VIII].



A nuclear fireball at the US Nevada Test Site dwarfs trees it will soon consume. (Photo: US Department of Energy).

The energy released when a nuclear weapon explodes is called the yield. The yield is usually measured in kilotons or megatons of TNT equivalent, i.e., as much energy as thousands or millions of tons of chemical high explosive. One ton of TNT releases 4.2 billion joules of energy upon detonation. The total amount of explosives used during the 1995 bombing of the Federal Building in Oklahoma City, USA, has been estimated to be around 2.2 tons. Besides extensive damage to the building, the explosion in Oklahoma City also killed 168 people and injured more than 500 others. The weapons used in Hiroshima and Nagasaki had yields of 15 and 22 kilotons respectively, nearly ten thousand times the amount of explosive used in Oklahoma City. Thermonuclear weapons, currently possessed by several countries, could have yields of hundreds or thousands of kilotons.

Most of the energy released is initially in the form of high energy x-rays. Since air molecules are not transparent to x-rays, the energy does not propagate freely and is absorbed. Absorption raises the temperature of the region surrounding the explosion point to millions of degrees[3] and a fireball is formed. The fireball expands outward at a tremendous rate. As it expands, the fireball cools down by emitting radiation. Within about 0.1 milliseconds after the explosion, the radius of the fireball is about 15 meters (m) and its temperature, about 300,000 degrees Celsius. The formation of the fireball is directly linked to many of the effects that we will study. In due course, the heated air combined with the products of the explosion and other debris rises to form a mushroom cloud — the symbol of the nuclear age.

The effects of nuclear weapons can be categorized into prompt effects and delayed effects.

1.2 PROMPT EFFECTS

In the first few seconds after the explosion, there are three effects directly related to the fireball — blast or shock, thermal radiation and prompt nuclear radiation. In addition, there are effects caused by the electromagnetic pulse produced by the interaction of charged particles generated by gamma rays with the earth's magnetic field. While the effects of this pulse are by no means negligible, they are relatively less important when studying the social and human costs of a nuclear explosion.

3 See Appendix 4.1 for an estimate of the temperature.

1.2.1 BLAST

> *Ah, that instant! I felt as though I had been struck on the back with some - thing like a big hammer, and thrown into boiling oil…. I seem to have been blown a good way to the north, and I felt as though the directions were all changed around.*
>
> *— A junior-college girl in Hiroshima [X]*

Before the expansion of the fireball stops, the shell of air that has been compressed and accelerated outward by the fireball's explosive expansion separates from the fireball and propagates outward as a shock wave. When this primary shock wave strikes the ground or water, a secondary shock wave is generated by reflection. The two waves propagate outward along the ground or water, forming a single reinforced shock wave called the Mach front. The amount by which the pressure in the shock wave exceeds atmospheric pressure, which, under normal conditions is 14.7 pounds per square inch (psi)[4], is indicative of the power of the blast and is termed the overpressure. The overpressure of the Mach front is roughly twice that of either the primary or secondary shock wave.

The first mechanical effect of the shock wave on any person or object in its path is a forceful blow from the instantaneous pressure jump in the front. This is followed immediately by the crushing effect of blast overpressure and a high velocity wind. These effects decrease gradually with time until the pressure reaches atmospheric pressure (i.e., zero overpressure). After this, there is a slight negative overpressure (i.e., a suction phase), along with a reversed blast wind [XI, p. 4]. Very close to the point of explosion, the overpressure can reach several thousands of psi. For the purposes of comparison, the overpressure in a pressure cooker is of the order of 1-15 psi. The velocity of the winds accompanying the explosion for different levels of overpressure is listed in Table 1. As can be seen from it, the winds that accompany even a low overpressure have velocities that are associated with hurricanes and can cause significant damage by themselves.

TABLE 1 — OVERPRESSUREAND WIND VELOCITY

Peak Static Overpressure (pounds per square inch)	Maxium Wind Velocity (miles per hour)
200	2,078
100	1,777
50	934
20	502
10	294
5	163
2	70

Besides the crushing effects and the wind, a third cause of damage due to blast, besides "static" overpressure and the wind, are "missiles," i.e., physical objects propelled outward by the explosion. Such missiles could result from debris or objects such as poles, cars, and so on, in the path of the blast wave. The velocities of such missiles could be substantial and can be faster than the blast wave itself [XI, p. 7]. In comparison to the rate at which the blast wave loses its energy with distance from the point of explosion, missiles lose their energy at a lower rate. Hence, in principle, missiles could carry energy from the explosion out to greater distances than the blast, though only in the direction in which they are travelling.

For a given explosion, the strength of the shock wave, measured by overpressure, at a given location depends on the distance from the explosion as well as its height above the Earth's

4 A mixture of units (SI/British/CGS) have been used.A table of conversion factors in provided in the Appendix 4.7.

surface. The general relationship between blast overpressure and distance is complicated and one has to resort to scaling laws and graphical means to perform calculations. From geometric or dimensional considerations, two explosions can be expected to give identical blast waves at distances that are proportional to the cube root of the respective energy releases [XI, pp. 107-115]. Thus, one could derive scaled distances that equal the actual distances divided by the cube root of the yield.[5] The distance could be either the height of burst or the distance at which a given overpressure is achieved. These scaled quantities allow the translation of overpressures from a reference explosion with given yield and height of burst to another explosion. It is typical to use a 1 kiloton explosion as a reference explosion.

Above: Unreinforced brick house before a nuclear explosion at the Nevada Test Site.
Below: Unreinforced brick house experiencing 5psi overpressure from a nuclear explosion at the Nevada Test Site.
(Photo: US Federal Emergency Management Agency)

The isobars (lines of constant overpressure) for a reference 1 kiloton explosion at different heights of burst are displayed in Figures 3.1, 3.2 and 3.3 (from Ref. I) in Appendix 3.2. For the case of a weapon with yield *W*, one first calculates a scaled-height-of-burst and scaled-distance from ground zero.[6] As mentioned earlier, these are obtained by dividing the actual height of burst and distance by $W^{1/3}$. Then one looks at the corresponding overpressure on the chart. More often, what is needed is the distance at which a certain overpressure would be experienced. This is calculated by computing the scaled-height-of-burst, i.e., actual height of burst divided by $W^{1/3}$, finding the scaled-distance at which the required overpressure is experienced, and multiplying this scaled-distance by $W^{1/3}$ to obtain the actual distance. An example of this kind of calculation is provided in Section 2.1.

Due to the complicated nature of the blast and varying standards of construction, it is difficult to predict exact levels of damage at various levels of overpressure. Nevertheless, one can make rough estimates. Light housing, such as huts and shacks, can be destroyed at 5 psi or more. Wooden frame houses and brick houses can be destroyed at overpressures of 10 psi or more. Reinforced concrete buildings can withstand larger overpressures of up to 20 psi. A high rise building with a steel frame may require up to 100 psi for the frame to collapse. However, even in concrete and high-rise buildings, non-supporting interior and exterior walls may collapse at overpressures as low as 5 to 10 psi. Thus, these would effectively be uninhabitable, and people in the building at the time of the explosion are likely to be killed or hurt by the debris. The damage characteristics corresponding to different overpressures are summarized in Table 2 (from [XII], p. 36)

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5 This assumes that the atmospheric density is a constant.If that were not the case, then one would have to multiply this scaled distance by the cube root of the density.

6 Ground zero,also known as hypocenter, is the point on the ground directly below the nuclear explosion.

The ruins of the Nagasaki Medical School Hospital. Of the estimated 1,800 staff in both the hospital and the college, 892 were killed instantly or died shortly afterwards.(Photo: U.S. Army)

The blast wave also crushes human bodies, damaging the lungs and circulatory systems. Lungs will be damaged by about 20 psi of overpressure. Eardrums rupture around the same level of overpressure. However, a more probable cause of death or injury to humans is the effects of the winds and missiles accompanying the shock wave. At 15-20 psi, the winds from an explosion can fling a person at several hundred km/hour. Near a glass window, at an overpressure of 5 psi, there could be more than 400 pieces of glass per square foot of surface (each weighing about 5 g on the average), flying at speeds of 200 km/hour or more [XIII]. These can cause many injuries — some 80 to 90% of the non-fatal wounds in the 1996 bombing at Khobar Towers in Saudi Arabia were caused by glass fragments [XIV].

TABLE 2 — DAMAGECHARACTERISTICS FORSPECIFIC OVERPRESSURES

Damage	Overpressure (in psi)
Light Housing destroyed	5
Brick Housing/commercial buildings destroyed	10
Reinforced concrete structures destroyed	20
Severe lung damage/eardrum rupture in humans	20-30
Death of humans	40-100
Shallow buried structures destroyed	45-280

An important difference between the blast effects of a nuclear weapon and an ordinary chemical explosive is that the shock wave for a nuclear weapon can be several feet in thickness. This could completely enclose a small structure simultaneously crushing it from all sides. Further, since it also takes much longer for the wave to pass through any structure, it subjects the structure to overpressure for a longer period of time.

Besides the effects of the blast wave, if the explosion occurs at low altitudes or on the surface of the Earth, it will also set off ground tremors similar to that of an earthquake. This will also affect the stability of buildings.

1.2.2 HEAT & LIGHT

> *I asked Dr. Koyama what his findings had been in patients with eye injuries.*
> *"Those who watched the plane had their eye grounds burned," he replied. "The flash of light apparently went through their pupils and left them with a blind area in the central portion of their visual fields."*
> *"Most of the eye-ground burns are third degree, so cure is impossible."*
> — *Michihiko Hachiya* **[XV]**

Since nothing travels faster than light, the first effect experienced by persons or objects exposed directly to the fireball is an intense flash of light and heat, comparable to that from "a thousand suns." Unlike chemical explosions, a large fraction of the energy in nuclear explosions is released as thermal, i.e., ultraviolet, visible and infrared radiation, primarily because of the tremendously high temperature of the fireball (see Appendix 4.1). This radiation is so intense that it leads to phenomena hitherto unobserved outside the laboratory. For example, the ground exposed to this radiation becomes so hot that sand explodes like popcorn (see Table 3). In Hiroshima, ceramic tiles within 600 m and granite stone out to about 1 km of ground zero melted. The corresponding radii for the larger Nagasaki bomb were 1 km and 1600 m respectively [XVI]. Polished granite surfaces roughened and flaked due to unequal expansion of the various constituents of the rock.

The fraction of the yield that is released as thermal radiation is known as the thermal partition factor (f); it is typically about one third for explosions high in the atmosphere ("air bursts"). For explosions close to the surface of the Earth, f is lower, about one fifth, due to the effects of dust and water vapor.

The thermal radiation pulse from a nuclear fireball has a characteristic "spike plus a hump" shape. The drop in intensity after the first pulse is due to the temporary masking of the fireball by various absorbing atomic and molecular species created as a result of the pulse of ionizing radiation emitted initially.

Like all electromagnetic radiation, the intensity of thermal radiation from an explosion falls off as the square of the distance from the source, in this case, the point of explosion. However, due to absorption and scattering by atoms and molecules in the atmosphere, the radiation is further attenuated, i.e., its intensity is decreased. An empirically determined factor, the transmittance , defined to be the fraction of the radiation that is transmitted, is introduced to account for this attenuation.

The attenuation of thermal radiation increases with the amount of dust and water vapor in the air. This factor is usually taken into account by measuring the visibility. The visibility on a given day is defined to be the longest distance at which one can see a large, dark object, such as a tree, at the horizon. On a clear day, the visibility could be 20-30 km. A cloudy or foggy day would have a much lower visibility. On a clear day, for the distances that are of interest (neither too close to the point of explosion nor too far), a typical value for the transmittance is 0.7.

The light and heat fluence (flux) at a distance R from the point of explosion is given by the product of the energy released (yield), the thermal partition fraction and the transmittance of the medium, divided by the surface area of a sphere of radius *R*. Expressing this in calories per square centimeter (cal/cm^2), and replacing *R* by *D*, the ground range, (i.e., ignoring the height of explosion, which is usually a good approximation), the fluence at a given point is given by the expression:

Equation (I.1)

$$Q\left(\frac{cal}{cm^2}\right) = \frac{7.9\, fW\tau}{D^2}$$

In this equation, *W* is the yield in kilotons, *D* is the ground-range in kilometers, *f* is the thermal partition factor, and is the transmittance of the medium. As mentioned earlier, *f* is about one third for airbursts.

Due to this radiant exposure, a nuclear explosion can set off fires for many miles. Buildings with inflammable material in them could catch fire. Clothes that are exposed to the radiation, for example those worn by people in the open, would burst into flames. The photographs of clothing patterns etched on the skins of people at Hiroshima and Nagasaki are graphic testimony to the intensity of this effect. The effects of thermal radiation on different surfaces at different exposure levels are summarized in Table 3.

Burns sustained by humans whose skin is exposed to thermal radiation are classified into primary and secondary thermal burns. Primary burns are those caused by the direct action of rays emanating from the fireball upon the human body; these are also called flash burns. Secondary burns are caused indirectly from fires set off by the explosion. These are similar to the ones more commonly experienced. Primary burns, on the other hand, are largely specific to a nuclear explosion. Indeed, medical studies into flash burns were initiated only after the attacks on Hiroshima and Nagasaki [XVII, p.118].

