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# THE EFFECTS OF NUCLEAR WEAPONS

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# *The Effects of* Nuclear Weapons

SAMUEL GLASSTONE
*Editor*

*Prepared by the*
UNITED STATES DEPARTMENT OF DEFENSE
*Published by the*
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# Foreword

This handbook, prepared by the Armed Forces Special Weapons Project of the Department of Defense in coordination with other cognizant government agencies and published by the United States Atomic Energy Commission, is a comprehensive summary of current knowledge on the effects of nuclear weapons. The effects information contained herein is calculated for yields up to 20 megatons and the scaling laws for hypothetically extending the calculations beyond this limit are given. The figure of 20 megatons however is not to be taken as an indication of capabilities or developments.

CHARLES E. WILSON
*Secretary of Defense*

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Atomic Energy Commission

THE FEDERAL CIVIL DEFENSE ADMINISTRATION commends this publication as the definitive source of information on the effects of nuclear weapons for the use of organizations engaged in Civil Defense activities. Its detailed treatment of the physical phenomena associated with nuclear explosions provides the necessary technical background for development of countermeasures against all nuclear effects of Civil Defense interest.

VAL PETERSON
*Administrator*
Federal Civil Defense Administration

# Acknowledgment

At the request of the Atomic Energy Commission, the Armed Forces Special Weapons Project prepared this book with the assistance of the Commission. Dr. Samuel Glasstone was responsible for the compiling, writing, and editing and, largely, for its successful completion.

Assistance in the preparation and review of the book was provided by individuals associated with the Atomic Energy Commission, the Department of Defense, the Federal Civil Defense Administration, and their contractors.

# Contents

# Preface

When "The Effects of Atomic Weapons" was first issued, in 1950, the explosive energies of the atomic bombs known at that time were equivalent to some thousands of tons of TNT. The descriptions of atomic explosions and their effects were therefore based on a so-called "nominal" bomb with an energy release equivalent to that of 20,000 tons (or 20 kilotons) of TNT. It is no longer possible to describe the effects in terms of a single nominal bomb. An essentially new presentation of weapons effects has consequently become necessary and is titled "The Effects of Nuclear Weapons."

The main purpose of this new handbook is to describe, within the limitations set by national security, the basic phenomena and the most recent data concerning the effects associated with explosions of nuclear weapons. The information has been obtained from observations made following the wartime nuclear bombings in Japan and at the tests carried out at the Eniwetok Proving Grounds and the Nevada Test Site, as well as from experiments with conventional high explosives and mathematical calculations. Tests have provided much important data on weapons effects; nevertheless, a distinction should be made between the consequences of such tests, when all conceivable precautions are taken to eliminate hazards to life and property, and of the consequences of the use of nuclear weapons in warfare, when the efforts of an enemy would be devoted to causing the maximum destruction and casualties. It is for use in planning against possible nuclear attack that this volume is intended.

The major portion of the book consists of a statement of the facts relating to nuclear explosions and of an objective, scientific analysis of these facts. In the final chapter some general conclusions are presented upon which protective measures may be based. It should be emphasized, however, that only the principles of protection are discussed; there is no intention of recommending the adoption of particular procedures. The responsibility for making and implementing policy with regard to such matters as protective construction, shelters, and evacuation lies with the Federal Civil Defense Administration and other United States Government agencies. The information presented in this book should prove useful to these agencies in planning defensive measures for the protection of civilian lives and property.

The phenomena of blast, shock, and various radiations associated with nuclear explosions are very complex. It is inevitable, therefore, that the description of these phenomena and their related effects should be somewhat technical in nature. However, this book has been organized in a manner that will serve the widest possible audience. With this end in view, each chapter, except Chapters IV, X, and XII, is in two parts: the first consists of a general treatment of a particular topic in a less technical manner, whereas the second part contains the more technical aspects. The material is so arranged that no loss of continuity will result to the reader from the omission of any or all of these more technical sections. It is hoped that this format will permit the general reader to obtain a good understanding of each subject without the necessity for coping with technical material with which he may not be concerned. On the other hand, the technical material is available for specialists, as for example architects engineers, medical practitioners, and others, who may have need for such details in their work connected with defense planning.

SAMUEL GLASSTONE

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*CHAPTER I*

# GENERAL PRINCIPLES OF NUCLEAR EXPLOSIONS

## CHARACTERISTICS OF NUCLEAR EXPLOSIONS

### INTRODUCTION

1.1 In general, an explosion is the release of a large amount of energy in a short interval of time within a limited space. The liberation of this energy is accompanied by a considerable increase of temperature, so that the products of the explosion become extremely hot gases. These gases, at very high temperature and pressure, move outward rapidly. In doing so, they push away the surrounding medium—air, water, or earth—with great force, thus causing the destructive (blast or shock) effects of the explosion. The term "blast" is generally used for the effect in air, because it resembles (and is accompanied by) a very strong wind. In water or under the ground, however, the effect is referred to as "shock," because it is like a sudden impact.

1.2 The atomic (or nuclear)[1] bomb is similar to the more conventional (or high explosive) type of bomb in so far as its destructive action is due mainly to blast or shock. However, apart from the fact that nuclear bombs can be many thousands of times more powerful than the largest TNT bombs, there are other more basic differences. First, a fairly large proportion of the energy in a nuclear explosion is emitted in the form of light and heat, generally referred to as "thermal radiation." This is capable of causing skin burns and of starting fires at considerable distances. Second, the explosion is accompanied by highly-penetrating and harmful, but invisible, rays, called the "initial nuclear radiation." Finally, the substances remaining after a nuclear explosion are radioactive, emitting similar radiations over an extended period of time. This is known as the "residual nuclear radiation" or "residual radioactivity" (Fig. 1.2).

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[1] *As will be seen below (§ 1.9), the terms* "atomic" and "nuclear" may be used interchangeably, as far as weapons or explosions are concerned.

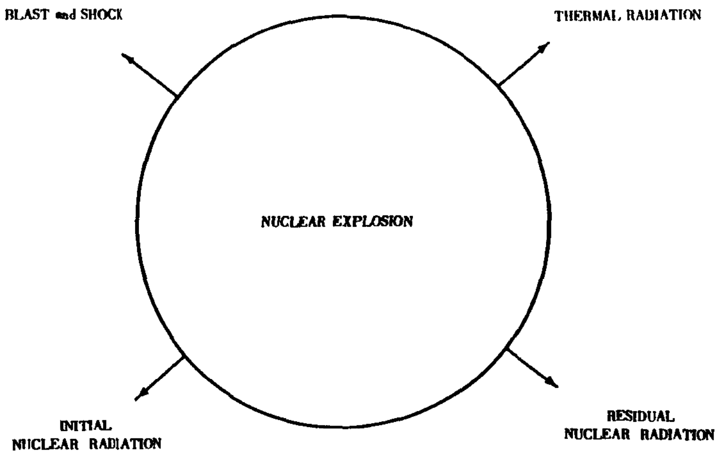

Figure 1.2. Effects of a nuclear explosion.

1.3 It is because of these fundamental differences between a nuclear and a conventional (TNT) explosion, as well as because of the tremendously greater power of the former, that the effects of nuclear weapons require special consideration. In this connection, a knowledge and understanding of the mechanical and radiation phenomena associated with a nuclear explosion are of vital importance.

1.4 The purpose of this book is to state the facts concerning the effects of nuclear weapons, and to make an objective analysis of these facts. It is hoped that this information will help those responsible for defense planning to make preparations to deal with the emergencies that may arise from nuclear warfare. In addition, architects and engineers may be able to utilize the data in the design of structures having increased resistance to damage by blast, shock, and fire, and greater ability to provide shielding against nuclear radiations.

## ATOMIC STRUCTURE AND ISOTOPES

1.5 All substances are made up from one or more of about ninety different kinds of simple materials known as "elements." Among the common elements are the gases hydrogen, oxygen, and nitrogen; the solid nonmetals carbon, sulfur, and phosphorus; and various metals, such as iron, copper, and zinc. A less familiar element, which has attained prominence in recent years because of its use as a source of atomic (or nuclear) energy, is uranium, normally a solid metal.

1.6 The smallest part of any element that can exist, while still retaining the characteristics of the element, is called an "atom" of that element. Thus, there are atoms of hydrogen, of iron, of uranium, and so on, for all the elements. The hydrogen atom is the lightest of all atoms, whereas the atoms of uranium are the heaviest of those found in nature. Heavier atoms, such as those of plutonium, also important for the release of atomic energy, have been made artificially from uranium.

1.7 Every atom consists of a relatively heavy central region or "nucleus," surrounded by a number of very light particles known as "electrons." Further, the atomic nucleus is itself made up of a definite number of fundamental particles, referred to as "protons" and "neutrons." These two particles have almost the same mass, but they differ in the respect that the proton carries a unit charge of positive electricity whereas the neutron, as its name implies, is uncharged electrically, i. e., it is neutral. Because of the protons present in the nucleus, the latter has a positive electrical charge, but in the normal atom this is exactly balanced by the negative charge carried by the electrons surrounding the nucleus.

1.8 The essential difference between atoms of different elements lies in the number of protons (or positive charges) in the nucleus; this is called the "atomic number" of the element. Hydrogen atoms, for example, contain only one proton, helium atoms have two protons, uranium atoms have 92 protons, and plutonium atoms 94 protons. Although all the nuclei of a given element contain the same number of protons, they may have different numbers of neutrons. The resulting atomic species, which have identical atomic numbers but which differ in their masses, are called "isotopes" of the particular element. All but about 20 of the elements occur in nature in two or more isotopic forms, and many other isotopes, which are unstable, i. e., radioactive, have been obtained in various ways.

## RELEASE OF NUCLEAR ENERGY: FUSION AND FISSION REACTIONS

1.9 As stated above, an explosion results from the very rapid release of a large amount of energy. In the case of a conventional explosion, this energy arises from rearrangement among the atoms present in the explosive material, e. g., the hydrogen, carbon, oxygen, and nitrogen atoms in TNT. In a nuclear explosion, on the other hand, the energy is produced by the redistribution or recombination of the protons and neutrons within the atomic nuclei. What is commonly referred to as atomic energy is thus, strictly, nuclear energy, since it results from particular nuclear interactions. It is for the same reason, too, that atomic bombs are also called nuclear weapons. The forces between the protons and neutrons within atomic nuclei are tremendously greater than those among the atoms as a whole; consequently, nuclear (or atomic) energy is of a much higher order of magnitude than conventional energy when equal masses are considered.

1.10 Many nuclear processes are known, but not all of these are accompanied by the release of energy. The basic requirement for energy release is that the total mass of the interacting species should be *more* than that of the resultant product (or products) of the reaction. There is a definite equivalence between mass and energy, and when a decrease of mass occurs in a nuclear reaction there is an accompanying release of a certain amount of energy related to the decrease in mass. These mass changes are really a reflection of the difference in the forces in the various nuclei. It is a basic law of nature that the conversion of any system in which the constituents are held together by weaker forces into one in which the forces are stronger must be accompanied by the release of energy, and a corresponding decrease in mass.

1.11 In addition to the necessity for the nuclear process to be one in which there is a net decrease in mass, the release of nuclear energy in amounts sufficient to cause an explosion requires that the reaction should be able to reproduce itself once it has been started. Two kinds of nuclear interactions can satisfy the conditions for the production of large amounts of energy in a short time. They are known as "fission" and "fusion." The former process takes place with some of the heaviest (high atomic number) nuclei, whereas the latter, at the other extreme, involves some of the lightest (low atomic number) nuclei.

1.12 The materials used to produce nuclear explosions by fission are certain isotopes of the elements uranium and plutonium. When a free (or unattached) neutron enters the nucleus of a fissionable atom, it can cause the nucleus to split into two smaller parts. This is the fission process, which is accompanied by the release of a large amount of energy. The smaller (or lighter) nuclei which result are called the "fission products." The complete fission of 1 pound of uranium or of plutonium can produce as much energy as the explosion of 9,000 tons of TNT.

1.13 In nuclear fusion, a pair of light nuclei unite (or fuse) together, to form a nucleus of a heavier atom. An example is the fusion of the hydrogen isotope known as deuterium or "heavy hydrogen." Under suitable conditions, two deuterium nuclei may combine to form the nucleus of a heavier element, helium, with the release of energy.

1.14 Nuclear fusion reactions can be brought about by means of very high temperatures, and they are thus referred to as "thermonuclear processes." The actual quantity of energy liberated, for a given mass of material, depends on the particular isotope (or isotopes) involved in the nuclear fusion reaction. As an example, the fusion of all the nuclei present in 1 pound of the hydrogen isotope deuterium would release roughly the same amount of energy as the explosion of 26,000 tons of TNT.

1.15 In certain fusion processes, among nuclei of the hydrogen isotopes, neutrons of high energy are liberated (see §1.55). These can cause fission in uranium and plutonium. Consequently, association of the appropriate fusion reactions with a fissionable material will result in a more complete utilization of the latter for the release of energy. A device in which fission and fusion (thermonuclear) reactions are combined can therefore produce an explosion of great power.

1.16 A distinction is sometimes made between atomic weapons in which the energy arises from fission, on the one hand, and hydrogen (or thermonuclear) weapons, involving fusion, on the other hand. In each case, however, the explosive energy results from nuclear reactions, so that they may both be correctly described as nuclear (or atomic) weapons. In this book, therefore, the general terms "nuclear bomb" and "nuclear weapon" will be used, irrespective of the type of nuclear reaction producing the energy of the explosion.

## Energy Yield of a Nuclear Explosion

1.17 The power of a nuclear weapon is expressed in terms of its total energy release (or yield) compared with the energy liberated by TNT when it explodes. Thus, a 1-kiloton nuclear bomb is one which produces the same amount of energy as the explosion of 1 kiloton (or 1,000 tons) of TNT. Similarly, a 1-megaton weapon would have the energy equivalent of 1 million tons (or 1,000 kilotons) of TNT. The earliest nuclear bombs, such as those dropped over Japan in 1945, and those used in the tests at Bikini in 1946, released roughly the same quantity of energy as 20,000 tons (or 20 kilotons) of TNT. Since that time, much more powerful weapons, with energy yields in the megaton range, have been developed.

1.18 From the statement in § 1.12 that the fission of 1 pound of uranium or plutonium will release the same amount of energy as 9,000 tons of TNT, it is evident that, in a 20-kiloton nuclear bomb, 2.2 pounds of material undergo fission. However, the actual weight of uranium or plutonium in such a bomb is greater than this amount. In other words, in a fission weapon, only part of the nuclear material suffers fission. The efficiency is thus said to be less than 100 percent.

### Distribution of Energy in Nuclear Explosions

1.19 In the explosion of a conventional (TNT) bomb nearly all the energy released appears immediately as kinetic (or heat) energy. Almost the whole of this is then converted, as described in § 1.1, into blast and shock. In a fission weapon, however, the situation is different. Only about 85 percent of the energy released in fission is in the form of heat (kinetic) energy, and only a part of this is utilized to produce blast and shock. The other part of this 85 percent appears as thermal radiation, i. e., heat and light rays. This is a result of the very much higher temperature attained in a nuclear, as compared with a conventional, explosion. The fraction of the fission energy emitted as thermal radiation varies with the nature of the weapon and with the conditions of the explosion, but for a bomb burst fairly high in the air it is roughly one-third. Consequently, about 50 percent of the total energy is then utilized to cause blast and shock (Fig. 1.19).

1.20 The remaining 15 percent of the energy of the nuclear explosion is released as various nuclear radiations. Of this, 5 percent constitute the initial nuclear radiations produced within a minute or so of the explosion; whereas the final 10 percent of the bomb energy is emitted over a period of time in the form of the residual nuclear radiation. This is due almost entirely to the radioactivity of the fission products present in the bomb residue after the explosion. It may be noted that in a conventional explosion, there are no nuclear radiations since the atomic nuclei are unaffected.

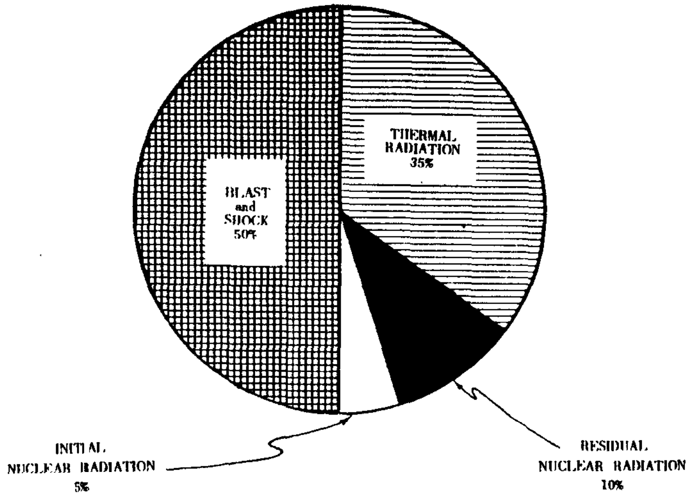

Figure 1.19. Distribution of energy in a typical air burst.

1.21 The initial nuclear radiations consist mainly of "gamma rays" (resembling X-rays) and neutrons. Both of these, especially the gamma rays, can travel great distances through the air and can even penetrate considerable thicknesses of material. It is because these radiations can neither be seen nor felt by human beings, but can have harmful effects even at a distance from their source, that they are an important aspect of a nuclear explosion.

1.22 In the course of their radioactive decay, the fission products emit gamma rays and another type of nuclear radiation called "beta particles." The latter are identical with electrons, i. e., subatomic particles carrying a negative electric charge (§ 1.7), moving with high speed. Beta particles, which are also invisible, are much less penetrating than gamma rays, but like the latter they also represent a potential hazard.

1.23 The spontaneous emission of beta particles and gamma rays from radioactive substances, such as the fission products, is a gradual process. It takes place over a period of time, at a rate depending upon the nature of the material and upon the amount present. Because of the continuous decay, the quantity of radioactive material and the rate of emission of radiation decreases steadily. This means that the residual nuclear radiation, due mainly to the fission products, is most intense soon after the explosion but diminishes in the course of time.

### Types of Nuclear Explosions

1.24 The immediate phenomena associated with a nuclear explosion, as well as the effects of shock and blast, and thermal and nuclear radiations, vary with the location of the point of burst in relation to the surface of the earth. For descriptive purposes four types of burst are distinguished, although many variations and intermediate situations can arise in practice. The main types, which will be defined below, are (1) air burst, (2) underwater burst, (3) underground burst, and (4) surface burst.

1.25 Almost at the instant of a nuclear explosion there is formed an intensely hot and luminous mass, roughly spherical in shape, called the "ball of fire" or "fireball." An "air burst" is defined as one in which the bomb is exploded in the air, above land or water, at such a height that the fireball (at maximum brilliance) does not touch the surface of the earth. For example, in the explosion of a 1-megaton bomb the ball of fire may grow until it is nearly 5,800 feet (1.1 mile) across, at maximum brilliance. This means that in the air burst of such a bomb the point at which the explosion occurs is at least 2,900 feet above the earth's surface.

1.26 The quantitative aspects of an air burst will be dependent upon the actual height of the explosion, as well as upon its energy yield, but the general phenomena are much the same in all cases. Nearly all of the shock energy appears as air blast, although if the explosion occurs close enough to the surface, there will also be some ground shock. The thermal radiation will travel large distances through the air and will be of sufficient intensity to cause moderately severe burns of exposed skin as far away as 12 miles from a 1-megaton bomb explosion, on a fairly clear day. The warmth may be felt at a distance of 75 miles. For air bursts of higher energy yields, the corresponding distances will, of course, be greater. Since the thermal radiation is largely stopped by ordinary opaque materials, buildings and clothing can provide protection.

1.27 The initial nuclear radiations from an air burst will also penetrate a long way in air, although the intensity falls off fairly rapidly at increasing distances from the explosion. Like X-rays, the nuclear radiations are not easily absorbed, and fairly thick layers of materials, preferably of high density, are needed to reduce their intensity to harmless proportions. For example, at a distance of 1 mile from the air burst of a 1-megaton nuclear bomb, an individual would probably need the protection of about 1 foot of steel or 4 feet of concrete to be relatively safe from the effects of the initial nuclear radiations.

1.28 In the event of a high or moderately high air burst, the fission products remaining after the nuclear explosion will be widely dispersed. The residual nuclear radiations arising from these products will be of minor consequence on the ground. On the other hand, if the burst occurs nearer the earth's surface, the fission products may fuse with particles of earth, much of which will fall to the ground at points close to the explosion. This dirt and other debris will be contaminated with radioactive material and may, consequently, represent a possible danger to living organisms.

1.29 If a nuclear explosion occurs under such conditions that its center is beneath the ground or under the surface of water, the situation is described as an "underground burst" or an "underwater burst," respectively. Since some of the effects of these two types of explosions are similar, they will be considered here together as subsurface bursts.

1.30 In a subsurface burst, most of the shock energy of the explosion appears as underground or underwater shock, but a certain proportion, which is less the greater the depth of the burst, escapes and produces air blast. Much of the thermal radiation and of the initial nuclear radiations will be absorbed within a short distance of the explosion. The energy of the absorbed radiations will merely contribute to the heating of the ground or body of water. Depending upon the depth of the explosion, some of the thermal and nuclear radiations will escape, but the intensities will be less than for an air burst. However, the residual nuclear radiations now become of considerable significance, since large quantities of earth or water in the vicinity of the explosion will be contaminated with radioactive fission products.

1.31 A "surface burst" is regarded as one which occurs either at the actual surface of the land or water or at any height above the surface such that the fireball (at maximum brilliance) touches the land or water. The energy of the explosion will then cause both air blast and ground (or water) shock, in varying proportions, depending upon the height of the burst point above the surface. Upon this will also depend the amounts of thermal radiation and initial nuclear radiations escaping from the ball of fire. The residual nuclear radiation can be a significant hazard because of the large quantities of contaminated dust or water that result from the nuclear explosion.

1.32 Although the four types of burst have been considered as being fairly distinct, there is actually no clear line of demarcation between them. It will be apparent that as the height of the explosion is decreased, an air burst will become a surface burst. Similarly, a surface burst merges into a subsurface explosion at a shallow depth, when part of the ball of fire actually breaks through the surface of the land or water. It is nevertheless a matter of convenience, as will be seen in later chapters, to divide nuclear explosions into the four general types defined above.

## SCIENTIFIC BASIS OF NUCLEAR EXPLOSIONS[2]

### The Fission Chain Reaction

1.33 The significant point about the fission of a uranium (or plutonium) nucleus by means of a neutron, in addition to the release of

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[2] The remaining sections of this chapter may be omitted without loss of continuity.

a large quantity of energy, is that the process is accompanied by the almost instantaneous emission of two or more other neutrons. The neutrons liberated in this manner are able to induce fission of additional uranium (or plutonium) nuclei, each such process resulting in the emission of more neutrons which can produce further fission, and so on. Thus, in principle, a single neutron could start off a chain of nuclear fissions, the number of nuclei involved, and the energy liberated, increasing at a tremendous rate.

1.34 Actually, not all the neutrons liberated in the fission process are available for causing more fissions; some of these neutrons escape and others are lost in nonfission reactions. It will be assumed, however, for simplicity, that for each uranium (or plutonium) nucleus undergoing fission, there are two neutrons produced capable of initiating further fissions. Suppose a single neutron is captured by a nucleus in a quantity of uranium, so that fission occurs. Two neutrons are then liberated and these cause two more nuclei to undergo fission. This results in the production of four neutrons available for fission, and so on.

1.35 Accordingly, the number of neutrons, and hence, the number of nuclei undergoing fission, is doubled in each generation. Starting with a single neutron the number would increase rapidly, thus, 1, 2, 4, 8, 16, 32, 64, . . . In less than 90 generations enough neutrons would have been produced to cause the fission of every nucleus in 50 kilograms (110 pounds) of uranium, resulting in the liberation of the same amount of energy as in the explosion of a million tons (1 megaton) of TNT.

1.36 The time required for the actual fission process is very short, and most of the resulting neutrons are emitted promptly. Consequently, the interval between successive generations is determined by the average time elapsing between the release of the neutron and its capture by a fissionable nucleus. This time depends, among other things, on the energy (or speed) of the neutron, and if most of the neutrons are of fairly high energy, generally referred to as "fast neutrons," the interval is about a one-hundred-millionth part of a second. In this event, the 90th generation would be attained in less than a millionth of a second. The release of the energy, equivalent of 1 megaton of TNT in such a short time would provide the conditions for a tremendous explosion.

1.37 It is seen, therefore, that because the fission process is accompanied by the instantaneous liberation of neutrons, as well as by the release of energy, it is possible, in principle, to produce a self-sustaining, chain reaction. As a result, a few pounds of fissionable material can be made to liberate, within a very small fraction of a second, as much energy as the explosion of thousands (or millions) of tons of TNT. This is the basic principle of the nuclear fission bomb.

### CRITICAL SIZE OF NUCLEAR FISSION BOMB

1.38 It was mentioned above that some of the neutrons produced in fission are lost by escape or by capture in nonfission processes. If the conditions are such that the neutrons are lost at a faster rate than they are formed by fission, the chain reaction would not be self-sustaining. Some energy would be produced, but the amount would not be large enough, and the rate of liberation would not be sufficiently fast, to cause an effective explosion. It is necessary, therefore, in order to achieve a nuclear explosion, to establish conditions under which the loss of neutrons is minimized. In this connection, it is important to consider, in particular, the neutrons which escape from the material undergoing fission.

1.39 The escape of neutrons occurs at the exterior of the uranium (or plutonium) mass. The rate of loss by escape will thus be proportional to the surface area. On the other hand, the fission process, which results in the formation of more neutrons, takes place throughout the whole of the material and its rate is, consequently, dependent upon the volume. The relative loss of neutrons by escape can, therefore, be reduced by increasing the size of the fissionable material, for in this manner the ratio of the area to the volume is decreased.

1.40 The situation may be understood by reference to Fig. 1.40, showing two spherical masses, one larger than the other, of fissionable material with fission being initiated by a neutron represented by a dot within a small circle. It is supposed that in each act of fission three neutrons are emitted; in other words, one neutron is captured and three are expelled. The removal of a neutron from the system is indicated by the head of an arrow. Thus, an arrowhead within the sphere means that fission has occurred and extra neutrons are produced, whereas an arrowhead outside the sphere implies the loss of a neutron. It is evident from Fig. 1.40 that a much greater fraction of the neutrons is lost from the smaller than from the larger sphere.

1.41 If the quantity of uranium (or plutonium) is small, i. e., if the ratio of the surface area to the volume is large, the proportion of neutrons lost by escape will be so great that the propagation of a nuclear fission chain, and hence the production of an explosion, will not be possible. But as the size of the piece of uranium (or plutonium) is increased, and the relative loss of neutrons is thereby decreased, a point is reached at which the chain reaction can become self-sustaining. This is referred to as the "critical mass" of the fissionable material.

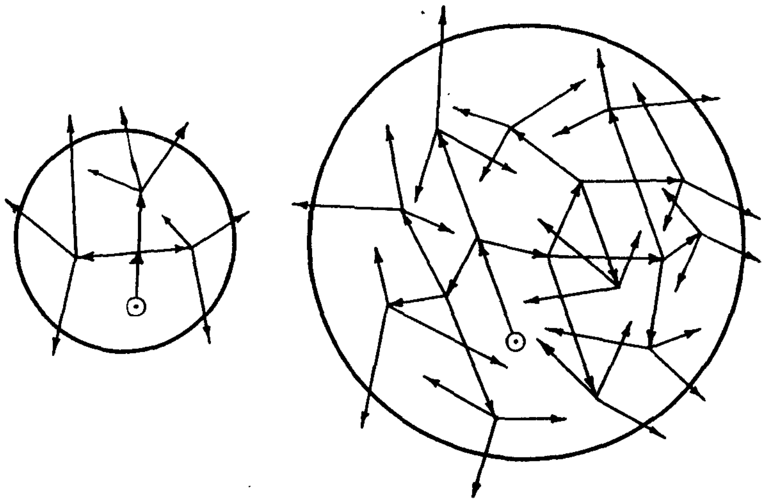

Figure 1.40. Effect of increased size of fissionable material in reducing the proportion of neutrons lost by escape.

1.42 For a nuclear explosion to take place, the weapon must thus contain a sufficient amount of uranium (or plutonium) for it to exceed the critical mass in the existing circumstances. Actually, the critical mass depends, among other things, on the shape of the material, the composition, and the presence of impurities which can remove neutrons in nonfission reactions. By surrounding the fissionable material with a suitable neutron "reflector," the loss of neutrons by escape can be reduced and the critical mass can thus be decreased.

## Attainment of Critical Mass

1.43 Because of the presence of stray neutrons in the atmosphere or the possibility of their being generated in various ways, a quantity of a suitable isotope of uranium (or plutonium) exceeding the critical mass would be likely to melt or possibly explode. It is necessary, therefore, that before the detonation of a nuclear bomb, it should contain no piece of fissionable material that is as large as the critical mass for the given conditions. In order to produce an explosion, the material must then be made supercritical, i. e., larger than the critical mass, in a time so short as to preclude a sub-explosive change in the configuration, such as by melting.

1.44 Two general methods have been described for bringing about a nuclear explosion, that is to say, for quickly converting a subcritical system into a supercritical one. In the first method, two or more pieces of fissionable material, each less than a critical mass, are brought together very rapidly in order to form one piece that exceeds the critical mass. This may be achieved in some kind of gun-barrel device, in which a high explosive is used to blow one subcritical piece of fissionable material from the breech end of the gun into another subcritical piece firmly held in the muzzle end.

1.45 The second method makes use of the fact that when a subcritical quantity of an appropriate isotope of uranium (or plutonium) is strongly compressed, it can become critical or supercritical. The reason for this is that by decreasing the size and, hence, the surface area (or neutron escape area) of a given quantity of fissionable material by compression, the rate of neutron loss by escape is decreased relative to the rate of production by fission. A self-sustaining chain reaction may then become possible with the same mass that was subcritical in the uncompressed state.

1.46 In a fission weapon, the compression may be achieved by means of a spherical arrangement of specially fabricated shapes of ordinary high explosive. In a hole in the center of this system is placed a subcritical sphere of fissionable material. When the high explosive is set off, by means of a number of detonators on the outside, an inwardly-directed "implosion" wave is produced. When this wave reaches the sphere of uranium (or plutonium), it causes the latter to be compressed so that it becomes supercritical and explodes.

## Fission Products

1.47 Many different fission fragments, i. e., initial fission product nuclei, are formed when uranium (or plutonium) nuclei capture neutrons and suffer fission. This is because there are 40 or so different ways in which the nuclei can split up when fission occurs. Most, if not all, of the approximately 80 fragments thus produced are the nuclei of radioactive forms (radioisotopes) of well-known, lighter elements. The radioactivity is usually manifested by the emission of negatively charged beta particles (§ 1.22). This is frequently, although not always, accompanied by gamma radiation, which serves to carry off excess energy. In a few special cases, gamma radiation only is emitted.

1.48 As a result of the expulsion of a beta particle, the nucleus of a radioactive substance is changed into that of another element, sometimes called the "decay product." In the case of the fission fragments, the decay products are generally also radioactive, and these in turn may decay with the emission of beta particles and gamma rays. On the average, there are about three stages of radioactivity for each fission fragment before a stable (nonradioactive) nucleus is formed. Because of the large number of different ways in which fission can occur and the several stages of decay involved, the fission product mixture becomes very complex.[3] Something like 200 or more different isotopes of 35 light elements, from zinc to gadolinium, have been identified among the fission products.

1.49 The rate of radioactive change, i. e., the rate of emission of beta particles and gamma radiation, is usually expressed by means of the "half-life" of the particular isotope involved. This is defined as the time required for the radioactivity of a given quantity of a particular radioisotope to decrease (or decay) to half of its original value. Each individual radioactive species has a definite half-life which is independent of its state or its amount. The half-lives of the fission products have been found to range from a small fraction of a second to something like a million years.

1.50 Although every radioisotope present among the fission products is known to have a definite half-life, the mixture formed after a nuclear explosion is so complex that it is not possible to represent the decay as a whole in terms of a half-life. Nevertheless, it has been found, from experimental measurements made over an extended period of time, that the decrease in the total radiation intensity from the fission products can be calculated by means of a fairly simple formula. This will be given and discussed in Chapter IX, but the general nature of the decay rate of fission products, based on this formula, will be apparent from Fig. 1.50. The residual radioactivity from the fission products at 1 hour after a nuclear detonation is taken as 100 and the subsequent decrease with time is indicated by the curve. It is seen that at 7 hours after the explosion, the fission product activity will have decreased to about one-tenth (10 percent) of its amount at 1 hour. Within approximately 2 days, the activity will have decreased to 1 percent of the 1-hour value.

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[3] The general term "fission products" is used to describe this complex mixture which is formed within a short time of fission.

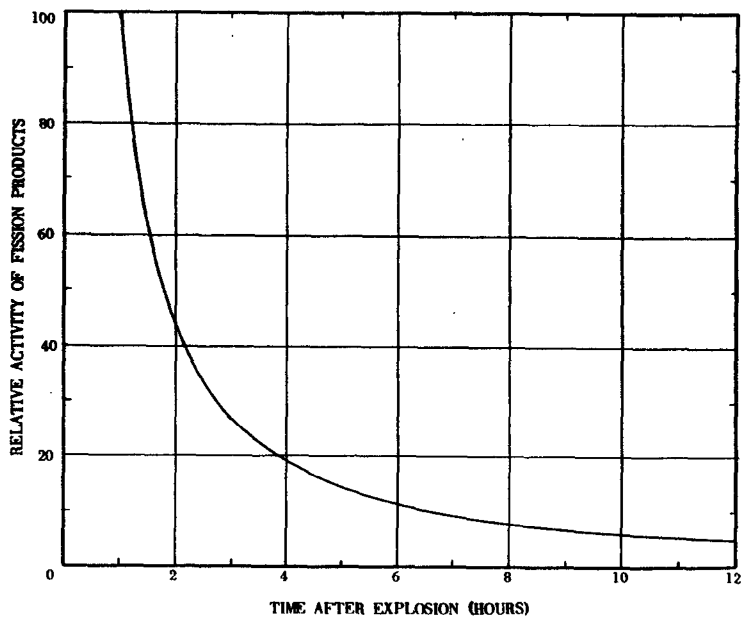

Figure 1.50. Rate of decay of fission products after a nuclear explosion (activity is taken as 100 at 1 hour after the detonation).

### Alpha-Particle Activity

1.51 In addition to the beta-particle and gamma-ray activity due to the fission products, there is another kind of residual radioactivity that should be mentioned. This is the activity of the fissionable material, part of which, as noted in §1.18, remains after the explosion. Both uranium and plutonium are radioactive, and their activity consists in the emission of what are called "alpha particles". These are a form of nuclear radiation, since they are emitted from atomic nuclei; but they differ from the beta particles arising from the fission products in being much heavier and carrying a positive electrical charge. Alpha particles are, in fact, identical with the nuclei of helium atoms.

1.52 Because of their greater mass and charge, alpha particles are much less penetrating than beta particles and gamma rays of the same energy. Thus, very few alpha particles from radioactive sources can travel more than 1 to 3 inches in air before being stopped. It is doubtful whether these particles can get through the unbroken skin, and they certainly cannot penetrate clothing. Consequently, the uranium (or plutonium) present in the bomb residues do not constitute a hazard if they are outside the body. However, if plutonium, in particular, enters the body in sufficient quantity, by ingestion, inhalation, or through skin abrasions, the effects may be serious.

## FUSION (THERMONUCLEAR) REACTIONS

1.53 Energy production in the sun and stars is undoubtedly due to fusion reactions involving the nuclei of various light (low atomic weight) atoms. From experiments made in laboratories with cyclotrons and similar devices, it was concluded that the fusion of isotopes of hydrogen was possible. This element is known to exist in three isotopic forms, in which the nuclei have masses of 1, 2, and 3, respectively. These are generally referred to as hydrogen ($H^1$), deuterium ($H^2$ or $D^2$), and tritium ($H^3$ or $T^3$). All the nuclei carry a single positive charge, i. e., they all contain one proton, but they differ in the number of neutrons. The lightest ($H^1$) nuclei (or protons) contain no neutrons; the deuterium ($H^2$) nuclei contain one neutron, and tritium ($H^3$) nuclei contain two neutrons.

1.54 Several different fusion reactions have been observed among the nuclei of the three hydrogen isotopes, involving either two similar or two different nuclei. In order to make these reactions occur to an appreciable extent, the nuclei must have high energies. One way in which this energy can be supplied is by means of a charged-particle accelerator, such as a cyclotron. Another possibility is to raise the temperature to very high levels. In these circumstances the fusion processes are referred to as "thermonuclear reactions," as mentioned earlier.