TABLE 3 — SOME THERMAL EFFECTS

Type of Material	Effect on Material	$Q(cal/cm^2)$
Painted aircraft	Skin of the aircraft blisters	30
Human skin	Third degree burns	10
Human skin	Second degree burns	6
Cotton shirt (khaki colored)	Ignites	21
Black rubber	Ignites	20
Siliceous sand	Explodes (popcorns)	20
Fine or course grass	Ignites	8-9
Deciduous leaves	Ignites	6
Paper	Ignites	4-10

Woman with severly burned back, Hiroshima, August 7, 1945. (Photo:Masahoshi Onuka, Hiroshima-Nagasaki Publishing Committee)

Primary and secondary burns can be important causes of deaths in the immediate aftermath of a nuclear explosion. In Hiroshima and Nagasaki it was estimated that 90-100% of people who were within 1 km of ground zero and unshielded from the fireball died within a week. Similarly, the mortality rates at an early stage among those exposed at distances of 1.5 to 2 km were about 14% for the shielded and about 83% for the unshielded.

The distance at which the over-pressure due to a weapon of yield W reaches some fixed value *P* scales as $W^{1/3}$. On the other hand, the distance at which the thermal fluence due to a weapon of yield *W* reaches some fixed value *Q* scales as $W^{1/2}$. Therefore, the range at which thermal effects cause damage increases faster with the yield than the range at which blast effects cause damage. Consequently, thermal effects become more important for large yield weapons.

TABLE 4 — MEDICAL EFFECTSOF BURNS

Level of Burns	Medical Effect
First	Mildest form of burn. Immediate pain followed by redness of affected area. Will heal without scar formation.
Second	Upper and intermediate layers of skin killed. Blisters and swelling develop, accompanied by persistent pain. Extensive burns require specialized treatment in sterile conditions. Healing over several weeks, leaving scarring.
Third	Full thickness of skin and some underlying tissue is charred. Skin is red or charred. Severe pain from edges of burns. Burns over 2 inches in diameter will heal only after extended specialized treat-ment including skin grafting. Untreated victim may die of shock if over 20% of the body is affected.

1.2.3 NUCLEAR RADIATION

The nuclear reactions that cause the explosion also create harmful nuclear radiation — gamma rays and neutrons. Initial radiation is defined, somewhat arbitrarily, as the radiation arriving at any given point during the first minute after an explosion [XIX , p. 246]. Both gamma rays and neutrons are harmful to the body, though they differ in the details of their interaction with cells and tissues. In general, a radiation dose[7] of about 400 rads will be lethal to 50% or more of the exposed population. However, even 225 rads would kill some persons, particularly the young, the old, those with pre-existing diseases and those with blast or burn injuries [XX]. Most of the people within about 1 km of ground zero at Hiroshima and Nagasaki, who were not killed by the

> *Survivors began to notice in themselves and others a strange form of illness. It consisted of nausea, vomiting, and loss of appetite; diarrhea with large amounts of blood in the stools; fever and weakness; purple spots on various parts of the body from bleeding into the skin…inflammation and ulceration of the mouth, throat and gums…bleeding from the mouth, gums, throat, rectum, and urinary tract…loss of hair from the scalp and other parts of the body…extremely low white blood cell counts when those were taken…and in many cases a progressive course until death.*
>
> — *Robert Jay Lifton* **[XVIII]**

effects of blast and/or burns, died of radiation sickness within 3-7 weeks [XVII, pp. 135-148]. Among the people who died before December 1945, within four months of the bombing when acute radiation sickness subsided, about 20% are estimated to have died of radiation sickness [XVI].

Table 5 lists the prevalence of symptoms and signs within 1000 meters of ground zero in Hiroshima [XXI, p. 79]. At this distance, the air dose has been estimated to be 447 rads.

Neutrons: On the average, a one kiloton explosion produces about 3.6 $\times 10^{23}$ neutrons. These are absorbed by air, especially by nitrogen molecules leading to a sharp decrease in the neutron intensity with distance.[9] Elastic and inelastic collisions with different molecules also slow the neutrons down.

TABLE 5 — PREVALENCE OFSYMPTOMS IN HIROSHIMA

Symptoms	Approximate percentage of people exposed
Hemmorhage	40
Bloody diarrhea	10
Diarrhea[8]	50
Epilation	68
Oropharyngeal lesions	56
Necrotic gingivitis	10
Purpura	49
Vomiting	35
Nausea	35
Anorexia	47
Fever	35
Malaise	48

7 See Appendix 4.3 for definitions of radiation units and a more detailed description of the effects of radiation on the human body.

8 The count for diarrhea includes that for bloody diarrhea.

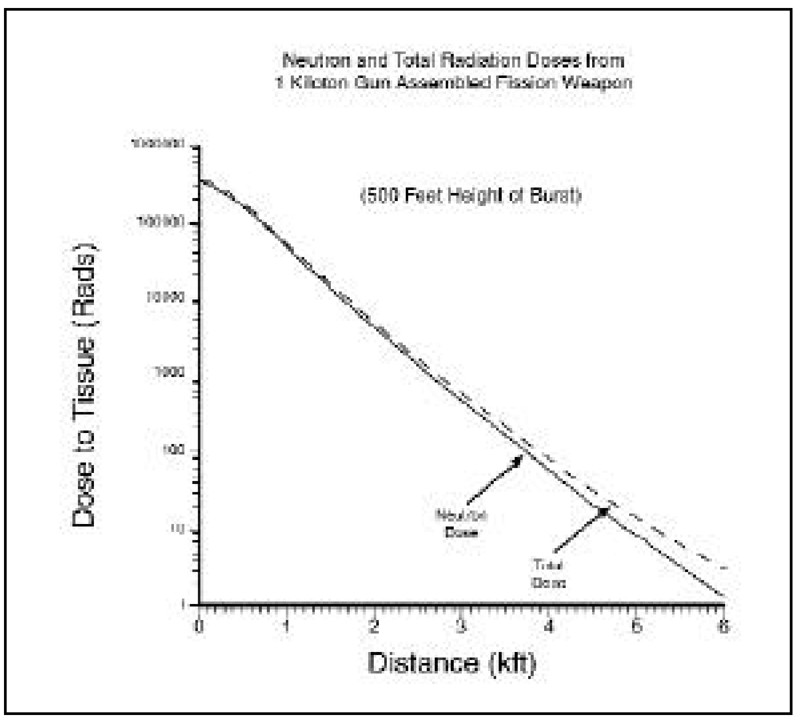
9 More precisely, the intensity falls off exponentially with distance, with a distance scale of approximately 250 m [I, pp.333-347]

Radiation victim.This 21-year-old man was in a wooden building 1 kilometer (.6 mile) from the hypocenter in Hiroshima.His back,right elbow, and abdomen were slashed. On August 18,while receiving treatment, his hair started falling out. Twelve days later, on August 29, his gums bled and purple spots of hypodermal bleeding appeared.After hospitalization on August 30, bleeding did not stop,and purpuric spots spread over his face and upper body. He died September 3, two hours after this photo was taken. (Photo: U.S. Army)

Gamma Rays: Gamma rays are about as numerous, carry about the same amount of energy and have about the same mean free path in air and water as neutrons. Gamma rays, however, are released both during the explosion as well as during subsequent decays. Due to the expansion of the fireball, the latter gamma rays travel through air that is considerably less dense. Thus, there are fewer molecules of nitrogen and other constituents of the atmosphere to absorb or scatter them. This effect allows the gamma rays to travel out to greater distances. Thus, victims could be exposed to large gamma ray doses for a significantly larger radius than those exposed to equally large neutron doses. The greater lethal radius of gamma rays is prominent for higher yield weapons. If the yield is less than 100 kilotons, gamma rays and neutron give comparable radiation doses.

For yields below 100 kilotons, the total amount of nuclear radiation released by a weapon is directly proportional to the yield. The radiation released also depends on the kind of weapon. For example, an enhanced radiation weapon (popularly known as a neutron bomb) releases significantly more radiation than a gun-type fission weapon. Since analytical formulae for the variation of the intensity of radiation with distance are complicated, they are usually represented graphically. Figure 1 shows the dose of neutron and gamma radiation

Figure 1: Prompt neutron and total (neutron + gamma) radiation dosages from a 1-kiloton gun-type fission weapon;figure taken from [I].



from a 1 kiloton gun-type fission weapon exploded at a height of 500 feet above the ground. The dosage for a weapon of yield *W* is the dosage for a 1 kiloton weapon multiplied by the yield *W*.

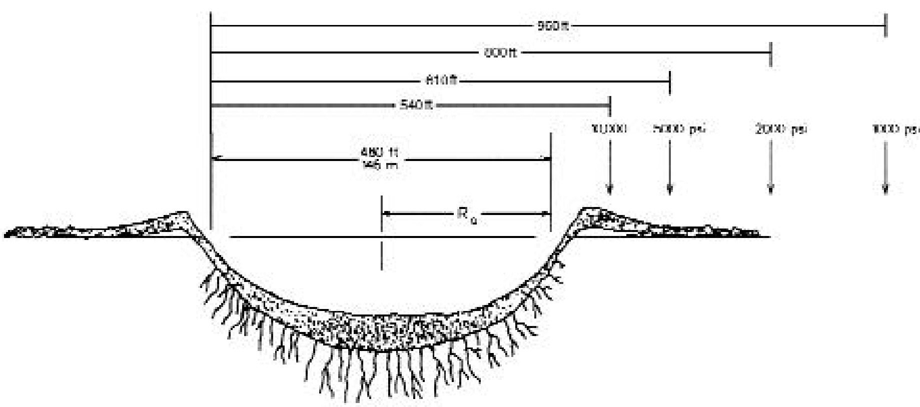
1.2.4 CRATERING

If the height of the explosion is low enough, the fireball touches the earth's surface. When this happens, a crater is formed as a result of the vaporization of the soil and other materials, and the removal of dirt and other materials by the blast wave and winds accompanying the explosion. Some of the material that is removed falls back into the crater, but most of it is deposited around the edge of the crater or scattered beyond the crater.

Sedan Crater was created by a 104 kilton explosion on July 6, 1962.(Photo: US Department of Energy)

The size of the crater depends on the yield and height of explosion as well as the composition of the soil. For a 1 kiloton explosion at the surface (i.e., height is zero), the apparent radius[10] of the crater in dry soil or dry soft rock is approximately 60 feet and the apparent depth is about 30 feet. The dimensions of a crater resulting from a surface burst[11] of yield *W* kilotons are related to those for a 1 kiloton weapon by the scaling factor $W^{0.3}$. The dimensions of a crater associated with a 100 kiloton surface burst is pictured below [II]. For the purposes of comparison, it also shows the associated overpressures.

Figure 2: Crater dimensions following a 100-kiloton surface explosion;the depth of the crater is approximately 120 ft.



[10] Apparent radius is defined as the radius of the crater at ground level;due to loose debris and soil thrown around, the crater may extend to a distance beyond the apparent radius.See Figure 2.

[11] A surface burst is defined as one where the scaled height of the explosion is 5 feet or less.

1.3 DELAYED EFFECTS

Delayed effects are those that occur after the formation of the fireball and the initial shock wave. In the case of the use of one or a few low-yield weapons, the most important delayed effects are large-scale fires and radioactive fallout. In the case of a major nuclear exchange with hundreds or thousands of bombs exploding, there could be climatic effects as well as the loss of parts of the ozone layer [XXII].

Hundreds of people sought refuge in the Asano Sentei Park. They had refuge from the approaching flames for a little while, but gradually, the fire forced them nearer and nearer the river, until at length everyone was crowded onto the steep bank over - looking the river….

Even though the river is more than one hundred meters wide along the border of the park, balls of fire were being carried through the air from the opposite shore and soon the pine trees in the park were afire. The poor people faced a fiery death if they stayed in the park and a watery grave if they jumped in the river. I could hear shouting and crying, and in a few minutes they began to fall like top - pling dominoes in the river at this deep, treacherous point and most were drowned.

— Michihiko Hachiya, "Hiroshima Diary"

1.3.1 FIRESTORMS

As a result of the intense flash of heat and light (described in section 1.2.2), several fires will be started. Within the course of a few minutes after the explosion, depending on the weather, these fires could start to coalesce and form super-fires. The devastation caused by such firestorms can hardly be overstated.

Many of the casualties at Hiroshima were a consequence of such a firestorm that developed approximately 20 minutes after the explosion and covered a roughly circular area with a radius of about 2 km. This corresponded approximately to the range at which thermal fluence of 7-10 calories/cm^2 or more was deposited by the fireball. One study estimates that about 60% of the people who died in Hiroshima were victims of burns, either from direct flash burns or from fires [XVI]. The physical conditions that would prevail in a superfire caused by a nuclear explosion resemble those within the regions ravaged by the fire storms that developed in Hamburg, Dresden and Tokyo following incendiary attacks by the allied forces during the Second World War. People hiding in basement shelters were overcome by asphyxiation due to carbon monoxide and the extreme temperatures generated. In spite of the fact that Hamburg was not subjected to blast or radiation effects during the July 1943 firebombing attack, the area destroyed during the attack was about 12 km^2 (about the same area as the conflagration in Hiroshima). The death toll was estimated to be between 50,000 and 60,000 [XXIII]. Likewise, the fire storm in Tokyo resulting from the air attack of 9 March 1945 is believed to have killed nearly 84,000 people [XXIV]. With increased urbanization, the effects of such firestorms could be more severe.

Charred boy 700 meters from the hypocenter, Nagasaki, Japan. (Photo: Yosuke Yamahata, Hiroshima-Nagasaki Publishing Committee)

Initially, due to non-homogeneous burning zones, these fires are accompanied by shifting winds. Once the fires have coalesced, due to the large area of the fire, the fire zone acts as a huge air pump, sucking in air from the surrounding areas and driving heated air upwards. This pumping action creates high velocity winds directed into the fire zone; in Hiroshima, the maximum velocity of these winds in the surrounding regions was estimated to be between 30 and 50 miles/hour (mph) [XXV]. Pilots involved in dropping incendiary bombs in Tokyo reported how the air above the fire storm was so violent that B-29 airplanes at 6000 feet were turned completely over, and the heat was so intense, even at that altitude, that the entire crew had to don oxygen masks [XXV]. These winds could bring in loose material, in many cases loosened by the effects of the blast, from surrounding areas, to add fuel to these fires. The temperature in the fire zone reaches several hundred degrees, making it almost impossible for anyone to survive. Further, the combination of hurricane force winds, thick smoke, destruction of water mains[12] and tanks, and debris from the blast blocking roads and access routes makes effective fire-fighting impossible [XXVI].

There are two ways of estimating the area that will be subject to such firestorms in a nuclear attack. The first is to assume that the region exposed to a thermal fluence of 10 cal/cm^2 or greater will be burnt. The second is to scale from the data on burning regions in Hiroshima. In this report, we will be using the former method in Section 2.1.2 to estimate the area of destruction from fires.

1.3.2 FALLOUT

When a bomb explodes at such a low altitude that the fireball touches or nearly touches the ground, a large amount of material can be vaporized, lifted into the fireball and carried aloft into the mushroom cloud. These then mix with the fireball's radioactive materials, which result from the raw materials used to manufacture the weapon, or their fission products, and result in a cloud of highly radioactive dust. Due to wind, this dust could travel large distances before ultimately falling back to the ground; this radioactive dust that falls down is called fallout. While these particles could be aloft for long periods of time, about 50-70% of radioactive nuclei return to the Earth within a day. This could be faster in case there is rain in the immediate aftermath of the explosion. Chances of rain depend on the moisture level of the air during the explosion. The effects of fallout persist for decades making the region uninhabitable for a long duration of time.

When the bomb exploded, I was twelve years old and I understood what was happening. I saw a very bright light all over Rongelap. In the afternoon the fallout came. In the evening I could not sleep, there was rash all over my body. The next morning I could not eat my food. I vomit, I could not eat.The rash was so itchy I could not bear. That day there was a plane that came to Rongelap to see the drinking waters. They said it was poison. They didn't stay even ten minutes. They didn't say anything to us so we just keep eating our food. Two days later the military men came to evacuate all the peoples to Kwajalein. They said not to take anything, just what we have on. Not the money or nothing.When we got to Kwajalein our hair fell out and burns started to show.

— Roko Laninvelik, recalling the "Bravo" nuclear test explosion of 1 March 1954 **[XXVII]**

In Hiroshima, a mild wind was blowing towards the west at the time of the explosion, and a "black rain" (rain with fallout) fell from the north to the west of ground zero. The black rain was sticky, and people at that time thought that oil had been dropped. A black spotty pattern remained wherever a raindrop struck. In Nagasaki, a 11 km/h wind was blowing at the time of

[12] During incendiary attacks on Hamburg,water mains were broken in 847 places [XXIV].

the explosion and the rain with the fallout came down near the Nishiyama water reservoir about 3 km east of ground zero. Radiochemical analysis of the soil in the area revealed strontium-90, cesium-137 and plutonium-239[13] among others [XVII, p.78]. The effects of a radiation dose due to fallout are similar to those of initial radiation. These have been described in Appendix 4.3. However, unlike initial radiation, fallout could be ingested along with food or water over a long period of time and this would add significantly to the lethality of the radiation [XIX, p. 274]. Table 6 shows a list of some fission products, their half-lives, production rates, and the chief health effects that result from exposure to these [LIV, LV].

TABLE 6 — SOME FISSION PRODUCTS,HALF-LIVES, PRODUCTIONRATES AND HEALTH EFFECTS

Fission Product	Half-life	Yield per Kiloton (kCi/kt)	Chief Health Effects
Strontium 90 — Sr^{90}	28 years	0.1	Bone cancer, leukemia
Iodine 131 — I^{131}	8 days	125.0	Thyroid cancer
Cesium 137 — Cs^{137}	30 years	0.16	Radiogenic cancers
Plutonium 239 — Pu^{239}	24,100 years	approximately 2.5 kg/explosion	Highly toxic, lung cancer

Fallout is significant for surface or low air bursts. A rough formula for the maximum height of burst for which there will be appreciable local fallout is given by:

$$H \approx 180W^{0.4} \quad \text{Equation (I.2)}$$

where H is measured in feet and W in kilotons. The heights estimated by this formula have errors of the order of ±30%. Furthermore, it must not be assumed that if the burst height exceeds the value from Eq. (I.2), then there will be absolutely no fallout, just that the amounts would be relatively low. For heights of burst below this value, there will be an appreciable amount of fallout, though it is difficult to predict exact amounts. Thus, for example, a 100 kiloton weapon exploded at a height lower than 1135 feet (or 346 m) will lead to appreciable local fallout. Including an error of 30%, this would go up to 1476 feet (or 450 m). In other words, unless the height of explosion is substantially greater than 1500 feet, there would be appreciable amounts of fallout from a 100 kiloton explosion.

A simple estimate (from [II]) of the quantity of fallout can be obtained by computing the amount of radioactive material produced during the explosion and assuming that a small fraction, 1-10%, comes back as fallout. A 1 kiloton explosion involves the fission of approximately 60 grams of uranium or plutonium. The residues undergo approximately 10^{21} disintegrations per second. If these are spread uniformly over an area of 1 km^2, the dose rate at a height of 1 m

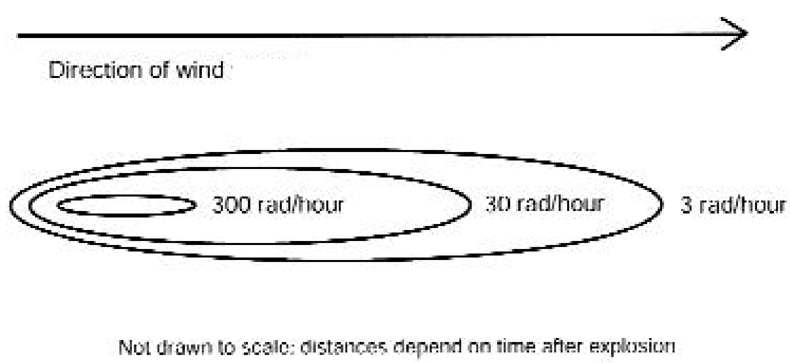
[13] The Pu^{239} results from un-fissioned material from the weapon or from neutron absorption by U^{238}.

above the ground[14] at one minute is approximately 1000,000 rads/hour; after an hour it reduces to approximately 7500 rads/hour. If 1% (10%) of the initial residues comes back as fallout over the same area, the dosage will be 75 (750) rads/hour. For a weapon with yield W kilotons, the dosage should be multiplied by W. A dose rate of about 400 rads would lead to death in approximately half the exposed population.

The actual dose rate experienced is modified by two factors: the decay of the radioactivity with time and the spreading of fallout with distance. Since fallout is a complex mixture of fission products and weapons residue, the radioactivity from fallout does not follow an exponential decay law. While each individual radioactive constituent does follow such a decay law, the aggregate decays as $t^{-1.2}$ for the first six months. In this formula, t is measured in hours. Subsequently, the decay is more rapid [XIX, p. 270]. Thus, at any given point, if the initial dose rate an hour after all fallout has been deposited is 100 rads/hour, then after 2 hours the dose rate is approximately 40 rads/hour and the dose rate after 6 hours is about 11 rads/hour. The total dose received by a person is found by integrating the dose rate over the time he or she is exposed to it.

It is difficult to predict detailed contours for fallout. Several sophisticated models have been developed, but since atmospheric conditions are highly variable, the most reliable estimates are of the total land area affected. Most models predict elliptical shaped contours (shown below) of equal dosage. In reality, these contours will be more irregular. There would also be local "hot spots" which experience increased amounts of fallout due to local weather conditions. The following figure shows equal dose fallout contours heuristically.

Figure 3 — Iso-Dose Contours for Radioactive Fallout



The length of these elliptical contours along the direction of the wind, and widths perpendicular to the direction of the wind, are given in Table 7 [I, p. 240]. These correspond to a wind velocity of 15 mph and a fission weapon with yield W kilotons. Since fusion reactions do not lead to appreciable fallout, in hydrogen bombs practically all the fallout comes from only the fission reactions. Hence the dosage should be multiplied by the fraction of the yield derived from fission.

[14] Approximately half the height of an average human being.

TABLE 7— DOWNWIND DISTANCE AND MAXIMUM WIDTH OF ISO-DOSE CONTOURS FOR FISSION WEAPON WITH YIELD W AND WINDVELOCITY OF 15 MPH

Dose (rads/hour)	Length (miles)	Width (miles)	Area (square miles)
3000	0.95 $W^{0.45}$	0.00076 $W^{0.86}$	0.0057 $W^{1.31}$
1000	1.8 $W^{0.45}$	0.036 $W^{0.78}$	0.051 $W^{1.23}$
300	4.5 $W^{0.45}$	0.13 $W^{0.66}$	0.46 $W^{1.11}$
100	8.9 $W^{0.45}$	0.38 $W^{0.60}$	2.7 $W^{1.05}$
30	16 $W^{0.45}$	0.76 $W^{0.56}$	9.6 $W^{1.01}$
10	24 $W^{0.45}$	1.4 $W^{0.53}$	26 $W^{0.95}$
3	30 $W^{0.45}$	2.2 $W^{0.50}$	52 $W^{0.95}$
1	40 $W^{0.45}$	3.3 $W^{0.48}$	103 $W^{0.93}$

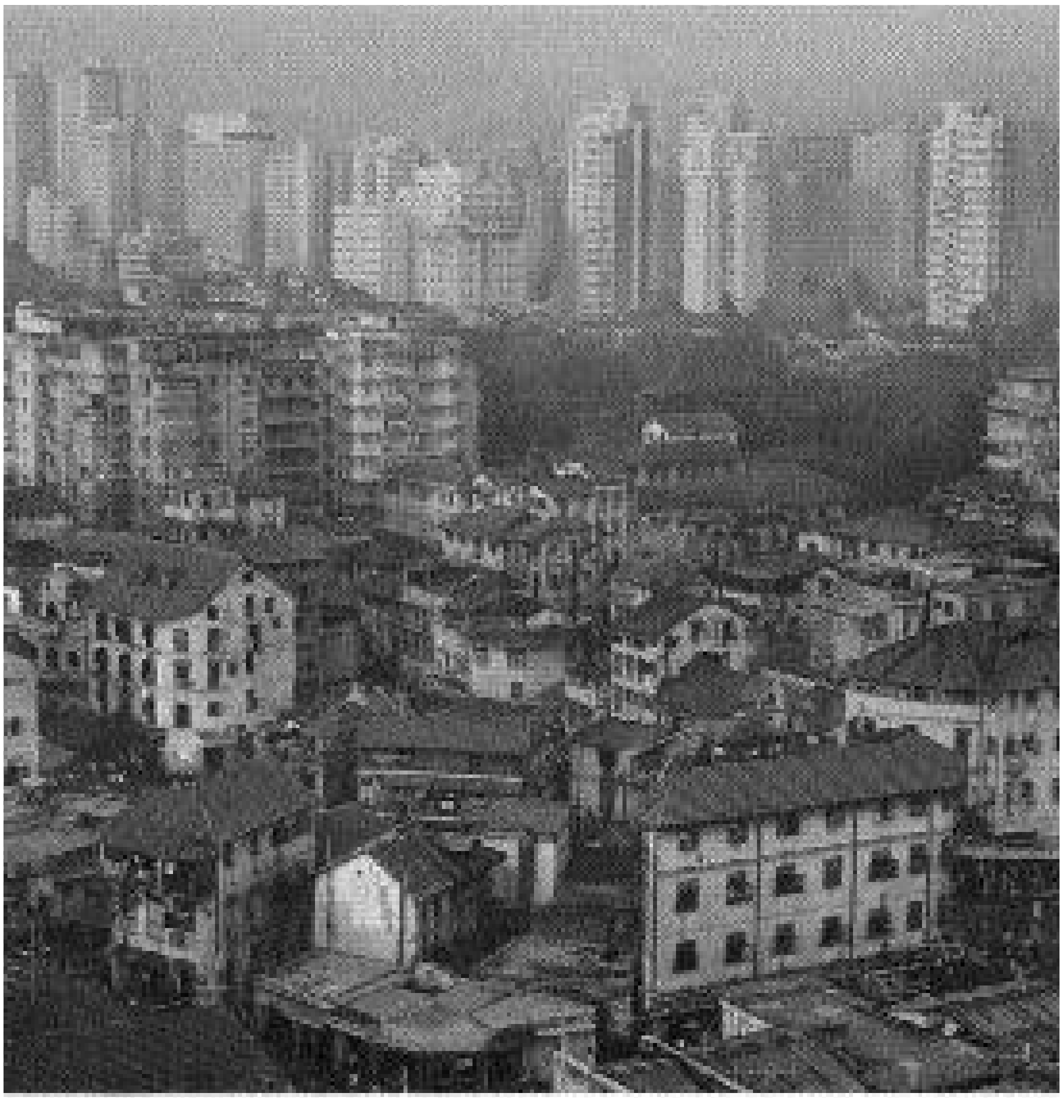
As mentioned earlier, these numbers are for an average wind velocity (with the average being calculated for altitudes ranging from zero to the top of the mushroom cloud) of 15 mph. If the wind velocity is greater, the downwind distances will increase since the fallout particles can travel further. For wind velocities between 15 mph and 45 mph, the downwind distance is to be scaled by a factor

$$F = 1 + \frac{(windspeed - 15)}{60}$$

For winds below 15 mph, but above 8 mph, the downwind distance should be scaled by

$$F = 1 + \frac{(windspeed - 15)}{30}$$

The change in the maximum width has been found to be negligible. These scaling factors are approximate and are based on empirical data as well as computer models.