1.55 Four thermonuclear fusion reactions appear to be of interest for the production of energy because they are expected to occur sufficiently rapidly at realizable temperatures.[4] These are:

$$\begin{aligned} H^2+H^2&=He^3+n+3.2\text{ Mev}\\ H^2+H^2&=H^3+H^1+4\text{ Mev}\\ H^3+H^2&=He^4+n+17\text{ Mev}\\ H^3+H^3&=He^4+2n+11\text{ Mev,} \end{aligned}$$

where He is the symbol for helium and $n$ (mass=1) represents a neutron. The energy liberated in each case is expressed in Mev (million electron volt) units.[5] Without going into details, it may be stated that the fission of a nucleus of uranium or plutonium, having a weight of nearly 240 atomic mass units, releases about 200 Mev. This may be compared with an average of about 24.2 Mev obtained from the fusion of 5 deuterium nuclei with a weight of 10 mass units. Weight for weight, therefore, the fusion of deuterium nuclei would produce nearly three times as much energy as the fission of uranium or plutonium.

1.56 In order to make the nuclear fusion reactions take place, temperatures of the order of a million degrees are necessary. The only known way in which such temperatures can be obtained on earth is by means of a fission explosion. Consequently, by combining a quantity of deuterium or tritium (or a mixture) with a fission bomb, it should be possible to initiate one or more of the thermonuclear fusion reactions given above. If these reactions, accompanied by energy evolution, can be propagated rapidly through a volume of the hydrogen isotope (or isotopes) a thermonuclear explosion may be realized.

1.57 It may be noted that the two reactions involving tritium ($H^3$) are of particular interest for several reasons. Not only do they occur more rapidly than those in which deuterium alone takes part and produce more energy, but in addition one or two neutrons are emitted in each case. These neutrons are able to contribute to the fission of uranium and plutonium, as stated in § 1.15, thus adding to the total energy release of the combined fission-fusion system.

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[4] L. N. Ridenour, *Scientific American*, *182*, No. 3, 11 (1950); H. Bethe, *ibid.*, *182*, No. 4, 18 (1950).

[5] An electron volt is the energy that would be acquired by a unit electric charge, i. e., an electron, if accelerated by a potential of 1 volt. The million electron volt unit, i. e., 1 Mev, is one million times as large, and is equivalent to $1.6\times10^{-6}$ erg or $1.6\times10^{-13}$ joule.

## *CHAPTER II*

# DESCRIPTIONS OF NUCLEAR EXPLOSIONS

## INTRODUCTION

2.1 A nuclear explosion is associated with a number of characteristic phenomena, some of which are visible, while others are not directly apparent. Certain aspects of these phenomena will depend on the type of burst, e. g., air, surface, or subsurface, as indicated in Chapter I. In addition, meteorological conditions, such as temperature, humidity, wind, precipitation, and atmospheric pressure may influence some of the observable effects, although the over-all characteristics, to be described below, remain unchanged.

2.2 The descriptions in this chapter refer mainly to the phenomena accompanying the explosion of a 1-megaton TNT equivalent nuclear bomb in the air (or near the surface of the ground). For a shallow underwater burst, the only information available was obtained at Bikini in 1946 when a 20-kiloton device was exploded in water about 200 feet deep. In addition, indications will be given of the results to be expected for explosions of other energy yields. As a general rule, however, the basic phenomena for a burst of a given type are not greatly dependent upon the energy of the explosion.

2.3 In the following discussion, it will be supposed, first, that the explosion takes place in the air at a considerable height above the surface. The modifications resulting from a surface burst will be included. Subsequently, some of the special phenomena associated with underwater and underground bursts will be described.

## DESCRIPTION OF AIR AND SURFACE BURSTS

### THE BALL OF FIRE

2.4 As already seen, the fission of uranium (or plutonium) in a nuclear weapon leads to the liberation of a large amount of energy in a very small period of time within a limited quantity of matter. As a result, the fission products, bomb casing, other weapon parts, and surrounding air are raised to extremely high temperatures, approaching those in the center of the sun. The maximum temperature attained in a fission bomb is probably several million degrees. This may be compared with a maximum of 5,000° C. (or 9,000° F.) in a conventional high-explosive (TNT) bomb. Due to the great heat produced by the nuclear explosion, all the materials are converted into the gaseous form. Since the gases, at the instant of explosion, are restricted to the region occupied by the original constituents in the bomb, tremendous pressures will be produced. These pressures are probably several hundreds of thousands times the atmospheric pressure, i. e., of the order of millions of pounds per square inch.

2.5 Within a few millionths of a second of the detonation of the bomb, the intensely hot gases at extremely high pressure formed in this manner appear as a roughly spherical, highly luminous mass. This is the ball of fire (or fireball) referred to in § 1.25; a typical ball of fire accompanying an air burst is shown in Fig. 2.5. Although the brightness decreases with time, after about seven-tenths (0.7) of a millisecond,[1] the fireball from a 1-megaton nuclear bomb would appear

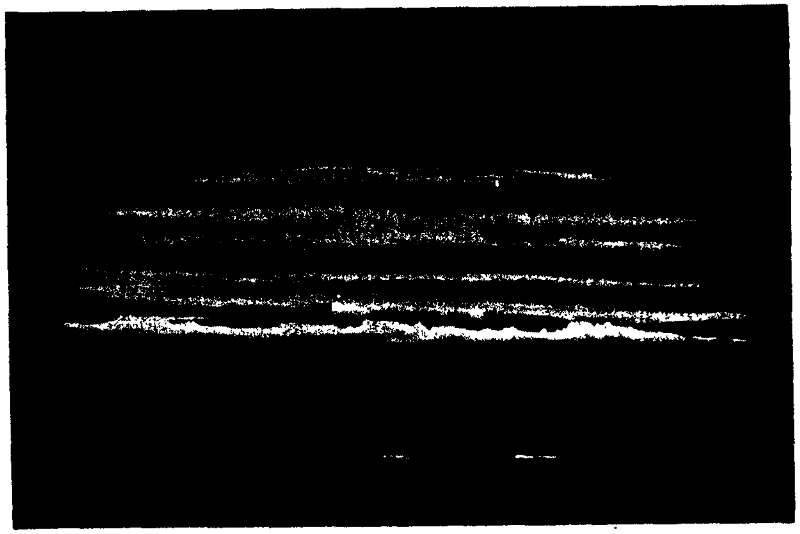

Figure 2.5. Ball of fire from an air burst in the megaton energy range, photographed from an altitude of 12,000 feet at a distance of about 50 miles. The fireball is partially surrounded by the condensation cloud (see § 2.43).

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[1] A millisecond is a one-thousandth part of a second.

to an observer 60 miles away to be more than 30 times as brilliant as the sun at noon. In several of the nuclear tests made at the Nevada Test Site, in all of which the energy yields were less than 100 kilotons, the glare in the sky, in the early hours of the dawn, has been visible 400 (or more) miles away.

2.6 As a general rule, the luminosity does not vary greatly with the energy (or power) of the bomb. The surface temperatures attained, upon which the brightness depends, are thus not very different, in spite of differences in the total amounts of energy released.

2.7 Immediately after its formation, the ball of fire begins to grow in size, engulfing the surrounding air. This growth is accompanied by a decrease in temperature (and pressure) and, hence, of the luminosity. At the same time, the fireball rises, like a hot-air balloon. Within seven-tenths of a millisecond from the detonation, the ball of fire from a 1-megaton bomb reaches a radius of about 220 feet, and this increases to a maximum value of about 3,600 feet in 10 seconds. The ball is then some 7,200 feet across and is rising at the rate of 250 to 350 feet per second. After a minute, the ball of fire has cooled to such an extent that it is no longer visible. It has then risen roughly 4.5 miles from the point of burst.

## The Atomic (Radioactive) Cloud

2.8 While the ball of fire is still luminous, the temperature, in the interior at least, is so high that all the bomb materials are in the form of vapor. This includes the radioactive fission products, uranium (or plutonium) that has escaped fission, and the casing (and other) materials of the bomb. As the fireball increases in size and cools, the vapors condense to form a cloud containing solid particles of the bomb debris, as well as many small drops of water derived from the air sucked into the ascending ball of fire.

2.9 The color of the atomic cloud formed in this manner is initially red or reddish brown, due to the presence of various colored compounds (nitrous acid and oxides of nitrogen) at the surface of the ball of fire. These result from the chemical interaction of nitrogen, oxygen, and water vapor in the air at the existing high temperatures. As the ball of fire cools and condensation occurs, the color of the cloud changes to white, mainly due, as in an ordinary cloud, to the water droplets.

2.10 Depending on the height of burst of the nuclear bomb, and the nature of the terrain below, a strong updraft with inflowing winds, called "afterwinds," is produced in the immediate vicinity. These afterwinds cause varying amounts of dirt and debris to be sucked up from the earth's surface into the atomic cloud (Fig. 2.10).

2.11 At first the rising mass of bomb residue carries the particles upward, but after a time they begin to fall slowly under the influence of gravity, at rates dependent upon their size. Consequently, a lengthening (and widening) column of cloud (or smoke) is produced. This cloud consists chiefly of very small particles of radioactive fission products and bomb residues, water droplets, and larger particles of dirt and debris carried up by the afterwinds.

2.12 The speed with which the top of the radioactive cloud continues to ascend depends on the meteorological conditions as well as on the energy yield of the bomb. An idea of the rate of rise is given by the results in Table 2.12 and the curve in Fig. 2.12. Thus, in general, the cloud will have attained a height of 3 miles in 30 seconds and 4.5 miles in about 1 minute. The average rate of rise during the first minute or so is roughly 260 miles per hour.

### Table 2.12

### RATE OF RISE OF RADIOACTIVE CLOUD

| *Height (miles)* | *Time (minutes)* | *Rate of rise (miles per hour)* |
|---|---|---|
| 2 | 0. 3 | 300 |
| 4 | 0. 75 | 200 |
| 6 | 1. 4 | 140 |
| 10 | 3. 8 | 90 |
| 14 | 6. 3 | 35 |

2.13 The eventual height reached by the radioactive cloud depends upon the heat energy of the bomb, and upon the temperature gradient and density of the surrounding air. The greater the amount of heat liberated the greater will usually be the upward thrust due to buoyancy and so the greater will be the distance the cloud ascends. It is probable, however, that the maximum height attainable by an atomic cloud is affected by the height of the top of the troposphere, i. e., by the base of the stratosphere, for atomic clouds which reach this level.

2.14 As a general rule, the temperature of the atmosphere decreases with increasing altitude. However, in some circumstances, an "inversion layer" occurs, where the temperature begins to increase with altitude. If the radioactive cloud should reach such a temperature inversion layer, it will tend to spread out to some extent. Nevertheless, due to buoyancy of the hot air mass, most of the cloud will usually pass through an inversion layer.

Figure 2.10 Dirt cloud sucked up by the afterwinds in an air burst.

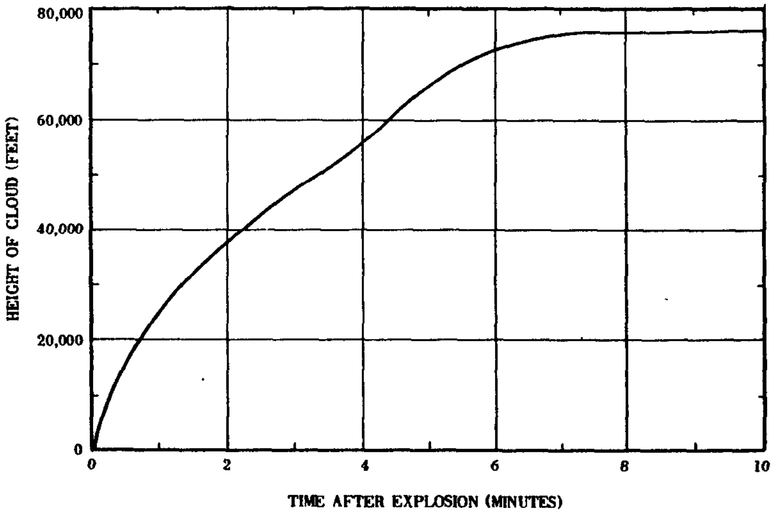

**Figure 2.12** **Height of cloud above burst height at various times after a 1-megaton explosion.**

2.15 Upon reaching a level where its density is the same as that of the surrounding air, or upon reaching the base of the stratosphere, part of the cloud slows its rise, and starts to spread out horizontally. This results in the formation of the mushroom-shaped cloud that is characteristic of nuclear explosions (Fig. 2.15). The maximum altitude of the bottom of the mushroom head, which is attained within about 8 to 10 minutes, is generally from 5 to 10 miles. The top of the cloud rises still higher, the altitude increasing with the energy yield of the explosion. In the tests with devices having energies in the megaton range, carried out in the Pacific during 1952 and 1954, for example, the tops of the clouds rose to heights of about 25 miles. The mushroom cloud generally remains visible for about an hour before it is dispersed by the winds into the surrounding atmosphere and merges with other clouds in the sky.

### Characteristics of a Surface Burst

2.16 Since many of the phenomena and effects of a nuclear explosion occurring on the earth's surface are similar to those associated with an air burst, it is convenient before proceeding further to refer to some of the special characteristics of the former. In a surface

**Figure 2.15.** The mushroom cloud formed in a nuclear explosion in the megaton energy range, photographed from an altitude of 12,000 feet at a distance of about 50 miles.

burst, the ball of fire, in its rapid initial growth, will touch the surface of the earth (Fig. 2.16a). Because of the intense heat, a considerable amount of rock, soil, and other material located in the area will be vaporized and taken into the ball of fire. It has been estimated that, if only 5 percent of a 1-megaton bomb's energy is spent in this manner, something like 20,000 tons of vaporized soil material will be added to the normal constituents of the fireball. In addition, the high winds at the earth's surface will cause large amounts of dirt, dust, and other particles to be sucked up as the ball of fire rises (Fig. 2.16b).

2.17 An important difference between a surface burst and an air burst is, consequently, that in the surface burst the atomic cloud is much more heavily loaded with debris. This will consist of particles ranging in size from the very small ones produced by condensation as the ball of fire cools to the much larger particles which have been raised by the surface winds. The exact composition of the cloud will, of

course, depend on the nature of the terrain and the extent of contact with the ball of fire.

2.18 For a surface burst associated with a moderate amount of debris, such as has been the case in several test explosions, in which the bombs were detonated near the ground, the rate of rise of the cloud is much the same as given earlier for an air burst (Table 2.12). The atomic cloud reaches a height of several miles before spreading out into a mushroom shape, as described in § 2.15.

2.19 The vaporization of dirt and other material when the ball of fire has touched the earth's surface, and the removal of material by the blast wave and winds accompanying the explosion, result in the formation of a crater. The size of the crater will vary with the height above the surface at which the bomb is exploded and with the character of the soil, as well as with the energy of the bomb. It is believed that, for a 1-megaton bomb, there would be no appreciable crater formation unless detonation occurs at an altitude of 450 feet or less.

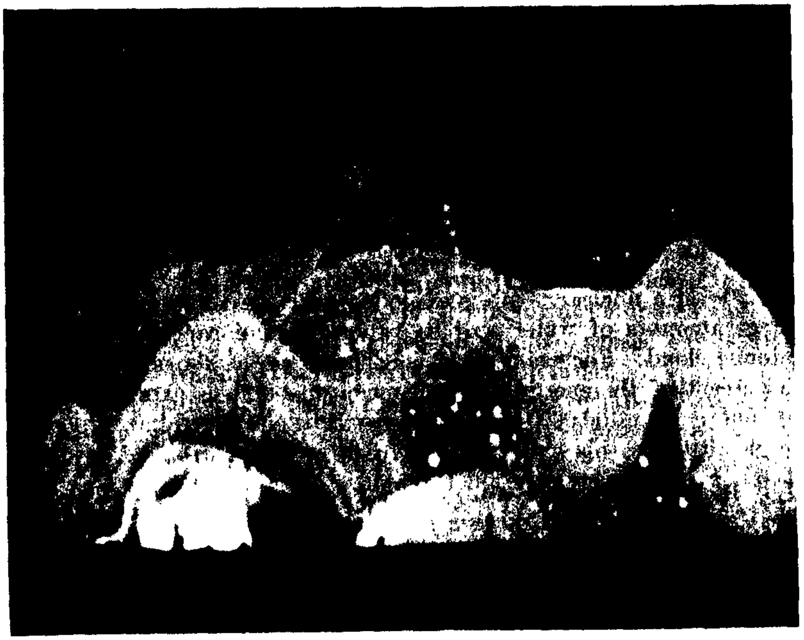

**Figure 2.16a.** Ball of fire formed by a nuclear explosion in the megaton energy range near the earth's surface. The maximum diameter of the fireball was 3¼ miles.

**Figure 2.16b. Formation of dirt cloud in a surface burst.**

2.20 If a nuclear bomb is exploded near the surface of the water, large amounts of water will be vaporized and carried up into the atomic cloud. For example, if it is supposed, as above (§ 2.16), that 5 percent of the energy of the 1-megaton bomb is expended in this manner, about 100,000 tons of water will be converted into vapor. At high altitudes this will condense to form water droplets, similar to those in an ordinary atmospheric cloud.

### THE FALLOUT

2.21 In a *surface burst*, large quantities of earth or water enter the fireball at an early stage and are fused or vaporized. When sufficient cooling has occurred, the fission products become incorporated with the earth particles as a result of the condensation of vaporized fission products into fused particles of earth, etc. A small proportion of the solid particles formed upon further cooling are contaminated fairly uniformly throughout with radioactive fission products and other bomb residues, but in the majority the contamination is found mainly in a thin shell near the surface. In water droplets, the small fission product particles occur at discrete points within the drops. As the violent disturbance due to the exploding bomb subsides, the contaminated particles and droplets gradually fall back to earth. This effect is referred to as the "fallout." It is the fallout, with its associated radioactivity which decays over a long period of time, that is the main source of the residual nuclear radiations referred to in the preceding chapter.[2]

2.22 The extent and nature of the fallout can range between wide extremes. The actual behavior will be determined by a combination of circumstances associated with the energy yield and design of the bomb, the height of the explosion, the nature of the surface beneath the point of burst, and the meteorological conditions. In the case of an air burst, for example, occurring at an appreciable distance above the earth's surface, so that no large amounts of dirt or water are sucked into the cloud, the contaminated particles become widely dispersed. The magnitude of the hazard from fallout in any moderate sized area will then be far less than if the explosion were a surface burst. Thus at Hiroshima and Nagasaki, where approximately 20-kiloton bombs were exploded about 1,850 feet above the surface, casualties due to fallout were completely absent.

2.23 On the other hand, a nuclear explosion occurring at or near the earth's surface can result in severe contamination by the radioactive fallout. In the case of the powerful thermonuclear device tested at Bikini Atoll on March 1, 1954, which was detonated close to the surface of a coral island, the ensuing fallout caused substantial contamination over an area of over 7,000 square miles.

2.24 The contaminated area was roughly cigar-shaped, extending approximately 20 (statute) miles up-wind and 220 miles down-wind. The width in the cross-wind direction was variable, the maximum being close to 40 miles. Actually, both the direction and the velocity of the wind, particularly in the upper atmosphere, have a significant influence on the shape and extent of the contaminated area. As will be seen later, the wind characteristics must be taken into consideration in attempting to predict the fallout pattern following a nuclear explosion.

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[2] Another, but much less important, source is the radioactivity induced in various materials by neutrons at the time of the explosion, particularly in regions fairly close to the point of burst.

2.25 It should be understood that the fallout is a gradual phenomenon extending over a period of time. In the Bikini explosion referred to above, for example, several (about 10) hours elapsed before the contaminated particles began to fall at the extremities of the 7,000 square mile area. By that time, the atomic cloud had thinned out to such an extent that it was no longer visible. This brings up the important fact that fallout can occur even when the radioactive atomic cloud cannot be seen. Nevertheless, most of the fallout generally results from the larger contaminated particles of dirt and debris which drop from the mushroom cloud at distances not too far from the region of the explosion. This is referred to as the "local fallout." There is, in addition, another kind of fallout, consisting of very fine particles which descend very slowly and eventually cover large areas in a fairly uniform manner. This is the "world-wide fallout" to which the residues from nuclear explosions of all types—air, surface, and subsurface—may contribute (see Chapter X).

2.26 Although the thermonuclear test of March 1, 1954 produced the most extensive local fallout yet recorded, it should be pointed out that the phenomenon was not necessarily characteristic of (nor restricted to) thermonuclear explosions. It is very probable that if the same device had been detonated at an appreciable distance above the coral island, so that the large ball of fire did not touch the surface of the ground, the local fallout would have been of insignificant proportions.

2.27 Of course, special circumstances might arise in which there would be appreciable local fallout even with an air burst. If it were to rain at the time of, or soon after, the explosion, the raindrops would carry down with them some of the radioactive particles. Such was the case in Test ABLE, at Bikini in July 1946, when a 20-kiloton nuclear bomb was detonated a few hundred feet above the surface of the lagoon. Within 2 or 3 hours of the explosion light rain showers developed in the vicinity, and the raindrops were found to be radioactive. The extent of the radioactivity in this case was, however, relatively small.

### THE BLAST WAVE

2.28 At a fraction of a second after the explosion, a high-pressure wave develops and moves outward from the ball of fire (Fig. 2.28). This is the "blast wave," to be considered subsequently in more detail, which is the cause of much destruction accompanying an air burst. The front of the blast wave, called the "shock front," travels rapidly away from the fireball, behaving like a moving wall of highly compressed air. After the lapse of 10 seconds, when the fireball of a 1-megaton nuclear bomb has attained its maximum size (7,200 feet across), the shock front is some 3 miles further ahead. At 50 seconds after the explosion, when the ball of fire is no longer visible, the blast wave has traveled about 12 miles. It is then moving at about 1,150 feet per second, which is slightly faster than the speed of sound at sea level.

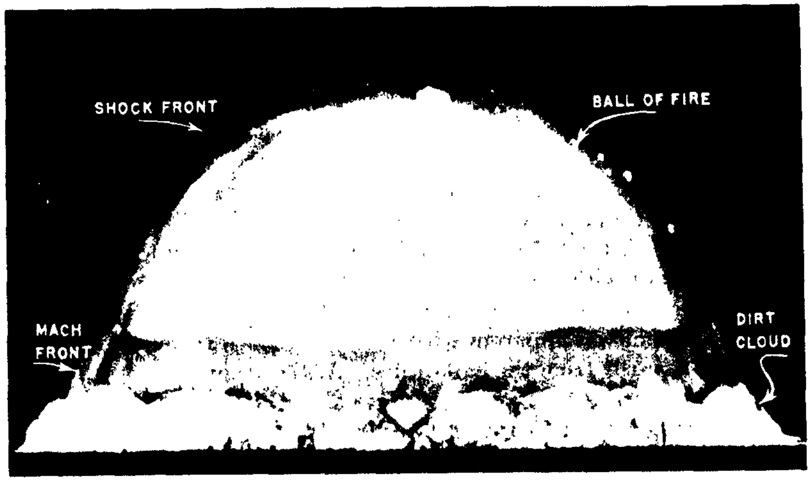

Figure 2.28. The faintly luminous shock front seen just ahead of the ball of fire soon after breakaway.

2.29 When the blast wave strikes the surface of the earth, it is reflected back, similar to a sound wave producing an echo. This reflected blast wave, like the original (or direct) wave, is also capable of causing material damage. At a certain region on the surface, the position of which depends chiefly on the height of the burst above the surface and the energy of the explosion, the direct and reflected shock fronts fuse. This fusion phenomenon is called the "Mach effect." The "overpressure," i. e., the pressure in excess of the normal atmospheric value, at the front of the Mach wave is generally about twice as great as that at the direct shock front.

2.30 For a typical air burst of a 1-megaton nuclear weapon (see § 2.47), the Mach effect will begin approximately 5 seconds after the explosion, in a rough circle at a radius of 1.3 miles from ground zero. The term "ground zero" refers to the point on the earth's surface immediately below (or above) the point of detonation.[3] For a burst over (or under) water, the corresponding point is generally called "surface zero."

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[3] In some publications, ground zero is called the "hypocenter" of the explosion.

2.31 At first the height of the Mach front is small, but as the shock front continues to move outward, the height increases steadily. At the same time, however, the overpressure, like that in the original shock wave, decreases correspondingly because of the continuous loss of energy and the ever-increasing area of the advancing front. After the lapse of about 40 seconds, when the Mach front from a 1-megaton nuclear bomb is 10 miles from ground zero, the overpressure will have decreased to roughly 1 pound per square inch.[4]

2.32 The distance from ground zero at which the Mach effect commences varies with the height of burst. Thus, as seen in Fig. 2.28, in the low-altitude detonation at the TRINITY (Alamogordo) test, the Mach front was apparent when the direct shock front had advanced only a few yards from the ball of fire. At the other extreme, in a very high air burst there might be no detectable Mach effect.

2.33 In addition to the ground wind (or afterwind) due to the updraft caused by the rising ball of fire (§ 2.10), strong transient winds are associated with the passage of the shock (and Mach) front. These winds may have peak velocities of several hundred miles per hour at points fairly near ground zero; and even at more than 6 miles from the explosion of a 1-megaton nuclear bomb, the peak velocity may be greater than 70 miles per hour. It is evident that such strong winds can contribute greatly to the blast damage following an air burst.

## THERMAL RADIATION

2.34 Immediately after the ball of fire is formed, it starts to emit thermal radiation. Because of the very high temperatures, this consists of ultraviolet (short wave length), as well as visible and infrared (long wave length) rays. Due to certain phenomena associated with the absorption of the thermal radiation by the air in front of the ball of fire (see § 2.76, *et seq.*), the surface temperature undergoes a curious change. The temperature of the interior falls steadily, but the surface temperature of the ball of fire decreases more rapidly for a small fraction of a second. Then, the apparent surface temperature increases again for a somewhat longer time, after which it falls continuously (see Fig. 2.92). In other words, there are effectively two surface-temperature pulses; the first is of very short duration, whereas the second lasts for a much longer time. The behavior is quite general, although the duration times of the pulses increase with the energy yield of the explosion.

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[4] The normal atmospheric pressure at sea level is 14.7 pounds per square inch.

2.35 Corresponding to the two temperature pulses, there are two pulses of emission of thermal radiation from the ball of fire (Fig. 2.35). In the first pulse, which lasts about a tenth part of a second for a 1-megaton explosion, the temperatures are mostly very high. As a result, much of the radiation emitted in this pulse is in the ultraviolet region. Moderately large doses of ultraviolet radiation can produce painful blisters, and even small doses can cause reddening of the skin. However, in most circumstances, the first pulse of thermal radiation is not a significant hazard, with regard to skin burns, for several reasons. In the first place, only about 1 percent of the thermal radiation appears in the initial pulse because of its short duration. Second, the ultraviolet rays are readily attenuated by the intervening air, so that the dose delivered at a distance from the explosion may be comparatively small. Further, it appears that the ultraviolet radiation from the first pulse could cause significant effects on the human skin only within ranges at which other radiation effects are much more serious.

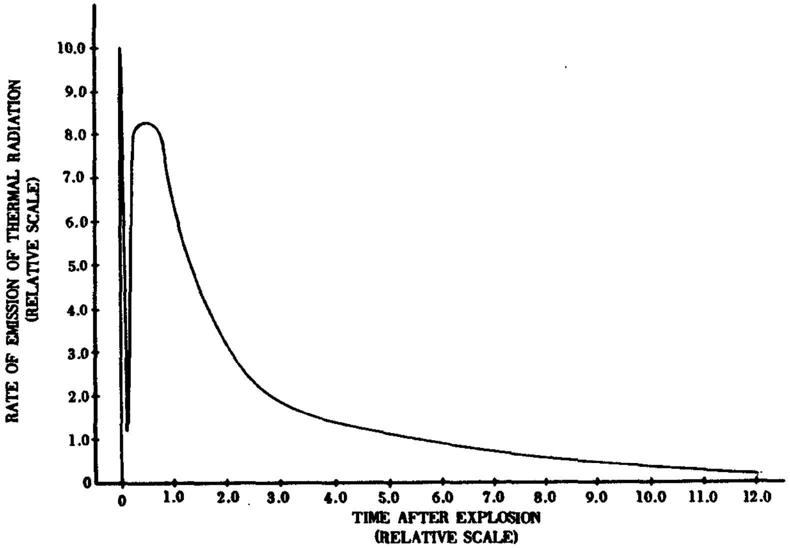

**Figure 2.35. Emission of thermal radiation in two pulses.**

2.36 The situation with regard to the second pulse is, however, quite different. This pulse may last for several seconds and carries about 99 percent of the total thermal radiation energy from the bomb.

Since the temperatures are lower than in the first pulse, most of the rays reaching the earth consist of visible and infrared (invisible) light. It is this radiation which is the main cause of skin burns of various degrees suffered by exposed individuals up to 12 miles or more from the explosion of a 1-megaton bomb. For bombs of higher energy, the effective damage range is greater, as will be explained in Chapter VII. The radiation from the second pulse can also cause fires to start under suitable conditions.

## Initial Nuclear Radiation

2.37 As stated in Chapter I, the explosion of a nuclear bomb is associated with the emission of various nuclear radiations. These consist of neutrons, gamma rays, and alpha and beta particles. Essentially all the neutrons and part of the gamma rays are emitted in the actual fission process. That is to say, these radiations are produced simultaneously with the nuclear explosion. Some of the neutrons liberated in fission are immediately absorbed (or captured) by various nuclei present in the bomb, and this capture process is usually also accompanied by the instantaneous emission of gamma rays. The remainder of the gamma rays and the beta particles are liberated over a period of time as the fission products undergo radioactive decay. The alpha particles are expelled, in an analogous manner, as a result of the decay of the uranium (or plutonium) which has escaped fission in the bomb.

2.38 The *initial nuclear radiation* is generally defined as that emitted from both the ball of fire and the atomic cloud within the *first minute after the explosion*. It includes neutrons and gamma rays given off almost instantaneously, as well as the gamma rays emitted by the radioactive fission products in the rising cloud. It should be noted that, although alpha and beta particles are present in the initial radiation, they have not been considered. This is because they are so easily absorbed that they will not reach more than a few yards, at most, from the atomic cloud.

2.39 The somewhat arbitrary time period of 1 minute for the duration of the initial nuclear radiations was originally based upon the following considerations. As a consequence of attenuation by the air, the effective range of the fission gamma rays and of those from the fission products from a 20-kiloton explosion is very roughly 2 miles. In other words, gamma rays originating from such a source at an altitude of over 2 miles can be ignored, as far as their effect at the earth's surface is concerned. Thus, when the atomic cloud has reached a height of 2 miles, the effects of the initial nuclear radiations are no longer significant. Since it takes roughly a minute for the cloud to rise this distance, the initial nuclear radiation was defined as that emitted in the first minute after the explosion.

2.40 The foregoing arguments are based on the characteristics of a 20-kiloton nuclear bomb. For a bomb of higher energy, the maximum distance over which the gamma rays are effective will be larger than given above. However, at the same time, there is an increase in the rate at which the cloud rises. Similarly for a bomb of lower energy, the effective distance is less, but so also is the rate of ascent of the cloud. The period over which the initial nuclear radiation extends may consequently be taken to be approximately the same, namely, 1 minute, irrespective of the energy release of the bomb.

2.41 Neutrons are the only significant nuclear radiations produced directly in the thermonuclear reactions mentioned in § 1.55. Alpha particles (helium nuclei) are also formed, but they do not travel very far from the explosion. Some of the neutrons will escape but others will be captured by the various nuclei present in the exploding bomb. Those neutrons absorbed by fissionable species may lead to the liberation of more neutrons as well as to the emission of gamma rays, just as described above for an ordinary fission bomb. In addition, the capture of neutrons in nonfission reactions is usually accompanied by gamma rays. It is seen, therefore, that the initial radiations from a bomb in which both fission and fusion (thermonuclear) processes occur consist essentially of neutrons and gamma rays. The relative proportions of these two radiations may be somewhat different than for a bomb in which all the energy release is due to fission, but for present purposes the difference may be disregarded.

## Other Nuclear Explosion Phenomena

2.42 There are a number of interesting phenomena associated with a nuclear air burst that are worth mentioning although they have no connection with the destructive or other harmful effects of the bomb. Soon after the detonation, a violet-colored glow may be observed, particularly at night or in dim daylight, at some distance from the ball of fire. This glow may persist for an appreciable length of time, being distinctly visible near the head of the atomic cloud. It is believed to be the ultimate result of a complex series of processes initiated by the action of gamma rays on the nitrogen and oxygen of the air.

2.43 Another early phenomenon following a nuclear explosion in certain circumstances is the formation of a "condensation cloud." This is sometimes called the Wilson cloud (or cloud-chamber effect) because it is the result of conditions analogous to those utilized by scientists in the Wilson cloud chamber. It will be seen in Chapter III that the passage of a high-pressure shock front in air is followed by a rarefaction (or suction) wave. During the compression (or blast) phase, the temperature of the air rises and during the decompression (or suction) phase it falls. For moderately low blast pressures, the temperature can drop below its original, preshock value, so that if the air contains a fair amount of water vapor, condensation, accompanied by cloud formation, will occur.

2.44 The condensation cloud which was clearly observed in the ABLE Test at Bikini in 1946, is shown in Fig. 2.44. Since the bomb was detonated just above the surface of the lagoon, the air was nearly saturated with water vapor and the conditions were suitable for the production of a Wilson cloud. It can be seen from the photograph that the cloud forms some way ahead of the ball of fire. The reason is that the shock front must travel a considerable distance before the blast pressure has fallen sufficiently for a low temperature to be attained in the subsequent decompression phase. At the time the temperature has dropped sufficiently for condensation to occur, the shock front has moved still further away, as is apparent in Fig. 2.44, where the disk-like formation on the surface of the water indicates the passage of the shock wave.

Figure 2.44. Condensation cloud formed in an air burst over water.

2.45 Because of the necessity for relatively high humidity of the air, the conditions for the formation of the condensation cloud are most favorable in nuclear explosions occurring over (or under) water, as in the Bikini tests in 1946. The cloud commenced to form 1 to 2 seconds after the detonation, and it had dispersed completely within another second or so, as the air warmed up and the water droplets evaporated. The original dome-like cloud first changed to a ring shape, as seen in Fig. 2.45, and then disappeared.

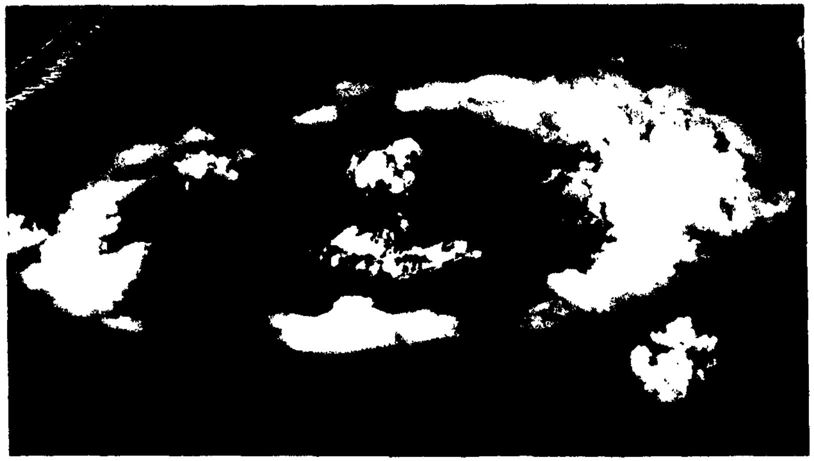

Figure 2.45. Late stage of the condensation cloud in an air burst over water.

2.46 Since the Wilson condensation cloud forms after the ball of fire has emitted most of its thermal radiation, it has little influence on this radiation. It is true that fairly thick clouds, especially smoke clouds, can attenuate the thermal radiation reaching the earth from the ball of fire. However, apart from being formed at too late a stage, the condensation cloud is too tenuous to have any appreciable effect in this connection.

### CHRONOLOGICAL DEVELOPMENT OF AN AIR BURST

2.47 The more important aspects of the description given above of a nuclear explosion in the air are summarized in Figs. 2.47a to 2.47e.

(Text continued on page 41)

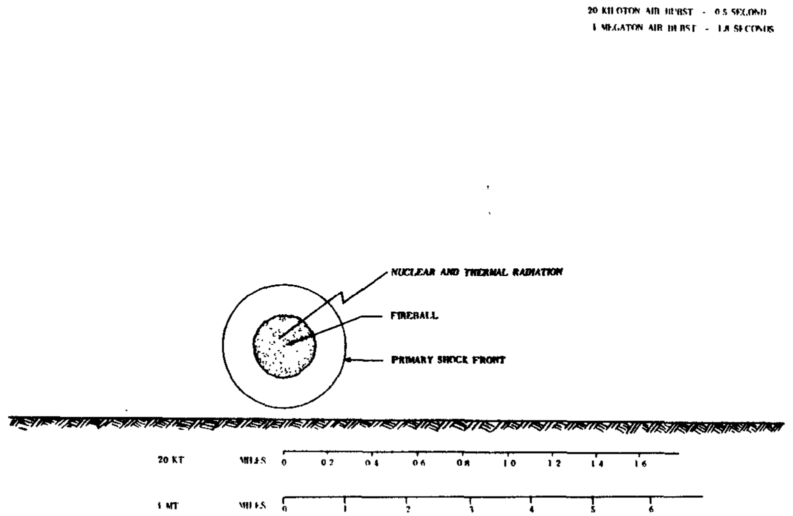

**Figure 2.47a. Chronological development of an air burst: 0.5 second after 20-kiloton detonation; 1.8 seconds after 1-megaton detonation.**

Immediately following the detonation of a nuclear bomb in the air, an intensely hot and luminous (gaseous) ball of fire is formed. Due to its extremely high temperature, it emits thermal (or heat) radiation capable of causing skin burns and starting fires in flammable material at a considerable distance. The nuclear processes which cause the explosion and the radioactive decay of the fission products are accompanied by harmful nuclear radiations (gamma rays and neutrons) that also have a long range in air. Very soon after the explosion, a destructive shock (or blast) wave develops in the air and moves rapidly away from the fireball.