A view of Bombay highrises.

Chapter 2

A Hypothetical Case Study

To better appreciate the physical effects of a nuclear explosion, we consider the effects of a hypothetical nuclear explosion over Bombay. As the largest commercial centre in India with a huge population of about 10 million, the city does present itself as a possible target of attack. It is India's largest financial and industrial centre, is a big naval and commercial port and has a large atomic research centre nearby. The question of how likely it is that Bombay will be subject to such an explosion is not easy to predict and is certainly beyond the scope of this study. The purpose of this exercise is not to speculate on the probability of Bombay being attacked (or, for that matter, who the aggressor might be). Instead, the aim is to further understanding of the consequences that result from a nuclear explosion.

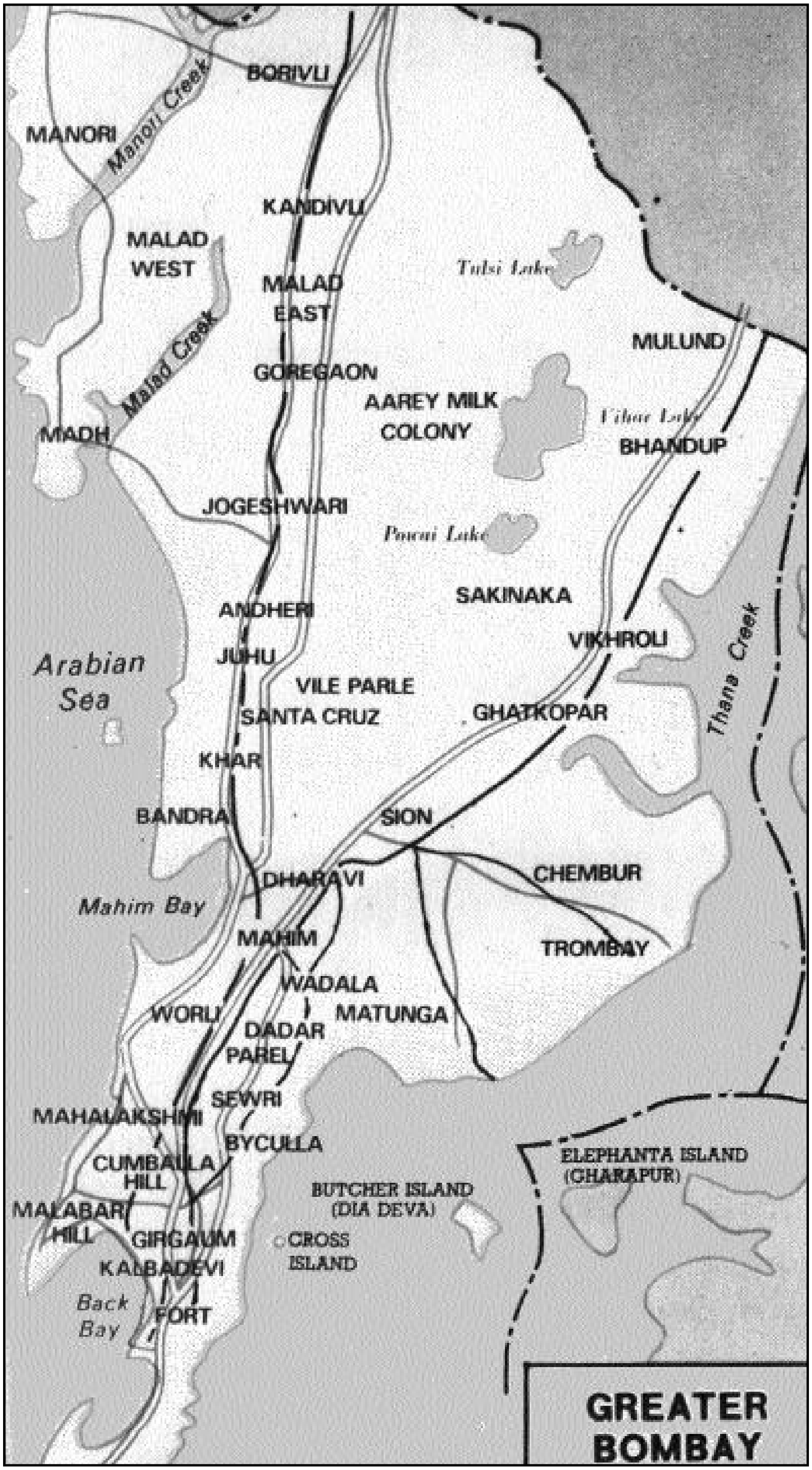
In exploding a nuclear weapon over a city, the attacker has the choice of weapon (yield), location of the point of attack, the height of burst and the time of the attack. Apart from general expectations, it may not be possible, especially if the attack is carried out during war, to choose a suitable weather pattern.

In order to continue with this study, we will make some assumptions about these choices. We will assume that the attack happens on a clear day and the weapon used is a fission bomb with a yield of 15 kilotons to be exploded at a height of 600 m. The choice of yield and altitude correspond closely to the weapon that was dropped on Hiroshima. This choice of height of burst will maximize the radius over which an overpressure of 10 psi or more occurs — about 1.1 km. Relative to a surface burst, this height of burst will result in over twice the area being subject to an overpressure of 10 psi.

Bombay's Marine Drive

With such a small yield, it is not possible to destroy the whole city. The precise location of the attack determines which region of Bombay is destroyed. For example, an attack in the Fort area, centered around

Figure 4 — Rough Map of Bombay



Hutatma Chowk, could destroy large parts of the financial district as well as the secretariat. Likewise, an attack centered around the Chembur area or the area near Parel and Sewri would result in the destruction of a large number of industries. In the latter case, the attack could also lead to damage to the Mazagaon docks, whereas in the former case, it could lead to some damage to the Bhabha Atomic Research Centre complex, India's largest nuclear research facility, in Trombay. There are also very densely populated areas like Dharavi; if the explosion is targeted in this area, the number of casualties will be very large. Figure 4 shows a rough map of Bombay to help visualize the layout of the city.

Let us now go through the steps to calculate the damage resulting from the different physical effects described earlier.

2.1 EFFECTS OF BLAST

As explained in Section 1.2.1, a blast overpressure of 10 psi would damage a large fraction of brick housing as well as commercial buildings that do not use reinforced concrete. Structures made of reinforced concrete would be damaged at blast overpressures of about 20 psi or above. Let us calculate the range at which these overpressures are experienced for the assumed parameters of the attack — a yield of 15 kilotons exploding at a height of 600 m. We first calculate the scaled height of burst corresponding to this choice of yield and altitude.

$$\textit{scaled height of burst} = \frac{600}{(15)^{1/3}} = 243.3\,m = 798\,ft$$

From Figure 4.2 in Appendix 4.2, the scaled ranges for 10 and 20 psi overpressures are 1450 ft and 450 ft respectively. Multiplying by the cube root of the yield, we get the actual ranges corresponding to these overpressures.

$$R(10\,psi) = 1450 \times (15)^{1/3} = 3576\,ft = 1090\,m$$
$$R(20\,psi) = 450 \times (15)^{1/3} = 1110\,ft = 338\,m$$

Thus, a circle of radius of 1.1 km will be more or less completely destroyed. In addition, there could be additional damage due to missiles, physical objects propelled outward by the shock wave, at considerably greater distances. But this would not be uniform; hence, we do not include these effects in calculating the range of destruction due to blast effects. If the attack were centered around Hutatma Chowk, then most of the buildings from Colaba to Victoria Terminus, along the entire width of the island, will be destroyed.

This scene from Hiroshima shows the utter devastation caused by an atomic blast.

The quality of construction, obviously, has a great effect on the amount of damage inflicted in an attack. If buildings are constructed to withstand higher stress loads, such as those designed to survive earthquakes, they are less likely to be damaged. Thus, in Nagasaki, all reinforced concrete buildings within approximately 500 m were destroyed, except those designed to be earthquake resistant.[15] In Hiroshima, some of the buildings, even those that were made of reinforced concrete but were deficient in some other details of construction — poorly designed reinforcing rod splices, weak concrete, etc. — collapsed and suffered structural damage up to 2000 ft of ground zero [XXV, p. 199]. This corresponds to an overpressure of approximately 13 psi.

Many of the buildings in Bombay, especially older ones, are poorly constructed. Every year, several hundred buildings collapse *by themselves*, especially during the rainy season (see Table 8, derived from [XXVIII]). Many of these would not even withstand the nominal 10-20 psi values used here. We will, however, continue to use these values in order to keep our estimates conservative.

TABLE 8 — BUILDINGCOLLAPSES IN BOMBAY

Year	Number of Collapsed Buildings
1984-85	382
1985-86	395
1986-87	391
1987-88	346
1988-89	406
1989-90	274
1990-91	319
1991-92	254
1992-93	242
1993-94	236
1994-95	257

2.2 EFFECTS OF FIRESTORMS

As mentioned in Section 1.3.1, at Hiroshima, the region burnt by firestorms had a radius of about 2 km. This corresponded to the range at which the fireball deposits a thermal fluence of 7 cal/cm^2 or more. In order to be conservative in our estimates, we will assume that the region subject to a thermal fluence of 10 cal/cm^2 is the one damaged by firestorms. We use equation (I.1) to estimate the range at which the fireball deposits a thermal fluence of 10 cal/cm^2 and 6 cal/cm^2; the latter corresponds to the range at which people exposed directly would develop second degree burns.

These radii are: R(10 cal/cm^2) = 1.66 km and R(6 cal/cm^2) = 2.14 km.

In the case of Hiroshima, the area destroyed by the firestorm was small enough so that most of the people who had not been trapped under collapsed buildings or otherwise incapacitated were able to escape before the environment in the fire area became lethal. Furthermore, since Japanese cities had already been subject to incendiary attacks, there had been extensive prepara-

15 As a check,one could calculate R (20 psi) for a 20 kiloton weapon exploded at the same scaled height of burst, which corresponds closely to the attack on Nagasaki;such a calculation yields R(20 psi) = 496 m,which corresponds closely to the observed damage radius for reinforced concrete buildings.

Struck by the force of thermal blast, almost all houses in Hiroshima were instantly demolished and thrown into flames. This photo of the explosion center was taken 25 minutes after the explosion.

tions for such an eventuality in the case of Hiroshima. In fact, on the very day of the atomic explosion, more than eight thousand schoolgirls were working outdoors in the central city helping to raze houses in order to clear firebreaks against the possibility of an allied incendiary attack [XXIX, p. 713]. In the case of Bombay, or any overcrowded city, the chances of people escaping a firestorm would be very low.

There are differences between the cities burnt during the Second World War and Bombay. Many of the houses in Germany and Japan were built of wood; these often had two or more floors, thus resulting in a large fuel content per unit area. In Bombay, houses in slum areas, where about 40% of the city's population lives, are often built with inflammable materials. However, these are low-rise structures. In richer areas, houses are often constructed with brick or concrete, which are less inflammable. However, such houses typically have greater amounts of furniture, clothes, carpets, and so on, all of which are likely to burn. This implies that while all regions have adequate inflammable material to sustain a fire, the fuel content per unit area may be low. Thus, the temperatures in these fires may not be as high as the temperatures reached in the firestorms that ravaged Dresden, Hamburg or Tokyo.

There are, however, factors that lead to a greater probability of small explosions in the fire zone, leading to greater chances of people being hurt, in addition to being burnt. For example, many of the houses would contain gas cylinders that are known to explode when exposed to fires. In addition, when compared to the cities of Japan and Germany during the Second World War, today's cities also have a much greater concentration of vehicles like cars, scooters, and buses that use petroleum-based fuels, as well as the corresponding storage and dispensing facilities for such fuels. These are highly inflammable and explosive.[16]

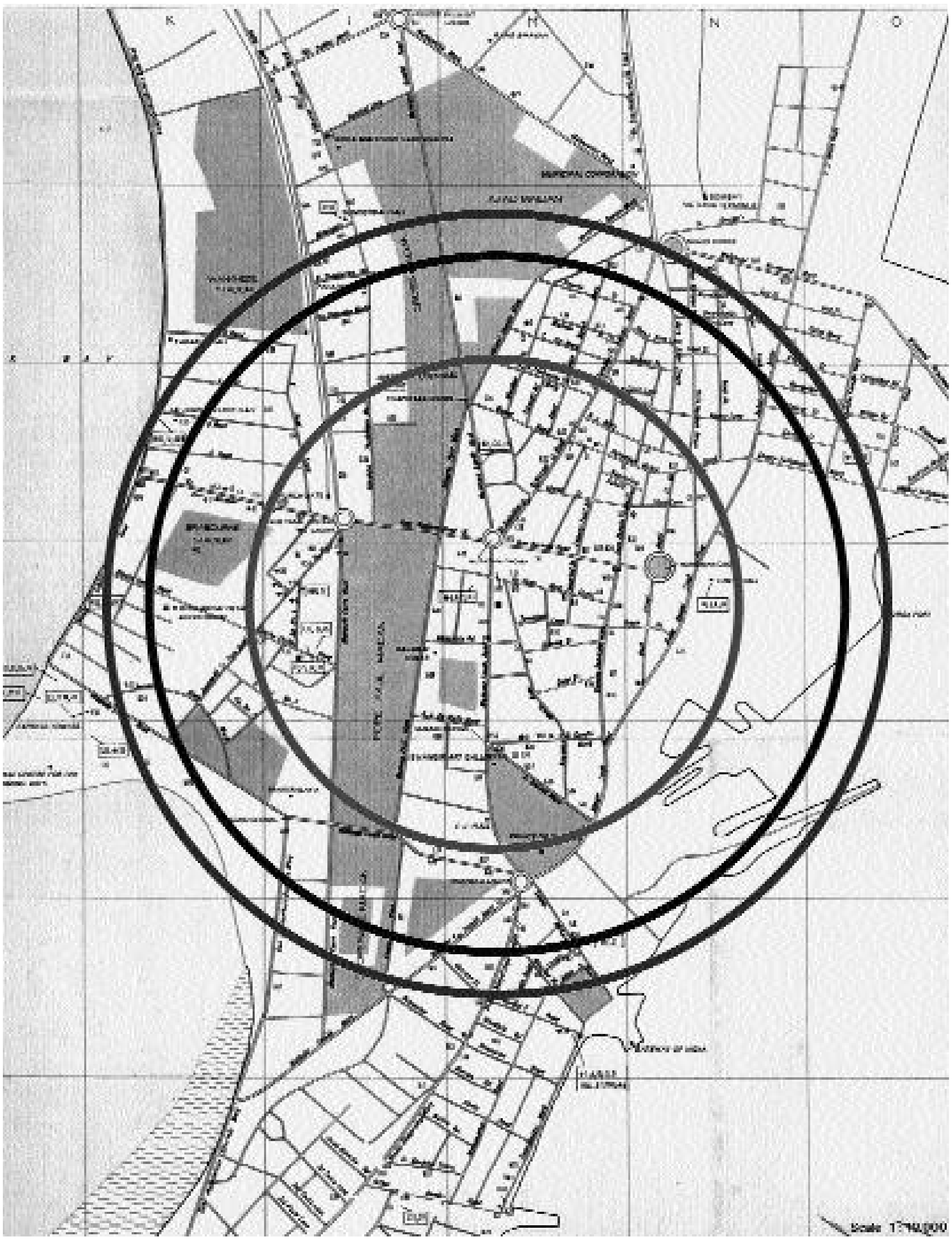
2.3 EFFECTS OF PROMPT RADIATION

Using Figure 1, we estimate the range at which the prompt radiation level is above 400 rads. This radius is approximately 4000 ft which is much smaller than the region that receives a thermal fluence of 10 cal/cm^2. Therefore, it is safe to assume that anyone subject to lethal levels of radiation will also be in the fire zone. The figure of 4000 ft is an overestimate because Figure 1 corresponds to a height of burst of only 500 ft. But, because even this figure is considerably smaller than the radius of the fire zone, there is little point to doing the complicated calculation needed to convert it to a different height of burst.

The ranges for the three effects discussed above are shown in Figure 5.

[16] An example of the effects of the burning of such vehicles is the fire in the Uphaar theater in Delhi in 1997. According to Delhi police and fire brigade sources,most of the victims died of asphyxiation when they were trapped in the thick smoke and intense heat generated by the burning of about 50 cars parked right below the Uphaar cinema hall.The fire was caused when an electric transformer burst.

Figure 5 — Map of Bombay Showing Effects of 15 Kt Explosion
The innermost circle encloses the high radiation zone, the middle circle encloses the zone damaged by blast and the outermost circle is the firestorm zone.



2.4 EFFECTS OF FALLOUT

According to Equation (I.2), there will be appreciable local fallout if the height of burst is lower than the height given by $H \quad 180W^{0.4}$. Substituting W = 15 kilotons, we calculate the height below which there will be significant fallout to be 162 m. Even assuming a 30% error, this is only about 200 m. Since the assumed height of burst (600 m) is much greater than this value, the amount of fallout will be fairly small. Bombay, being close to the sea, has high levels of water vapour in the atmosphere. This could lead to water droplets condensing around radioactive particles and descending as rain, as was the case with Hiroshima and Nagasaki where black rain came down for several hours after the attack. We will, however, disregard this effect in calculating casualty rates in Section 2.7.

If, on the other hand, *we assume that the explosion happens at the surface,* the areas subject to different levels of fallout (based on formulae in Table 7) are given in Table 9. This assumes a wind velocity of 15 mph. Since the direction of wind is unknown, it is not possible to predict which areas will be subject to these levels of radioactivity. The regions subject to high levels of fallout, above approximately 300 rads/hour an hour after the explosion, will have high levels of radiation sickness and casualties. But, even people who live in areas subject to lower levels of radiation, unless they are immediately evacuated, will be victims of radiation sickness. Given the large population of Bombay and the likely damage to transportation infrastructure (train stations and tracks, roads, petrol stations, dockyards, airports etc.) evacuation of all inhabitants will be impossible.

TABLE 9 — AREAS SUBJECT TO FALLOUT FOR A SURFACE EXPLOSIONWITH A YIELDOF 15 KILOTONS

Dose (rads/hour)	Length (miles)	Width (miles)	Area (square miles)
3000	3.2	0.08	0.2
1000	6	0.3	1.4
300	15	0.8	9.4
100	30	1.9	44.8
30	54	3.5	148.5
10	81	5.9	375.4
3	101	8.5	674.4
1	135	12	1272.5

While fallout becomes important in the case of a surface explosion, when compared to an air burst, the areas affected by the blast and fire for a surface explosion will be smaller. Owing to the smaller value of the transmittance, the area exposed to the same levels of thermal fluence is roughly 60%; and the area subject to 10 psi overpressure is about 50% of the corresponding values for an air burst. However, because fallout contours are elongated in the direction of the wind, there will be little overlap between the regions damaged by blast or fires and the regions that experience a large fallout dose. This will have to be taken into account when estimating the numbers of casualties in Section 2.7.

2.5 POPULATION

According to the 1991 census, the population of Greater Bombay is 9,910,000; if Thane is also included, the population is 12,572,000 [XXX]. However, since the decadal growth rate for Bombay during the decade preceding this census was 20.21%, the numbers quoted above may understate the population significantly. Further, there is also some evidence that the 1991 census undercounted the population [XXXI].

The Corporation of Bombay lists the area of the city as 438 km^2. This leads to an average population density of about 23,000 people/km^2. However, there are regions where the population density exceeds 100,000 people per square kilometer. The official population density figures are listed in Table 10.

TABLE 10 — POPULATION DENSITY FIGURES FOR REGIONS WITHIN BOMBAY

Wards	Area in km^2	Density (1981 census) in persons/km^2	Density (1991 census) in persons/km^2
Colaba	10.46	16083	18628
Sanhurst Road	2.44	60374	48247
Marine Lines	1.77	152941	111428
Grant Road	7.21	61774	55693
Byculla	6.79	67115	60504
Parel	6.29	77221	66317
Matunga	12.60	26110	34182
Dadar/Plaza	7.37	60509	65465
Elphinstone	10.48	51244	49723
Bandra	6.58	35170	49054
Khar/Santacruz	12.98	36627	36668
Andheri (East)	23.59	22435	29359
Andheri (West)	23.64	16770	23270
Goregaon	21.22	13953	17235
Malad	42.45	8661	13262
Kandivalli	21.19	815	17378
Borivali	55.45	7017	10994
Kurla	13.30	32625	46360
Chembur	54.28	10423	15161
Ghatkopar	36.58	16387	13869
Bhandup	37.80	7860	15027
Mulund	15.42	13223	18687
All Wards	429.89	19173	23089

According to the census, the literacy rate is only 72%. Thus, there will be a significant number of people who may not be in a position to read any publications on emergency measures that may be available before or after the attack.

2.6 MODELS FOR ESTIMATING NUMBER OF CASUALTIES

There are three ways to estimate the number of casualties from a nuclear explosion. All of these are based on empirical data from Hiroshima when the casualties are expressed as a function of different variables — radius, overpressure, and thermal fluence, respectively.[17] The overpressure and thermal fluence models have different extrapolations to other yields. Since the first model only expresses the casualty rate as a function of radius and does not specify any particular physical mechanism for causing casualties, it is not possible to extrapolate that to other yields. In each case, we calculate the number of fatalities (or injuries) from the mortality rate (at different distances from the point of explosion) using the following formula.

$$Number\ of\ fatalities = \rho \sum p(r) \times A(r)$$

In this formula is the population density (assumed to be constant), (r) is the mortality rate at distance r from ground zero and $A(r)$ is the area of the region (circle or annulus) with that mortality rate.

The first method assumes that the mortality probabilities (i.e. percentages) at the same distance from the centre of explosion are the same as that in Hiroshima. The casualty rates in November 1945 are summarized in Table 11. [XVII, p. 348] It must be emphasized that there is considerable uncertainty in calculating casualty rates since the figures used for the exact population of Hiroshima at the time of the bombing are subject to debate.

Using the formula for casualty estimates and the mortality figures in Table 11 [XVII, p. 348], we obtain the total number of deaths to be 7.39 .

TABLE 11 — MORTALITY FIGURES IN HIROSHIMAIN NOVEMBER 1945

Distance (km) from ground zero	Mortality (November 1945)
0.0 - 0.5	96.5%
0.5 - 1.0	83.0%
1.0 - 1.5	51.6%
1.5 - 2.0	21.9%
2.0 - 2.5	4.9%
2.5 - 3.0	2.7%
3.0 - 4.0	2.5%
4.0 - 5.0	1.1%

[17] Being a larger city, the effects of the explosion over Hiroshima were more uniform than in Nagasaki;the mountains surrounding the city as well as the rivers running through it also complicate effects in the case of Nagasaki.

This method does not require one to calculate all the detailed effects of blast, fires, radioactive fallout, etc. Since this model does not distinguish between the different physical effects of a nuclear explosion and their consequences, it is not possible to extrapolate from this to explosions of a different magnitude or under different circumstances. Nevertheless, we include this method in order to show how different procedures for estimating casualty figures result in different, but comparable, estimates.

The second model has been put forward by the Office of Technology Assessment (OTA), USA [XXXII, p. 19]. It assumes that the primary cause of death and injury is the blast and winds associated with it. Therefore, according to this model, the mortality and injury rates can be correlated with the overpressure experienced in the region. This is summarized in Table 12.[18]

TABLE 12 — OTA MODEL FOR MORTALITY AND INJURY RATES

Overpressure (psi)	Fraction Dead	Fraction Injured
>12	98%	2%
5-12	50%	40%
2-5	5%	45%
1-2	0%	25%

Based on Figure 4.3 in Appendix 4.2, and following the procedure outlined in Section 1.2.1, we can determine the radii corresponding to these overpressures for the parameters assumed for the attack. These are: R(12 psi) = 1.02 km; R(5 psi) = 1.66 km; R(2 psi) = 3 km; and R(1 psi) = 4.67 km. The areas of the different zones are: A(>12 psi) = 3.3 km^2; A (5 - 12 psi) = 5.4 km^2; A(2 - 5 psi) = 19.6 km^2; A(1 - 2 psi) = 40.3 km^2. The number of deaths = 6.91 , where is the population density. The number of injured people = 21.12 .

The third model, which we call the superfires model, assumes that the primary cause of death and injuries are the firestorms that are started in the aftermath of a nuclear explosion [II, XXIII]. Therefore, the region that is subject to a thermal fluence of 10 cal/cm^2 is assumed to have a mortality rate close to 100%, and everyone in the region subject to thermal fluences between 6 and 10 cal/cm^2 is injured. From Section 2.2, we know that R(10 cal/cm^2) = 1.66 km[19] and R(6 cal/cm^2) = 2.14 km. Therefore, according to this model, there will be 8.66 deaths and 5.73 injured people; again, is the population density.

2.7 CASUALTY ESTIMATES FOR BOMBAY

As explained in Section 2.5, the average population density of Bombay is about 23,000 people/km^2. Therefore, the number of deaths according to the three models are 1.7 lakhs (1 lakh = 100,000), 1.6 lakhs, and 2.0 lakhs respectively. However, the more crowded parts of Bombay

18 As mentioned earlier, there is considerable uncertainty in casualty figures from the bombing of Hiroshima.This is reflected in the differences between the data in Table 11 and the figures used by the OTA.

19 For these chosen paramaters,R(10 cal/cm^2) = R(5 psi).This is a numerical coincidence. But,this implies that the third model predicts the same number of deaths as another popular model (one that we are not using),the so-called “cookie-cutter”model of casualties,which assumes that everyone within the circle of radius R(5 psi) is killed and everyone outside the radius survives.More precisely, the assumption is that the number of survivors within the circles of radius R(5 psi) is equal to the number of casualties outside this circle.

have population densities exceeding 100,000 people/km^2. Therefore, the number of deaths could easily be as high as 6.9 to 8.6 lakhs. Because a nuclear explosion and its effects are complicated physical phenomena, and because there are several effects happening around the same time, it is impossible to predict numbers of casualties or injuries with any reasonable accuracy. The numbers, derived from these three models, can only be rough estimates and should be treated that way. Nevertheless, it is clear that about 150,000 to 800,000 people will die within the first few months after the attack. In addition, somewhere between 130,000 to 2,100,000 people will be injured.