At the times indicated, the ball of fire has almost attained its maximum size, as shown by the figures given below:

| | *Diameter of fireball (feet)* | |
|---|---|---|
| | *20 kilotons* | *1 megaton* |
| At time indicated | 1,460 | 6,300 |
| Maximum | 1,550 | 7,200 |

The shock front in the air is seen to be well ahead of the fireball, about 750 feet for the 20-kiloton explosion and a little over one-half mile for the 1-megaton detonation.

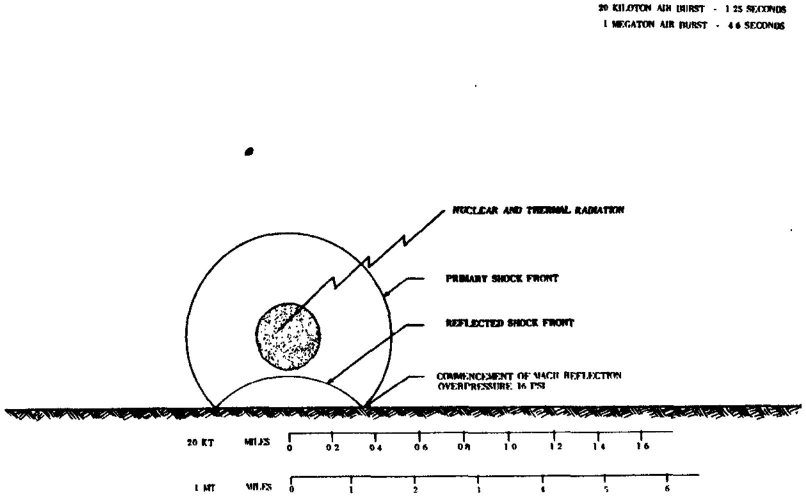

**Figure 2.47b. Chronological development of an air burst: 1.25 seconds after 20-kiloton detonation; 4.6 seconds after 1-megaton detonation.**

When the primary shock (or blast) wave from the explosion strikes the ground, another shock (or blast) wave is produced by reflection. At a certain distance from ground zero, which depends upon the height of burst and the energy of the bomb, the primary and reflected shock fronts fuse near the ground to form a single, reinforced Mach front (or stem).

The time and distance at which the Mach effect commences for a typical air burst are as follows:

| *Explosion yield* | *Time after detonation (seconds)* | *Distance from ground zero (miles)* |
|---|---|---|
| 20 kilotons | 1.25 | 0.35 |
| 1 megaton | 4.6 | 1.3 |

The overpressure at the earth's surface is then 16 pounds per square inch.

Significant quantities of thermal and nuclear radiations continue to be emitted from the ball of fire.

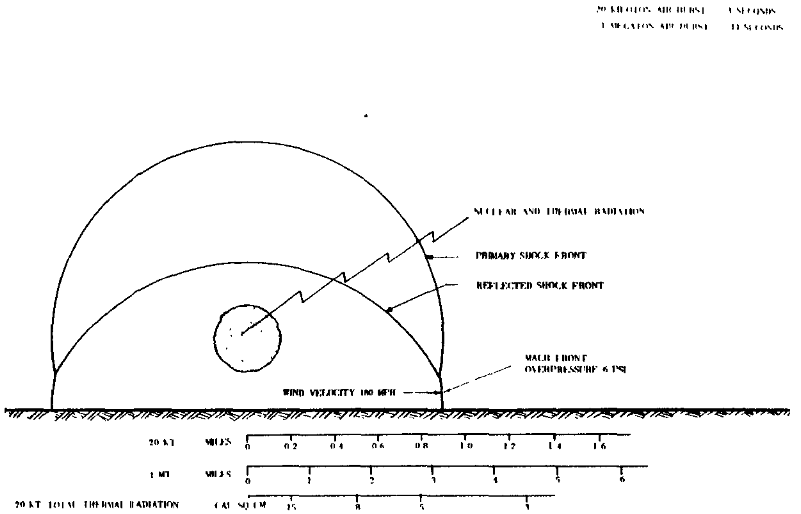

Figure 2.47c. Chronological development of an air burst: 3 seconds after 20-kiloton detonation; 11 seconds after 1-megaton detonation.

As time progresses, the Mach front (or stem) moves outward and increases in height. The distance from ground zero and the height of the stem at the times indicated are as follows:

| Explosion yield | *Time after detonation (seconds)* | *Distance from ground zero (miles)* | *Height of stem (feet)* |
|---|---|---|---|
| 20 kilotons | 3 | 0.87 | 185 |
| 1 megaton | 11 | 3.2 | 680 |

The overpressure at the Mach front is 6 pounds per square inch and the blast wind velocity immediately behind the front is about 180 miles per hour.

Nuclear radiations still continue to reach the ground in significant amounts. But after 3 seconds from the detonation of a 20-kiloton bomb, the fireball, although still very hot, has cooled to such an extent that the thermal radiation is no longer important. The total accumulated amounts of thermal radiation, expressed in calories per square centimeter, received at various distances from ground zero after a 20-kiloton air burst, are shown on the scale at the bottom of the figure (for further details, see Chapter VII). Appreciable amounts of thermal radiation still continue to be emitted from the fireball at 11 seconds after a 1-megaton explosion; the thermal radiation emission is spread over a longer time interval than for an explosion of lower energy yield.

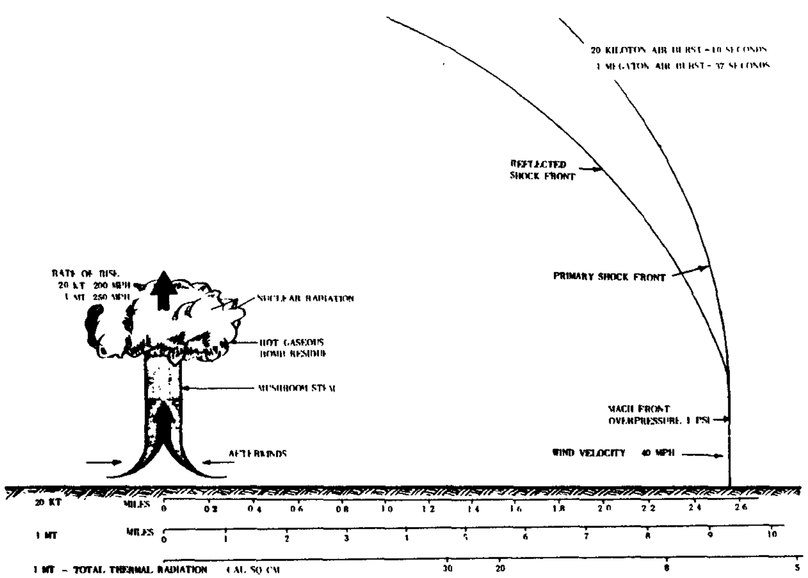

Figure 2.47d. Chronological development of an air burst: 10 seconds after 20-kiloton detonation; 37 seconds after 1-megaton detonation.

At 10 seconds after a 20-kiloton explosion the Mach front is over 2½ miles from ground zero, and 37 seconds after a 1-megaton detonation it is nearly 9½ miles from ground zero. The overpressure at the front is roughly 1 pound per square inch, in both cases, and the wind velocity behind the front is 40 miles per hour. Apart from plaster damage and window breakage, the destructive effect of the blast wave is essentially over. Thermal radiation is no longer important, even for the 1-megaton burst, the total accumulated amounts of this radiation, at various distances, being indicated on the scale at the bottom of the figure. Nuclear radiation, however, can still reach the ground to an appreciable extent; this consists mainly of gamma rays from the fission products.

The ball of fire is no longer luminous, but it is still very hot and it behaves like a hot-air balloon, rising at a rapid rate. As it ascends, it causes air to be drawn inward and upward, somewhat similar to the updraft of a chimney. This produces strong air currents, called afterwinds, which raise dirt and debris from the earth's surface to form the stem of what will eventually be the characteristic mushroom cloud.

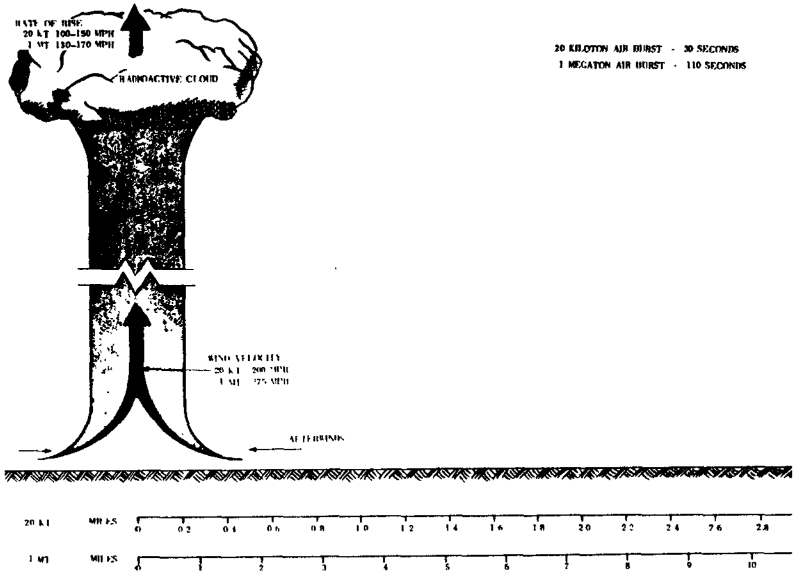

**Figure 2.47e. Chronological development of an air burst: 30 seconds after 20-kiloton detonation; 110 seconds after 1-megaton detonation.**

The hot residue of the bomb continues to rise and at the same time it expands and cools. As a result, the vaporized fission products and other bomb residues condense to form a cloud of highly radioactive particles. The afterwinds, having velocities of 200 or more miles per hour, continue to raise a column of dirt and debris which will later join with the radioactive cloud to form the characteristic mushroom shape. At the times indicated, the cloud from a 20-kiloton explosion will have risen about 1½ miles and that from a 1-megaton explosion about 7 miles. Within about 10 minutes, the bottom of the mushroom head will have attained an altitude of 5 to 15 miles, according to the energy yield of the explosion. The top of the cloud will rise even higher. Ultimately, the particles in the cloud will be dispersed by the wind, and, except under weather conditions involving precipitation, there will be no appreciable local fallout.

Although the atomic cloud is still highly radioactive, very little of the nuclear radiation reaches the ground. This is the case because of the increased distance of the cloud above the earth's surface and the decrease in the activity of the fission products due to natural radioactive decay.

(Text continued from page 35)

These show the chronological development of the various phenomena associated with a typical air burst, defined as a burst at such a height above the earth that it is expected to cause the maximum blast damage to an average city. Because of the operation of certain simple rules, called scaling laws (see Chapter III), it is possible to represent times and distances for two different explosion energies, namely 20 kilotons and 1 megaton, on one set of drawings.

2.48 It should be noted that the drawings are schematic only, and do not represent what can be seen. All the eye is likely to see, if not blinded by the brilliance, is the ball of fire and the atomic cloud. (The Wilson condensation cloud is not included since this requires high humidity and is, in any event, not of practical significance.) The blast accompanying shock passage can be felt, and the skin is sensitive to the thermal radiation, but none of the human senses can detect the nuclear radiations in moderate amounts. At very high intensities, however, nuclear radiations cause itching and tingling of the skin.

## DESCRIPTION OF AN UNDERWATER BURST

### UNDERWATER EXPLOSION PHENOMENA

2.49 Although there are certain characteristic phenomena associated with an underwater nuclear explosion, the details will undoubtedly vary with the energy yield of the bomb, the distance below the surface at which the detonation occurs, and the depth and area of the body of water. The description given here is based on the observations made at the BAKER test at Bikini in 1946. In this test, a 20-kiloton nuclear bomb was detonated well below the surface of the lagoon which was about 200 feet deep. In 1955, a nuclear device was exploded deep under water, but the observations made were not applicable to civilian defense.

2.50 In an underwater nuclear detonation, a ball of fire is formed, but it is probably smaller than in the case of an airburst. At the BAKER test, the water in the vicinity of the explosion was lighted up by the luminosity of the ball of fire. The distortion caused by the natural waves on the surface of the lagoon prevented a clear view of the fireball, and the general effect was similar to that of light seen through a ground glass screen. The luminosity remained for a few thousandths of a second, but it disappeared as soon as the bubble of hot, high-pressure gases constituting the ball of fire reached the water surface. At this time, the gases were expelled and cooled, so that the fireball was no longer visible.

2.51 In the course of its rapid expansion, the hot gas bubble, while still under water, initiates a shock wave. The trace of this wave, as it moves outward from the burst, is evident, on a reasonably calm surface, as a rapidly advancing circle, apparently whiter than the surrounding water. This phenomenon, sometimes called the "slick," is visible in contrast to the undisturbed water because small droplets of water at the surface are hurled short distances into the air, and the resulting entrainment of air makes the shocked water surface look white.

2.52 Following immediately upon the appearance of the slick, and prior to the formation of the Wilson cloud, a mound or column of broken water and spray, called the "spray dome," is thrown up over the point of the burst (Fig. 2.52). This is a consequence of the reflection of the shock wave at the surface. The initial upward velocity of the water is proportional to the pressure of the direct shock wave, and so it is greatest directly above the detonation point. Consequently, the water in the center rises more rapidly (and for a longer time) than water farther away. As a result, the sides of the spray dome become steeper as the water rises. The upward motion is terminated by the downward pull of gravity and the resistance of the air. The total time of rise and the maximum height attained depend upon the energy of the explosion, and upon its depth below the water surface. For a very deep underwater burst, the spray dome may not be visible at all.

2.53 If the depth of burst is not too great, the bubble of hot, compressed gases remains essentially intact until it rises to the surface of the water. At this point the gases, carrying some liquid water by entrainment, are expelled into the atmosphere. Part of the shock wave passes through the surface into the air and because of the high humidity, the conditions are suitable for the formation of a condensation cloud (Fig. 2.53a). As the pressure of the bubble is released, water rushes into the cavity, and the resultant complex phenomena cause the water to be thrown up as a hollow cylinder or chimney of spray called the "column." The radioactive contents of the gas bubble are vented through this hollow column and form a cauliflower-shaped cloud at the top (Fig. 2.53b).

2.54 In the shallow underwater (BAKER) burst at Bikini, the spray dome began to form at about 4 milliseconds after the explosion. Its initial rate of rise was roughly 2,500 feet per second, but this was rapidly diminished by air resistance and gravity. A few milliseconds later, the hot gas bubble reached the surface of the lagoon and the column began to form, quickly overtaking the spray dome. The maxi-

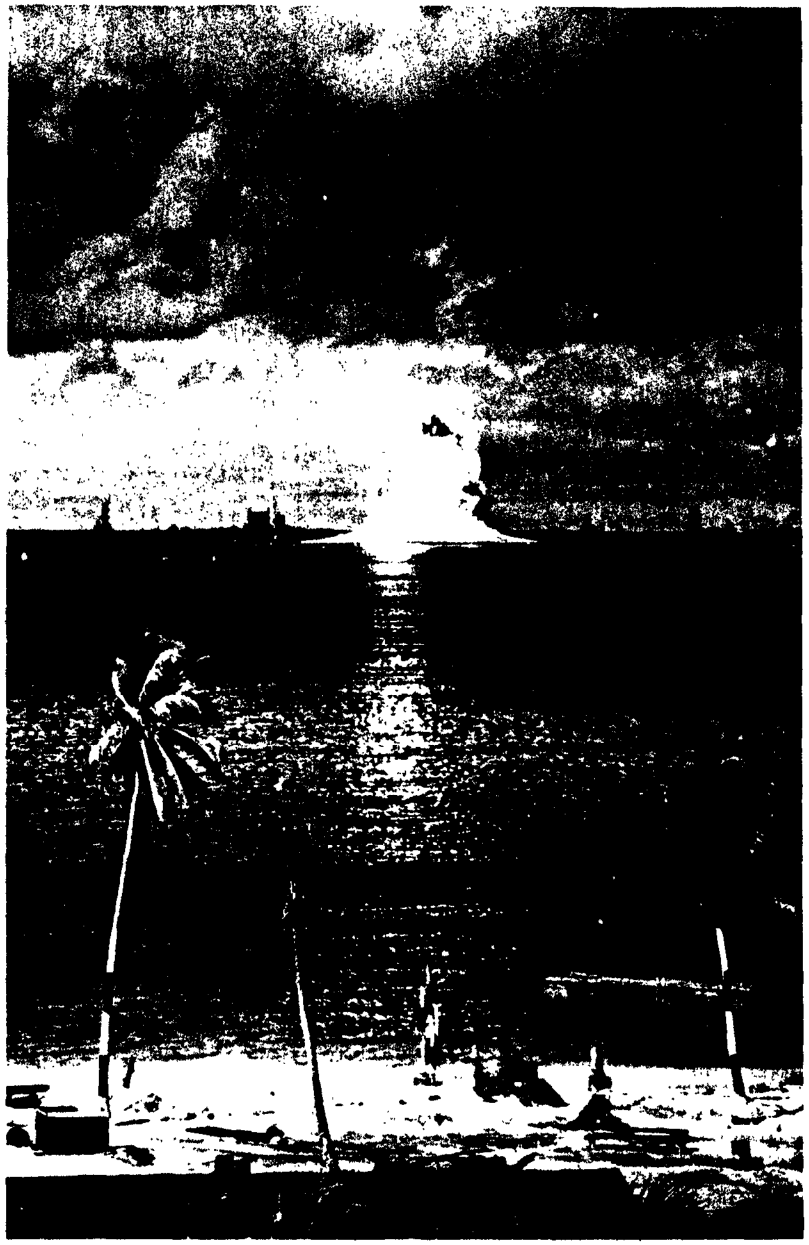

Figure 2.52. The "spray dome" formed over the point of burst in an underwater explosion.

Figure 2.53a. The condensation cloud formed after a shallow underwater explosion. (The "slick," due to the shock wave, can be seen on the water surface.)

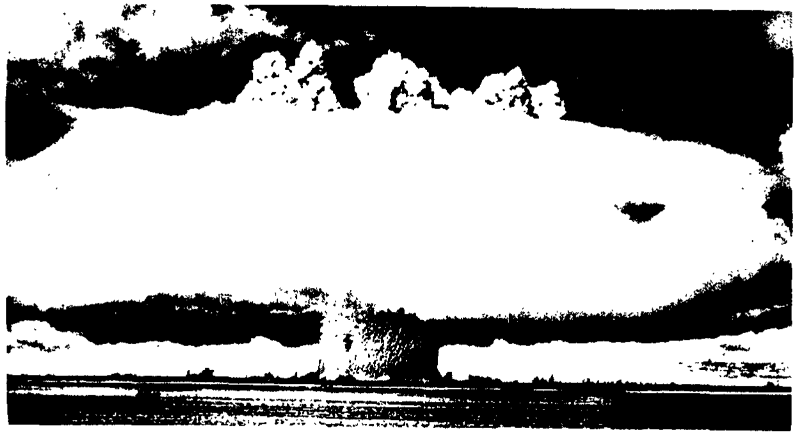

Figure 2.53b. Formation of the hollow column in an underwater explosion, the top is surrounded by a late stage of the condensation cloud.

mum height attained by the hollow column, through which the gases vented, could not be estimated exactly because the upper part was surrounded by the atomic cloud (Fig. 2.54). The column was probably some 6,000 feet high and the maximum diameter was about 2,000 feet. The walls were probably 300 feet thick, and approximately a million tons of water were raised in the column.

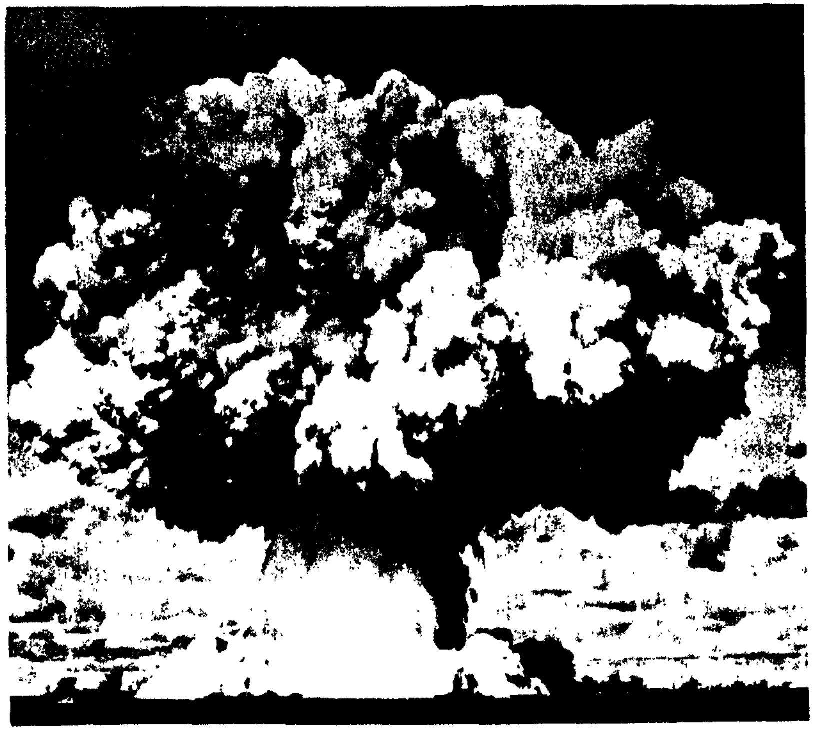

Figure 2.54. The radioactive cloud and first stages of the base surge following an underwater burst. Water is beginning to fall back from the column into the lagoon.

2.55 The cauliflower-shaped cloud, which concealed part of the upper portion of the column, contained some of the fission products and other bomb residues, as well as a large quantity of water in small droplet form. In addition, there is evidence that material sucked up from the bottom of the lagoon was also present, for a calcareous (or chalky) sediment, which must have dropped from the atomic cloud, was found on the decks of ships some distance from the burst. The cloud was roughly 6,000 feet across and ultimately rose to a height of nearly 10,000 feet before being dispersed. This is considerably less than the height attained by an atomic cloud in an air burst.

2.56 The disturbance created by the underwater burst caused a series of waves to move outward from the center of the explosion across the surface of Bikini lagoon. At 11 seconds after the detonation, the first wave had a maximum height of 94 feet and was about 1,000 feet from surface zero. This moved outward at high speed and was followed by a series of other waves. At 22,000 feet from surface zero, the ninth wave in the series was the highest with a height of 6 feet.

### The Base Surge

2.57 As the column of water and spray fell back into the lagoon in the BAKER test, there developed a gigantic wave (or cloud) of mist completely surrounding the column at its base (Fig. 2.54). This doughnut-shaped cloud, moving rapidly outward from the column, is called the "base surge." It is essentially a dense cloud of water droplets, much like the spray at the base of Niagara Falls (or other high waterfalls), but having the property of flowing almost as if it were a homogeneous fluid.

2.58 The base surge at Bikini commenced to form at 10 or 12 seconds after the detonation. The surge cloud, billowing upward, rapidly attained a height of 900 feet, and moved outward at an initial rate of more than a mile a minute. Within 4 minutes the outer radius of the cloud, growing rapidly at first and then more slowly, was nearly 3½ miles across and its height had then increased to 1,800 feet. At this stage, the base surge gradually rose from the surface of the water and began to merge with the atomic cloud and other clouds in the sky (Fig. 2.58).

2.59 After about 5 minutes, the base surge had the appearance of a mass of strato-cumulus clouds which eventually reached a thickness of several thousand feet (Fig. 2.59). A moderate to heavy rainfall, moving with the wind and lasting for nearly an hour, developed from the cloud mass. In its early stages the rain was augmented by the small water droplets still descending from the atomic cloud.

2.60 From the weapons effects standpoint, the importance of the base surge lies in the fact that it is likely to be highly radioactive due to fission products present either at its inception, or dropped into it from the atomic cloud. Because of its radioactivity, it may represent a serious hazard for a distance of several miles, especially in the downwind direction (see Chapter IX). Any object over which the base surge passes is likely to become contaminated, due to the deposition of water droplets to which fission products may have become attached. The base surge and the fallout or "rainout" from the atomic cloud constitute the sources of the residual nuclear radiation following an underwater nuclear explosion.

Figure 2.58. The development of the base surge following an underwater explosion.

2.61 The necessary conditions for the formation of a base surge have not been definitely established. However, base surge formation will occur if an appreciable column is formed. The probability of such an occurrence increases with an increase in the depth of burst, up to reasonable depths.

2.62 In the event of a sufficiently deep underwater nuclear explosion, the hot gas bubble loses its identity in a mass of turbulent water before reaching the surface. In these circumstances, there is no large column of water and spray and, hence, little or no base surge. The disintegration of the gas bubble into a large number of small bubbles, which are churned up with the water, will produce a radioactive foam or froth. When this reaches the surface, a small amount of mist is formed, but most of the activity is retained in the water. There is thus

Figure 2.59. Final stage in the development of the base surge.

no atomic cloud from a deep underwater burst and, consequently, no extensive fallout. The deposition of the highly active foam on a nearby shore, however, could constitute a hazard.

### THERMAL AND NUCLEAR RADIATIONS

2.63 Essentially all the thermal radiation emitted by the ball of fire while it is still submerged is absorbed by the surrounding water. When the hot gases reach the surface and expand, the cooling is so rapid that the temperature drops almost immediately to a point where there is no further appreciable emission of thermal radiation. It follows, therefore, that in an underwater nuclear explosion the thermal radiation can be ignored, as far as its effects on personnel and as a source of fire are concerned.

2.64 It is probable, too, that most of the neutrons and gamma rays liberated within a short time of the initiation of the explosion will also be absorbed by the water. But, when the fireball reaches the surface and the gases are expelled, the gamma rays (and beta particles) from the fission products will represent a form of initial nuclear radiation. In addition, the radiation from the fission (and induced radioactive) products, present in the column, atomic cloud, and base surge, all three of which are formed within a few seconds of the burst, will contribute to the initial effects.

2.65 However, the water fallout (or rainout) from the cloud and the base surge are also responsible for the residual nuclear radiations, as described above. For an underwater burst, it is thus less meaningful to make a sharp distinction between initial and residual radiations, such as is done in the case of an air burst. The initial nuclear radiations merge continuously into those which are produced over a period of time following the nuclear explosion.

### CHRONOLOGICAL DEVELOPMENT OF A SHALLOW UNDERWATER BURST

2.66 The series of drawings in Figs. 2.66a to 2.66e give a schematic representation of the chronological development of the phenomena associated with a shallow, underwater burst of a 100-kiloton nuclear bomb. The data supplement the information relating to a 20-kiloton explosion given above. Essentially all the effects, other than the shock front and the nuclear radiation, are visible to the eye.

## DESCRIPTION OF AN UNDERGROUND BURST

### UNDERGROUND EXPLOSION PHENOMENA

2.67 When a nuclear bomb is exploded under the ground, a ball of fire is formed consisting of extremely hot gases at high pressures, including vaporized earth and bomb residues. If the detonation occurs at not too great a depth, the fireball may be seen as it breaks through the surface, before it is obscured by clouds of dirt and dust. As the gases are released, they carry up with them into the air large quantities of earth, rock, and debris in the form of a cylindrical column, analogous to that observed in an underwater burst. In the underground test explosion at a shallow depth, made in Nevada in 1951, the column assumed the shape of an inverted cone, fanning out as it rose to cause a radial throw-out (Fig. 2.67). Because of the large amount of material removed by the explosion, a crater of considerable size was left in the ground.

2.68 It is estimated from tests made in Nevada that, if a 1-megaton bomb were dropped from the air and penetrated underground in

(Text continued on page 55)

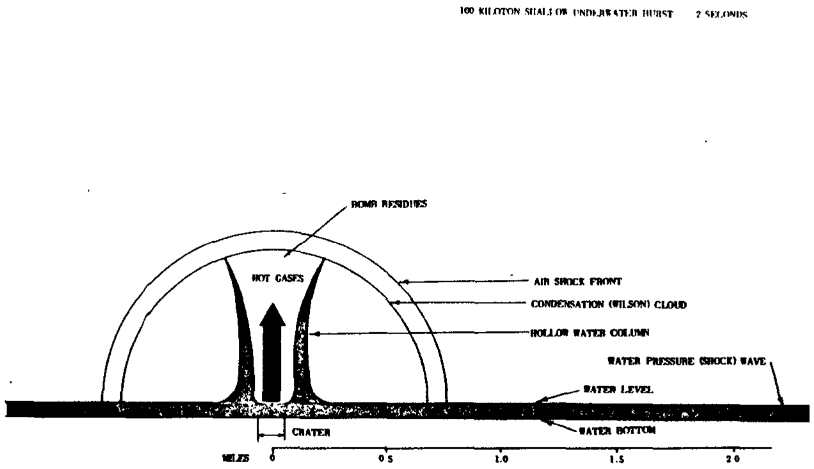

Figure 2.66a. Chronological development of a 100-kiloton shallow underwater burst: 2 seconds after detonation.

When a nuclear bomb is exploded under the surface of water, a bubble of intensely hot gases is formed which will burst through the surface if the detonation occurs at a shallow depth. As a result, a hollow column of water and spray is shot upward, reaching a height of over 5,000 feet in 2 seconds after a 100-kiloton explosion. The gaseous bomb residues are then vented through the hollow central portion of the water column.

The shock (or pressure) wave produced in the water by the explosion travels outward at high speed, so that at the end of 2 seconds it is more than 2 miles from surface zero. The expansion of the hot gas bubble also results in the formation of a shock (or blast) wave in the air, but this moves less rapidly than the shock wave in water, so that the front is some 0.8 mile from surface zero.

Soon after the air shock wave has passed, a dome-shaped cloud of condensed water droplets, called the condensation cloud, is formed for a second or two. Although this phenomenon is of scientific interest, it has apparently no significance as far as nuclear attack or defense is concerned.

For an underwater burst at moderate (or great) depth, essentially all of the thermal radiation and much of the initial nuclear radiation is absorbed by the water.

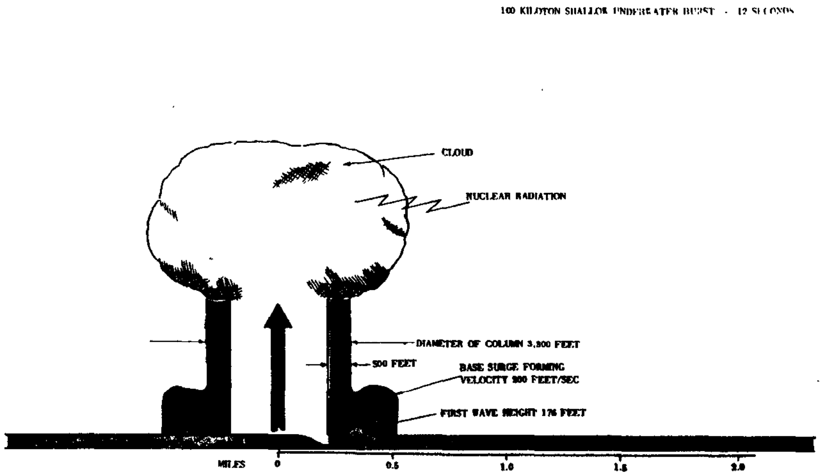

Figure 2.66b. Chronological development of a 100-kiloton shallow underwater burst: 12 seconds after detonation.

At 12 seconds after the 100-kiloton explosion, the diameter of the water column is about 3,300 feet, and its walls are some 500 feet thick. The bomb residues venting through the hollow central portion condense and spread out to form the cauliflower-shaped atomic cloud, partly obscuring the top of the column. The cloud is highly radioactive, due to the presence of fission products, and hence it emits nuclear radiations. Because of the height of the cloud these radiations are a minor hazard to persons near the surface of the water.

At 10 to 12 seconds after a shallow underwater explosion, the water falling back from the column reaches the surface and produces around the base of the column a ring of highly radioactive mist, called the base surge. This ring-shaped cloud moves outward, parallel to the water surface, at high speed, initially 200 feet per second (135 miles per hour).

The disturbance due to the underwater explosion causes large water waves to form on the surface. At 12 seconds after a 100-kiloton explosion, the first of these is about 1,800 feet (0.34 mile) from surface zero, and its height, from crest to trough, is 176 feet.

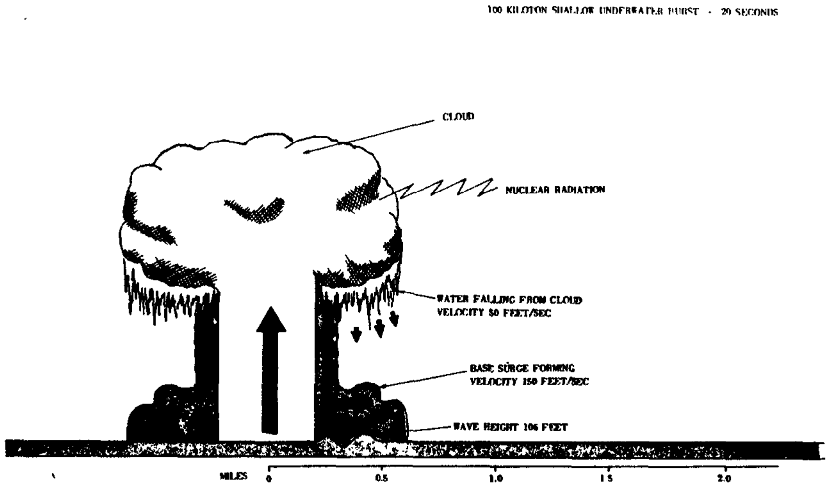

**Figure 2.66c. Chronological development of a 100-kiloton shallow underwater burst: 20 seconds after detonation.**

As the water and spray forming the column continue to descend, the base surge cloud develops, billowing upward and moving outward across the surface of the water. At 20 seconds after the 100-kiloton explosion the height of the base surge is about 1,000 feet and its front is nearly ½ mile from surface zero. It is then progressing outward at a rate of approximately 150 feet per second (100 miles per hour).

At about this time, large quantities of water, sometimes referred to as the massive water fallout, begin to descend from the atomic cloud. The initial rate of fall is about 50 feet per second. Because of the loss of water from the column, in one way or another, its diameter has now decreased to 2,000 feet.

By the end of 20 seconds, the first water wave has reached about 2,000 feet (0.38 mile) from surface zero and its height is roughly 106 feet.

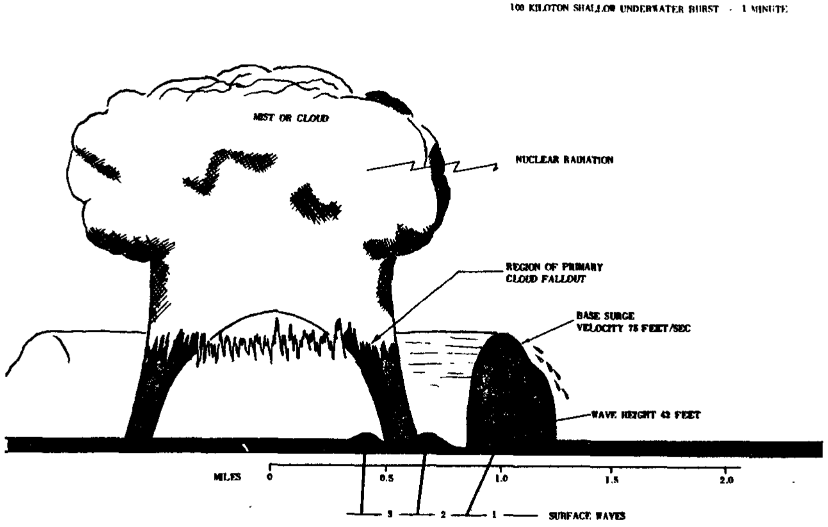

**Figure 2.66d. Chronological development of a 100-kiloton shallow underwater burst: 1 minute after detonation.**

At 1 minute after the underwater burst, the water falling from the atomic cloud reaches the surface, forming a region of primary cloud fallout. There is consequently a continuous ring of water and spray between the cloud and the surface of the water.

At about this time, the base surge has become detached from the bottom of the column, so that its ring-like character is apparent. The height of the base surge cloud is now 1,300 feet and its front, moving outward at some 75 feet per second (50 miles per hour), is about 1.2 miles from surface zero. Because of the radioactivity of the water droplets constituting the base surge, the latter represents a hazard to personnel.

Several water waves have now developed, the first, with a height of 42 feet, being approximately 1 mile from surface zero.

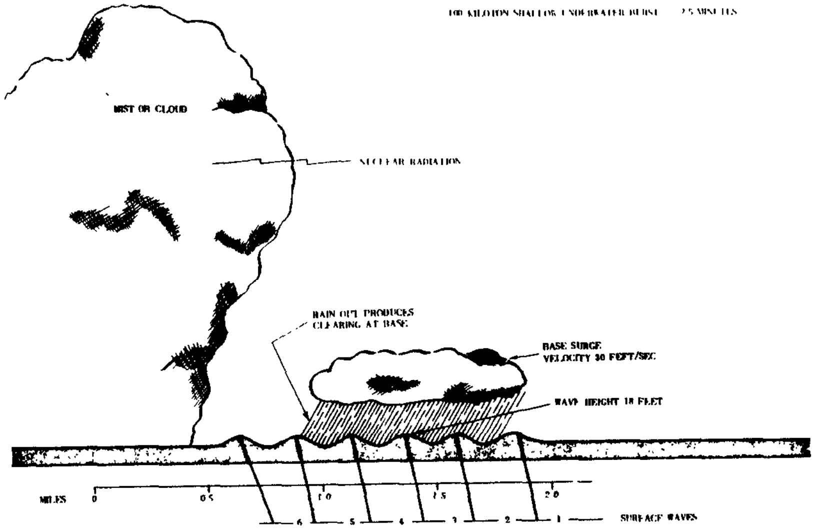

Figure 2.66e. Chronological development of a 100-kiloton shallow underwater burst: 2.5 minutes after detonation.

By 2½ minutes after the 100-kiloton underwater explosion, the front of the base surge is nearly 2 miles from ground zero and its height is roughly 2,000 feet. The greatest effective spread of the base surge cloud, reached in 4 minutes, is approximately 2½ miles from surface zero, i. e., 5 miles across. The base surge now appears to be rising from the surface of the water. This effect is attributed to several factors, including an actual increase in altitude, thinning of the cloud by engulfing air, and raining out of the larger drops of water. Owing to natural radioactive decay of the fission products, to rainout, and to dilution of the mist by air, the intensity of the nuclear radiation from the base surge at 2½ minutes after the explosion is only one-twentieth of that at 1 minute.

The descent of water and spray from the column and from condensation in the atomic cloud results in the formation of a continuous mass of mist or cloud down to the surface of the water. Ultimately, this merges with the base surge, which has spread and increased in height, and also with the natural clouds of the sky, to be finally dispersed by the wind.

Figure 2.67. Shallow underground burst.

(Text continued from page 49)

sandy soil to a depth of 50 feet before exploding, the resulting crater would be about 190 feet deep and nearly 1,400 feet across. This means that approximately 10 million tons of soil and rock would be hurled upward from the earth's surface. The volume of the crater and the mass of material thrown up by the force of the explosion will increase roughly in proportion to the energy of the bomb. As they descend to earth, the finer particles of soil may initiate a base surge, as will be described below.

2.69 The rapid expansion of the bubble of hot, high-pressure gases formed in the underground burst initiates a shock wave in the earth. Its effects are somewhat similar to those of an earthquake of moderate intensity, except that the disturbance originates fairly near the surface instead of at a great depth. The difference in depth of origin means that the pressures in the underground shock wave caused by a nuclear bomb probably fall off more rapidly with distance than do those due to earthquake waves. Further, both the energy of a nuclear explosion and the duration of the shock wave are less than for an earthquake.

2.70 As in an underwater burst, part of the energy released by the bomb in an underground explosion appears as a blast wave in the air. The fraction of the energy imparted to the air in the form of blast depends primarily upon the depth of the burst. The greater the penetration of the bomb before detonation occurs, the smaller is the proportion of the shock energy that escapes into the air.

### BASE SURGE AND FALLOUT

2.71 When the material thrown up as a column of dirt in an underground explosion falls back to earth, it will, in many instances, produce an expanding cloud of fine soil particles similar to the base surge observed in the Bikini BAKER test. For example, the early stages of a base surge formation can be seen in Fig. 2.71, which resembles Fig. 2.58 in many respects. The base surge of dirt particles moves outward from the center of the explosion and is subsequently carried downwind. Eventually the particles settle out and produce radioactive contamination over a large area, the extent of which will depend upon the depth of burst, the nature of the soil, and the atmospheric conditions, as well as upon the energy yield of the bomb. It is believed that a dry sandy terrain will be particularly conducive to base surge formation in an underground burst.

Figure 2.71. Base surge formation in underground burst.

2.72 The atomic cloud resulting from an underground explosion will inevitably contain a very large amount of soil, rocks, and a variety of debris. There will, consequently, be a considerable fallout of contaminated matter. The larger pieces thrown up by the explosion will be the first to reach the earth and so they will be deposited near the location of the burst. But the smaller particles will remain suspended in the air for some time and may be carried great distances by the wind before they eventually settle out.

### THERMAL AND NUCLEAR RADIATIONS

2.73 The situation as regards thermal and nuclear radiations from an underground burst are quite similar to those described above in connection with an underwater explosion. As a general rule, the thermal radiation will be almost completely absorbed by the soil material, so that it does not represent a significant hazard. Most of the neutrons and early gamma rays will also be removed, although the capture of the neutrons may cause a considerable amount of induced radioactivity in various materials present in the soil. This will constitute a small part of the residual nuclear radiation, of importance only in the close vicinity of the point of burst. The remainder of the residual radiation will be due to the contaminated base surge and fallout.

2.74 For the same reasons as were given in § 2.64 for an underwater burst, the initial and residual radiations from an underground burst tend to merge into one another. The distinction which is made in the case of an air burst is consequently less significant in a subsurface explosion.

### CHRONOLOGICAL DEVELOPMENT OF A SHALLOW UNDERGROUND BURST

2.75 The chronological development of some of the phenomena associated with an underground nuclear explosion, having an energy yield of 100 kilotons, at a shallow depth is represented by Figs. 2.75a to 2.75d.

(Text continued on page 62)

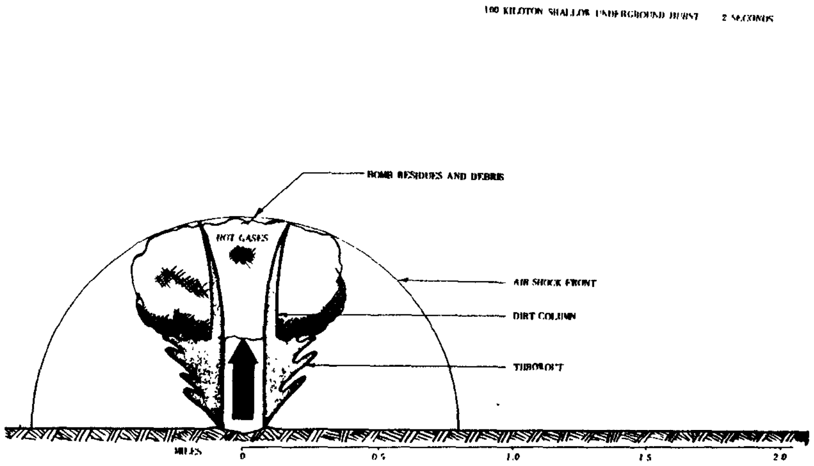

Figure 2.75a. Chronological development of a 100-kiloton shallow underground burst: 2.0 seconds after detonation.

When a nuclear explosion occurs at a shallow depth underground, the ball of fire breaks through the surface of the earth within a fraction of a second of the instant of detonation. As the fireball penetrates the surface, the intensely hot gases at high pressure are released and they carry up with them into the air large quantities of soil, rock, and debris in the form of a hollow column. For a burst at a shallow depth, the column tends to assume the shape of an inverted cone which fans out as it rises to produce a radial throw-out. A highly radioactive cloud, which contains large quantities of earth, is formed above the throw-out as the hot vapors cool and condense. Because of the mass displacement of material from the earth's surface, a crater is formed. For a 100-kiloton bomb exploding 50 feet beneath the surface of dry soil, the crater would be about 120 feet deep and 720 feet across. The weight of the material removed would be over a million tons.

In addition to the shock (or pressure) wave in the ground, somewhat related to an earthquake wave, the explosion is accompanied by a shock (or blast) wave in the air. At 2 seconds after the explosion, the shock front in air is about ¾ mile from surface zero.

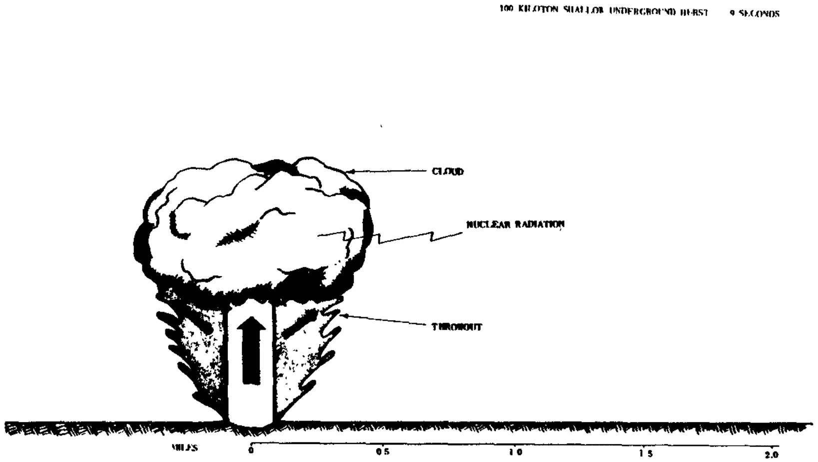

Figure 2.75b. Chronological development of a 100-kiloton shallow underground burst: 9.0 seconds after detonation.

The atomic cloud continues to rise, giving off intense nuclear radiations which are still a hazard on the ground at 9 seconds after the detonation. At this time, the larger pieces of rock and debris in the throw-out begin to descend to earth.

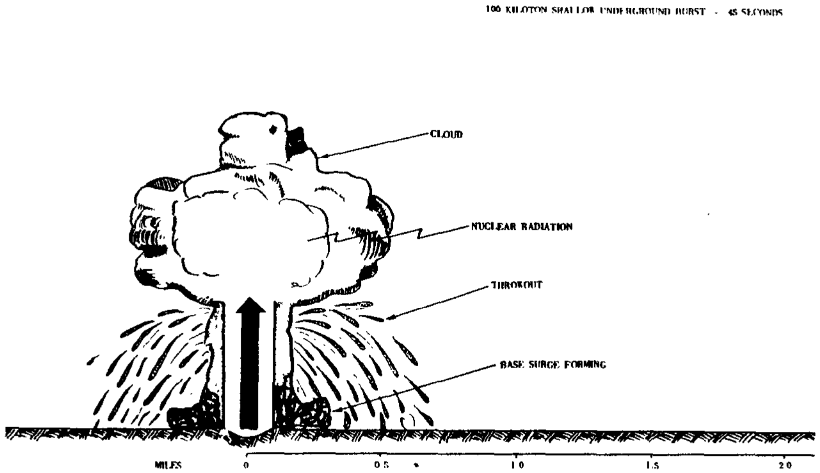

Figure 2.75c. Chronological development of a 100-kiloton shallow underground burst: 45 seconds after detonation.

As the material from the column descends, the finer soil particles attain a high velocity and upon reaching the ground they spread out rapidly to form a base surge similar to that in an underwater explosion. The extent of the base surge, which is likely to be radioactive, depends upon many factors, including the energy yield of the explosion, the depth of burst, and the nature of the soil. It is believed that a dry sandy terrain will be particularly conducive to base surge formation.

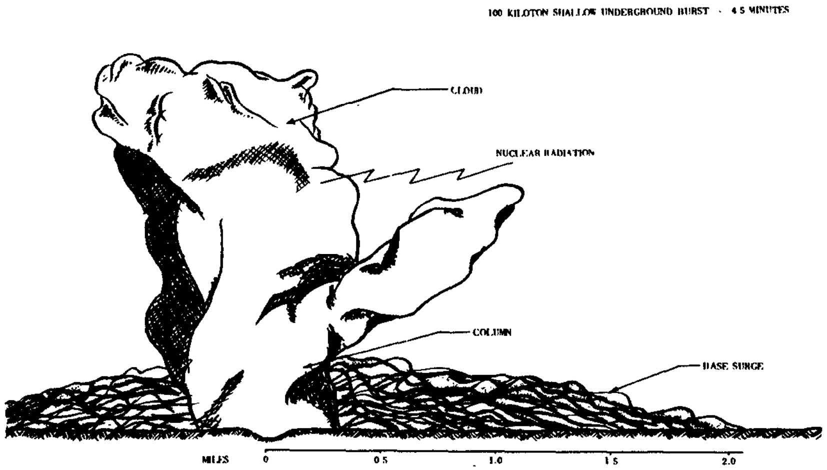

Figure 2.75d. Chronological development of a 100-kiloton shallow underground burst: 4.5 minutes after detonation.

The base surge increases in height and area and soon begins to merge with the atomic cloud of bomb residues, etc., part of which descends and spreads out under the influence of the prevailing winds. In due course, the radioactive clouds disperse, but the contaminated particles descend to earth to produce a hazardous fallout over a large area, especially in the downwind direction, during the course of a few hours.

(Text continued from page 57)

## SCIENTIFIC ASPECTS OF NUCLEAR EXPLOSION PHENOMENA[5]

### Development of the Ball of Fire in an Air Burst

2.76 In the very earliest stages of its formation, the temperature throughout the ball of fire is uniform. The energy produced as a result of fission (and fusion) can travel rapidly as radiation between any two points within the sphere of hot gases, and so there are no appreciable temperature gradients. Because of the uniform temperature, the system is referred to as an "isothermal sphere" which, at this stage, is identical with the ball of fire.

2.77 As the ball of fire grows and a blast wave develops in the air, as stated above, the shock front at first coincides with the surface of the isothermal sphere and the ball of fire. However, when the temperature falls below about 300,000° C. (540,000° F.), the shock front advances more rapidly than the isothermal sphere. In other words, the transport of energy by the blast wave is now faster than by radiation.

2.78 Since thermal radiation consists of "photons," traveling with the speed of light, it is not immediately obvious why the transport of energy as radiation should be slower than by the blast wave. A simplified explanation of this phenomenon is somewhat as follows. Because of the high temperature of the ball of fire, most (about 70 percent) of the radiation is concentrated in the ultraviolet region of the spectrum in which the wave lengths are less than 1,860 A. In cold air, through which the radiation is transmitted as the fireball grows in size, such radiation is strongly absorbed and the mean free path, i. e., the average distance a photon travels before it is absorbed by an atom or a molecule, is very small, of the order of 0.01 cm. or less.

2.79 On the average, each photon moves with the velocity of light for a distance of a mean free path. It is then absorbed by an atom, molecule, or gaseous ion, usually of nitrogen or oxygen present in the air, which is thereby converted into a high-energy (or excited) state. The material remains in the excited state for a certain time, after which it reverts to its lower energy (or ground) state by the emission of a photon. This photon then moves on in a random direction, with the speed of light, only to be subsequently captured by an atom or molecule of the air, followed by a re-emission, and so on. Because of the short mean free path of the radiations of wave length less than 1,860 A, and also on account of the fact that the photons move in a random path, due to their successive absorptions and emissions, the over-all rate of transport of such radiation is relatively small.

2.80 It should be understood that this slow transport applies only to radiations in the very short wave length region of the spectrum. For thermal radiations of longer wave length, i. e., in excess of 1,860 A, the proportion of which increases as the surface of the ball of fire cools, the mean free path in air is greatly increased. Consequently, those radiations lying in the near ultraviolet and in the visible and infrared regions of the spectrum are propagated from the fireball with the velocity of light.

2.81 As the shock front moves ahead of the isothermal sphere it causes a tremendous compression of the air before it. As a result, the temperature is increased to a sufficient extent to render the air incandescent. The ball of fire now consists of two concentric regions. The inner (hotter) region is the isothermal sphere of uniform temperature, and this is surrounded by a layer of luminous, shock-heated air at a somewhat lower, but still very high, temperature. The surface of separation between the very hot core and the somewhat cooler outer layer is called the "radiation front."

2.82 The phenomena described above are represented schematically in Fig. 2.82; qualitative temperature gradients are shown at the left and pressure gradients at the right of a series of photographs of the ball of fire at various intervals after detonation of a 20-kiloton nuclear bomb. It is seen that in the first three pictures the temperature is uniform throughout the fireball, which is then identical with the isothermal sphere. This is indicated by the horizontal temperature lines within the ball of fire and a sharp drop at the exterior. After the lapse of about 0.5 millisecond, two temperature regions commence to form, as the front of the fireball, i. e., the shock front, moves away from the isothermal sphere. The outer region of the ball of fire absorbs the radiation and so prevents the isothermal sphere from being visible. The photographs, therefore, show only the exterior surface of the fireball.

2.83 From the shape of the curves at the right of Fig. 2.82, the nature of the pressure changes in the ball of fire can be understood. In the early (isothermal) stages the pressure is uniform throughout, but after about 0.5 millisecond the shock front begins to separate from the isothermal sphere, as is indicated by the somewhat higher

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[5] The remaining sections of this chapter may be omitted without loss of continuity.

pressure near the surface of the fireball. Within less than 1 millisecond the steep-fronted shock wave has traveled some distance ahead of the isothermal region. The rise of the pressure in the fireball to a peak, which is characteristic of a shock wave, followed by a sharp drop at the external surface, implies that the latter is identical with the

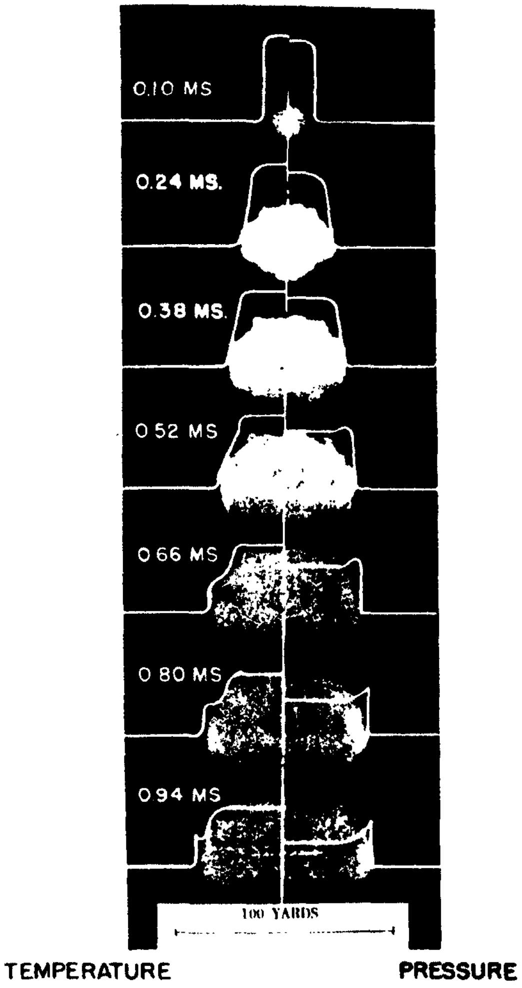

Figure 2.82. Variation of temperature and pressure in the ball of fire. (Times and dimensions apply to a 20-kiloton explosion.)

shock front. It will be noted, incidentally, from the photographs, that the surface of the ball of fire, which has hitherto been somewhat uneven, has now become sharply defined.

2.84 For some time the ball of fire continues to grow in size at a rate determined by the propagation of the shock front in the surrounding air. During this period the pressure at the shock front decreases steadily, so that the air through which it travels is rendered less and less luminous. Eventually, the faintly visible shock front moves ahead of the much hotter and still incandescent interior of the ball of fire (Fig. 2.28). The onset of this condition, at about 0.017 second after detonation of a 20-kiloton bomb, for example, is referred to as the "breakaway".

2.85 Following the breakaway, the visible ball of fire continues to increase in size at a slower rate than before, the maximum dimensions being attained after about a second or so. The manner in which the radius increases with time, in the period from roughly 0.1 millisecond ($10^{-4}$ second) to 1 second after the detonation of a 20-kiloton nuclear bomb, is shown in Fig. 2.85. Attention should be called to the fact that both scales are logarithmic, so that the lower portion of the curve (at the left) does not represent a constant rate of growth, but

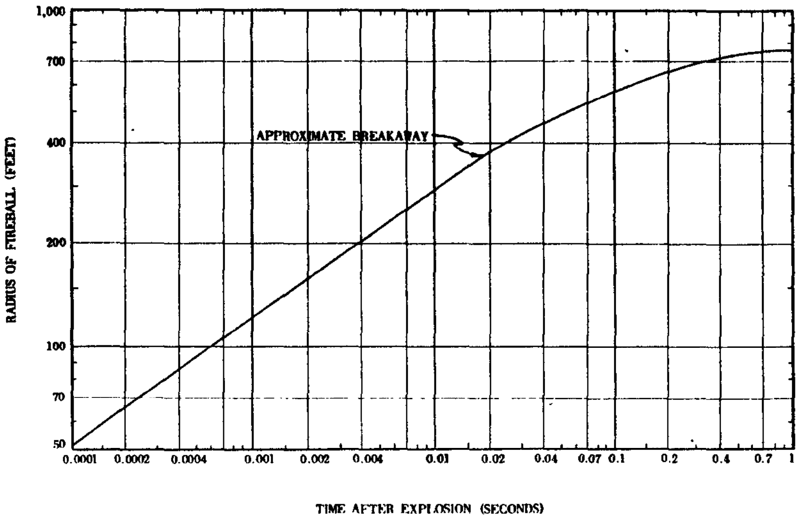

Figure 2.85. Variation of radius of luminous ball of fire with time in a 20-kiloton explosion.

rather one that falls off with time. Nevertheless, the marked decrease in the rate at which the fireball grows after the breakaway is apparent from the flattening of the curve at this time.

## Bomb Energy and Size of Ball of Fire

2.86 The results of numerous tests have shown that the maximum size of the luminous ball of fire may be represented by a scaling law in the form of the equation

$$\frac{R}{R_0}=\left(\frac{W}{W_0}\right)^{2/5},$$

where $R$ is the maximum radius of the luminous fireball for a bomb with an energy yield of $W$ kilotons TNT equivalent and $R_0$ is the (known) value for a reference bomb of $W_0$ kilotons.

2.87 By making use of this scaling law, together with the results obtained at various nuclear test explosions, it is possible to derive the relationship

$$R\text{ (feet)}=230W^{2/5}, \qquad (2.87.1)$$

from which the maximum radius of the luminous fireball (in feet) for a bomb energy of $W$ kilotons TNT equivalent can be readily calculated.

2.88 The fireball radius required to estimate the height of burst above which a given explosion will cause negligible local fallout, has been found to correspond to that at the time of the second thermal maximum (see Fig. 2.92). The appropriate expression for a bomb of $W$ kilotons energy is

$$R\text{(feet)}=180W^{2/5}, \qquad (2.88.1)$$

where $R$ is now the minimum height for negligible local fallout. This expression is plotted in Fig. 2.88. For a bomb of 1,000 kilotons i. e., 1 megaton, it can be found from Fig. 2.88 or equation (2.88.1) that the fireball radius for negligible local fallout is 2,900 feet. Consequently, if a 1-megaton bomb is detonated at a height greater than 2,900 feet it is to be expected that in most cases the local fallout following such an explosion would not be a serious problem.

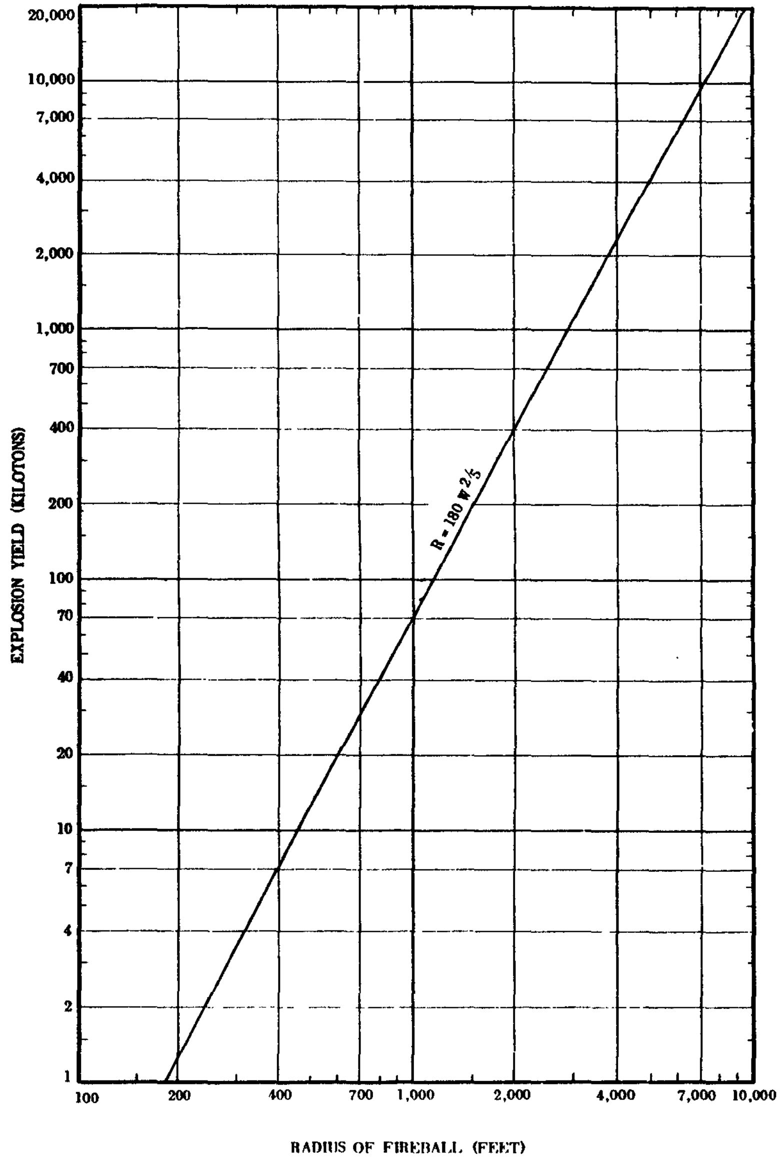

Figure 2.88. Fireball radius for local fallout.

## TEMPERATURE OF THE BALL OF FIRE

2.89 As indicated earlier, the interior temperature of the ball of fire decreases steadily, but the apparent surface temperature, which influences the emission of thermal radiation, decreases to a minimum and then increases to a maximum before the final steady decline. The basic fact upon which this peculiar behavior depends is that at temperatures over 2,300° C. (4,200° F.) heated air both absorbs and emits thermal radiation very readily, but at lower temperatures it does not absorb or radiate appreciably.

2.90 As the shock front, which then coincides with the exterior of the ball of fire, expands in the early stages of the explosion, its strength decreases. The surface temperature, due to the shock-heated air, then falls rapidly. According to well-established laws, the rate of emission of radiation from the ball of fire should be proportional to $R^2T^4$, where $R$ is the radius at any instant and $T$ is the corresponding surface (absolute) temperature (see §7.109). Although $R$ is increasing with time, $T$ is decreasing so rapidly that the quantity $R^2T^4$ also decreases. Near the breakaway point, this has become so small that the shock-heated air is no longer incandescent, that is to say, the rate of emission of radiation from the shock front is then negligible.

2.91 Since it cannot radiate, the shock front cannot now absorb radiation, and so the air behind the shock front, which has a higher temperature, begins to be visible. Thus the apparent surface temperature, having dropped to a minimum of about 2,100° C. (3,800° F.), commences to increase. As the shocked air ahead of the radiation front loses its incandescence, the apparent surface temperature of the fireball increases steadily, due to the gradual unmasking of the hot isothermal sphere, until the temperature of the latter is reached. This corresponds to the maximum of about 8,000° C. (14,400° F.) attained about 0.15 second after the explosion of a 20-kiloton nuclear bomb, and 1 second after a 1-megaton explosion. Subsequently, the temperature of the whole ball of fire, which is now fairly uniform again, falls continuously due to cooling of the hot gases by radiation and expansion.

2.92 The variation with time of the apparent surface temperature of the ball of fire, from $10^{-4}$ second to 3 seconds after a 20-kiloton nuclear explosion, is shown in Fig. 2.92. Corresponding with the rapid growth of the fireball, within the first hundredth of a second (Fig. 2.85), the apparent surface temperature drops sharply from about 15,000° C. at $10^{-4}$ second (0.1 millisecond) to about 2,100° C. at 0.013 second (13 milliseconds), the thermal minimum. Subsequently, there is a relatively slow rise to the maximum of 8,000° C. at about 0.15 second, followed by the steady decrease over a period of several seconds, until the ambient atmospheric temperature is reached. By this time the ball of fire is, of course, no longer visible as such and its place has been taken by the atomic cloud.

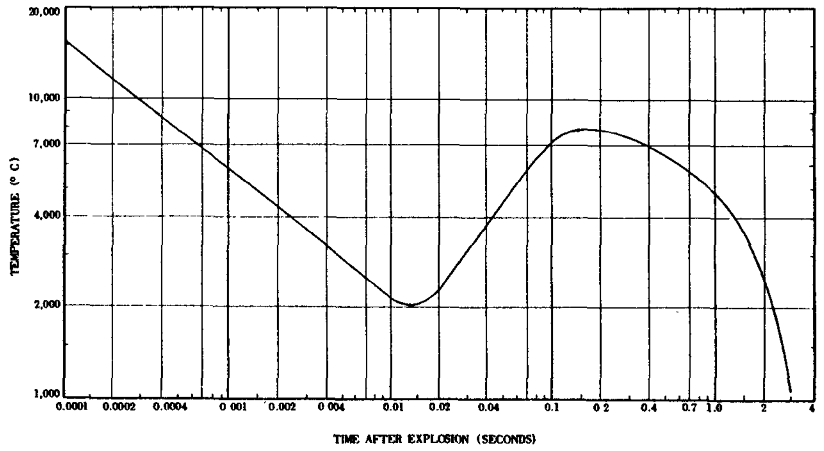

Figure 2.92. Variation of apparent surface temperature with time in a 20-kiloton explosion.

2.93 As stated above, the curves in Figs. 2.85 and 2.92 apply to a 20-kiloton nuclear burst, but similar results are obtained for explosions of other energy yields. The rate of growth of the fireball depends on the actual yield, and so does the radius, as shown by equations (2.87.1) and (2.88.1). The time of breakaway increases with the energy yield, as also does the time at which the subsequent maximum temperature occurs (see § 7.112). The respective temperatures, however, are essentially independent of the explosion energy.

## NUCLEAR BOMBS AND THE WEATHER

2.94 There has been speculation, from time to time, especially after a series of test detonations in the Pacific or in Nevada, concerning the possible influence of nuclear explosions on the weather. This speculation is based primarily on two considerations. First, it was thought that the energy added to the atmosphere by the explosions might change the existing weather pattern, and second, that the products of the explosion might serve as a trigger to divert some much larger natural store of energy from the path it might otherwise have followed.

2.95 The addition of energy to the atmosphere does not appear to be an important factor since the amount of energy released in a nuclear explosion is not large in comparison with that associated with most meteorological phenomena. Further, it is not produced in a manner that is likely to be conducive to weather changes. There is a possibility that the atmosphere may be in an unstable state, and so the sudden impulse of a nuclear explosion might cause a change in the weather that would otherwise not take place. As far as thunderstorm formation is concerned, it is believed that the release of energy in a nuclear explosion is so rapid that the atmospheric conditions could not be rearranged within the limited time, to take advantage of the extra energy.

2.96 There are three ways, which appear reasonable, whereby the products of a nuclear explosion might indirectly, e. g., by trigger action, produce changes in the weather. These are (1) the debris thrown into the air by the explosion may have an effect in seeding (nucleating) existing clouds, thus changing the pattern of cloudiness or precipitation over large areas; (2) the radioactive nature of the bomb residues will change the electrical conductivity of the air and this may have an influence on observable meteorological phenomena; and (3) the debris entering the stratosphere may interfere with the transmission of radiant energy from the sun and so serve to decrease the temperature of the earth. These possibilities will be considered in turn.

2.97 Although the techniques for testing seeding efficiency are not too well developed and are being given further study, the evidence obtained so far indicates that bomb debris is not effective as a cloud-seeding agent. It is true that rain fell after the nuclear explosion over Hiroshima in August 1945, but it seems certain that this was largely, if indirectly, due to widespread fires which sustained convection for several hours after the detonation had occurred. A similar phenomenon has been observed, under suitable air mass conditions, as a result of a "fire storm" over large forest fires and over burning cities during World War II. However, there has been no analogous effect in connection with the numerous explosions of nuclear test devices, since these were not accompanied by large fires.

2.98 Within two or three hours after the Bikini ABLE (air) burst in 1946, light rain showers developed throughout the northern Marshall Islands. Some attempt was made to relate the formation of the showers to the atomic cloud. But the showers were very widespread and were readily explained on the basis of the existing meteorological conditions. The records show that the only detectable changes which occurred in the wind or atmospheric structure were the momentary effects of the blast and thermal radiation. In any event, such changes were significant only in the immediate vicinity of the burst. The main cloud pattern over the lagoon was unchanged apart from the atomic cloud directly associated with the explosion.

2.99 The amount of ionization produced by the radioactive material, even for a high-energy nuclear explosion, is believed to be insufficient to have any significant effect on general atmospheric conditions. It appears improbable, therefore, that the ionization accompanying a nuclear explosion can affect the weather.

2.100 The dust raised in severe volcanic eruptions, such as that at Krakatao in 1883, is known to cause a noticeable reduction in the sunlight reaching the earth, but it has not been established that this decrease has any great effect on the weather. The amount of debris remaining in the atmosphere after the explosion of even the largest nuclear weapons is probably not more than about 1 percent or so of that raised by the Krakatao eruption. Further, solar radiation records reveal that none of the nuclear explosions to date has resulted in any detectable change in the direct sunlight recorded on the ground.

2.101 The variability of weather phenomena due to natural causes makes it difficult to prove (or disprove) that any change in the weather following a nuclear explosion was due to the detonation. However, the general opinion of competent meteorologists, both in the United States and in other countries, is that, apart from localized effects in the vicinity of the test area, there has been no known influence of nuclear explosions on the weather.

## *CHAPTER III*

# AIR BLAST PHENOMENA AND EFFECTS

## CHARACTERISTICS OF THE BLAST WAVE IN THE AIR

### Development of the Blast Wave

3.1 Most of the material damage caused by an air burst nuclear bomb is due mainly—directly or indirectly—to the shock (or blast) wave which accompanies the explosion. The majority of structures will suffer some damage from air blast when the overpressure in the blast wave, i. e., the excess over the atmospheric pressure (14.7 pounds per square inch at standard sea level conditions), is about one-half pound per square inch or more. The distance to which this overpressure level will extend depends on the yield or size of the explosion, and on the height of the burst. It is consequently desirable to consider, in some detail, the phenomena associated with the passage of a blast wave through the air.

3.2 A difference in the air pressure acting on separate surfaces of a structure produces a force on the structure. In considering the destructive effect of a blast wave, one of its important characteristics is the overpressure. For this reason the variation in the overpressure with time and distance will be described in succeeding sections. The maximum value, i. e., at the shock front, is called the "peak overpressure." Other characteristics of the blast wave such as dynamic pressure, duration, and time of arrival will also be discussed.

3.3 As already seen in Chapter II, the expansion of the intensely hot gases at extremely high pressures in the ball of fire causes a blast wave to form in the air, moving outward at high velocity. The main characteristic of this wave is that the pressure is highest at the moving front and falls off toward the interior region of the explosion. In the very early stages, for example, the variation of the pressure with distance from the center of the fireball, at a given instant, is somewhat as illustrated in Fig. 3.3 It is seen that, prior to breakaway (§ 2.84), pressures at the shock front are about twice as high as those in the interior of the fireball which are of considerable magnitude.

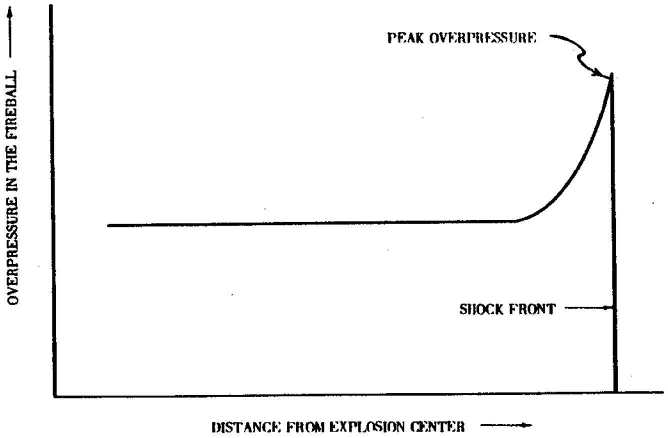

**Figure 3.3. Variation of overpressure with distance in the fireball.**

3.4 As the blast wave travels in the air away from its source, the overpressure at the front steadily decreases, and the pressure behind the front falls off in a regular manner. After a short time, when the shock front has traveled a certain distance from the fireball, the pressure behind the front drops below that of the surrounding atmosphere and a so-called "negative phase" of the blast wave forms. This development is seen in Fig. 3.4, which shows the overpressures at six successive times, indicated by the numbers 1, 2, 3, 4, 5, and 6. In the curves marked $t_1$ through $t_5$ the pressure in the blast wave has not fallen below atmospheric, but in the curve marked $t_6$ it is seen that at some distance behind the shock front the overpressure has a negative value. In this region the air pressure is below that of the original (or ambient) atmosphere.