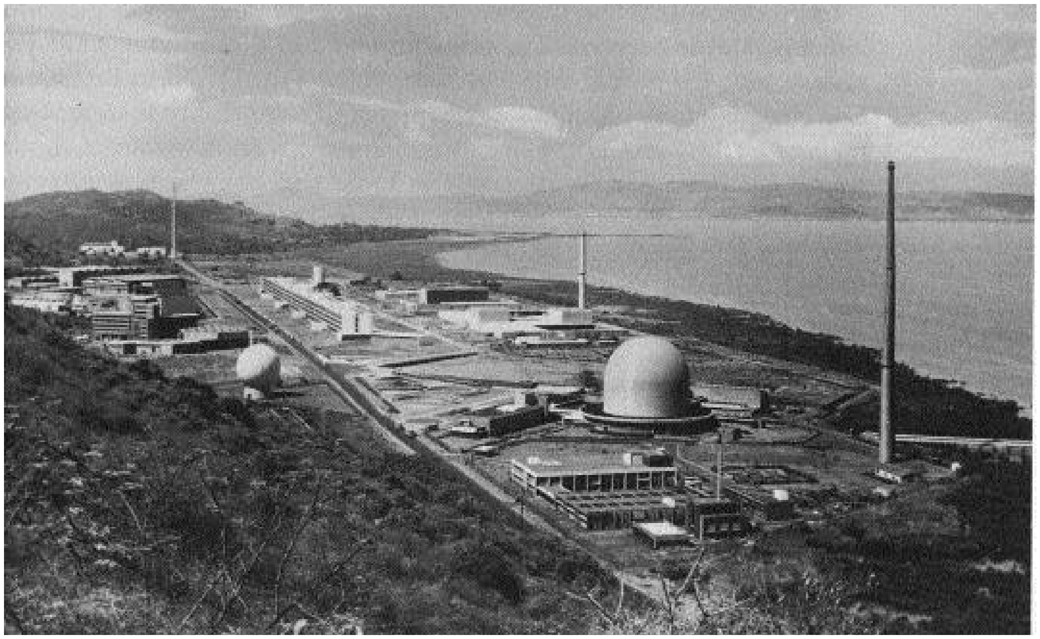
Just as a way of showing how these effects scale with a larger yield, we also calculate the casualty figures for a weapon with a yield of 150 kilotons, i.e., 10 times as large as the case we have been considering and typical of more modern hydrogen bombs. The numbers in this case are much larger and demonstrate how the fires caused by the explosion become much more important. Since Bombay is an island, fires may not spread to very large distances, except in specific directions. Hence the number of casualties may be somewhat smaller. Nevertheless we include the larger figure so that one may get a sense of the range of variation. This would be more typical of a large city like Delhi. We don't carry out this calculation for the first model because it cannot be extrapolated to other yields.

TABLE 13 — COMPARISONS OFCASUALTY ESTIMATES FOR DIFFERENT YIELDS

	density = 23000 & yield =15 kt	density = 100000 & yield = 15 kt	density = 23000 & yield = 150 kt	density = 100000 & yield = 150 kt
OTA Model	160,000	690,000	736,000	3,200,000
Superfire Model	200,000	866,000	2,000,000	8,660,000

In all these models, only the numbers of "prompt" casualties (i.e., those who are injured or die within a few weeks of the explosion) are estimated. There will certainly be many more that die of long-term effects, especially due to radiation-related causes. Among the survivors at Hiroshima, several hundreds died due to leukemia, thyroid cancer, breast cancer and lung cancer (for a study of incidence of lung cancer, see Ref. [XXXIII]). Studies involving survivors at Hiroshima and Nagasaki reveal that the mortality rates for all diseases, leukemia and malignancies other than leukemia, among people exposed to over 200 rads, were 1.16, 17.6 and 1.42 times higher when compared to a control group that had not been exposed to radiation [XVII, p. 238]. There would also be numerous non-fatal health effects such as growth of keloids, cataracts, malformations and other birth defects, mental retardation in fetuses or young children exposed to radiation, and so on.

In the case of a surface explosion (discussed in Section 2.4), the areas damaged by blast and fires are somewhat smaller, about 50% and 60% of the corresponding areas in the case of an air burst, respectively. However, there could be significant numbers of casualties resulting from fallout. As mentioned earlier, we assume that a radiation dose of 400 rads is lethal to 50% of the population. Further, we assume that everyone living within the region that receives 300 rads/hour receives this dose (implying that they stay for about 3 hours within this area). From Table 9, this area is 9.4 miles^2 or 24 km^2. This is a very conservative assumption given the damage to the transportation infrastructure. Despite making these assumptions, we cannot calculate the number of deaths unless we know the direction of winds. Since this is hard to predict, we could calculate a high estimate by assuming that the wind blows all the fallout to populated areas (with a population density of 23000 people/km^2) and a low estimate by assuming that the wind blows all the fallout to uninhabited regions, such as the sea. This would give us a plausible range for the


Bhabha Atomic Research Center, Trombay, India

casualty estimates in the case of a surface explosion. As mentioned in Section 2.4, there will be little overlap between the regions damaged by blast or fires and the regions that experience a large fallout. Hence, the casualty estimates from these separate effects must be added up. The high estimates for the number of casualties (N) are:

N = 0.5 x 160000 + 0.5 x 24 x 23000 = 356,000 (*OTA Model*)
N = 0.6 x 200000 + 0.5 x 24 x 23000 = 396,000 (*Superfires Model*)

The low estimates, which correspond to no short-term fallout deaths, are:

N = 0.5 x 160000 = 80,000 (*OTA Model*)
N = 0.6 x 200000 = 120,000 (*Superfires Model*)

2.8 DATA ON MEDICAL FACILITIES

Medical facilities that could possibly help the survivors are likely to be destroyed, or otherwise damaged, during the attack. The numbers of hospitals and physicians as a proportion of the population in Bombay is extremely limited to begin with. (See Table 14, [LIII]). Hence, it is extremely likely that the injured, estimated to be between 1.3 and 21 lakhs, will not find any medical treatment to help them survive.

TABLE 14 — RATIOS OF PHYSICIANS AND HOSPITAL BEDS TO POPULATIONS

	Physicians	Hospital Beds
India	1/2337	1/1324
Pakistan	1/2364	1/1706
USA	1/406	1/211
Japan	1/588	1/74

There are also a number of reasons to believe that the casualty numbers cited above would be an underestimate in a city like Bombay. First, the assumed population densities are lower than the actual density. Apart from reasons of undercounting and variations between regions, a substantial number of people come in every day from places as far away as Pune (four hours by train) to work in Bombay. The census does not take such commuters into account. An attack, if

These soldiers,atomic bomb victims in Hiroshima,are crowded into a makeshift tent put up to replace the Second Army hospital that had been blown away by the blast. (Photo: Yotsugi Kawahara)

if it is carried out by air, is likely to be during the day (in order to maximize visibility for bombing). Hence, many of these people will also be killed or injured. Second, casualties from fallout effects have not been included in the estimates. Since fallout, even if present only in small quantities, can spread out to large regions and cause local hot spots, this is potentially important. Third, there are a large numbers of industries in Bombay and its vicinity. For example, central Bombay is home to several mills. India's highest concentration of chemical industries is in the Trans-Thane creek area; this area has over 2,000 factories. These could cause additional fires, explosions, and spreading of toxic substances and consequently more deaths. The Union Carbide accident in Bhopal, which was responsible for an estimated 5,000-15,000 deaths and many more long-term, non-fatal health effects, is an example of the kinds of effects that are possible due to escape of toxic chemicals. The possibilities for chemical contamination are discussed in greater detail in Appendix 4.4. In addition to chemical industries, India's largest nuclear laboratory, the Bhabha Atomic Research Centre, is in Trombay, just outside Bombay. A nuclear explosion in the vicinity of the reactors (CIRUS or Dhruva) at the Centre or near the reprocessing plant or the facilities storing radioactive waste and/or spent fuel could lead to releases of large amounts of radioactivity in addition to the quantities resulting from the explosion itself. Such releases would increase the amounts of fallout significantly. The different levels of damage to reactors are discussed in Appendix 4.5. Last, conservative figures for blast damage and fire regions have been deliberately chosen. The actual areas are likely to be higher, implying a greater number of casualties.

Chapter 3

Conclusion

Nuclear weapons are, clearly, extremely destructive. As we have seen the key effects of a nuclear explosion are:

- Thermal (heat) radiation and resulting large-scale firestorms that could cause burns and other severe injuries
- Shock waves and accompanying high-speed winds could crush people or throw them around
- Prompt radiation as well as radioactive fallout that could cause radiation sickness as well as long-term consequences ranging from cancers to genetic mutations.

Based on the available population data, the historical experiences of Hiroshima and Nagasaki and different physical models, we have estimated short-term casualties from a hypothetical explosion over Bombay. For a 15 kiloton explosion, the number of deaths would range between 160,000 to 866,000. A 150 kiloton weapon could cause somewhere between 736,000 and 8,660,000 deaths. In addition, there would be several hundreds of thousands of people who would suffer from injuries or burns. Many of them may die without prompt medical aid, which is quite unlikely. These estimates are conservative and there are a number of reasons to expect that the actual numbers would be much higher. Further, these estimates do not include the long-term effects like cancers that would afflict thousands of people in the following years or genetic mutations that would affect future generations.

The immense scale of these effects, and that too resulting from just a single fission weapon with a low yield, should make it clear that the possible use of such weapons would lead to a major catastrophe. The only guarantee that such a tragedy would never occur is complete elimination of nuclear weapons, both from the region and from the world, and the means to manufacture them.

Appendices

4.1 ESTIMATION OF TEMPERATURE

In order to estimate the energy density, we perform the following crude calculation. The critical mass of plutonium, the material used in the weapon that destroyed Nagasaki, is about five kilograms (kg) when a reflector is used. Assuming a weapon with twice this mass of plutonium,[20] i.e., 10 kg, and assuming the density of plutonium to be 16 g/cc = 16,000 kg/m^3, the volume of the spherical fissile core of such a weapon is 0.000625 m^3. A single fission releases about 180 Mega electron volts (MeV) as explosive energy, which is released in the form of the kinetic energy of neutrons and fission products, as well as gamma rays. If the entire sphere were to completely undergo fission, it would release about 170 kilotons of TNT equivalent. In practice, only a few percent of the plutonium undergoes fission and so the actual energy released will be of the order of 10-20 kilotons. Assuming that the yield is 15 kilotons, the energy density in the core will be

$$\omega = \frac{15 \times 10^3 \, tons \times 4.2 \times 10^9 \, (J / tons)}{0.000625 m^3} \cong 10^{17} \, {}^{J}\!/_{m^3} .$$

The temperature T can be calculated by the following formula, which is valid if the escape of radiation during the explosion can be neglected: $\cong 10^{17} J/m^3 = C_V \; T + aT^4$ where is the energy density, C_V is the thermal coefficient, is the mass density of the explosive, and a is the Stefan Boltzmann constant. The first term is the thermal energy density in the mass of the warhead and the second term, the dominant one, is the energy density in the radiation field. Using $a = 7.6 \times 10^{-16} J/m^3K^4$, this translates to a temperature of about $10^8 K$ or about 100 million degrees. This is only an approximate estimate. The actual temperature is likely to be somewhat less — in the tens of millions of degrees. For comparison, a chemical explosion reaches a temperature of only about 5000 degrees.

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[20] The bomb dropped on Nagasaki used 6.2 kg of plutonium;about 20% of it underwent fission.

4.2 OVERPRESSURE GRAPHS

Figure 4.1 — Peak overpressures on the ground for a 1-kiloton burst (high-pressure range)

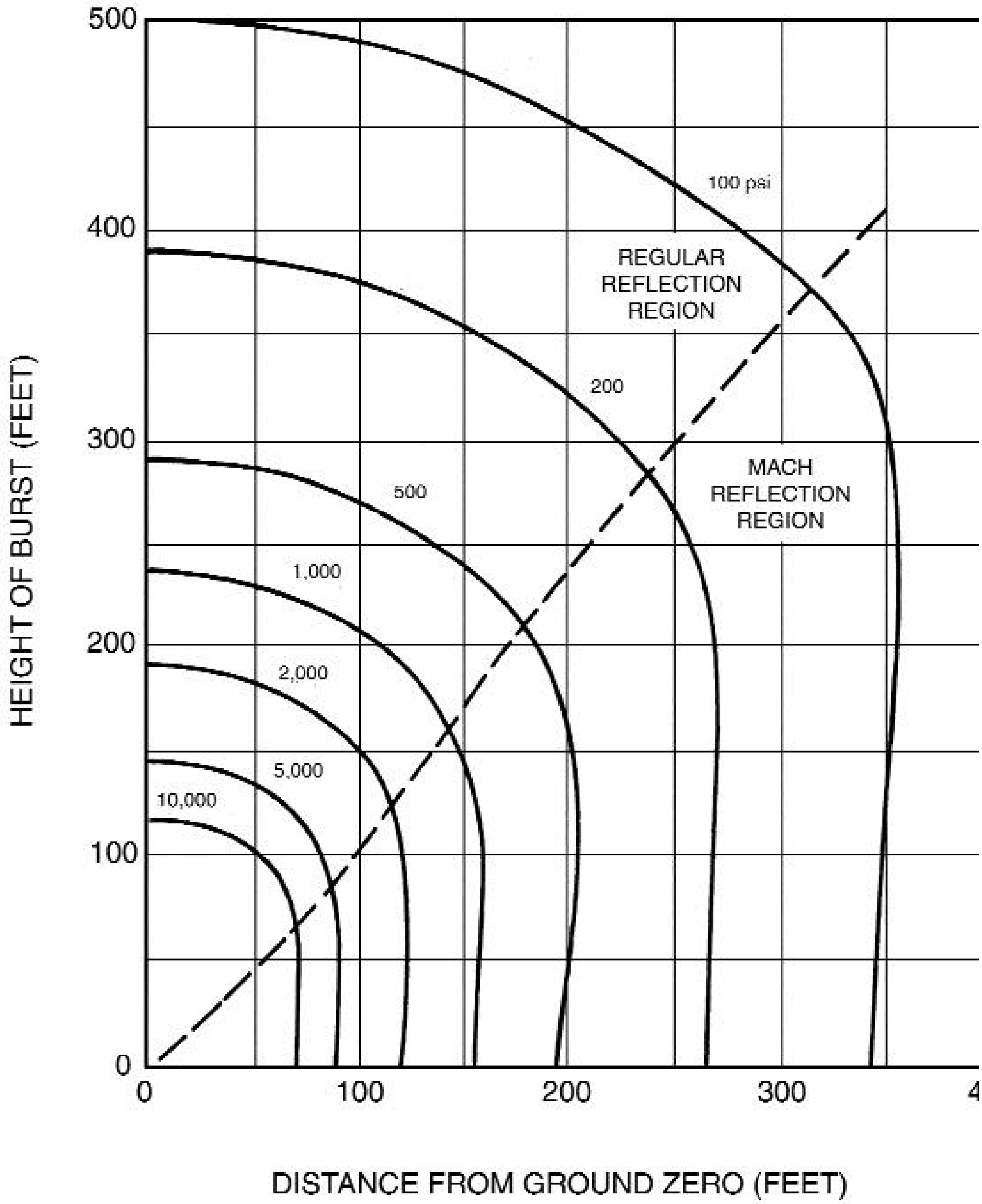


Figure 4.2 — Peak overpressures on the ground for a 1-kiloton burst (intermediate-pressure range).

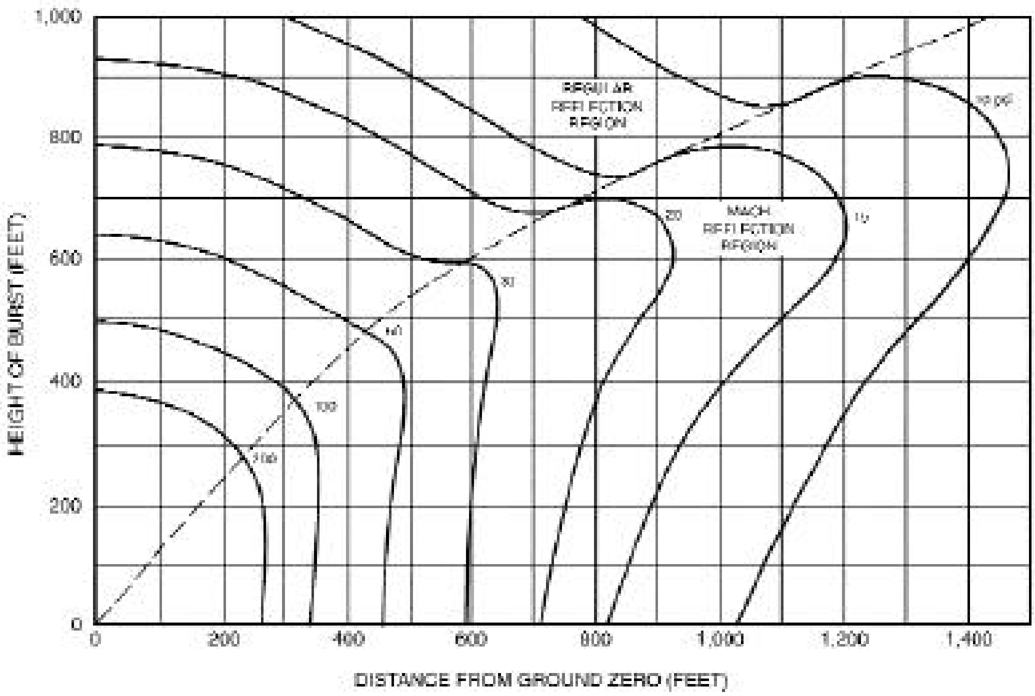
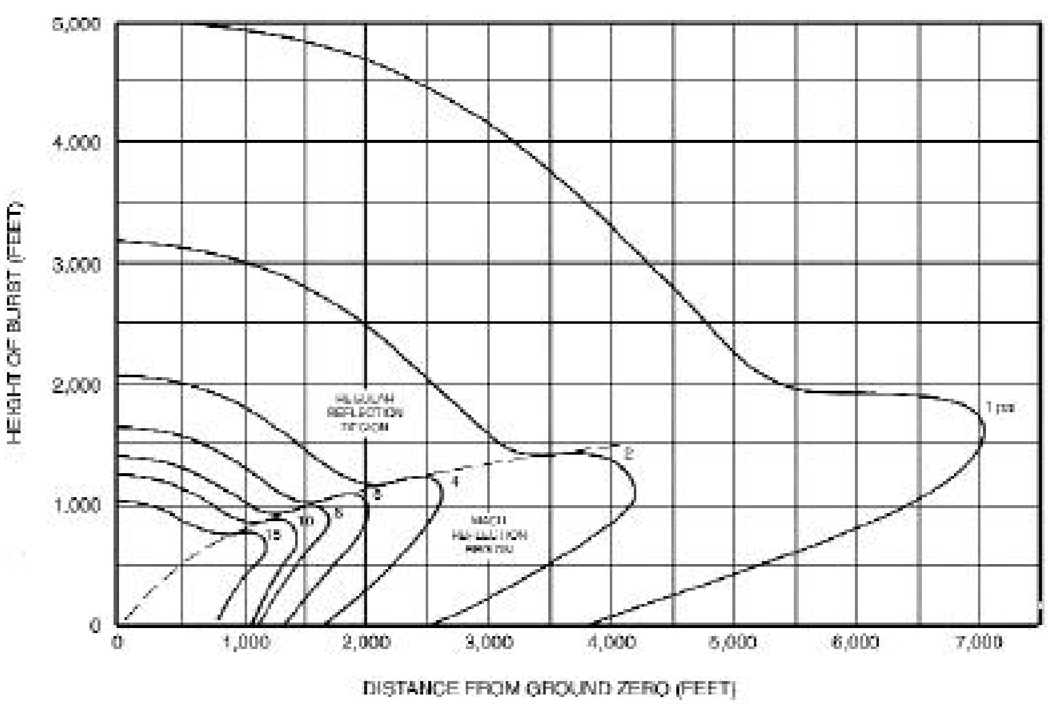


Figure 4.3 — Peak overpressures on the ground for a 1-kiloton burst (low-pressure range).



4.3 RADIATION EFFECTS

The fundamental physical mechanism that harms living beings when exposed to radiation is ionization — i.e., the splitting of an electrically neutral atom into positive and negative ions. Radiation that leads to ionization comes in four chief varieties: alpha particles, beta particles, photons (x-rays and gamma rays) and neutrons. The primary radiation coming from the nuclear explosion is in the form of neutrons and gamma rays. However, radiation doses from fallout as well as induced radioactivity could contain alpha and beta particles as well.

These different sources of ionizing radiation have different levels of penetration. The dead layer of the skin stops alpha particles. Beta particles could pierce the skin and cause skin burns, but they do not enter deep into the body. X-rays, gamma rays and neutrons can cause radiation doses to internal organs.

4.3.1 RADIATION UNITS

Before going on to the effects of radiation, it is useful to consider the different units involved in measuring radiation. In the SI system, a radioactive sample decaying at the rate of 1 disintegration per second is defined as having an activity of 1 becquerel (Bq). A more traditional unit for activity, based on the rate of decay of one gram of radium-226, is the curie. One curie (Ci) is defined as the activity of a radionuclide decaying at the rate of 3.7×10^{10} disintegrations per second.

Since the effects of radiation on humans depend on the energy deposited in human tissue, radiation dose is defined in terms of this energy deposition. The SI unit for radiation dose is a gray, which corresponds to the deposition of one joule of energy per kilogram of tissue. The older unit is a rad, which equals 0.01 gray (Gy).

Gamma radiation measurements often use the traditional unit, the roentgen. It is defined as the quantity of radiation (x-rays or gamma rays) that produces a total charge of 2.58×10^{-4} coulombs of charge (due to ionization) in 1 kg of dry air. It is approximately equal to 0.93 rads for soft body tissue. In bone, however, the energy deposition due to a roentgen of radiation is significantly larger; hence, the number of rads is much larger than the number of roentgens [XXXIV, pp. 566-567].

In living organisms, the amount of damage caused to a cell per unit of energy depends on both the cell type and the kind of radiation. Hence a weighting factor (empirically determined) is introduced. Using a reference value of 1 for gamma rays, the weighting factor is 1 for beta rays, 5 to 20 (depending on energy) for neutrons and 20 for alpha particles. The equivalent dose for biological damage is defined as the absorbed dose times the weighting factor. In SI units, where the absorbed dose is measured in grays, the dose equivalent is measured in sieverts (Sv). The older unit is the rem (for radiation equivalent in man) which corresponds to measuring the absorbed dose in rads.

4.3.2 HEALTH EFFECTS

The health effects of a radiation dose depend on several factors including the rate of exposure and the population that is exposed to it. For example, old people, sick people, women and children would all exhibit different levels and kinds of response. Further, the effects also depend on which part of the body is exposed. This particularly important in the case of internal exposures, which results from the ingestion or inhalation of radiation sources, and their subsequent accumulation in different parts of the body [XIX, p. 298].

Ionizing radiation can cause random (or stochastic) and deterministic (or non-stochastic) effects.

Deterministic effects appear if a minimum radiation dose is exceeded. In adults, this threshold is about one sievert [XXXV]. Single radiation doses above this threshold cause radiation sickness; acute effects include nausea, vomiting, and diarrhea, sometimes accompanied by malaise, fever, and hemorrhage. The victim may die in a few hours, days, or weeks. Other acute effects can include sterility and radiation burns.

The lethality of a dose level is usually expressed in terms of the percentage of exposed population that dies within a specific number of days following exposure. For example, LD 50-60/30 means that the dose is lethal to 50-60% of the population in 30 days. The effects of radiation as a function of dose are shown in Table 15. [XIX, p. 298]

TABLE 15 — EFFECTS OFHIGH DOSES OfRADIATION

Dose (sieverts)	Effects on Exposed Population
0.05-0.2	Possible late effect; possible chromosonal aberrations.
0.2-1.0	Temporary reduction in leukocytes; temporary sterility in men for doses above 0.5 Sv.
1.0-2.0	Mild radiation sickness within a few hours: vomiting, diarrhea, fatigue; reduction in resistance to infection; possible bone growth retardation in children.
2.0-3.0	Serious radiation sickness; effects as in 1.0-2.0 above; also bone marrow syndrome (loss of blood-producing tissue), hemorrhage; LD 10-35/30.
3.0-4.0	Serious radiation sickness as above; also marrow and intestine destruction; permanent sterility in women; LD 50-70/30.
4.0-10.0	Acute illness and early death; LD 60-95/30
10.0-50.0	Acute illness and death in days; LD 100/10
Over 50.0	Acute illness and death in hours to days; LD 100/2

For radiation doses less than about 1 Sv, stochastic effects are more likely to be important. The most important stochastic effects, cancer and inheritable genetic damage, may appear many years or decades after exposure. It is thought that there is no minimum threshold for these effects; as dose decreases, the effects are still expected to occur, but with lower frequency. However, the uncertainties at low doses (10 millisieverts or less) are very large. Estimates of the magnitude of low-dose radiation effects have tended to rise over the years, but remain the subject of controversy. In order to avoid extremely large or small estimates, one could use estimates made by different scientific bodies. These include: the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [XXXVI], the U.S. National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation (BEIR) [XXXVII] and the International Commission on Radiological Protection (ICRP) [XXXVIII]. Their estimates are derived mainly from studies of the survivors of the Hiroshima and Nagasaki bombings, and also from various groups of people given radiation for therapeutic and diagnostic purposes or who have been exposed at work, such as radium dial painters and uranium miners. Studies of survivors of the atomic bombings of Hiroshima and Nagaski indicate statistically significant excess cancers for doses greater than 0.2 grays.

While these estimates suffer from various limitations, most cancer projections continue to utilize the cancer risk factors estimated by established radiological protection committees. Their current estimates are as follows:

- UNSCEAR, 1988: 0.11 fatal cancers per person-sievert for high doses (comparable to those experienced by the survivors of the Hiroshima and Nagasaki bombings).
- BEIR Committee, 1990: 0.08 fatal cancers per person-sievert for a single dose.
- ICRP, 1991: 0.05 fatal cancers per person-sievert for the entire population and 0.04 fatal cancers per person-sievert for adult workers, with both estimates being for low doses. The cancer rate for high doses will be about twice as large.

Estimates of the risk per unit dose may be revised substantially again (upward or downward). As the BEIR committee pointed out:

> *Most of the A-bomb survivors are still alive, and their mortality experience must be followed if reliable estimates of lifetime risk are to be made. This is particularly important for those survivors irradiated as children or in utero who are now entering the years of maximum cancer risk.*

TABLE 16 — ACCIDENTS INVOLVING CHEMICALS (1985-1993) IN BOMBAY

Year	Nature of Accident	Numbers Affected
1985	Chlorine gas leak, Thane	1 killed, 129 injured
1985	Benzylchloride gas leakage	95 injured
1985	Chlorine gas leak, Chembur	1 killed, 149 injured
1985	Chlorine gas leak, Thane	149 affected
1988	Refinery blaze, Chembur	35 killed
1990	Gas leak, Nagothane	32 killed
1991	Accident during transport of liquid natural Gas, Bombay-Ahmedabad highway	100 killed
1993	Gas leak, Kalyan	9 killed, 123 injured

4.4 CHEMICAL HAZARDS

Bombay is home to several industries involving chemicals; many of these, if released, could be injurious to human health. With over 2,000 factories, India's highest concentration of chemical industries is in the Trans-Thane creek area. In the aftermath of the Union Carbide accident in Bhopal, which was responsible for an estimated 5,000-15,000 deaths and many more long-term non-fatal health effects, it is not necessary to elaborate on the kinds of health hazards that could result from the escape of toxic chemicals. Nor was the Bhopal gas leak the only chemical accident to have happened in India. Just within the greater Bombay area there were at least 8 chemical-related accidents between 1985 and 1993 [XXXIX, p.45]. The details are given in Table 16.