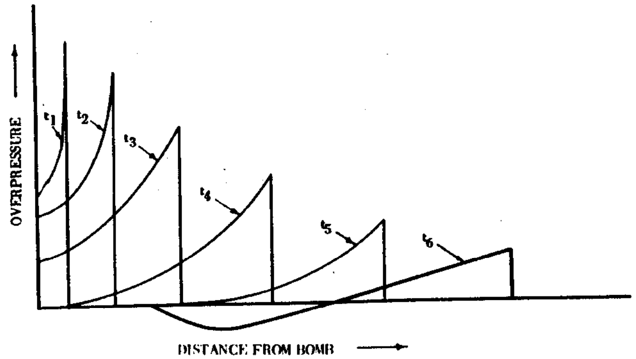

**Figure 3.4. Variation of overpressure with distance at successive times.**

3.5 During the negative overpressure (rarefaction or suction) phase, a partial vacuum is produced and the air is sucked in, instead of being pushed away, as it is when the overpressure is positive. In the positive (or compression) phase, the wind, associated with the blast wave, blows away from the explosion, and in the negative phase its direction is reversed. At the end of the negative phase, the pressure has essentially returned to ambient. The peak negative values of the overpressure are small compared with the peak positive overpressures.

## VARIATION OF BLAST OVERPRESSURE WITH TIME

3.6 From the practical standpoint, it is of interest to examine the changes of overpressure in the blast wave with time at a fixed location. The variation of overpressure with time that would be observed at such a location in the few seconds (possibly up to half a minute) following the detonation is shown in Fig. 3.6. The corresponding general effects to be expected on a light structure, a tree, and a small animal are indicated at the left of the figure.

3.7 For a short interval after the detonation there will be no increase in pressure, since it takes the blast wave some time to travel the distance from the point of the explosion to the given location. When the shock front arrives, the pressure will suddenly increase to a large value, i. e., to the peak overpressure referred to earlier. In Fig. 3.6 the numeral 1 represents the time of the explosion, and 2 indicates the time of arrival of the shock front. At the latter point, a strong wind commences to blow away from the explosion. This is often referred to as a "transient" wind because its velocity decreases fairly rapidly with time.

3.8 Following the arrival of the shock front, the pressure falls rapidly and at the time corresponding to the point 3 in Fig. 3.6 it is the same as that of the original (or ambient) atmosphere. Although the overpressure is now zero, the wind will continue in the same direction for a short time. The interval from 2 to 3, roughly one-half to one second for a 20-kiloton weapon, and two to four seconds for a 1-megaton explosion, represents the passage of the positive (or compression) phase of the blast wave. It is during this interval that most of the destructive action of the air burst will be experienced.

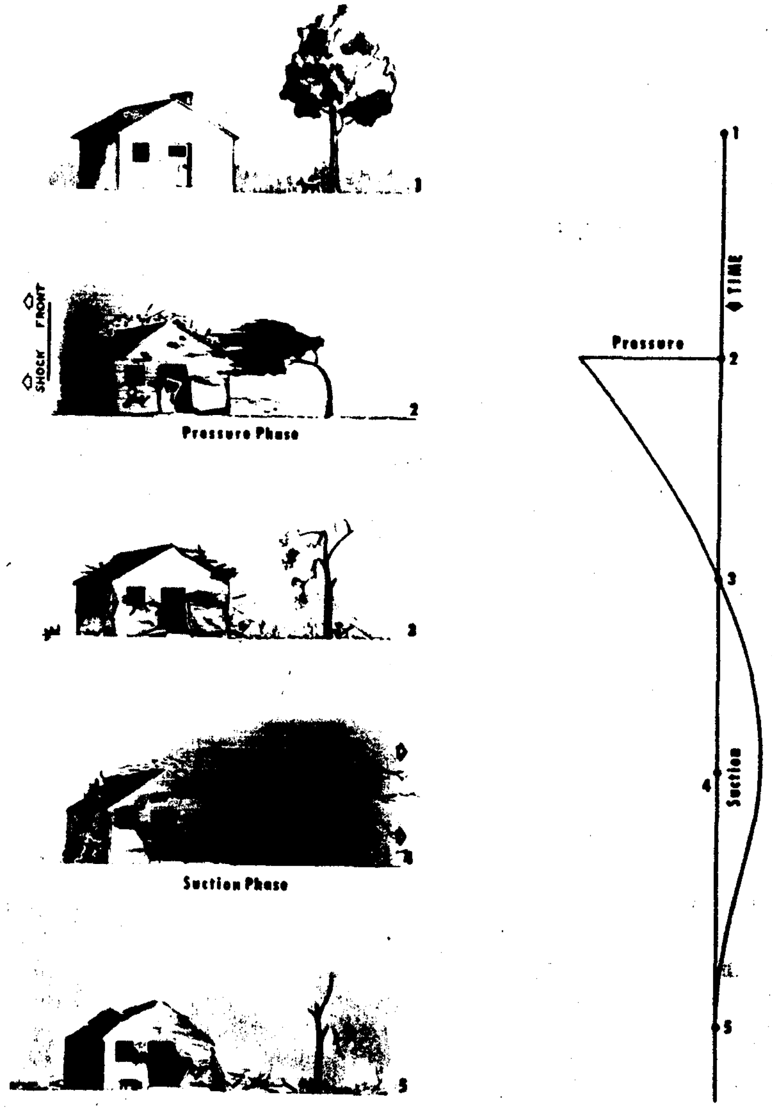

Figure 3.6. Variation of pressure with time at a fixed location and effect of blast wave passing over a structure.

3.9 As the pressure in the blast wave continues to decrease, it sinks below that of the surrounding atmosphere. In the time interval from 3 to 5 in Fig. 3.6, which may be several seconds, the negative (or suction) phase of the blast wave passes the given location. For most of this period, the transient wind blows in the direction toward the explosion. There may be some destruction during the negative phase, but, since the maximum negative overpressure is always smaller than the peak overpressure at the shock front, it is generally quite minor in character. During the passage of the negative phase, the pressure at first decreases and then increases toward that of the ambient atmosphere which is reached at the time represented by the numeral 5. The blast wind has then effectively ceased and the direct destructive action of the air blast is over. There may still, however, be indirect destructive effects caused by fire (see Chapter VII).

## THE DYNAMIC PRESSURE

3.10 Although the destructive effects of the blast wave have usually been related to values of the peak overpressure, there is another quantity of equivalent importance called the "dynamic pressure." For a great variety of building types, the degree of blast damage depends largely on the drag force associated with the strong (transient) winds accompanying the passage of the blast wave. The drag force is influenced by certain characteristics (primarily the shape and size) of the structure, but is generally dependent upon the peak value of the dynamic pressure and its duration at a given location.

3.11 The dynamic pressure is a function of the wind velocity and the density of the air behind the shock front. Both of these quantities may be related to the overpressure under ideal conditions at the shock front by certain equations, which will be given later (see § 3.80). For very strong shocks the dynamic pressure is larger than the overpressure, but below 69 pounds per square inch overpressure at sea level the dynamic pressure is smaller. Like the peak shock overpressure, the peak dynamic pressure decreases with increasing distance from the explosion center, although at a different rate. Some indication of the corresponding values of peak overpressure, peak dynamic pressure, and maximum blast wind velocities in air at sea level are given in Table 3.11. The dynamic pressure is seen to decrease more rapidly with distance than does the shock overpressure.

TABLE 3.11

OVERPRESSURE, DYNAMIC PRESSURE, AND WIND VELOCITY IN AIR AT SEA LEVEL

| *Peak overpressure (pounds per square inch)* | *Peak dynamic pressure (pounds per square inch)* | *Maximum wind velocity (miles per hour)* |
|---|---|---|
| 72 | 80 | 1, 170 |
| 50 | 40 | 940 |
| 30 | 16 | 670 |
| 20 | 8 | 470 |
| 10 | 2 | 290 |
| 5 | 0. 7 | 160 |
| 2 | 0. 1 | 70 |

3.12 At a given location, the dynamic pressure changes with time in a manner somewhat similar to the change in the overpressure, but the rate of pressure decrease behind the shock front is different. This may be seen from Fig. 3.12 which indicates qualitatively how the two pressures vary in the course of the first second or so following arrival of the shock front. Both pressures increase sharply when the shock front reaches the given point and subsequently they decrease. The curves show the overpressure and dynamic pressure becoming zero at the same time. Actually, the wind velocity (and the dynamic pressure) will drop to zero at a somewhat later time, due largely to the inertia of the moving air, but for purposes of estimating damage the difference is not significant.

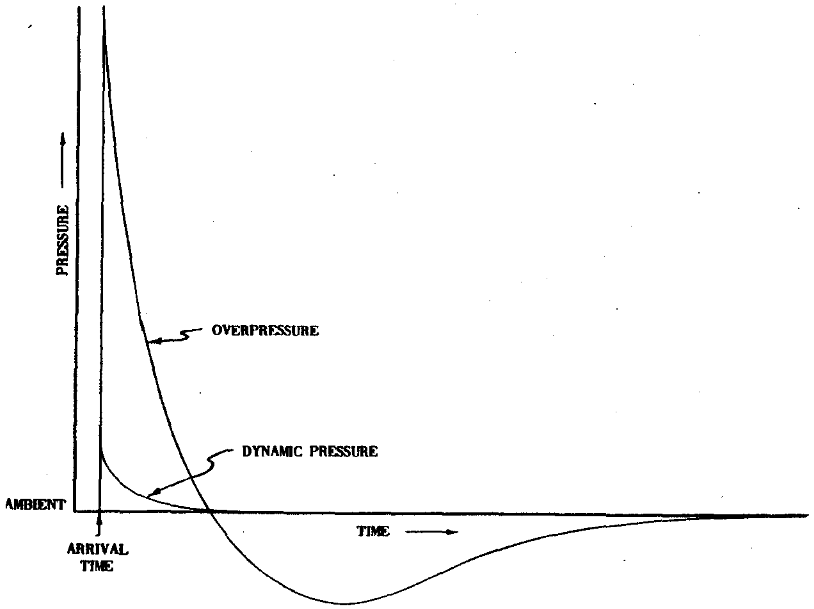

Figure 3.12. Variation of overpressure and dynamic pressure with time at a fixed location.

3.13 During the negative overpressure phase of the blast wave the dynamic pressure is very small and acts in the opposite direction. Therefore, dynamic pressure (or drag force) damage sustained during the negative overpressure phase is also small.

## ARRIVAL TIME AND DURATION

3.14 As stated previously, there is a finite time interval required for the blast wave to move out from the explosion center to any particular location. This time interval (or arrival time) is dependent upon the energy yield of the explosion and the distance involved; thus, at 1 mile from a 1-megaton burst, the arrival time would be about 4 seconds. Initially, the velocity of the shock front is quite high, many times the speed of sound, but as the blast wave progresses outward, it slows down as the shock front weakens. Finally, at long ranges, the blast wave becomes essentially a sound wave and its velocity approaches ambient sound velocity.

3.15 The duration of the blast wave at a particular location also depends on the energy of the explosion and the distance from the point of burst. The positive phase duration is shortest at close ranges and increases as the blast wave moves outward. At 1 mile from a 1-megaton explosion, for example, the duration of the positive phase of the blast wave is about 2 seconds. There is a minimum positive duration associated with blast wave development which occurs prior to the formation of a negative phase.

3.16 It was noted in § 3.12 that the transient wind velocity behind the shock front decays to zero, and then reverses itself, at a somewhat later time than the end of the overpressure positive phase. Consequently, durations of dynamic pressure may exceed durations of overpressure by varying amounts depending on the pressure level involved. However, dynamic pressures existing after the overpressure positive phase are so low that they are not significant. Therefore the period of time over which the dynamic pressure is effective may be taken as essentially the positive phase duration of the overpressure as shown in Fig. 3.12.

## REFLECTION OF BLAST WAVE AT A SURFACE

### INCIDENT AND REFLECTED WAVES

3.17 When the incident blast wave from an explosion in air strikes a more dense medium such as the earth's surface, e. g., either land or water, it is reflected. The formation of the reflected shock wave in these circumstances is represented in Fig. 3.17. This figure shows four stages in the outward motion of the spherical blast originating from an air burst bomb. In the first stage the shock front has not reached the ground; the second stage is somewhat later in time, and in the third stage, which is still later, a reflected wave, indicated by the dotted line, has been produced.

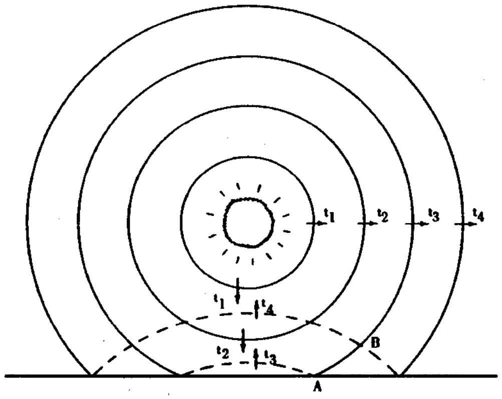

Figure 3.17. Reflection of blast wave at the earth's surface in an air burst; $t_1$ to $t_4$ represent successive times.

3.18 When such reflection occurs, an individual or object precisely at the surface will experience a single shock, since the reflected wave is formed instantaneously. Consequently, the value of the overpressure thus experienced at the surface is generally considered to be entirely a reflected pressure. In the region near ground zero, this total reflected overpressure will be more than twice the value of the peak overpressure of the incident blast wave. The exact value of the reflected pressure (see §§ 3.80, 3.81) will depend on the strength of the incident wave and the angle at which it strikes the surface. The variation in overpressure with time, as observed at a point actually on the surface not too far from ground zero,[1] such as A in Fig. 3.17, will be as depicted in Fig. 3.18. The point A may be considered as lying within the region of "regular" reflection, i. e., where the incident and reflected waves do not merge above the surface.

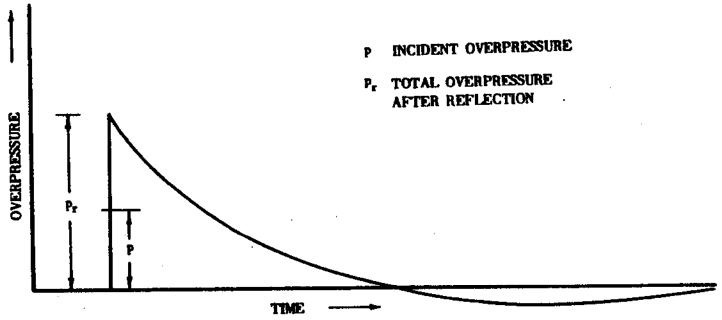

Figure 3.18. Variation of overpressure with time at a point on the surface in the region of regular reflection.

3.19 At any location somewhat above the surface in this region, two separate shocks will be felt, the first being due to the incident blast wave and the second to the reflected wave, which arrives a short time later (see Fig. 3.19). This situation can be illustrated by considering the point B in Fig. 3.17, which is also in the regular reflection region. When the incident shock front reaches this point, the reflected wave is still some distance away. There will, consequently, be a short interval before the reflected wave reaches the point above the

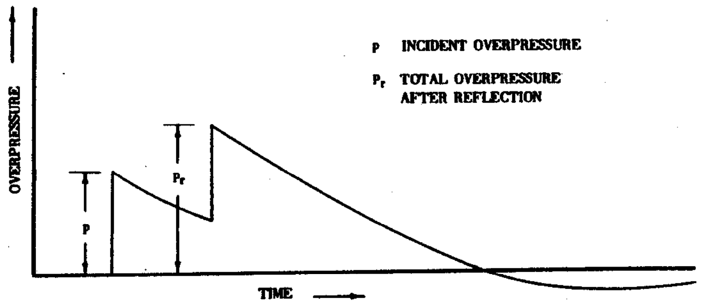

Figure 3.19. Variation of overpressure with time at a point above the surface in the region of regular reflection.

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[1] For an explanation of the term "ground zero," see § 2.30.

surface. At the same time, the reflected wave has spread out to some extent, so that its peak overpressure will be less than the value obtained at surface level. In determining the effects of air blast on structures in the regular reflection region, allowance must be made for the magnitude and also the directions of motion of both the incident and reflected waves. After passage of the reflected wave, the transient wind near the surface becomes essentially horizontal.

### The Mach Effect

3.20 The foregoing discussion concerning the delay between the arrival of the incident and reflected shock fronts at a point above the surface, such as B in Fig. 3.17, is based on the tacit assumption that the two waves travel with approximately equal velocities. This assumption is reasonably justified in the early stages, when the shock front is not far from ground zero. However, it will be evident that the reflected wave always travels through air that has been heated and compressed by the passage of the incident wave. As a result, the reflected shock front moves faster than the incident shock and, under certain conditions, eventually overtakes it so that the two shock fronts fuse to produce a single shock. This process of wave interaction is called "Mach" or "irregular" reflection. The region in which the two waves have merged is therefore called the Mach (or irregular) region in contrast to the regular region where they have not merged.

3.21 The fusion of the incident and reflected shock fronts is indicated schematically in Fig. 3.21, which shows a portion of the profile of the blast wave close to the surface. Fig. 3.21a represents the situation at a point fairly close to ground zero, such as A in Fig. 3.17. At a later stage, farther from ground zero, as in Fig. 3.21b, the steeper front of the reflected wave shows that it is traveling faster than, and is catching up with, the incident wave. At the stage represented by Fig. 3.21c, the reflected shock near the ground has overtaken and fused with the incident shock to form a single shock front called the "Mach stem." The point at which the incident shock, reflected shock, and Mach fronts meet is called the "triple point." [2]

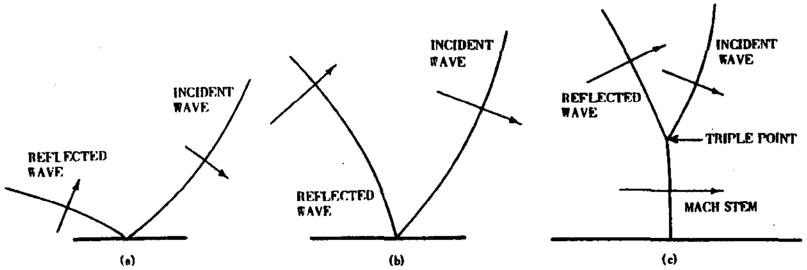

Figure 3.21. Fusion of incident and reflected waves and formation of Mach stem.

3.22 As the reflected wave continues to overtake the incident wave, the triple point rises and the height of the Mach stem increases (Fig. 3.22). Any object located either at or above the ground, within the Mach region, and below the triple point path, will experience a single shock. The behavior of this fused or Mach shock is the same as that previously described for shock fronts in general. The overpressure at a particular location will fall off with time and the positive (compression) phase will be followed by a negative (suction) phase, as in Fig. 3.6.

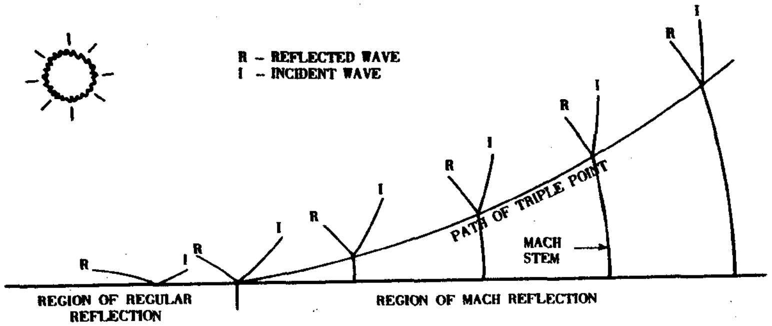

Figure 3.22. Outward motion of the blast wave near the surface in the Mach region.

3.23 At points in the air above the triple point path, such as at an aircraft or at the top of a high building, two shocks will be felt. The first will be due to the incident blast wave and the second, a short time later, to the reflected wave. When a bomb is detonated at the surface, i. e., in a contact surface burst, only a single merged wave develops. Consequently, only one shock will be experienced either on or above the ground.

3.24 As far as the destructive action of the air blast is concerned, there are at least two important aspects of the reflection process to which attention should be drawn. First, only a single shock is experienced in the Mach region below the triple point as compared to the

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[2] The so-called "triple point" is not really a point but a circle; it appears as a point on a sectional drawing, such as Fig. 3.21c.

separate incident and reflected waves in the region of regular reflection. Second, since the Mach stem is nearly vertical, the accompanying blast wave is traveling in a horizontal direction at the surface, and the transient winds are approximately parallel to the ground (Fig. 3.21). Thus, in the Mach region, the blast forces on aboveground structures and other objects are directed nearly horizontally, so that vertical surfaces are loaded more intensely than horizontal surfaces.

3.25 The distance from ground zero at which Mach fusion commences and the Mach stem begins to form depends upon the yield of the detonation and the height of the burst above the ground. For a typical air burst of 1-megaton energy yield the Mach stem begins to form about 1.3 miles from ground zero. As the burst point approaches the surface, this distance is reduced. If the bomb is exploded at a greater height, then Mach fusion commences farther away. If the air burst takes place at a sufficiently great height above the ground, regular reflection will occur and no Mach stem may be formed.

## HEIGHT OF BURST AND BLAST DAMAGE

3.26 The height of burst and energy yield (or size) of the nuclear explosion are important factors in determining the extent of damage at the surface. These two quantities generally define the variation of pressure with distance from ground zero and other associated blast wave characteristics, such as the distance from ground zero at which the Mach stem begins to form. As the height of burst for an explosion of given energy yield is decreased, the consequences are as follows: (1) Mach reflection commences nearer to ground zero, and (2) the overpressure at the surface near ground zero becomes larger. An actual contact surface burst leads to the highest possible overpressures near ground zero. In addition, cratering and ground shock phenomena are observed, as will be described in Chapter V. Further reference to the difference in air blast characteristics between a contact surface burst and a typical air burst will be made below.

3.27 Because of the relationships between the energy yield of the explosion and the height of burst required to produce certain blast effects, a very large yield weapon may be detonated at a height of several thousand feet above the ground and the accompanying blast wave phenomena will approach those of a near surface burst. On the other hand, explosions of weapons of smaller energy yields at these same heights will have the characteristics of typical high air bursts.

3.28 In the nuclear explosions over Japan during World War II, at Hiroshima and Nagasaki, the height of burst was about 1,850 feet. It was estimated, and has since been confirmed by nuclear test explosions, that a 20-kiloton bomb burst at this height would cause maximum blast damage to structures on the ground for the particular targets concerned. Actually, there is no single optimum height of burst, with regard to blast effects, for any specified explosion energy yield, because the chosen height of burst will be determined by the nature of the target. As a rule, strong (or hard) targets will require low air or surface bursts. For weaker targets, which are destroyed or damaged at relatively low overpressures or dynamic pressures, the height of burst may be raised in order to increase the area of damage, since the Mach effect extends the distances at which low pressures result.

## CONTACT SURFACE BURST

3.29 The general air blast phenomena resulting from a contact surface burst are somewhat different from those of an air burst described above. In a surface explosion, the front of the blast wave in the air is hemispherical in form as shown in Fig. 3.29. There is no region of regular reflection, and all objects and structures on the surface, even close to ground zero, are subjected to air blast similar to that in the Mach region below the triple point for an air burst. Therefore, the shock front may be assumed to be vertical for most structures near the ground, with both overpressure and dynamic pressure decaying at different rates behind the shock front as previously described. The transient winds behind the shock front near the surface are essentially horizontal.

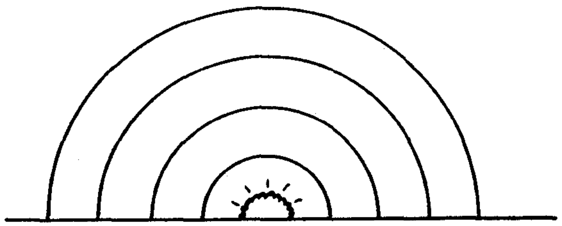

**Figure 3.29. Blast wave from a contact surface burst; incident and reflected waves coincide.**

## MODIFICATION OF AIR BLAST PHENOMENA

### TERRAIN EFFECTS

3.30 Large hilly land masses tend to increase air blast effects in some areas and to decrease them in others. The increase or decrease in peak values of overpressure at the surface appears to depend on the change in slope from the horizontal. For very steep slopes, there may be a transient increase (or "spike") in peak overpressure of short duration up to a factor of two on the forward side of a hill as a result of the reflection process. Some reduction in peak overpressure may be expected on the reverse slope if it is also quite steep. In general, the variation in peak overpressure at any point on a hill from that expected if the hill were not present depends on the dimensions of the hill with respect to the size and location of the explosion. Since the time interval in which the pressure increase or decrease occurs is short compared to the length of the positive phase, the effects of terrain on the blast wave are not expected to be significant for a large variety of structural types.

3.31 It is important to emphasize, in particular, that shielding from blast effects behind the brow of a large hill is not dependent upon line-of-sight considerations. In other words, the fact that the point of the explosion cannot be seen from behind the hill by no means implies that the blast effects will not be felt. It will be shown later that blast waves can easily bend (or diffract) around apparent obstructions.

3.32 Although prominent terrain features may shield a particular target from thermal radiation, and perhaps also to some extent from the initial nuclear radiation, little reduction in blast damage to structures may be expected, except in very special circumstances. However, considerable protection from missiles and drag forces may be achieved for such movable objects as heavy construction equipment by placing them below the surface of the ground in open excavations or deep trenches or behind steep earth mounds. This subject will be discussed more fully in Chapter XII.

3.33 The departure from idealized or flat terrain presented by a city complex may be considered as an aspect of topography. It is to be expected that the presence of many buildings close together will cause local changes in the blast wave, especially in the dynamic pressure. Some shielding may result from intervening objects and structures; however, in other areas multiple reflections between buildings and the channeling caused by streets may increase the overpressure and dynamic pressure. It would seem, therefore, that on the whole, the resulting effect on damage is relatively small.

### METEOROLOGICAL CONDITIONS

3.34 The presence of large amounts of moisture in the atmosphere may affect the properties of a blast wave in the low overpressure region. But the probability of encountering significant concentrations of atmospheric liquid water that would influence damage is considered to be small.

3.35 Under suitable meteorological conditions, window breakage, light structural damage, and noise may be experienced at ranges from an explosion at which such damage and noise are not to be expected. These phenomena have been observed in connection with large TNT detonations as well as with nuclear explosions. They are caused by the bending back to earth of the blast waves by the atmosphere, in one or other of (at least) two different ways. The first is due to temperature gradients and wind conditions at relatively low levels, within the bottom 6 miles of the atmosphere, whereas the second arises from conditions at considerably greater heights, 25 miles or more from the ground.

3.36 If there is a decrease in air temperature at increasing distance from the ground, such as usually occurs in the daytime, combined with a wind whose velocity increases at a rate of more than 3 miles per hour for each 1,000-foot increase in altitude, the blast wave will be reflected back to the ground within the first few thousand feet of the atmosphere. When the conditions are such that several shock rays converge at one location on the ground, the concentration of blast energy there will greatly exceed the value that would otherwise occur at that distance. Usually the first (or direct striking) focus is limited to a distance of about 8 or 10 miles from the explosion. But, since the concentration of blast energy is reflected from the ground and is again bent back by the atmosphere, the focus may be repeated at regularly spaced distances. Thus, the explosion of a 20-kiloton bomb has been known to break windows 75 to 100 miles away.

3.37 A somewhat similar enhancement of pressure (and noise) from large explosions has been reported at greater distances, 70 to 80 miles in winter and 120 to 150 in summer. This has been attributed to downward refraction (or bending) and focusing of the shock rays by a layer of relatively warm air, called the ozonosphere, at a height of 25 to 40 miles. Repeated reflection from the ground, and associated refraction by the ozonosphere, causes this pattern to be repeated at intervals. Thus, a large explosion may be distinctly heard at even greater distances than those mentioned above.

## EFFECT OF ALTITUDE

3.38 The relations between overpressure, distance, and time that describe the propagation of a blast wave in air depend upon the ambient atmospheric conditions, and these vary with the altitude. In reviewing the effects of elevation on blast phenomena, two cases will be considered: one in which the point of burst and the target are essentially at the same altitude, but not necessarily at sea level, and the second, when the burst and target are at different altitudes.

3.39 For a surface burst, the peak overpressure at a given distance from the explosion will depend on the ambient atmospheric pressure and this will vary with the burst altitude. There are a number of simple correction factors, which will be given later (see § 3.89), that can be used to allow for differences in the ambient conditions, but for the present it will be sufficient to state the general conclusions. With increasing altitude of both target and burst point, the overpressure at a given distance from an explosion of specified yield will generally decrease. Correspondingly, an increase may usually be expected in both the arrival time of the shock front and in the duration of the positive phase of the blast wave. For elevations of less than 5,000 feet or so above sea level, the changes are fairly small, and since most surface targets are at lower altitudes, it is rarely necessary to make the corrections.

3.40 The effect when the burst and target are at different elevations, such as for a high air burst, is somewhat more complex. Since the blast wave is influenced by changes in air temperature and pressure in the atmosphere through which it travels, some variations in the pressure-distance relationship at the surface might be expected. Within the range of significant damaging overpressures, these differences are small for weapons of low energy yield. For large weapons, where the blast wave travels over appreciably longer distances, local variations, such as temperature inversions and refraction, may be expected. Consequently, a detailed knowledge of the atmosphere on a particular day would be necessary in order to make precise calculations. For planning purposes, however, the correction factors referred to above may be applied at target ambient conditions, if necessary, for an air burst when the target is at some appreciable elevation above sea level.

## SURFACE EFFECTS

3.41 For a given height of burst and explosion energy yield, some variation in blast wave characteristics may be expected over different surfaces. These variations are determined primarily by the type and extent of the surface over which the blast wave passes. A certain amount of energy loss will occur for a low air or surface burst where a shock wave in the ground is produced; this will be discussed further in § 3.43. The nature of the reflecting surface and its roughness may affect the pressure-distance relationship, as well as Mach stem formation and growth, for air bursts. On the whole, however, these mechanical effects on the blast wave are small and have little influence on damage. The results presented later in this chapter are for average surface conditions.

3.42 Somewhat related to the condition of the surface are the effects of objects and material picked up by the blast wave. Damage may be caused by missiles such as rocks, boulders, and pebbles, as well as by smaller particles such as sand and dust. This particulate matter carried along by the blast wave does not necessarily affect the overpressures at the shock front. In extremely dusty areas, it is possible that enough dust may be present to affect the dynamic pressure of the blast wave and, consequently, the action on a particular target, but this effect would probably be small.

## GROUND SHOCK FROM AIR BLAST

3.43 Another aspect of the blast wave problem is the possible effect of an air burst on underground structures. If an explosion occurs moderately near the surface, some of the energy is transferred into the ground. As a result, a minor oscillation of the surface is experienced and a mild ground shock wave is produced. The pressure acting on the earth's surface due to the air blast is thus transmitted downward, without appreciable attenuation, to superficially buried objects in the ground. The major principal stress in the soil will be nearly vertical and about equal in magnitude to the air blast overpressure. These phenomena will be discussed in more detail in Chapters V and VI.

3.44 In general, it appears that for high air bursts, where relatively large blast pressures are not expected at ground zero, the effects of ground shock induced by air blast will be negligible. Even directly underneath the point of burst, moderately strong underground structures will not be seriously affected. Certain public utilities, such as sewer pipes and drains, at shallow depths, close to ground zero, may be damaged by earth movement, but metal pipe will not normally be disrupted. In the case of a surface burst when cratering occurs, the situation is quite different, as will be seen in Chapter VI.

## INTERACTION OF BLAST WAVE WITH STRUCTURES

### Air Blast Loading

3.45 The behavior of an object or structure exposed to the blast wave from a nuclear explosion may be considered under two main headings. The first is called the "loading," i. e., the forces which result from the action of the blast pressure. The second is the "response" or distortion of the structure due to the particular loading. As a general rule, response may be taken to be synonymous with damage since permanent distortion of a sufficient amount will impair the usefulness of a structure. Damage may also arise from a movable object striking the ground or another object which is more or less fixed. For example, tumbling vehicles are damaged primarily as they strike the ground. Further, glass, wood splinters, bricks, pieces of masonry, and other objects loosened by the blast wave and hurled through the air form destructive missiles. Indirect damage of these types is, of course, greatly dependent upon circumstances.

3.46 Direct damage to structures due to air blast can take various forms. For example, the blast may deflect structural steel frames, collapse roofs, dish-in walls, shatter panels, and break windows. In general, the damage results from some type of displacement (or distortion) and the manner in which such displacement can arise as the result of a nuclear explosion will be examined below.

3.47 For an air burst, the direction of propagation of the incident blast wave will be perpendicular to the ground at ground zero. In the regular reflection region, the forces exerted upon structures will also have a considerable vertical component (prior to passage of the reflected wave). Consequently, instead of the loading being largely lateral (or sideways) in nature, as it is in the Mach region (§ 3.24), there will also be an appreciable downward force initially, which tends to cause crushing toward the ground, e. g., dished-in roofs, in addition to distortion due to translational motion.

### Diffraction Loading

3.48 When the front of an air pressure wave strikes the face of a building, reflection occurs. As a result the overpressure builds up rapidly to at least twice (and generally several times) that in the incident shock front. The actual pressure attained is determined by various factors, such as the strength of the incident shock and the angle between the direction of motion of the shock wave and the face of the building. As the shock front moves forward, the overpressure on the face drops rapidly toward that produced by the blast wave without reflection.[3] At the same time, the air pressure wave bends or "diffracts" around the structure, so that the structure is eventually engulfed by the blast, and approximately the same pressure is exerted on all the walls and the roof.

3.49 The developments described above are illustrated in a simplified form in Fig. 3.49;[4] this shows, in plan, a building which is being struck by an air blast (Mach) wave moving in a horizontal direction. In Fig. 3.49a the shock front is seen approaching the structure with the direction of motion perpendicular to the face of the building exposed to the blast. In Fig. 3.49b the wave has just reached its front

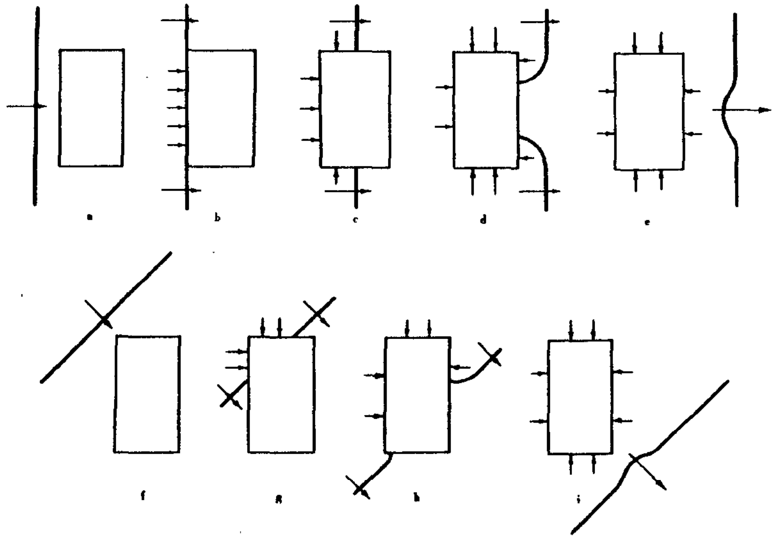

Figure 3.49. Stages in the diffraction of a blast wave by a structure.

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[3] This is often referred to as the "side-on overpressure," since it is the same as that experienced by the side of the structure, where there is no appreciable reflection in the simple case considered below.

[4] A more detailed treatment is given in Chapter VI.

face, producing a high overpressure. In Fig. 3.49c the blast wave has proceeded about half way along the building and in Fig. 3.49d it has reached the back. The pressure on the front face has dropped to some extent and it is building up on the sides as the blast wave diffracts around the structure. Finally when, as in Fig. 3.49e, the shock front has passed, approximately equal air pressures are exerted on all the walls (and roof) of the structure. If the structure is oriented at an angle to the blast wave, the pressure would immediately be exerted on two faces, instead of one, but the general behavior would be the same as just described (Figs. 3.49f, g, h, and i).

3.50 Under such conditions, that the blast wave has not yet completely surrounded the structure, there will be a considerable pressure differential between the front and back faces. Such a pressure differential will produce a lateral (or translational) force, tending to cause the structure to move bodily in the same direction as the blast wave. This force is known as the "diffraction loading" because it operates while the blast wave is being diffracted around the structure. The extent and nature of the actual motion will depend upon the size, shape, and weight of the structure and how firmly it is attached to the ground. Other characteristics of the building are important in determining the response, as will be seen later.

3.51 When the blast wave has engulfed the structure (Fig. 3.49e or 3.49i), the pressure differential has dropped almost to zero because the actual pressure is now approximately the same on all faces. However, since these pressures will remain in excess of the ambient atmospheric pressure until the positive phase of the shock wave has passed, the diffraction loading will be replaced by an inwardly directed pressure, i. e., a compression or squeezing action. In a structure with no openings, this will cease only when the overpressure drops to zero.