A nuclear explosion in a heavily industrialized region (or even one industry with a large stock of chemicals) could lead to additional damage and contamination [XL, pp.156-160]. The two greatest hazards associated with chemicals are explosions and the dispersion of toxic chemicals. There could also be additional fires, but since a nuclear explosion would set off several fires in any case, this would not be a significant extra hazard.

Much of the equipment used in industries use inflammable chemicals that could explode; examples are storage tanks, stacks, pipes, and cylinders [XLI]. Among these, storage tanks are the most vulnerable to damage. It is easy to see why such damage is quite probable; even in the absence of any external accidents there have been numerous explosions of storage tanks. One estimate puts the probability of an explosion at approximately once in 1,000 years per tank [XLI, pp. 97-98].

One class of inflammable chemicals that are particularly susceptible to catching fire, and consequent explosions, are liquefied flammable gases (LFG). Many of these are derived from petroleum and are known as liquefied petroleum gas (LPG). LPG is commonly used for domestic cooking. Besides LPG, materials like ethylene oxide, vinyl chloride and methylamines are common LFGs.

An explosion involving a large stock of chemicals would lead to another small fireball. The temperature of the fireball and the resultant thermal fluence due to this can be calculated in the same way as in the case of a nuclear explosion. The only difference would be that the source of the energy in this case is chemical; hence one needs the amount of chemical burnt and its heat capacity.

In most cases the escape of chemicals would result from damage to the facility due to the blast wave following a nuclear explosion. If the chemicals are inflammable, they could be set on fire by the fires that would have been started by the initial thermal radiation from the nuclear explosion. This is likely to lead to further small explosions. Storage tanks, in particular are very vulnerable to damage due to blast; most are designed to withstand less than 1 psi of overpressure [XLI, pp. 91-95]. This vulnerability is compounded by the initial thermal radiation that heats up the tank. Storage tanks and pressure vessels are designed to be operated within specific temperature ranges. For example, above temperatures of the order of 700 degrees in the case of Ni-Cr steel and 500 degrees in the case of "killed" carbon steel, the yield stress falls below 2×10^{-4}N/m and catastrophic failures such as that giving rise to a "petal" fracture can occur [XLII]. Given the high temperatures reached in the vicinity of a nuclear explosion (see Sections 1.2.2 and 1.3.1), such failures would be likely.

If the emitted chemicals were gases, they would disperse by mixing with the atmosphere. The affected regions would depend on the direction and intensity of the wind and may be estimated by using the puff model [XLIII, pp. 31-32, 123-124]. If the emitted chemicals are liquids, the chief mechanism for dispersal is mixture with some nearby waterway — a river or a canal. Calculating the dispersal rate in this case is complicated and depends on several factors. Among them are the detailed chemical and physical properties of the spilled chemical — such as the various transfer coefficients, surface tension, density, viscosity, volatilization rates (if the chemical is volatile) — as well as the properties of the water flow. Chemicals deposited in the soil could also disperse over a long period of time.

If the nuclear explosion takes place sufficiently close to the chemical facility, it is also probable that the chemical will be sucked into the mushroom cloud and come down as non-radioactive fallout. This is somewhat analogous to the phenomenon of acid rain. If the (solid or liquid) chemical is not sucked into the mushroom cloud or dispersed through any waterway, then the chief hazard is from contamination of the soil and, possibly, groundwater, leading to long-term, low-level doses to the inhabitants of the region.

4.5 DAMAGE TO NUCLEAR FACILITIES

It has been recognized that the possible consequences of a nuclear attack, deliberate or accidental, on a nuclear reactor or other associated facilities could be catastrophic [XLIV, XLV, XLVI, XLVII]. Such an attack would clearly release large amounts of radioactivity and thus its consequences would be similar to those due to fallout from a nuclear weapon explosion or a major reactor accident.[21] However, there are some differences. A large nuclear weapon initially releases a far greater amount of radioactivity than a reactor accident. But this includes a much larger proportion of short-lived isotopes. The contamination from a nuclear reactor accident is longer lived.

There are other differences between a reactor accident and a nuclear weapon explosion. A reactor accident releases comparatively little heat. As a result, the plume of its debris remains at low altitude, and it deposits its radioactivity rather promptly.[22] Thus, the land area contaminated is much smaller. This might not be the case if a nuclear weapon explodes sufficiently close to the reactor. Then, at least some part of the radioactive inventory of the reactor could be sucked up by either the fireball itself, or by the winds and updraft that ensue due to the fire storms that could be raging in the aftermath (described in Section 1.3.1). This radioactive inventory would come down later as fallout.

Apart from the reactor itself, nuclear energy complexes often contain other related facilities such as reprocessing plants and radioactive waste storage facilities. Unlike nuclear reactors, such facilities are not protected by multiple levels of shielding. Hence it is likely that they will be damaged during a nuclear explosion leading to radioactive contamination. Further, these facilities tend to have larger radioactive inventories than reactor cores. Reprocessing plants, especially ones that are known or suspected to be involved in extracting plutonium for weapons use, could be important wartime targets.

The exact amount of fallout, of course, depends on the radioactivity inventory of the reactor or the facility that is damaged. For example, the reprocessing plant in Trombay has a capacity of about 30 metric tons of spent fuel per year. A large fraction of that amount is likely to be present at any given time.

When assessing long-term doses, the most hazardous radioactive inventory is that held in spent-fuel ponds [XLVIII, pp. 191-198]. Such storage tanks for high-level nuclear waste are even known to have exploded spontaneously. For example, on 29 September 1957, a large explosion (estimated to be between 5 and 100 tons of TNT equivalent) occurred at the Mayak nuclear weapons facility in the then Soviet Union; it contained 70-80 tons of highly radioactive waste with a total radioactivity of 20 million curies [XLIX, pp. 80-83]. The chief long-lived component was strontium-90; in the most contaminated fallout areas, this resulted in over 10,000 curies per square kilometer [L, pp. 334-335]. Fallout settled along a 400 km-long swath of land, covering an area of over 20,000 km^2 [LI].

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[21] Such consequences could also result from damage to the reactor due to the use of non-nuclear, chemical explosives.However, this is much less probable due to the smaller magnitude of blast or incendiary effects of chemical explosives.Furthermore, in the case of a nuclear attack,it is possible that the attack is not focused on the reactor, but some nearby military or industrial installation and the reactor or other assocaited facilities are damaged due to the much larger distance scale of effects of nuclear explosives.This is important in the case of India and Pakistan because on December 31,1988,they signed a mutual agreement prohibiting attacks against each other's nuclear installations and facilities.

[22] However, in the case of Chernobyl,the plume was a mile high and its radioactive effects were found as far away as Maine, USA.

Due to the multiple levels of protection surrounding them, nuclear reactors are not easy targets to damage. Nevertheless, if sufficiently close, a nuclear explosion could cause different levels of damage to a nuclear reactor. In order of increasing severity, these are:

1) there is loss of power, but there is no reactor meltdown;
2) the weapon causes a reactor meltdown, but the containment structure is not breached;
3) the weapon breaches the containment, but the radioactivity escapes only after the fire storms have died down;
4) the containment and other reactor facilities are destroyed and some volatile fission products escape immediately;
5) the weapon ruptures the pressure vessel and some or all of the reactor core is carried into the fireball or mushroom cloud.

A nuclear explosion can cause damage to a reactor, at any of these above levels, through one of many ways. Chief among them are the blast wave that follows the explosion, projectiles (often termed missiles) that may come flying at high speeds due to the blast, the crater that is created and the ground shock. Reactors are built to withstand shocks and earthquakes of reasonable magnitude, but if the nuclear explosion happens sufficiently close to the reactor, then its effects will overwhelm even the best built structures. If a nuclear facility is a direct target of attack, then the strategy most likely to damage the structure is to explode the weapon as close to the facility as possible, i.e., on the surface.

For such explosions, it has been estimated that there is a high probability that the structure would fail when exposed to a blast wave with an overpressure of 60 psi. The most damage results if the reactor is within about 1.25 times the crater radius (R_a). In that case, it is physically impossible for the reactor to survive and a large fraction of the reactor debris will be carried into the radioactive cloud to come back later as fallout. The range at which damage due to projectiles from crater ejecta can breach the containment has been estimated to correspond roughly to the range at which an overpressure of 10-25 psi is experienced. This implies that ejecta loads can be more damaging than blast loads. Reactors are designed to withstand earthquakes that cause a maximum horizontal acceleration of about 0.25g (acceleration due to gravity). If one assumes that the reactor containment will be damaged at ground accelerations of approximately 1.0 g, then the corresponding distance within which the explosion must take place has been estimated to be the same as the distance where an overpressure of 10-150 psi (depending on soil type) is experienced. However, all these individual effects could combine together in a synergistic fashion and damage could be caused at even greater distances from the point of explosion.

It is not possible to evaluate the probability of these different levels of damage since that depends on the means of delivery. The means of delivery affects the precision with which the weapon lands on the target. The accuracy of the delivery mechanism is usually described by the CEP (Circular Error Probable), which is the radius of a hypothetical circle about the target point within which half of the weapons land. Thus, the probability P_{hit} of landing within a distance of R_L of an intended aim-point is given by:

$$P_{Hit} = 1 - 0.5^{\left(\frac{R_L}{CEP}\right)^2}$$

The CEP is often loosely termed the accuracy of delivery. To take an Indian example, when analysts quote a figure of 150 m as the accuracy of the Prithvi missile, it is the CEP that they refer to. Thus, a Prithvi missile would land with a probability of ﬁ within 150 m of the target. Clearly, a smaller CEP is more likely to lead to greater damage to the target. This expression can be used along with the graphs for overpressures to estimate the probability of destruction of different targets. Since this study does not consider any particular scenario of attack, we will not make any assumptions about the accuracy with which the bomb is delivered. Hence, we will not try to estimate the probability of these different levels of damage that could result from an attack on a nuclear reactor.

To sum up, an attack on a nuclear facility could lead to large amounts of long-lived radioactive fallout dispersed over large areas. This would be in addition to the effects of the nuclear explosion itself.

4.6 POPULATION FIGURES

Below is the list of Indian cities with populations of over a million according to the 1991 census [XXX]. In the cases where it is available, the population density is also included [LII]. For some cities, the density quoted is for a sub-section of the city.

TABLE 17 — INDIAN CITIES WITH POPULATIONS OVER 1 MILLION

Rank	City	Population	Population Density (per km^2)
1	Greater Bombay	12,596,243	16,461
2	Calcutta	11,021,918	23,733
3	Delhi	8,419,084	8,359
4	Madras	5,421,985	22,077
5	Hyderabad	4,344,437	17,168
6	Bangalore	4,120,288	21,129
7	Ahmadabad	3,312,216	15,402
8	Pune	2,493,987	10,722
9	Kanpur	2,029,889	N.A.
10	Lucknow	1,669,204	5,221
11	Nagpur	1,664,006	7,481
12	Surat	1,518,950	13,483
13	Jaipur	1,518,235	6,956
14	Kochi	1,140,605	3,634
15	Vadodra	1,126,824	9,527
16	Indore	1,109,056	8,387
17	Coimbatore	1,100,746	7,730
18	Patna	1,099,647	9,223
19	Madurai	1,085,914	20,025
20	Bhopal	1,062,771	3,370
21	Vishakapatnam	1,057,118	9,601
22	Ludhiana	1,042,740	7,743
23	Varanasi	1,030,863	N.A.

4.7 USEFUL CONVERSION FACTORS

TABLE 18 — CONVERSION FACTORS

To convert from:	to (SI units):	Multiply by the following factor
inch	meter (m)	2.54×10^{-2}
foot	meter (m)	0.3048
yard	meter (m)	0.9174
mile	kilometer (km)	1.609
liter	cubic meter (m^3)	10^{-3}
gallon	cubic meter (m^3)	3.78×10^{-3}
pound	kilogram (kg)	0.4536
ounce	gram (g)	28.35
calorie	joule (J)	4.187
erg	joule (J)	10^{-5}
Btu (British thermal Unit)	joule (J)	1.05×10^{3}
ton (TNT equivalent)	joule (J)	4.2×10^{9}
atm (atmosphere)	pascal (Pa)	$1.013 \mathrm{X} 10^{5}$
psi (lb per square inch)	pascal (Pa)	6895
bar (kg per square cm)	pascal (Pa)	100,000
Fahrenheit	centigrade (C)	9C/5 - 32
rads (dosage)	gray (Gy)	1.0×10^{-2}
rads/hour	Gy/s	2.778×10^{-6}
Curie	becquerel (Bq)	3.7×10^{10}
Roentgen	coulomb/kg	2.58×10^{-4}
Roentgen	gray (Gy)	9.3×10^{-3}
rem (dose equivalent)	sievert (Sv)	1.0×10^{-2}

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