3.52 The damage caused during the diffraction stage will be determined by the magnitude of the loading and by its duration. The loading is related to the peak overpressure in the blast wave and this is consequently an important factor. If the structure under consideration has no openings, as has been tacitly assumed so far, the duration of the loading will be very roughly the time required for the shock front to move from front to back of the building. The size of the structure will thus affect the diffraction loading. For a structure 75 feet long, the diffraction loading will operate for a period of the order of one-tenth of a second. For thin structures, e. g., telegraph or utility poles and smokestacks, the diffraction period is so short that the corresponding loading is negligible.

3.53 If the building exposed to the blast wave has openings, or if it has windows, panels, light siding, or doors which fail in a very short space of time, there will be a rapid equalization of pressure between the inside and outside of the structure. This will tend to reduce the pressure differential while diffraction is occurring. The diffraction loading on the structure as a whole will thus be decreased, although the loading on interior walls and partitions will be greater than for an essentially closed structure, i. e., one with few openings. Further, if the building has many openings after the diffraction stage, the subsequent squeezing (crushing) action, due to the pressure being higher outside than inside, will not occur.

### Drag (Dynamic Pressure) Loading

3.54 During the whole period that the positive phase of the air pressure wave is passing (and for a short time thereafter) a structure will be subjected to the dynamic pressure loading or "drag loading" caused by the strong transient winds behind the shock front. Like the diffraction loading, the drag loading, especially in the Mach region, is equivalent to a lateral (or translational) force acting upon the structure or object exposed to the blast.

3.55 Except at high shock strengths, the dynamic pressures at the face of a building are much less than the peak overpressures due to the blast wave and its reflection (Table 3.11). However, the drag loading on a structure may persist for a relatively long period of time, compared to the diffraction loading. It was stated in § 3.15 that the duration of the positive phase of the blast wave from a 1-megaton nuclear explosion is about 2 seconds at a distance of 1 mile. On the other hand, the diffraction loading is effective for a small fraction of a second only, even for a large structure.

3.56 It is the effect of drag loading on structures which constitutes an important difference between nuclear and high-explosive detonations. For the same peak overpressure in the blast wave, a nuclear bomb will prove to be more destructive than a conventional bomb, especially for buildings which respond to drag loading. This is because the blast wave is of much shorter duration for a high-explosive bomb, e. g., a few thousandths of a second. Because of the increased length of the positive phase of the blast wave from weapons of high energy yield, such weapons cause more destruction than might be expected from the peak overpressures alone.

## STRUCTURAL CHARACTERISTICS AND AIR BLAST LOADING

3.57 In analyzing the response to blast loading, either quantitatively, by the use of mathematical procedures (see Chapter VI), or qualitatively, as will be done here, it is convenient to consider structures in two categories, i. e., diffraction-type structures and drag-type structures. As these names imply, in a nuclear explosion the former would be affected mainly by diffraction loading and the latter by drag loading. It should be emphasized, however, that the distinction is made in order to simplify the treatment of real situations which are, in fact, very complex. While it is true that some structures will respond mainly to diffraction forces and others mainly to drag forces, actually all buildings will respond to both types of loading. The relative importance of each type of loading in causing damage will depend upon the type of structure as well as on the characteristics of the blast wave. These facts should be borne in mind in connection with the ensuing discussion.

3.58 Large buildings having a moderately small window and door area and fairly strong exterior walls respond mainly to diffraction loading. This is because it takes an appreciable time for the blast wave to engulf the building, and the pressure differential between front and rear exists during the whole of this period. Examples of structures which respond mainly to diffraction loading are multistory, reinforced-concrete buildings with small window area, large wall-bearing structures, such as apartment houses, and wood-frame buildings like dwelling houses.

3.59 Because, even with large structures, the diffraction loading will usually be operative for a fraction of the duration of the blast wave, the length of the latter will not have any appreciable effect. In other words, a blast wave of longer duration will not materially affect the magnitude of the net translational loading (or the resulting damage) during the diffraction stage. A diffraction-type structure is, therefore, primarily sensitive to the peak overpressure in the shock wave to which it is exposed. Actually it is the associated reflected overpressure on the structure that largely determines the diffraction loading, and this may be several times the incident shock overpressure (see § 3.81).

3.60 When the pressures on different areas of a structure (or structural element) are quickly equalized, either because of its small size, the characteristics of the structure (or element), or the rapid formation of numerous openings by action of the blast, the diffraction forces operate for a very short time. The response of the structure is then mainly due to the dynamic pressures (or drag forces) of the blast wind. Typical drag-type structures are smokestacks, telephone poles, radio and television transmitter towers, electric transmission towers, and truss bridges. In all these cases the diffraction of the shock wave around the structure or its component elements requires such a very short time that the diffraction processes are negligible, but the drag loading may be considerable.

3.61 The drag loading on a structure is determined not only by the dynamic pressure, but also by the shape of the structure (or structural element). The shape factor (or drag coefficient) is less for rounded or streamlined objects than for irregular or sharp-edged structures or elements. For example, for a unit of area, the loading on a telephone pole or a smokestack will be less than on an I-beam.

3.62 Steel (or reinforced-concrete) frame buildings with light walls made of asbestos cement, aluminum, or corrugated steel, quickly become drag-sensitive because of the failure of the walls at low overpressures. This failure, accompanied by pressure equalization, occurs very soon after the blast wave strikes the structure, so that the frame is subject to a relatively small diffraction loading. The distortion, or other damage, subsequently experienced by the frame, as well as by narrow elements of the structure, e. g., columns, beams, and trusses, is then caused by the drag forces.

3.63 For structures which are fundamentally of the drag type, or which rapidly become so as a result of blast action, the response of the structure or of its components is determined by both the drag loading and its duration. Thus, the damage is dependent upon the length of the positive phase of the blast wave as well as upon the overpressures, to which the dynamic pressures are related. Consequently, for a given peak overpressure, a bomb of high energy yield will cause more damage to a drag-type structure than will one of lower yield because of the longer duration of the positive phase in the former case.

## STRUCTURAL DAMAGE RANGES: SCALING RULES

3.64 The range (or area) over which a particular type of structural damage is experienced will depend, of course, upon the energy yield of the explosion and the type (and height) of burst. As will be shown in the more technical section of this chapter (§ 3.78, *et seq.*), there are scaling rules which relate the distance at which a given peak overpressure is attained in the blast wave to the explosion energy. Hence, for structures damaged primarily during the diffraction phase, where peak overpressure is the important factor in determining the response to blast, the effect of bomb energy on the range (or area) within which a particular type of damage is sustained can be readily calculated.

3.65. Assuming equivalent heights of burst, in the sense discussed in §3.27 (see also §3.87), the range for a specified damage to a structure that is essentially diffraction-sensitive increases in proportion to the cube root, and the damage area in proportion to the two-thirds power, of the energy of the explosion. This means for example, that a thousand-fold increase in the energy will increase the range for a particular kind of diffraction-type damage by a factor of roughly ten; the area over which the damage occurs will be increased by a factor of about a hundred.

3.66 Where the damage depends to an appreciable extent on drag loading during the whole of the positive blast phase, the length of this phase is important, in addition to peak overpressure. The greater the energy of the bomb, the farther will be the distance from the explosion at which the peak overpressure has a specific value and the longer will be the duration of the positive phase at this overpressure. Since there is increased drag damage with increased duration at a given pressure, the same damage will extend to lower overpressures. Structures which are sensitive to drag loading will therefore be damaged over a range that is larger than is given by the cube root rule for diffraction-type structures. In other words, as the result of a thousand-fold increase in bomb energy, the range for a specified damage to a drag-sensitive structure will be increased by a factor of more than ten, and the area by more than a hundred.

## FACTORS AFFECTING RESPONSE

### STRENGTH AND MASS

3.67 There are numerous factors associated with the characteristics of a structure which influence the response to the blast wave accompanying a nuclear explosion. Those considered below include various aspects of the strength and mass of the structure, general structural design, and ductility of the component materials and members.

3.68 The basic criterion for determining the response of a structure to blast is its strength. As used in this connection, "strength" is a general term, for it is a property influenced by many factors some of which are obvious and others are not. The most obvious indication of strength is, of course, massiveness of construction, but this is modified greatly by other factors not immediately visible to the eye, e. g., resilience and ductility of the frame, the strength of the beam and corner connections, the redundancy of supports, and the amount of diagonal bracing in the structure. Some of these factors will be examined further below.

3.69 The strongest structures are heavily framed steel and reinforced-concrete buildings, whereas the weakest are probably certain shed-type industrial structures having light frames and long beam spans. Some kinds of lightly-built frame construction also fall into the latter category, but well constructed frame houses have higher strength.

3.70 The resistance to blast of structures having load-bearing, masonry walls, e. g., of brick or concrete blocks, without reinforcement, is not very good. This is due to the lack of resilience and to the moderate strength of the connections which are put under stress when the blast load is applied laterally to the building. The use of steel reinforcement with structures of this type greatly increases the strength, as will be seen in due course.

### STRUCTURAL DESIGN

3.71 Except for those regions in which fairly strong earthquake shocks may be expected, most structures in the United States are designed to withstand the lateral loadings due only to moderately strong winds. For design purposes, such loading is assumed to be static (or stationary) in character because natural winds build up relatively slowly and remain fairly steady. The blast from a nuclear explosion, however, causes a lateral dynamic (rather than static) loading; the load is applied extremely rapidly and it lasts for a second or more with continuously decreasing strength. The inertia, as measured by the mass of the structure or member, is an important factor in determining response to a dynamic lateral load, although it is not significant for static loading.

3.72 Of existing structures, those intended to be earthquake resistant, which are capable of withstanding a lateral load equal to about 10 percent of the weight, will probably be damaged least by blast. Such structures, stiffened by diaphragm walls and having continuity of joints to provide additional rigidity, may be expected to withstand appreciable lateral forces without serious damage.

### DUCTILITY

3.73 The term ductility refers to the ability of a material or structure to absorb energy inelastically without failure; in other words, the greater the ductility, the greater the resistance to failure. Materials which are brittle have poor ductility and fail easily.

3.74 There are two main aspects of ductility to be considered. When a force (or load) is applied to a material so as to deform it, as is the case in a nuclear explosion, for example, the initial deformation is said to be "elastic." Provided it is still in the elastic range, the material will recover its original form when the loading is removed. However, if the "stress" produced by the load is sufficiently great, the material passes into the "plastic" range. In this state the material does not recover completely after removal of the stress, that is to say, the deformation is permanent, but there is no failure. Only when the stress reaches the "ultimate strength" does failure, i. e., breakage, occur.

3.75 Ideally, a structure which is to suffer little damage from blast should have as much elasticity as possible. Unfortunately, structural materials are generally not able to absorb much energy in the elastic range, although many common materials can take up large amounts of energy in the plastic range before they fail. The problem in blast-resistant design, therefore, is to decide how much permanent (plastic) deformation can be accepted before a particular structure is rendered useless. This will, of course, vary with the nature and purpose of the structure. Although deformation to the point of collapse is definitely undesirable, some lesser deformation may not seriously interfere with the continued use of the structure.

3.76 It is evident that ductility is a desirable property of structural materials required to resist blast. Structural steel and steel reinforcement have this property to a considerable extent. They are able to absorb large amounts of energy, e. g., from a blast wave, without failure and thus reduce the chances of collapse of the structure in which they are used. Steel has the further advantage of a higher yield point (or elastic limit) under dynamic than under static loading.

3.77 Although concrete alone is not ductile, when steel and concrete are used together, as in reinforced-concrete structures, the ductile behavior of the steel will usually predominate. The structure will then have considerable ductility and, consequently, resistance to blast. Without reinforcement, masonry walls are completely lacking in ductility and readily suffer brittle failure, as stated above.

## TECHNICAL ASPECTS OF BLAST WAVE PHENOMENA[5]

### PROPERTIES OF BLAST WAVE AT SURFACE

3.78 The characteristics of the blast wave have been discussed in a qualitative manner in the earlier parts of this chapter, and the remaining sections will be devoted to a consideration of some of the quantitative aspects of blast wave phenomena in air.[6] The basic relationships among the properties of a blast wave, having a sharp front at which there is a sudden pressure discontinuity, are derived from the Rankine-Hugoniot conditions based on the conservation of mass, energy, and momentum at the shock front. These conditions, together with the equation of state for air, permit the derivation of the required relations involving the shock velocity, the particle (or wind) velocity, the overpressure, the dynamic pressure, and the density of the air behind the ideal shock front.

3.79 The blast wave properties in the region of regular reflection are somewhat complex and depend on the angle of incidence of the wave with the ground and the shock strength. For a contact surface burst, when there is but a single hemispherical (fused) wave, as stated in § 3.29, and in the Mach region below the triple point path for an air burst, the various blast wave characteristics at the shock front are uniquely related by the Rankine-Hugoniot equations. It is for these conditions, in which there is a single shock front, that the following results are applicable.

3.80 The shock velocity, $U$, and the particle velocity (or peak wind velocity behind the shock front), $u$, are expressed by

$$U=c_0(1+6p/7P_0)^{1/2}$$

and

$$u=\frac{5p}{7P_0}\cdot\frac{c_0}{(1+6p/7P_0)^{1/2}},$$

where $p$ is the peak overpressure (behind the shock front), $P_0$ is the ambient pressure (ahead of the shock), and $c_0$ is the ambient sound velocity (ahead of the shock). The density, $\rho$, of the air behind the shock front is related to the ambient density, $\rho_0$, by

$$\frac{\rho}{\rho_0}=\frac{7+6p/P_0}{7+p/P_0}.$$

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[5] The remaining sections of this chapter may be omitted without loss of continuity.

[6] The technical aspects of blast loading and response of structures, and other related topics, are treated in Chapter VI.

The dynamic pressure, $q$, is defined by

$$q=\tfrac{1}{2}\rho u^2,$$

and the introduction of the appropriate Rankine-Hugoniot equations leads to

$$q=\frac{5}{2}\cdot\frac{p^2}{7P_0+p}$$

for the peak dynamic pressure. The variations of shock velocity, particle (or peak wind) velocity, and dynamic pressure with the peak overpressure at sea level, as derived from the foregoing equations, are shown graphically in Fig. 3.80.

3.81 When the blast wave strikes a surface, such as that of a structure, at normal incidence, i. e., head on, the instantaneous value of the reflected overpressure, $p_r$ is given by

$$p_r=2p\left(\frac{7P_0+4p}{7P_0+p}\right). \qquad (3.81.1)$$

It can be seen from this expression that the value of $p_r$ approaches $8p$ for large values of the incident overpressure (strong shocks) and tends toward $2p$ for small overpressures (weak shocks). A curve showing the variation of the instantaneous reflected pressure with the peak incident overpressure is included in Fig. 3.80.

3.82 The equations in § 3.80 give the peak values of the various blast wave parameters at the shock front. As seen earlier, however, the overpressure and dynamic pressure both decrease with time, although at different rates. For many situations, the variation of the overpressure behind the shock front with time at a given point can be represented by the simple empirical equation

$$p(t)=p\left(1-\frac{t}{t_+}\right)e^{-t/t_+}, \qquad (3.82.1)$$

where $p(t)$ is the overpressure at any time, $t$, after the arrival of the shock front, $p$ is the peak overpressure, and $t_+$ is the duration of the positive phase of the blast wave. This expression is represented graphically in Fig. 3.82, in which the "normalized" overpressure, i. e., the value relative to the peak overpressure, is plotted against the "normalized" time, i. e., the time relative to the duration of the positive phase. It may be noted that in the event of the interaction of the blast wave with a structure, this equation is used in determining the air blast loading.

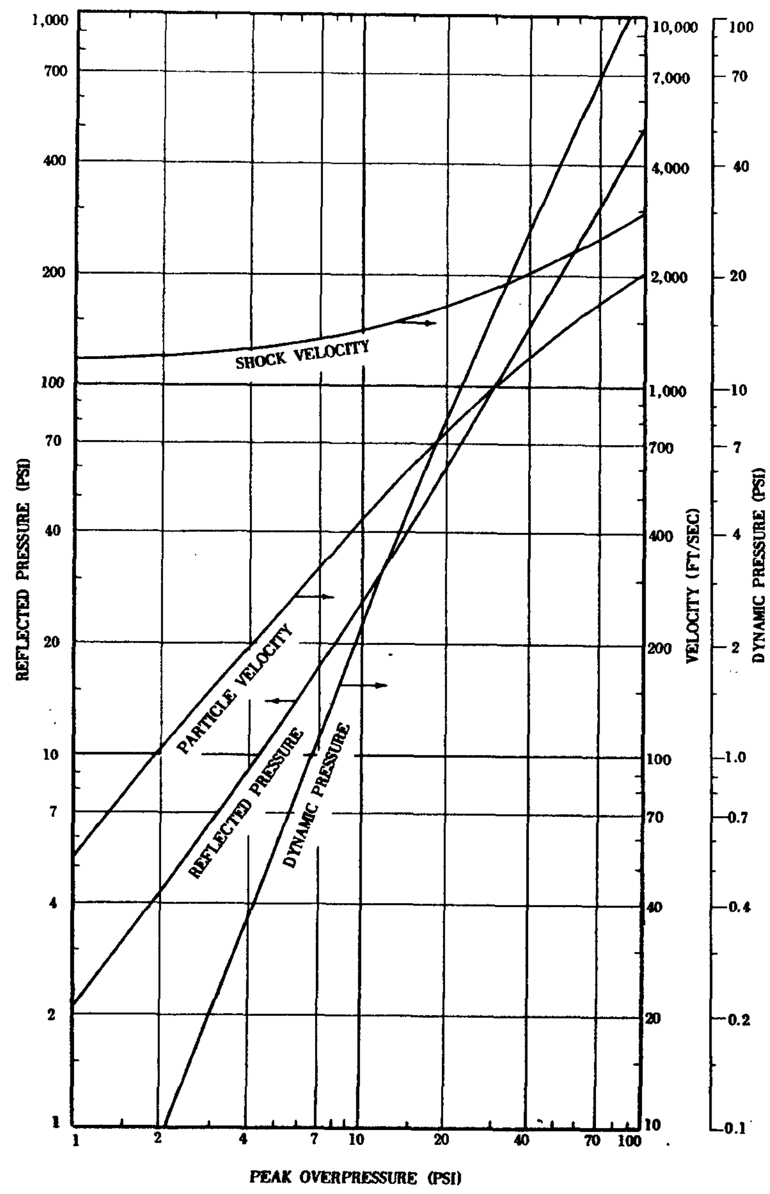

Figure 3.80. Relation of blast wave characteristics at the shock front to peak overpressure.

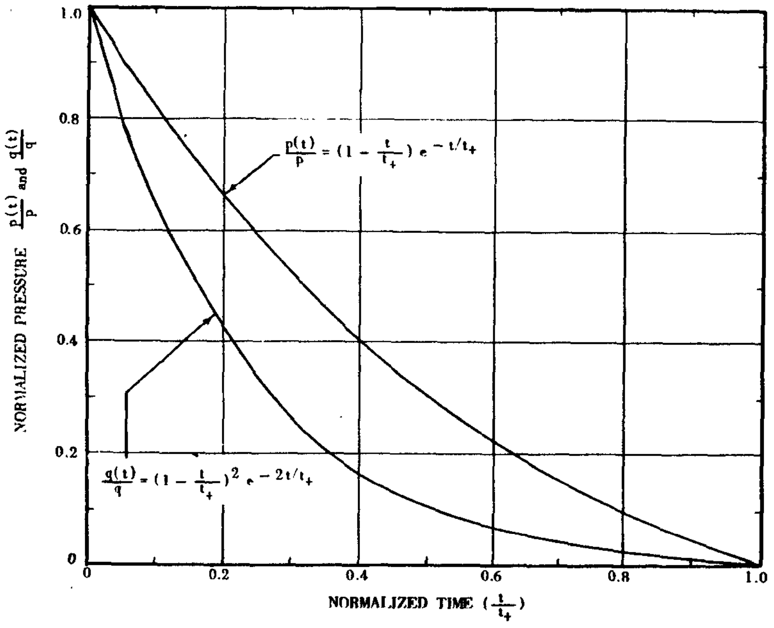

Figure 3.82. Normalized overpressure and dynamic pressure versus normalized time.

3.83 A similar empirical expression for the variation of the dynamic pressure with time behind the shock front is

$$q(t)=q\left(1-\frac{t}{t_+}\right)^2 e^{-2t/t_+},$$

where $q(t)$ is the value of the dynamic pressure at any time, $t$, after the arrival of the shock front, and $q$ is the peak dynamic pressure. A plot of this equation is also shown in Fig. 3.82.

3.84 Another important blast damage parameter is the "impulse," which takes into account the duration of the positive phase and the variation of the overpressure during that time. Impulse may be defined as the total area under the overpressure-time curve, such as that shown in Fig. 3.82, at a given location. The positive phase overpressure impulse, $I$, (per unit area) may then be represented mathematically by

$$I=\int_0^{t_+} p(t)dt,$$

where $p(t)$ may be expressed analytically, if desired, by means of equation (3.82.1). The positive phase dynamic impulse can be defined by a similar expression in which $q(t)$ replaces $p(t)$.

3.85 In order to be able to calculate the characteristic properties of the blast wave from an explosion of any given energy if those for another energy are known, appropriate scaling laws are applied. With the aid of such laws it is possible to express the data for a large range of energies in a simple form. One way of doing this, which will be illustrated below, is to draw curves showing how the various properties of the blast wave at the surface change with increasing distance from the detonation in the case of a 1-kiloton nuclear bomb. Then, with the aid of the scaling laws, the values for an explosion of any specified energy can be readily determined.

3.86 Theoretically, a given pressure will occur at a distance from an explosion that is proportional to the cube root of the energy yield. Full scale tests have shown this relationship between distance and energy yield to hold for yields up to (and including) the megaton range. Thus, cube root scaling may be applied with confidence over a wide range of explosion energies. According to this law, if $D_0$ is the distance (or slant range) from a reference explosion of $W_0$ kilotons at which a certain overpressure or dynamic pressure is attained, then for any explosion of $W$ kilotons energy these same pressures will occur at a distance $D$ given by

$$\frac{D}{D_0}=\left(\frac{W}{W_0}\right)^{1/3}. \qquad (3.86.1)$$

As stated above, the reference explosion is conveniently chosen, as having an energy yield of 1 kiloton, so that $W_0=1$. It follows, therefore, from equation (3.86.1) that

$$D=D_0\times W^{1/3}, \qquad (3.86.2)$$

where $D_0$ refers to the distance from a 1-kiloton explosion. Consequently, if the distance $D$ is specified, then the value of the explosion energy, $W$, required to produce a certain effect, e. g., a given peak overpressure, can be calculated. Alternatively, if the energy, $W$, is specified, the appropriate distance, $D$, can be evaluated from equation (3.86.2).

3.87 When comparing air bursts having different energy yields, it is convenient to introduce a scaled height of burst, defined as

$$\text{Scaled height of burst} = \frac{\text{Actual height of burst}}{W^{1/3}}.$$

It can be readily seen, therefore, that for explosions of different energies having the same scaled height of burst, the cube root scaling law may be applied to distances from ground zero, as well as to distances from the explosion. Thus, if $d_0$ is the distance from ground zero at which a particular overpressure or dynamic pressure occurs for a 1-kiloton explosion, then for an explosion of $W$ kilotons energy the same pressures will be observed at a distance $d$ determined by the relationship

$$d = d_0 \times W^{1/3}. \qquad (3.87.1)$$

This expression can be used for calculations of the type referred to in the preceeding paragraph, except that the distances involved are from ground zero instead of from the explosion (slant ranges).

3.88 Cube root scaling can also be applied to arrival time of the shock front, positive phase duration, and impulse, with the understanding that these quantities concerned are themselves scaled according to the cube root law. The relationships may be expressed in the form

$$\frac{t}{t_0} = \frac{d}{d_0} = \left(\frac{W}{W_0}\right)^{1/3} \quad \text{and} \quad \frac{I}{I_0} = \frac{d}{d_0} = \left(\frac{W}{W_0}\right)^{1/3},$$

where $t_0$ represents arrival time or positive phase duration and $I_0$ is the impulse for a reference explosion of energy $W_0$, and $t$ and $I$ refer to any explosion of energy $W$; as before, $d_0$ and $d$ are distances from ground zero. If $W_0$ is taken as 1 kiloton, then the various quantities are related as follows:

$$t = t_0 \times W^{1/3} \text{ at a distance } d = d_0 \times W^{1/3}$$

and

$$I = I_0 \times W^{1/3} \text{ at a distance } d = d_0 \times W^{1/3}.$$

Examples of the use of the equations developed above will be given later.

## ALTITUDE CORRECTIONS

3.89 The foregoing equations apply to a strictly homogeneous atmosphere, that is, where ambient pressure and temperature at the burst point and target are the same for all cases. If the ambient conditions are markedly different for a specified explosion as compared with those in the reference explosion, then the correction factors referred to in § 3.39 must be applied. The general relationships which take into account the possibility that the absolute temperature $T$ and ambient pressure $P$ are not the same as $T_0$ and $P_0$ respectively, in the reference (1-kiloton) explosion are as follows. For the overpressure,

$$p = p_0 \frac{P}{P_0},$$

where the $p$'s refer to the respective overpressures at a given distance. The corrected values of distance for a specified pressure are then given by

$$d = d_0 W^{1/3} \left(\frac{P_0}{P}\right)^{1/3},$$

and for arrival time or positive phase duration at the appropriate scaled distance by

$$t = t_0 W^{1/3} \left(\frac{P_0}{P}\right)^{1/3} \left(\frac{T_0}{T}\right)^{1/2}.$$

3.90 It is seen that when $T$ is equal to $T_0$ and $P$ to $P_0$, these expressions become identical with the corresponding ones in §§ 3.86 and 3.87, for strictly homogeneous conditions. As a general rule, the reference values for the blast wave properties, such as those to be given shortly, are for a standard sea level atmosphere, where $P_0$ is 14.7 pounds per square inch and the temperature is 59° F. or 15° C, so that $T_0$ is 519° Rankine or 288° Kelvin. As noted previously in § 3.39, for bursts at elevations within 5,000 feet or so above sea level, these corrections will be no more than a few percent.

## STANDARD CURVES AND CALCULATIONS OF BLAST WAVE PROPERTIES

3.91 In order to estimate the damage which might be expected to occur at a particular range from a given explosion, it is necessary to define the characteristics of the blast wave as they vary with time and distance. Consequently, standard curves of the various air blast wave properties are given here to supplement the general discussion already presented. These curves show the variation of peak overpressure, peak dynamic pressure, arrival time, positive phase duration, and overpressure impulse with distance from ground zero, for a contact surface burst and a typical air burst. For the case of the air burst, a curve showing the path of the triple point, i. e., the Mach stem height as a function of distance from ground zero, is also given.

3.92 From these curves the values of the blast wave properties at the surface can be calculated and the results used to determine the loading and response of a particular target. It should be mentioned that the data represent the behavior of the blast wave under average conditions over a flat surface at (or near) sea level. Hence, the values of peak overpressure and dynamic pressure may be regarded as the basic information to be used in applying the procedures to be discussed in Chapter VI for the determination of blast damage to be expected under various conditions.

3.93 These standard curves show the blast wave properties for a 1-kiloton explosion. An example showing the use of the curves will be given on the page facing each figure. To simplify the calculations that will be made, Fig. 3.93 is provided; this gives the values of cube roots required in the application of the scaling laws.

3.94 The variation of the peak overpressure with distance from ground zero for a contact surface burst is shown in Figure 3.94a and for a typical air burst in Fig. 3.94b for a 1-kiloton explosion.[7] For the sake of completeness, a so-called "free air" overpressure curve is included in Fig. 3.94a. This is based on the supposition that a contact surface burst of $W$ kilotons energy is equivalent in blast characteristics to an explosion of $2W$ kilotons high in the air and prior to any reflection. This would be true only if the ground were an absolutely rigid reflecting surface. The energy transmitted to the lower hemisphere of the blast wave in the absence of the ground will then be reflected into the upper hemisphere in coincidence with the energy normally sent there in an explosion high in the air. The distances in this (free air) case are the slant ranges or actual distances from the explosion. Fig. 3.94c shows the height of the Mach stem for a 1-kiloton air burst, as a function of distance from ground zero, as defined by the path of the triple point.

3.95 In Fig. 3.95 the curves represent the horizontal component of the dynamic pressure versus distance from ground zero for a contact surface burst and a typical air burst of 1-kiloton yield. The vertical component of the dynamic pressure is small enough to be neglected except near ground zero in the case of an air burst. Since only the value of the horizontal component is given, the dynamic pressure in the regular reflection region for an air burst becomes smaller as the distance from ground zero decreases beyond a certain point.

(Text continued on page 120.)

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[7] For the definition and description of a "typical" air burst, see § 2.47. The scaled height of burst is assumed to be the same for all energy yields.

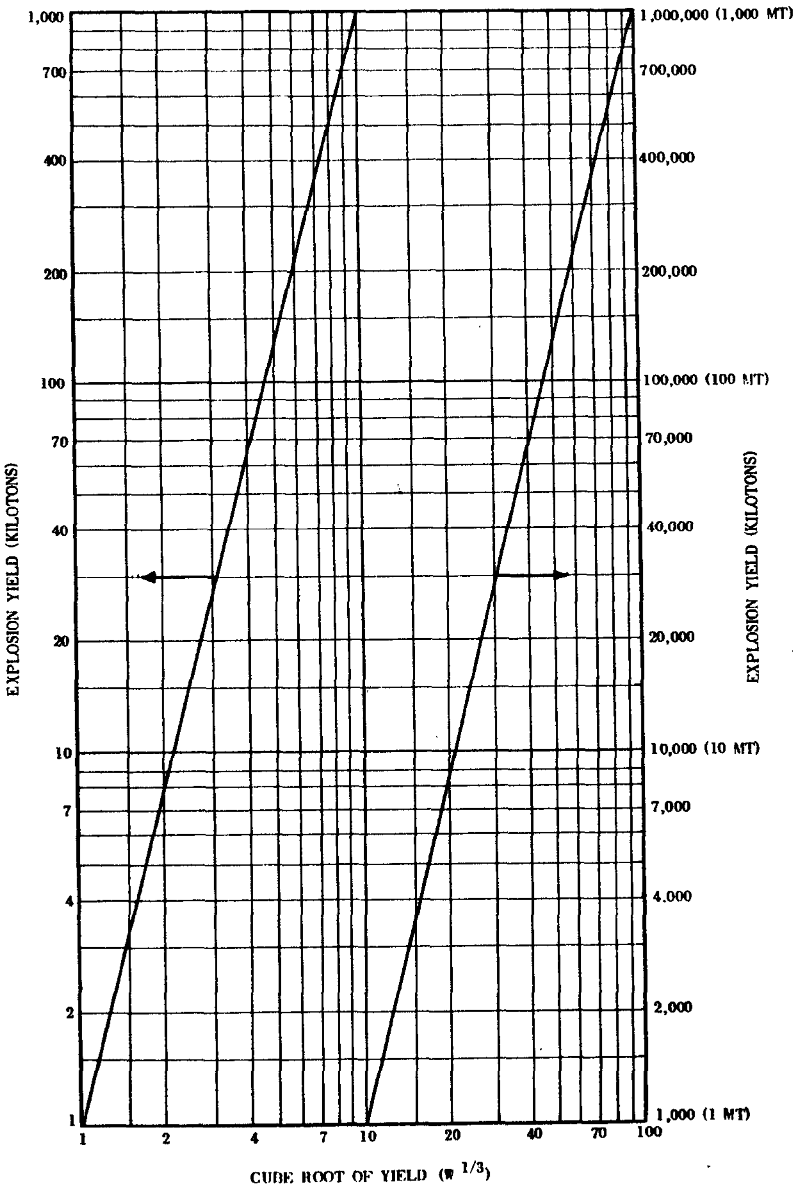

Figure 3.93. Cube roots of explosion yield values.

The curves show the variation of peak overpressure with distance for a 1 KT surface burst and for a 1 KT free-air burst (based on the 2*W* assumption in § 3.94) in a standard sea level atmosphere.

*Scaling.* For yields other than 1 KT, the range to which a given overpressure extends scales as the cube root of the yield, i. e.,

$$d = d_0 \times W^{1/3},$$

where, for a given overpressure,

$d_0$ is the distance from the explosion for 1 KT,

and

$d$ is the distance from the explosion for $W$ KT.

*Example*

*Given:* A 1 MT surface burst.

*Find:* The distance to which 2 psi extends.

*Solution:* From Fig. 3.93 the cube root of 1000 is 10. From Fig. 3.94a, a peak overpressure of 2 psi occurs at a distance of 0.53 mile from a 1 KT surface burst. Therefore, for a 1 MT surface burst,

$$d = d_0 \times W^{1/3} = 0.53 \times 10 = 5.3 \text{ miles.} \quad \textit{Answer}$$

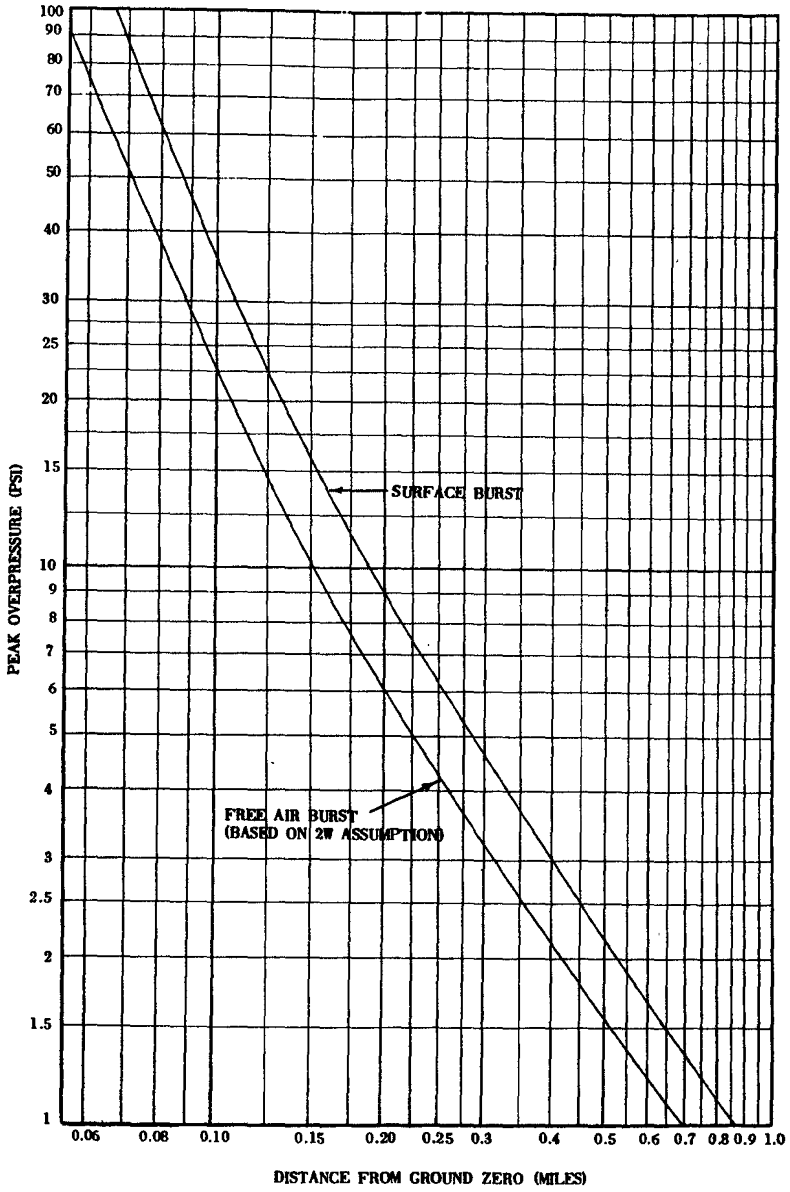

Figure 3.94a. Peak overpressure for a 1-kiloton surface burst and free air burst.

The curve shows the variation of peak overpressure on the surface with distance from ground zero for a 1 KT typical air burst in a standard sea level atmosphere under average surface conditions.

*Scaling.* For yields other than 1 KT, the range to which a given overpressure extends scales as the cube root of the yield, i. e.,

$$d=d_0\times W^{1/3},$$

where, for a given peak overpressure,

$d_0$ is the distance from ground zero for 1 KT,

and

$d$ is the distance from ground zero for $W$ KT.

*Example*

*Given:* A 1 MT typical air burst.

*Find:* The distance from ground zero to which 8 psi extends.

*Solution:* From Fig. 3.93 the cube root of 1,000 KT is 10. From Fig. 3.94b a peak overpressure of 8 psi occurs at 0.28 mile from ground zero for a 1 KT typical air burst. For a 1 MT typical air burst, therefore,

$$d=d_0\times W^{1/3}=0.28\times 10=2.8 \text{ miles.} \quad \textit{Answer}$$

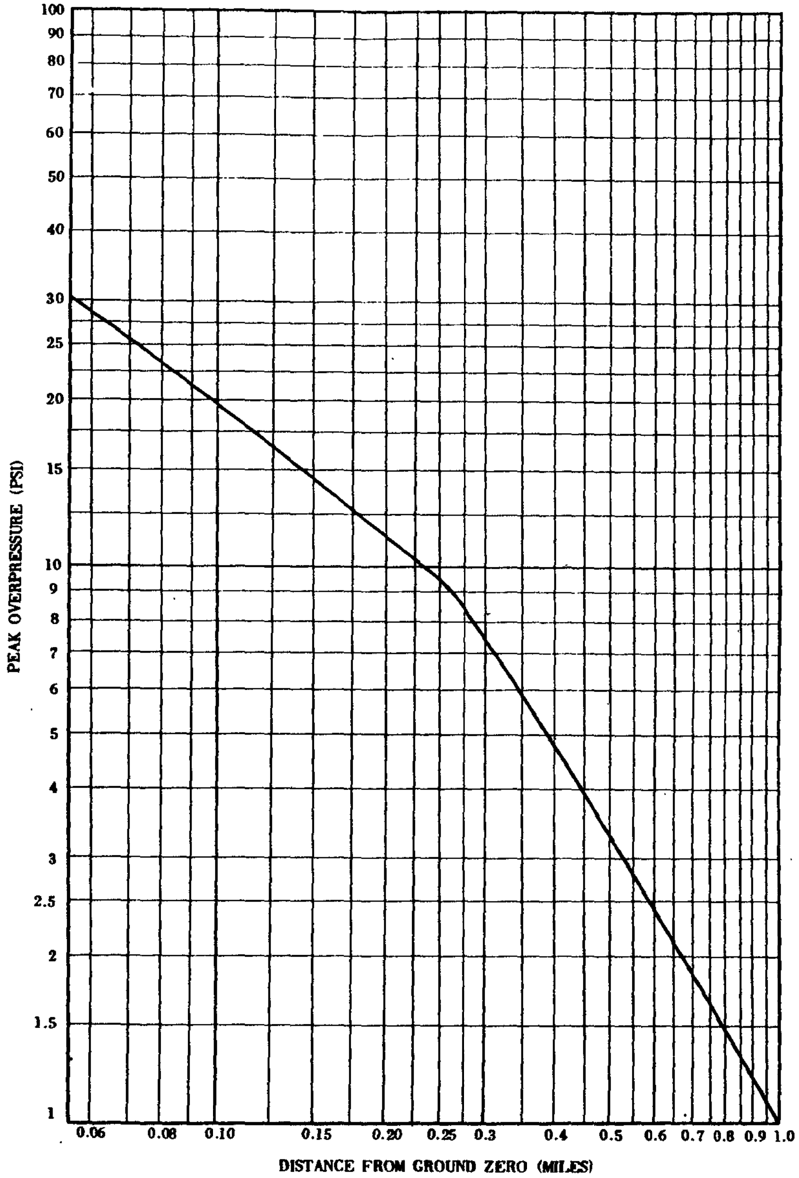

**Figure 3.94b.** Peak overpressure on the surface for a 1-kiloton typical air burst.

The curve shows the increase in height of the Mach stem with distance from ground zero for a 1 KT typical air burst in a standard sea level atmosphere under average surface conditions.

*Scaling.* For yields other than 1 KT, the height and distance of the Mach stem scale as the cube root of the yield, i. e.,

$$h=h_0 \times W^{1/3} \text{ at } d=d_0 \times W^{1/3},$$

where

$h_0$ is the height of Mach stem at a distance $d_0$ for 1 KT,

and

$h$ is the height of Mach stem at a distance $d$ for $W$ KT.

*Example*

*Given:* A 1 MT typical air burst.

*Find:* (*a*) The distance from ground zero at which the Mach effect commences.

(*b*) The height of the Mach stem at 2.75 miles from ground zero.

*Solution:* (*a*) Where the Mach effect commences, $h$ and $h_0$ are the same, i. e., zero, so that in this case $d=d_0 \times W^{1/3}$. From Fig. 3.93, the cube root of 1,000 KT is 10, and from Fig. 3.94c, the Mach effect for a 1 KT air burst sets in at 0.13 mile from ground zero. Hence, for the 1 MT air burst the Mach effect will commence at a distance from ground zero given by

$$d=d_0 \times W^{1/3}=0.13 \times 10=1.3 \text{ miles. } \textit{Answer.}$$

(*b*) The distance $d_0$ for 1 KT corresponding to 2.75 miles for 1 MT is

$$d_0=\frac{d}{W^{1/3}}=\frac{2.75}{10}=0.275 \text{ mile.}$$

The height of the Mach stem at this distance from ground zero for a 1 KT air burst is found from Fig. 3.94c to be 37 feet. Hence, for the 1 MT typical air burst,

$$h=h_0 \times W^{1/3}=37 \times 10=370 \text{ feet. } \textit{Answer.}$$

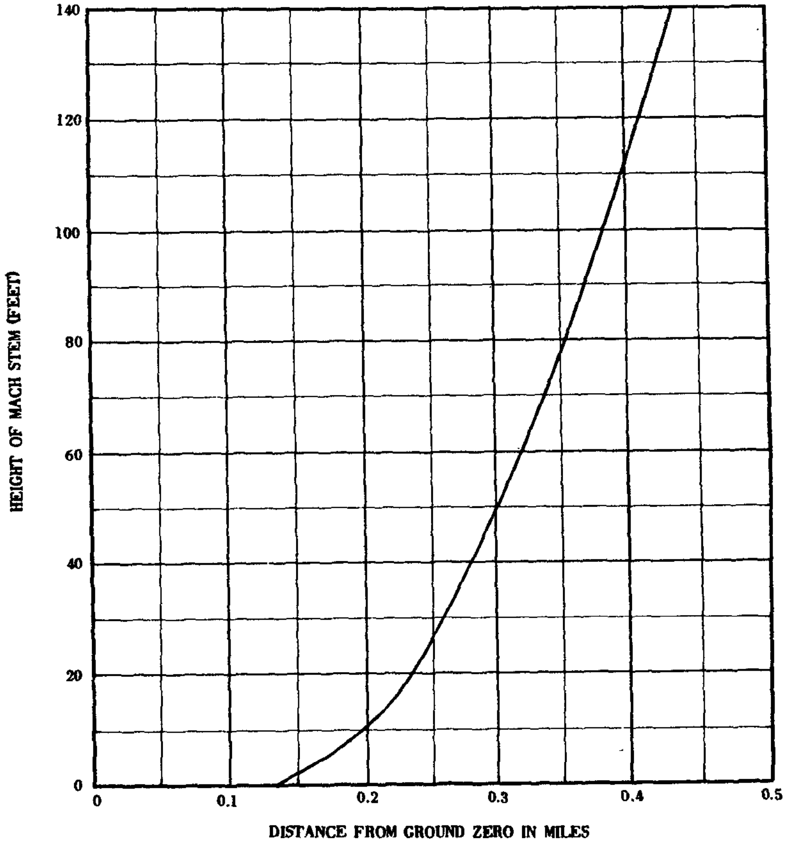

**Figure 3.94c.** Height of Mach stem (path of triple point) for a 1-kiloton air burst.

The curves show the variation of the horizontal component of the peak dynamic pressure with distance from ground zero for 1 KT air and surface bursts in a standard sea level atmosphere under average surface conditions.

*Scaling.* For yields other than 1 KT, the range in which a given dynamic pressure level extends scales as the cube root of the yield, i. e.,

$$d=d_0\times W^{1/3},$$

where, for a given peak dynamic pressure,

$d_0$ is the distance from ground zero for 1 KT,

and

$d$ is the distance from ground zero for $W$ KT.

*Example*

*Given:* A 1 MT surface burst.

*Find:* The horizontal component of the peak dynamic pressure to be expected at 1.8 miles from ground zero.

*Solution:* From Fig. 3.93, the cube root of 1,000 KT is 10.

$$d_0=\frac{d}{W^{1/3}}=\frac{1.8}{10}=0.18 \text{ mile for 1 KT.}$$

From Fig. 3.95 the horizontal component of the peak dynamic pressure at 0.18 mile from a 1 KT contact surface burst is 2.8 psi. Therefore, the horizontal component of the peak dynamic pressure at 1.8 miles from ground zero for a 1 MT contact surface burst is 2.8 psi. *Answer.*

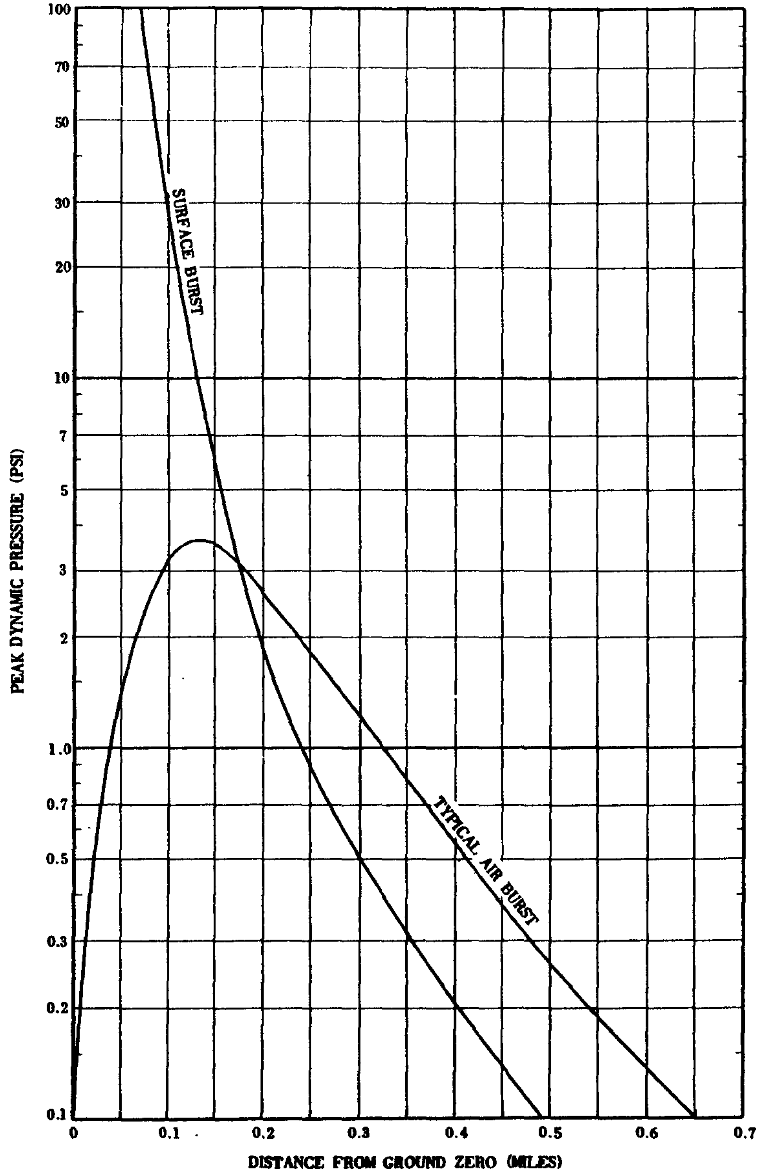

**Figure 3.95.** Horizontal component of peak dynamic pressure for a 1-kiloton explosion.

The curves show the dependence of the arrival time and the duration of the positive overpressure phase on distance from ground zero for 1 KT air and surface bursts in a standard sea level atmosphere under average surface conditions.

*Scaling.* For yields other than 1 KT, the duration and distance may be scaled in the following manner:

$$t=t_0\times W^{1/3} \text{ at } d=d_0\times W^{1/3},$$

where

$t_0$ is the arrival time and positive phase duration for 1 KT at a distance $d_0$,

and

$t$ is the arrival time or positive phase duration for $W$ KT at a distance $d$.

*Example*

*Given:* A 1 MT bomb is exploded on the surface.

*Find:* The time of arrival and duration of the positive phase at a distance of 5.5 miles.

*Solution:* From Fig. 3.93, the cube root of 1,000 KT is 10.

$$d_0=\frac{d}{W^{1/3}}=\frac{5.5}{10}=0.55 \text{ mile for 1 KT.}$$

From Fig. 3.96, the time of arrival at 0.55 mile for a 1 KT contact surface burst is 1.9 seconds and the duration is 0.44 second. For a 1 MT surface burst,

Arrival time: $t=t_0\times W^{1/3}=1.9\times 10=19$ seconds. *Answer.*

Duration: $t=t_0\times W^{1/3}=0.44\times 10=4.4$ seconds. *Answer.*

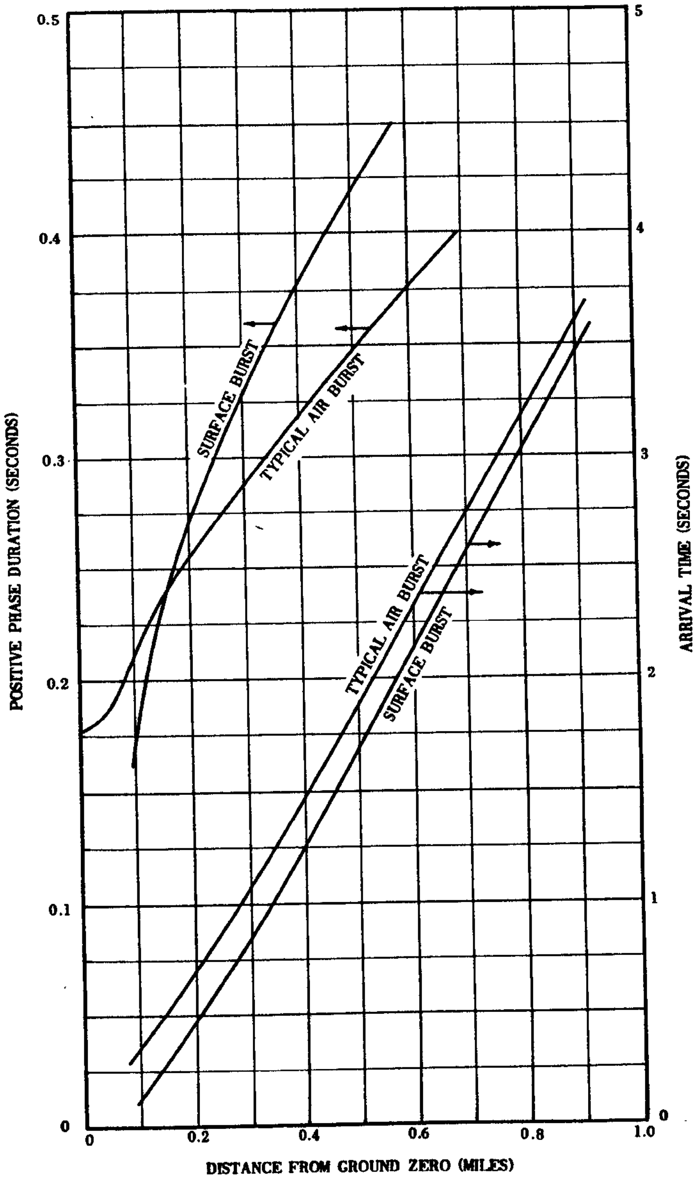

**Figure 3.96.** Times of arrival and positive phase durations at the surface for a 1-kiloton explosion.

The curves show the variation of overpressure and dynamic pressure (horizontal component) impulses in the positive phase with distance for 1 KT air and surface bursts in a standard sea level atmosphere under average surface conditions.

*Scaling.* For yields other than 1 KT, the impulse and distance may be scaled as follows:

$$I=I_0\times W^{1/3} \text{ at } d=d_0\times W^{1/3}$$

where

$I_0$ is the impulse for 1 KT at a distance $d_0$

and

$I$ is the impulse for $W$ KT at a distance $d$.

*Example*

*Given:* A 1 MT typical air burst.

*Find:* The distance at which the positive phase overpressure impulse is 5.5 lb-sec/in².

*Solution:* From Fig. 3.93, the cube root of 1,000 KT is 10.

$$I_0=\frac{I}{W^{1/3}}=\frac{5.5}{10}=0.55 \text{ lb-sec/in}^2.$$

From Fig. 3.97, the distance at which the positive phase overpressure impulse for a 1 KT typical air burst equals 0.55 lb-sec/in.² is 0.40 mile. For a 1 MT typical air burst,

$$d=d_0\times W^{1/3}=0.40\times 10=4.0 \text{ miles. } \textit{Answer.}$$

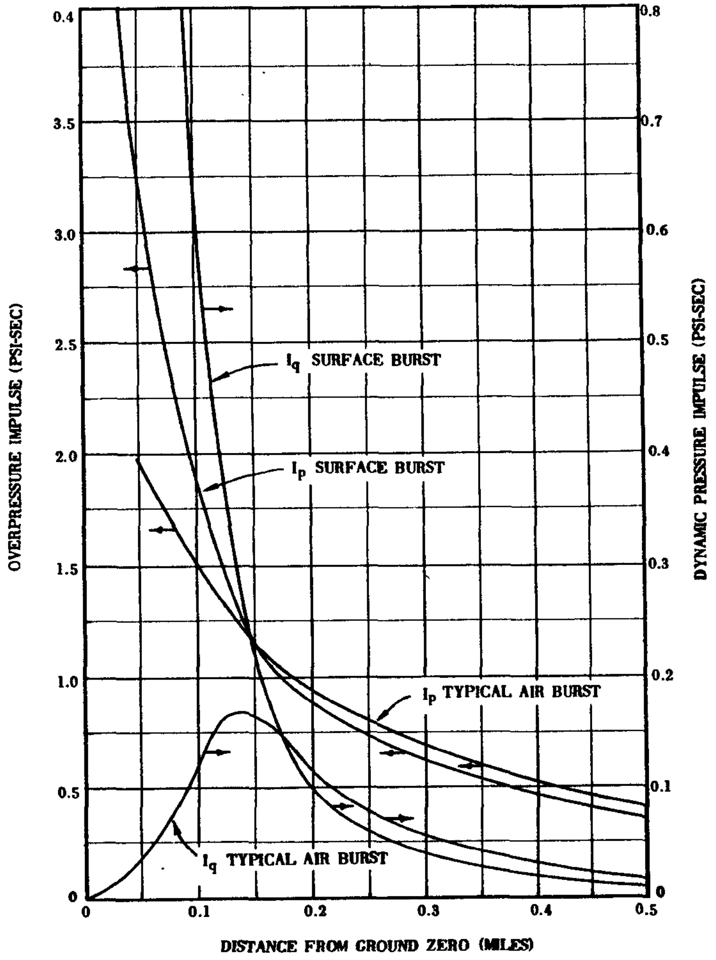

**Figure 3.97.** Overpressure and dynamic pressure positive phase impulse for a 1-kiloton explosion.

(Text continued from page 106.)

3.96 The dependence of the time of arrival of the shock front and the duration of the positive phase of the blast wave on the ground zero distance from a 1-kiloton contact surface burst and a typical air burst of the same energy are shown in Fig. 3.96.

3.97 Finally, Fig. 3.97 gives the overpressure positive phase and dynamic pressure impulses, $I_p$ and $I_q$, respectively, as a function of distance from ground zero for a contact surface burst and a typical air burst of a 1-kiloton bomb. As in all the other cases, the results apply to an explosion in a standard sea level atmosphere under average surface conditions.

## *CHAPTER IV*

# STRUCTURAL DAMAGE FROM AIR BLAST

## INTRODUCTION

### General Observations

4.1 The preceding chapter has dealt with the general principles of air blast and its effect on structures. Now some consideration will be given to the actual damage to buildings of various types, bridges, utilities, and vehicles, caused by a nuclear explosion. Some of the information, especially for large structures, has been obtained from surveys made at Hiroshima and Nagasaki. Over each of these Japanese cities a nuclear bomb of approximately 20-kilotons energy was detonated at a height of about 1,850 feet. More recently, this has been supplemented by much data secured in connection with various tests, especially those carried out at the Nevada Test Site in the United States. The present chapter is largely descriptive in character; a more technical analysis of structural damage will be given in Chapter VI.

4.2 Before proceeding with detailed descriptions of the behavior of structures of specific types, attention may be called to an important difference between the blast effects of a nuclear weapon and those due to a conventional high-explosive bomb. The combination of high peak overpressure and longer duration of the positive (compression) phase of the blast wave in the former case results in "mass distortion" of buildings, similar to that caused by earthquakes. An ordinary explosion will usually damage only part of a large structure, but the nuclear blast can surround and destroy whole buildings.

4.3 An examination of the areas in Japan affected by nuclear bombing shows that small masonry buildings were engulfed by the oncoming pressure wave and collapsed completely. Light structures and residences were totally demolished by blast and subsequently destroyed by fire. Industrial buildings of steel construction were denuded of roofing and siding, and only the twisted frames remained. Nearly everything at close range, except structures and smokestacks of strong reinforced concrete, was destroyed. Some buildings leaned away from ground zero as though struck by a wind of stupendous proportions. Telephone poles were snapped off at ground level, as in a hurricane, carrying the wires down with them. Large gas holders were ruptured and collapsed due to the crushing action of the blast wave.

4.4 Many buildings, that at a distance appeared to be sound, were found on close inspection to be damaged and gutted by fire. This was frequently an indirect result of blast action. In some instances the thermal radiation may have been responsible for the initiation of fires, but in many other cases fires were started by overturned stoves and furnaces and the rupture of gas lines. The loss of water pressure by the breaking of pipes, mainly due to the collapse of buildings, and other circumstances arising from the explosions, contributed greatly to the additional destruction by fire.

4.5 A highly important consequence of the tremendous power of a nuclear explosion is the formation of enormous numbers of flying missiles consisting of bricks (and other masonry), glass, pieces of wood and metal, etc. These caused considerable amounts of minor damage to structures as well as numerous casualties. In addition, the large quantities of debris resulted in the blockage of streets, thus making rescue and fire-fighting operations extremely difficult (Fig. 4.5).

Figure 4.5. Debris after the atomic bomb explosion at Hiroshima.

4.6 It may be pointed out that many structures in Japan were designed to be earthquake-resistant, which probably made them stronger than most of their counterparts in the United States. On the other hand, some construction was undoubtedly lighter than in this country. However, contrary to popular belief concerning the flimsy character of Japanese residences, it was the considered opinion of a group of architects and engineers, who surveyed the nuclear bomb damage, that the resistance to blast of American residences in general would not be markedly different from that of the houses in Hiroshima and Nagasaki. This has been borne out by the observations made at the Nevada tests in 1953 and 1955.

4.7 The descriptions of various types of blast damage in the subsequent parts of this chapter are grouped into three main sections, as follows: (1) structures and their contents, including residences of different kinds, industrial, commercial, and administrative structures, and bridges; (2) transportation, including automobiles and other vehicles, railroad facilities, aircraft, and ships; and (3) utilities, including electricity, gas, and water supply systems, and communications equipment.

## STRUCTURES AND THEIR CONTENTS

### RESIDENTIAL STRUCTURES

4.8 There were many wood-framed residential structures with adobe walls in the Japanese cities which were subjected to nuclear attack, but such a large proportion were destroyed by fire that very little detailed information concerning blast damage was obtained. It appeared that, although the quality of the workmanship in framing was usually high, little attention was paid to good engineering principles. On the whole, therefore, the construction was not well adapted to resist wracking action. For example, mortise and tenon joints were weak points in the structure and connections were in general poor. Timbers were often dapped more than was necessary or splices put in improper locations, resulting in an over-all weakening (Fig. 4.8).

4.9 In Nagasaki, dwellings collapsed at distances up to 7,500 feet (1.4 miles) from ground zero, where the peak overpressure was estimated to be about 3 pounds per square inch, and there was moderately severe structural damage up to 8,500 feet (1.6 miles). Roofs, wall panels, and partitions were damaged out to 9,000 feet (1.7 miles),

Figure 4.8. *Upper photo:* Wood-frame building; 1.0 mile from ground zero at Hiroshima. *Lower photo:* Frame of residence under construction, showing small tenons.

where the overpressure was approximately 2 pounds per square inch, but the buildings would probably have been habitable with moderate repairs.

4.10 A considerable amount of information on the blast response of residential structures of several different kinds was obtained in the studies made at the Nevada Test Site in 1953 and, especially, in 1955. The nuclear device employed in the test of March 17, 1953 was detonated at the top of a 300-foot tower; the energy yield was about 15 kilotons. In the test of May 5, 1955, the explosion took place on a 500-foot tower and the yield was roughly 30 kilotons. In each case, air pressure measurements made possible a correlation, where it was justified, between the blast damage and the peak overpressure.

4.11 The main objectives of the tests on residential structures were as follows: (1) to determine the elements most susceptible to blast damage and consequently to devise methods for strengthening structures of various types; (2) to provide information concerning the amount of damage to residences that might be expected as a result of a nuclear explosion and to what extent these structures could be subsequently rendered habitable without major repairs; and (3) to determine how persons remaining in their houses during a nuclear attack might be protected from the effects of blast and radiations. Only the first two of these aspects of the tests will be considered here, since the present chapter is intended to deal primarily with blast effects. The problem of protection will be considered later (Chapter XII).

## Two-Story, Wood-Frame House: 1953 Test

4.12 In the 1953 test, two essentially identical houses, of a type that is common in the United States, were employed at different locations. They were of typical wood-frame construction, with two stories, basement, and a brick chimney (Fig. 4.12). The interiors were plastered but not painted. Since the tests were intended for studying the effects of blast, precautions were taken to prevent the houses from burning. The exteriors were consequently painted white (except for the shutters), to reflect the thermal radiation. For the same purpose, the windows facing the explosion were equipped with metal venetian blinds having an aluminum finish. In addition, the houses were roofed with light gray shingles; these were of asbestos cement for the house nearer to the explosion where the

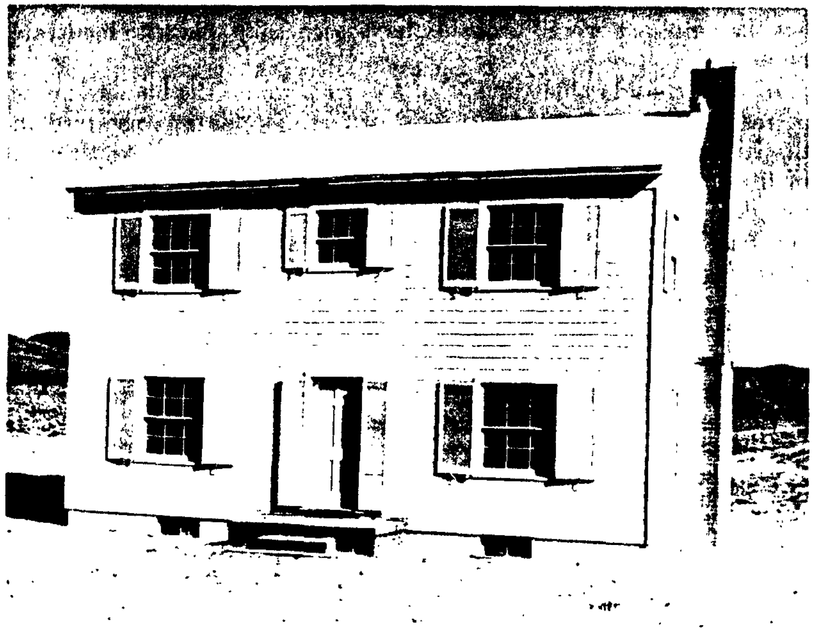

**Figure 4.12** Wood-frame house before a nuclear explosion, Nevada Test Site.

chances of fire were greater, whereas asphalt shingles were used for the other house. There were no utilities of any kind.

4.13 One of the two houses was located in the region of Mach reflection where the peak incident shock overpressure was close to 5 pounds per square inch. It was expected, from the effects in Japan, that this house would be almost completely destroyed—as indeed it was—but the chief purpose was to see what protection might be obtained by persons in the basement. The peak overpressure of the incident shock wave at the second house, farther from the burst, was 1.7 pounds per square inch. Here partial destruction only was expected, so that the test might provide data for structural improvements.

4.14 Some indication of the blast damage suffered by the dwelling nearer to the explosion can be obtained from Fig. 4.14. It is apparent that the house was ruined beyond repair. The first story was completely demolished and the second story, which was very badly damaged, dropped down on the first floor debris. The roof was blown off in several sections which landed at both front and back of the house. The gable end walls were blown apart and outward, and the brick chimney was broken into several pieces.

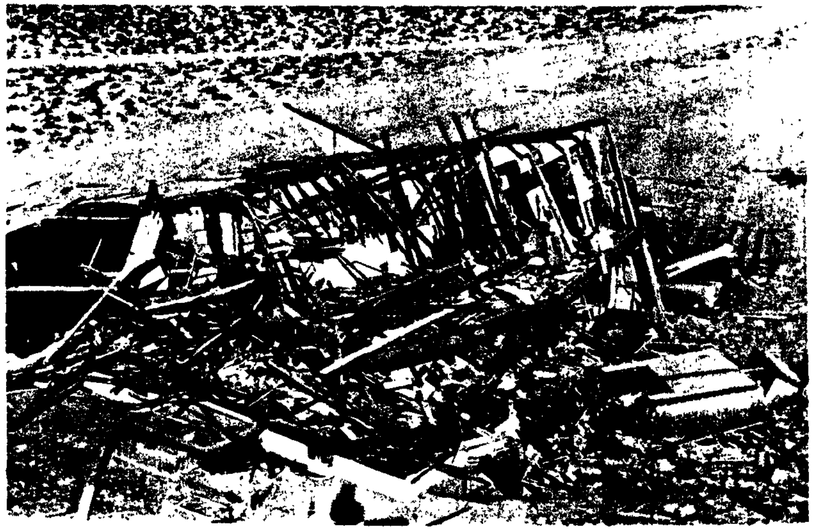

**Figure 4.14.** Wood-frame house after the nuclear explosion (5 psi overpressure).

4.15 The basement walls suffered some damage above grade, mostly in the rear, i. e., away from the explosion. The front basement wall was pushed in slightly, but was not cracked except at the ends. The joists supporting the first floor were forced downward (probably because of the air pressure differential between the first floor and the largely enclosed basement) and the supporting pipe columns were inclined to the rear. However, only in limited areas did a complete breakthrough from first floor to basement occur. The rest of the basement was comparatively clear and the shelters located there were unaffected.

4.16 The second house, exposed to an incident peak overpressure of 1.7 pounds per square inch, was badly damaged both internally and externally, but it remained standing (Fig. 4.16). Although complete restoration would have been very costly, it is believed that, with the window and door openings covered, and shoring in the basement, the house would have been habitable under emergency conditions.

4.17 The most obvious damage was suffered by doors and windows, including sash and frames. The front door was broken into pieces and the kitchen and basement entrance doors were torn off their hinges.

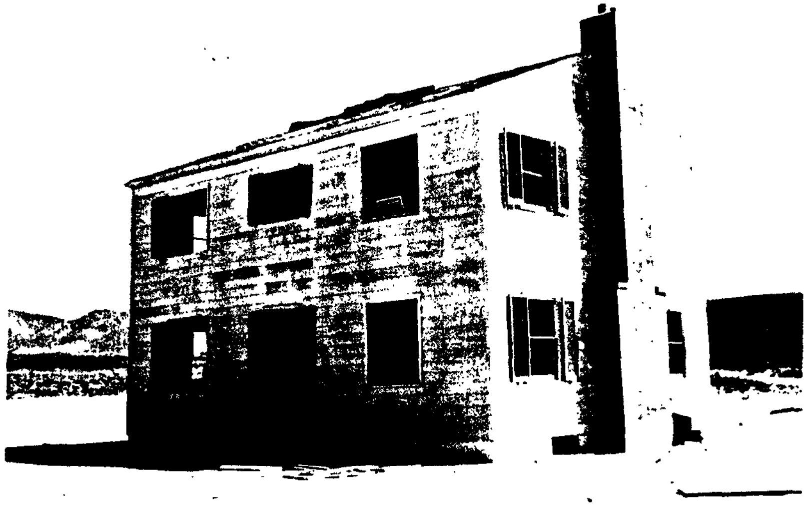

Figure 4.16. Wood-frame house after the nuclear explosion (1.7 psi overpressure).

Damage to interior doors varied; those which were open before the explosion suffered least. Window glass throughout the house was broken into fragments, and the force on the sash, especially in the front of the house, dislodged the frames.

4.18 Principal damage to the first floor system consisted of broken joists. Most breakages originated at knots in the lower edges of the 2 x 8 inch timbers (16-inch spacing). Most of the studs (2 x 4 inches with 16-inch spacing) at the front end of the house were cracked.

4.19 The second-story system suffered relatively little in structural respects, although windows were broken and plaster cracked. Damage to the roof consisted mainly of broken rafters (2 x 6 inches with 16-inch spacing). All but one of those at the front side were affected, but none of the rafters at the back was badly damaged. The roof (span 14 feet from front wall to ridge) was sprung slightly at the ridge.

4.20 The basement showed no signs of damage except to the windows, and the entry door and frame. The shelters in the basement were intact.

Figure 4.22. Strengthened wood-frame house after a nuclear explosion (4 psi overpressure).

### Two-Story Wood-Frame House: 1955 Test

4.21 Based upon the results described above, certain improvements in design were incorporated in two similar wood-frame houses used in the 1955 test. The following changes, which increased the estimated cost of the houses some 10 percent above that for normal construction, were made: (1) improved connection between exterior walls and foundations; (2) reinforced-concrete shear walls to replace the pipe columns in the basement; (3) increase in size and strengthening of connections of first-floor joists; (4) substitution of plywood for lath and plaster; (5) increase in size of rafters (to 2 x 8 inches) and wall studs; and (6) stronger nailing of window frames in wall openings.

4.22 Even with these improvements, it was expected that almost complete destruction would occur at 5 pounds per square inch peak overpressure, and so one of the houses was located where the overpressure at the Mach front would be 4 pounds per square inch. Partly because of the increased strength and partly because of the lower air blast pressure the house did not collapse (Fig. 4.22). However, the superstructure was so badly damaged that it could not have been occupied without expensive repair which would not have been economically advisable.

**Figure 4.24 First floor joists of strengthened wood-frame house after a nuclear explosion (4 psi overpressure).**

4.23 The front half of the roof was broken at midspan and the entire roof framing was deposited on the ceiling joists. The rear half of the roof was blown off and fell to the ground about 25 feet behind the house. Most of the rafters were split lengthwise, in spite of the increased dimensions.

4.24 The first-floor joists were split or broken and the floor was near collapse; it was held up principally by the sub- and finish-flooring which was largely intact (Fig. 4.24). The second floor and the ceiling of the first floor showed little damage, indicating rapid pressure equalization above and below the floor. This was made possible by the fact that practically all doors and windows were blown out. The upper portion of the chimney fell outward and although the lower part remained standing, it was dislocated in places.

4.25 The other strengthened two-story frame house was in a location where the incident peak overpressure was about 2.6 pounds per square inch; this was appreciably greater than the lower overpressure of the 1953 test. Relatively heavy damage was experienced, but the condition of the house was such that it could be made available for emergency shelter by shoring and not too expensive repairs (Fig. 4.25). Although there were differences in detail, the over-all damage was much the same degree as that suffered by the corresponding house without the improved features at an overpressure of 1.7 pounds per square inch.

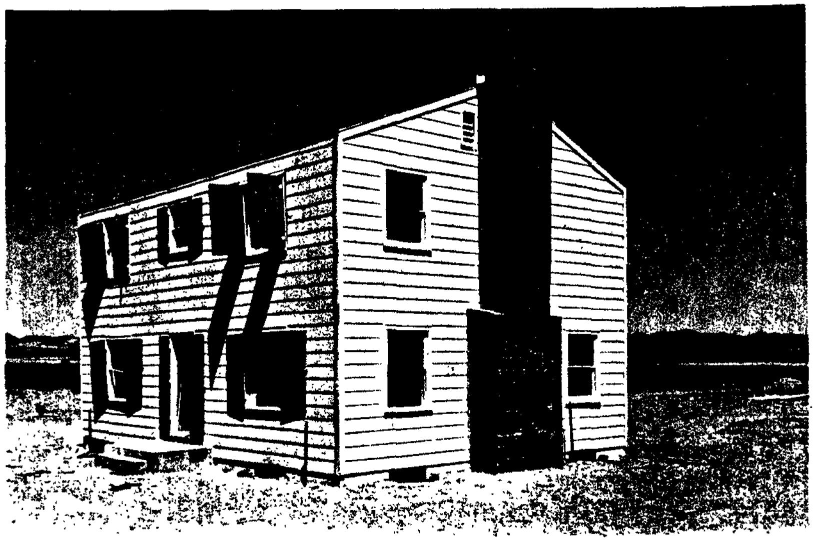

**Figure 4.25. Strengthened wood-frame house after a nuclear explosion (2.6 psi overpressure).**

4.26 In addition to the doors and windows, the framing of the house, especially that of the roof, suffered most severely from the blast. The cornice board on the side facing the explosion was blown off and it appeared that a slightly higher blast pressure might have lifted the roof completely from its attachment to the structure. Part of the ceiling framing was raised several inches, a ridge board was broken, and some of the rafters were fractured; one of the center girders was also pulled away from the ceiling joists, and part of the plywood ceiling was blown off. However, relatively few of the second-floor ceiling joists themselves were damaged.

4.27 The ceilings and walls of the first floor were only slightly affected. The floor joists were cracked and fractured, but no debris was deposited in the basement, as the subflooring remained intact (Fig. 4.27).

4.28 The wood window-sashes on the front and sides of the house were blown in and smashed, although at the back they suffered less. Exterior doors were blasted in, and some of the interior doors were

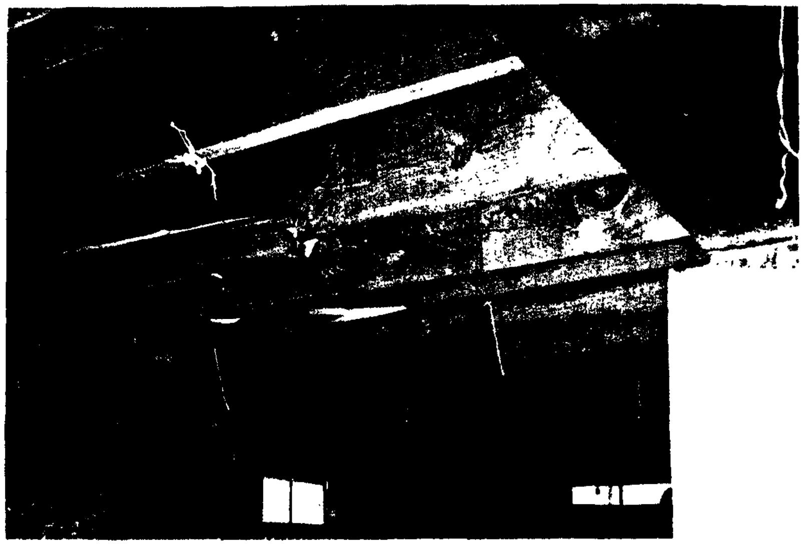

Figure 4.27. First floor joists of strengthened wood-frame house after a nuclear explosion (2.6 psi overpressure).

blown off their hinges. The brick chimney was sheared in at least two places, but it remained standing.

### Two-Story, Brick-Wall-Bearing House

4.29 For comparison with the tests on the two-story wood frame structures, made in 1953, two brick-wall-bearing houses of conventional construction, similar in size and layout, were exposed to 5 and 1.7 pounds per square inch overpressure, respectively, in the 1955 tests (Fig. 4.29). The exterior walls were of brick veneer and cinder block and the foundation walls of cinder block; the floors, partitions, and roof were wood-framed.

4.30 At an incident overpressure of 5 pounds per square inch, the brick-wall house was damaged beyond repair (Fig. 4.30). The exterior walls were exploded outward, so that very little masonry debris fell on the floor framing. The roof was demolished and blown off, the rear part landing 50 feet behind the house. The first floor had partially collapsed into the basement as a result of fracturing of the floor joists at the center of the spans and the load of the second floor which fell upon it. The chimney was broken into several large sections.

Figure 4.29. Unreinforced brick house before a nuclear explosion, Nevada Test Site.

Figure 4.30. Unreinforced brick house after the nuclear explosion (5 psi overpressure).

Figure 4.31. Unreinforced brick house after the nuclear explosion (1.7 psi overpressure).

4.31 Farther from the explosion, where the overpressure was 1.7 pounds per square inch, the corresponding structure was damaged to a considerable extent. Nevertheless, its condition was such that it could be made available for habitation by shoring and some fairly inexpensive repairs (Fig. 4.31).

4.32 There was no apparent damage to the masonry of the house, but the roof and second-floor ceiling framing suffered badly. The connections to the rear rafters at the ridge failed and the rafters dropped several inches. The ridge was split in the center portion and some of the 2 x 4-inch collar beams were broken in half. The ceiling joists at the rear were split at midspan, and the lath and plaster ceiling was blown downward. The second-floor framing was not appreciably affected and only a few of the first-floor joists were fractured. The interior plastered wall and ceiling finish were badly damaged.

4.33 The glass in the front and side windows was blown in, but the rear windows suffered much less. The exterior doors were demolished and several interior bedroom and closet doors were blown off their hinges.

### ONE-STORY, WOOD-FRAME (RAMBLER TYPE) HOUSE

4.34 A pair of the so-called "rambler" type, single-story, wood-frame houses were erected on concrete slabs poured in place, at grade. They were of conventional design except that each contained a shelter, above ground, consisting of the bathroom walls, floor, and ceiling of reinforced concrete with blast-door and shutter (Fig. 4.34).

4.35 When exposed to an incident overpressure of about 5 pounds per square inch, one of these houses was demolished beyond repair. However, the bathroom shelter was not damaged at all. Although the latch bolt on the blast shutter failed, leaving the shutter unfastened, the window was found to be still intact. The roof was blown off and the rafters were split and broken. The side walls at gable ends were blown outward, and fell to the ground. A portion of the front wall remained standing, but it was leaning away from the direction of the explosion (Fig. 4.35).

4.36 The other house of the same type, subjected to a peak overpressure of 1.7 pounds per square inch, did not suffer too badly, and it could easily have been made habitable. Windows were broken, doors blown off their hinges, and plaster-board walls and ceilings were badly damaged. The main structural damage was a broken midspan rafter support beam and wracking of the frame. In addition, the porch roof was lifted 6 inches off its supports.

### ONE-STORY, PRECAST CONCRETE HOUSE

4.37 Another residential type of construction tested in 1955 was a single-story house made of precast, light-weight (expanded shale aggregate) concrete wall and partition panels, joined by welded matching steel lugs. Similar roof panels were anchored to the walls by special countersunk and grouted connections. The walls were supported on concrete piers and a concrete floor slab, poured in place on a tamped fill after the walls were erected. The floor was anchored securely to the walls by means of perimeter reinforcing rods held by hook bolts screwed into inserts in the wall panels. The over-all design was such as to comply with the California code for earthquake-resistant construction (Fig. 4.37).

4.38 This house stood up well, even at a peak overpressure of 5 pounds per square inch, and, by replacement of demolished or badly damaged doors and windows, it could have been made available for occupancy (Fig. 4.38).

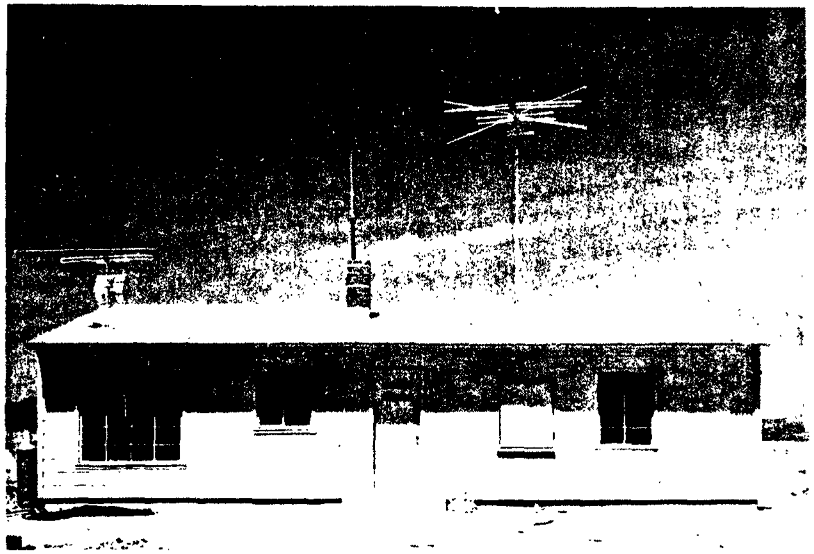

Figure 4.34. Rambler-type house before a nuclear explosion, Nevada Test Site. (Note blast door over bathroom window at right.)

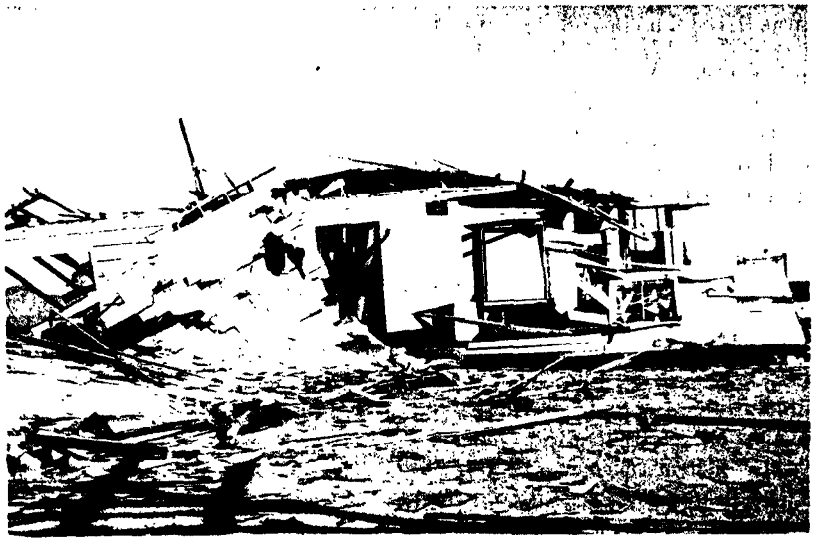

Figure 4.35. Rambler-type house after the nuclear explosion (5 psi overpressure).

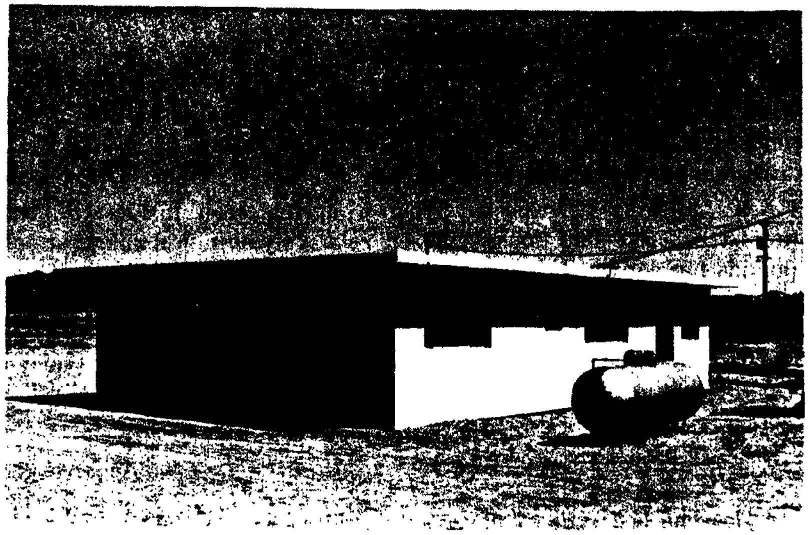

Figure 4.37. Reinforced precast concrete house before a nuclear explosion, Nevada Test Site.

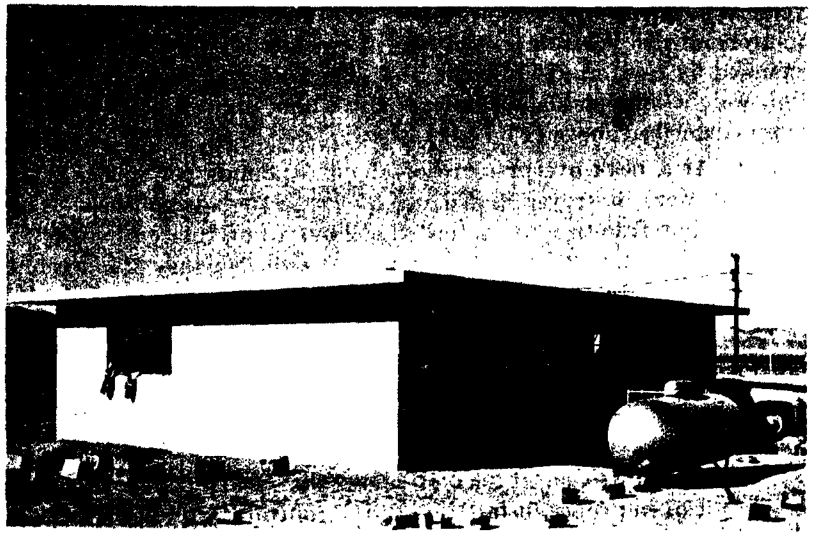

Figure 4.38. Reinforced precast concrete house after the nuclear explosion (5 psi overpressure). The LP-gas tank, sheltered by the house, is essentially undamaged.

4.39 There was some indication that the roof slabs at the front of the house were lifted slightly from their supports, but this was not sufficient to break any connections. Some of the walls were cracked slightly and others showed indications of minor movement. In certain areas the concrete around the slab connections was spalled, so that the connectors were exposed. The steel window-sashes were somewhat distorted, but they remained in place.

4.40 As may be expected from what has been just stated, the precast concrete-slab house suffered relatively minor damage at 1.7 pounds per square inch peak overpressure. Glass was broken extensively, and doors were blown off their hinges and demolished, as in other houses exposed to the same air pressure. But, apart from this and distortion of the steel window sash, the only important damage was spalling of the concrete at the lug connections.

### One-Story, Reinforced-Masonry House

4.41 The last type of house subjected to test in 1955 was also of earthquake-resistant design. The floor was a concrete slab, poured in place at grade. The walls and partitions were built of lightweight (expanded shale aggregate) 8-inch masonry blocks, reinforced with vertical steel rods anchored into the floor slab. The walls were also reinforced with horizontal steel rods at two levels, and openings were spanned by reinforced lintel courses. The roof was made of precast, lightweight concrete slabs, similar to those used in the precast concrete houses described above (*Fig.* 4.41).

4.42 At a peak overpressure of about 5 pounds per square inch, windows were destroyed and doors blown in and demolished. The steel window-frames were distorted, although nearly all remained in place. The house suffered only minor structural damage and could have been made habitable at relatively small cost (Fig. 4.42).

4.43 There was some evidence that the roof slabs had been moved, but not sufficiently to break any connections. The masonry wall under the large window (Fig. 4.42) was pushed in about 4 inches on the concrete floor slab; this appeared to be due to the omission of dowels between the walls and the floor beneath window openings. Some cracks developed in the wall above the same window, probably as a result of improper installation of the reinforced lintel course and the substitution of a pipe column in the center span of the window.

4.44 A house of the same type exposed to the blast at a peak overpressure of 1.7 pounds per square inch suffered little more than the

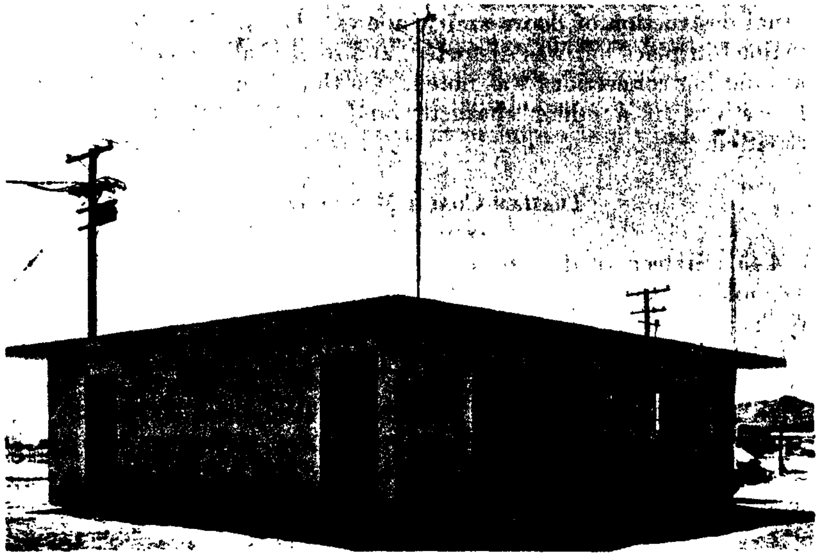

**Figure 4.41. Reinforced masonry-block house before a nuclear explosion, Nevada Test Site.**

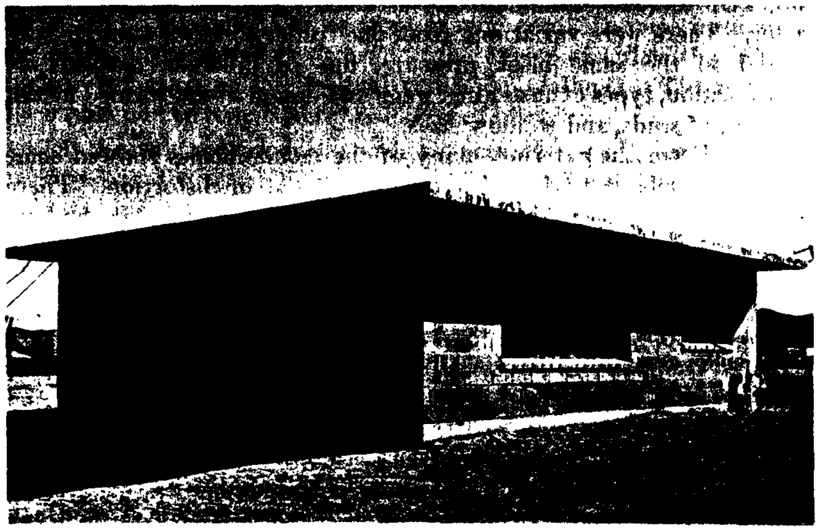

**Figure 4.42. Reinforced masonry-block house after the nuclear explosion (5 psi overpressure).**

usual destruction of doors and windows. The steel window-sash remained in place but was distorted, and some spalling of the concrete around lug connections was noted. On the whole, the damage to the house was of a minor character and it could have been readily repaired.

### TRAILER-COACH MOBILE HOMES

4.45 Sixteen trailer coaches, of various makes, intended for use as mobile homes, were subjected to blast in the 1955 test. Trailer parks and dealer stocks are generally situated at the outskirts of cities, and so the mobile homes to be tested were placed at a considerable distance from ground zero. Nine trailer-coach mobile homes were located where the peak blast overpressure was 1.7 pounds per square inch, and the other seven where the overpressure was about 1 pound per square inch. They were parked at various angles with respect to the direction of travel of the blast wave.

4.46 At the higher overpressure two of the mobile homes were tipped over by the explosion. One of these was originally broadside to the blast, whereas the second, at an angle of about 45°, was of much lighter weight. All the others at both locations remained standing. On the whole, the damage sustained was not of a serious character. There were variations from one trailer-coach to another subjected to the same blast pressure, due to different methods of construction, types of fastening, gage and design of die-formed metal, spacing of studs, and window sizes.

4.47 From the exterior, many of the mobile homes showed some dents in walls or roof, and a certain amount of distortion. There were, however, relatively few ruptures. Most windows were broken, but there was little or no glass in the interior, especially in those coaches having screens fitted on the inside. Where there were no screens or venetian blinds, and particularly where there were large picture windows, glass was found inside.

4.48 The interiors of the mobile homes were usually in a state of disorder due to ruptured panels, broken and upset furniture, and cupboards, cabinets, and wardrobes which had been torn loose and damaged. Stoves, refrigerators, and heaters were not displaced, and the floors were apparently unharmed. The plumbing was, in general, still operable after the explosion. Consequently, by rearranging the displaced furniture, repairing cabinets, improving window coverings, and cleaning up the debris, all trailer-coaches could have been made habitable for emergency use.

4.49 At the 1 pound per square inch overpressure location some windows were broken, but no major damage was sustained. The principal repairs required to make the mobile homes available for occupancy would be window replacement or improvised window covering.

### FOOD PRODUCTS

4.50 To determine the effects of a nuclear explosion on foodstuffs, some 90 food products were exposed in the 1955 tests. The selection was based on an evaluation of the American diet, so as to insure the inclusion of items which were used either most frequently or in largest volume. About half of the products were staples, e. g., flour and sugar; semi-perishables, e. g., potatoes, fruits, and processed meats; and perishables, e. g., fresh meats and frozen foods. The other half consisted of heat-sterilized foods canned in metal or glass containers. In addition to the extensive variety of foodstuffs, a number of different kinds of retail and wholesale packaging materials and methods were tested.

4.51 Food samples were exposed at distances ranging from a quarter of a mile to about 15 miles from ground zero. In some instances, the main purpose was to determine the effects of either the initial nuclear radiation or the residual radiation (fallout). The present discussion will be restricted to the effects of blast.

4.52 Fresh food products, such as potatoes, apples, and onions, packaged in the usual light wooden boxes, suffered from bruising and crushing. Apart from this, there was relatively little direct blast damage. There were very few (if any) failures of glass or metal containers due to the high overpressures, although some were pierced by sharp missiles, especially flying glass. The damage to packaged goods resulted mainly from dislodgement from the shelves in the kitchen and subsequent breakage of glass containers. Where the cans or jars had been stored on shelves in the basement, the damage was negligible, even when the main structure of the house was demolished.

4.53 Containers made of soft materials, such as paper, polyethylene (plastic), or cardboard, were badly damaged by flying missiles. In these cases the food products were often seriously contaminated with splintered glass. Where there was adequate protection, however, the direct and indirect consequences of blast were not serious.

## INDUSTRIAL STRUCTURES

### Japanese Experience

4.54 In Nagasaki there were many buildings used for industrial purposes of the familiar type, consisting of a steel frame with roof and siding of corrugated sheet metal or of asbestos cement. In somes cases, there were rails for gantry cranes, but the cranes were usually of low capacity. In general, construction of industrial-type buildings was comparable to that in the United States.

4.55 Severe damage of these structures occurred up to a distance of about 6,000 feet (1.14 miles) from ground zero. Moderately close to ground zero, the buildings were pushed over bodily, and at greater distances they were generally left leaning away from the source of the blast (Figs. 4.55 a and b). The columns being long and slender offered little resistance to the lateral loading. Sometimes columns failed due to a lateral force, causing flexture, combined with a simultaneous small increase in the downward load coming from the impact of the blast on the roof. This caused buckling and, in some instances, complete collapse. Roof trusses were buckled by compression resulting from lateral blast loading on the side of the building facing the explosion.

4.56 A difference was noted in the effect on the frame depending upon whether a frangible material, like asbestos cement, or a material of high tensile strength, such as corrugated sheet iron, was used for roof and siding. Asbestos cement broke up more readily permitting more rapid equalization of pressure, and, consequently, less structural damage to the frame.

4.57 Fire caused heavy damage to unprotected steel members, so that it was impossible to tell exactly what the blast effect had been. In general, steel frames were badly distorted, and would have been of little use, even if siding and roofing material had been available for repairs.

4.58 In some industrial buildings wood trusses were used to support the roof. These were more vulnerable to blast because of poor framing and connections, and were readily burned out by fire. Concrete columns were employed in some cases with steel roof trusses; such columns appeared to be more resistant to buckling than steel.

4.59 Damage to machine tools (Fig. 4.59) was caused by debris, resulting from the collapse of roof and siding, by fire in wood-frame structures, and by dislocation and overturning as a result of damage to the building. In many instances the machine tools were

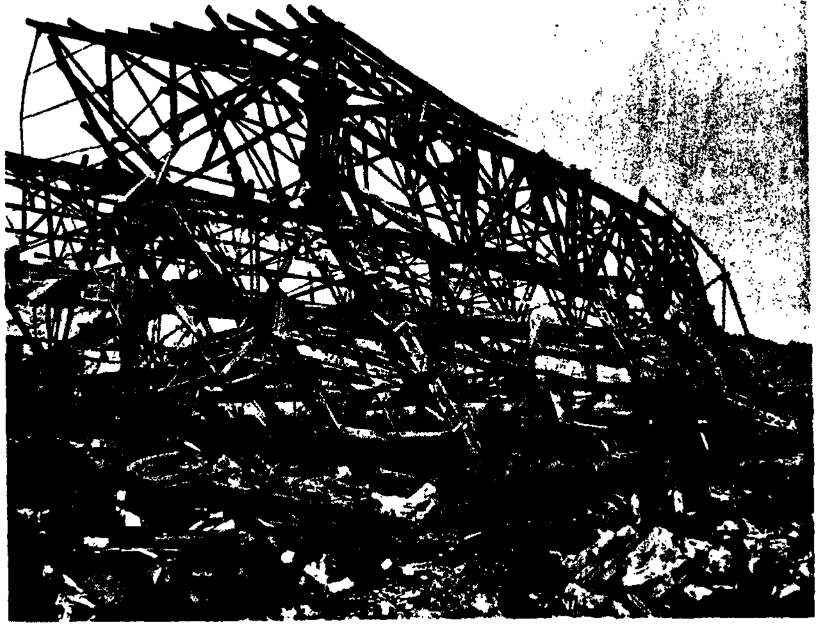

**Figure 4.55a. Industrial-type steel-frame building (0.35 mile from ground zero at Hiroshima). Wooden beams should be noted.**

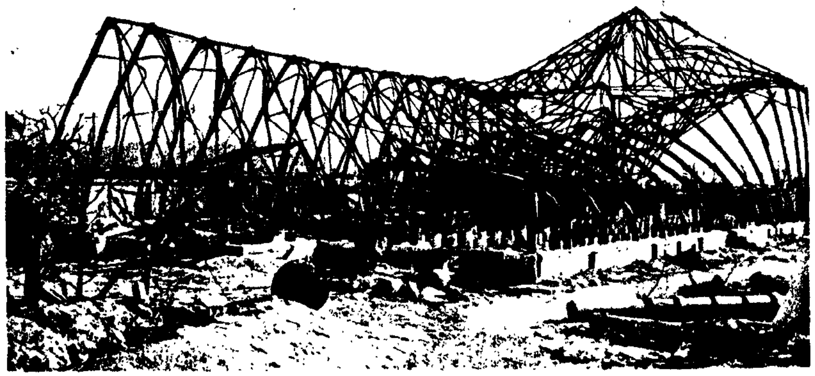

**Figure 4.55b. Single story, light steel-frame building (0.8 mile from ground zero at Hiroshima); partially damaged by blast and further collapsed by subsequent fire.**

Figure 4.59. Damage to machine tools in steel-frame building (0.6 mile from ground zero at Hiroshima).

belt-driven, so that the distortion of the building pulled the machine tool off its base, damaging or overturning it.

4.60 Smokestacks, especially those of reinforced concrete, proved to have considerable blast resistance (Fig. 4.60a). Because of their shape, they are subjected essentially to drag loading only and, if sufficiently strong, their long period of vibration makes them less sensitive to blast than many other structures. An example of extreme damage to a reinforced-concrete stack is shown in Fig. 4.60b. Steel structures performed reasonably well, but being lighter in weight and subject to crushing were not comparable to reinforced concrete. On the whole, well-constructed masonry stacks withstood the blast somewhat better than did those made of steel.

### Nevada Tests of 1955

4.61 Three types of metal buildings of standard construction, such as are used for various commercial and industrial purposes, were exposed at peak overpressures of 3.1 and 1.2 pounds per square inch. The main objectives of the Nevada tests were to determine the blast pressures at which these structures would survive, in the sense that they could still be used after moderate repairs, and to provide information upon which could be based improvements in design to resist blast.

### Steel Frame with Aluminum Panels

4.62 The first industrial type building had a conventional rigid steel frame, which is familiar to structural engineers, with aluminum-sheet panels for roofing and siding (Fig. 4.62a). At a blast overpressure of 3.1 pounds per square inch this building was severely damaged. The welded and bolted steel frame remained standing, but was badly distorted, and pulled away from the concrete footings.

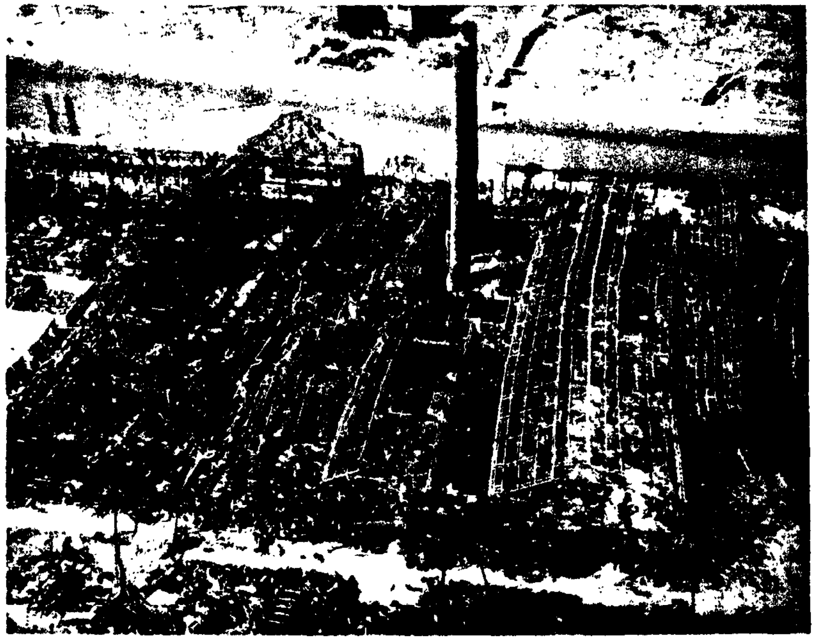

Figure 4.60a. Destroyed industrial area showing smokestacks still standing (0.51 mile from ground zero at Nagasaki).

Figure 4.60b. A circular, 60 feet high, reinforced-concrete stack (0.34 mile from ground zero at Hiroshima). The failure caused by the blast wave occurred 15 feet above the base.

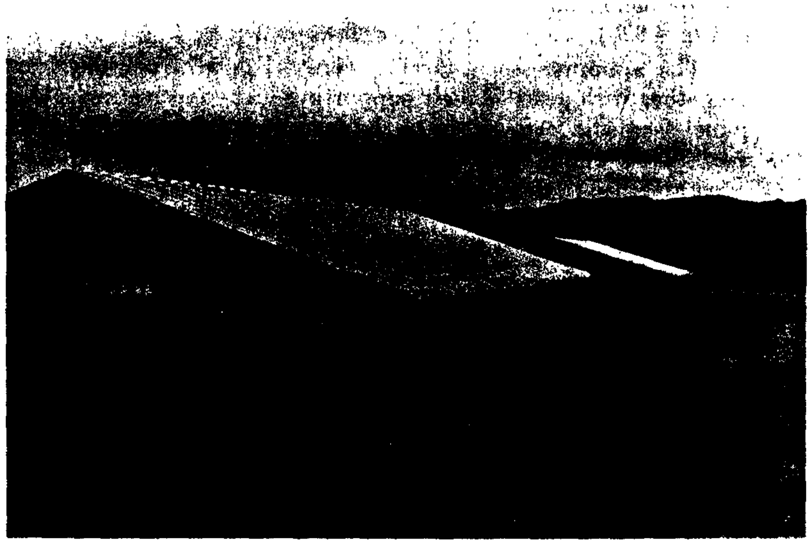

Figure 4.62a. Rigid steel-frame building before a nuclear explosion, Nevada Test Site.

Figure 4.62b. Rigid steel-frame building after the nuclear explosion (3.1 psi overpressure).

On the side facing the explosion the deflection was about 1 foot at the eaves (Fig. 4.62b).

4.63 The aluminum-sheet panels were stripped from the front wall, together with most of their supporting girts and purlins. Girt and panel segments were blown to the rear, damaging machinery on the way. Most of the aluminum panels on the ends and back wall remained attached to the structure. Similarly, those on the rear slope of the roof were still in place but they were mostly disengaged from their fasteners.

4.64 At a peak overpressure of 1.2 pounds per square inch the main steel frame suffered only slight distortion. The aluminum roofing and siding was not blown off, although the panels were disengaged from the bolt fasteners on the front face of the steel columns and girts. Wall and roof panels facing the explosion were dished inward. The center girts were torn loose from their attachments to the columns in the front of the building. The aluminum panels on the side walls were dished inward slightly, but on the rear wall and rear slope of the roof, the sheeting was almost undisturbed.

4.65 As presently designed, these structures may be regarded as being repairable, provided blast pressures do not exceed 1 pound per square inch. Increased blast resistance would probably result from improvement in the design of girts and purlins, in particular. Better fastening between sill and wall footing and increased resistance to transverse loading would also be beneficial.

### SELF-FRAMING WITH STEEL PANELS

4.66 A frameless structure with self-supporting walls and roof of light, channel-shaped, interlocking, steel panels (16 inches wide) represented the second standard type of industrial building (Fig. 4.66a). The one subjected to 3.1 pounds per square inch overpressure was completely demolished (Fig. 4.66b). One or two segments of wall were blown as far as 50 feet away, but, in general, the bent and twisted segments of the building remained approximately in their original locations. Most of the wall sections were still attached to their foundation bolts on the side and rear walls of the building. The roof had collapsed completely and was resting on the machinery in the interior.

4.67 Although damage at 1.2 pounds per square inch peak overpressure was much less, it was still considerable in parts. The front wall panels were buckled inward from 1 to 2 feet at the center, but the rear wall and rear slope of the roof were undamaged. In general,

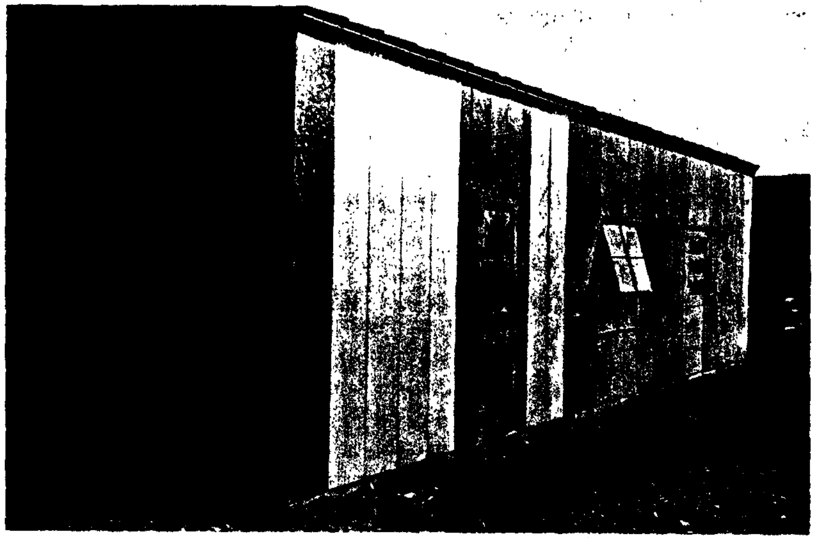

**Figure 4.66a.** Exterior of self-framing steel panel building before a nuclear explosion, Nevada Test Site.

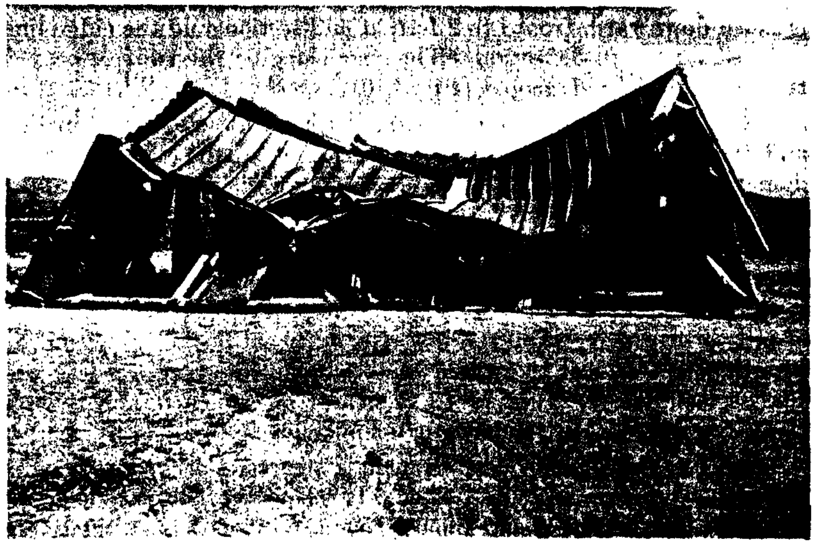

**Figure 4.66b.** Self-framing steel panel building after the nuclear explosion (3.1 psi overpressure).

the roof structure remained intact, except for some deflection near the center.

4.68 It appears that the steel-panel type of structure is repairable if exposed to overpressures of not more than about ¾ to 1 pound per square inch. The buildings are simple to construct but they do not hold together well under blast. Blast-resistant improvements would seem to be difficult to incorporate while maintaining the essential simplicity of design.

### Self-Framing with Corrugated Steel Panels

4.69 The third type of industrial building was a completely frameless structure made of strong, deeply-corrugated, 43-inch wide panels of 16-gage steel sheet. The panels were held together with large bolt fasteners at the sides, and at the eaves and roof ridge the wall panels were bolted to the concrete foundation. The entire structure was self-supporting, without frames, girts, or purlins (Fig. 4.69).

4.70 At a peak overpressure of 3.1 pounds per square inch a structure of this type was fairly badly damaged, but all the pieces remained bolted together, so that the structure still provided good protection for its contents from the elements. The front slope of the roof was crushed downward, from 1 to 2 feet, at mid-section, and the ridge line suffered moderate deflection. The rear slope of the roof appeared to be essentially undamaged (Fig. 4.70).

4.71 The front and side walls were buckled inward several inches, and the door in the front was broken off. All the windows were damaged to some extent, although a few panes in the rear remained in place.

4.72 Another building of this type, exposed to 1.2 pounds per square inch overpressure, experienced little structural damage. The roof along the ridge line showed indications of downward deflections of only 1 or 2 inches, and there was no apparent buckling of roof or wall panels. Most of the windows were broken, cracked, or chipped. Replacement of the glass when necessary and some minor repairs would have rendered the building completely serviceable.

4.73 The corrugated steel, frameless structure proved to be the most blast-resistance of those tested. It is believed that, provided the blast pressure did not exceed about 3 pounds per square inch, relatively minor repairs would make possible continued use of the building. Improvement in the design of doors and windows, so as to reduce the missile hazard from broken glass, would be advantageous.

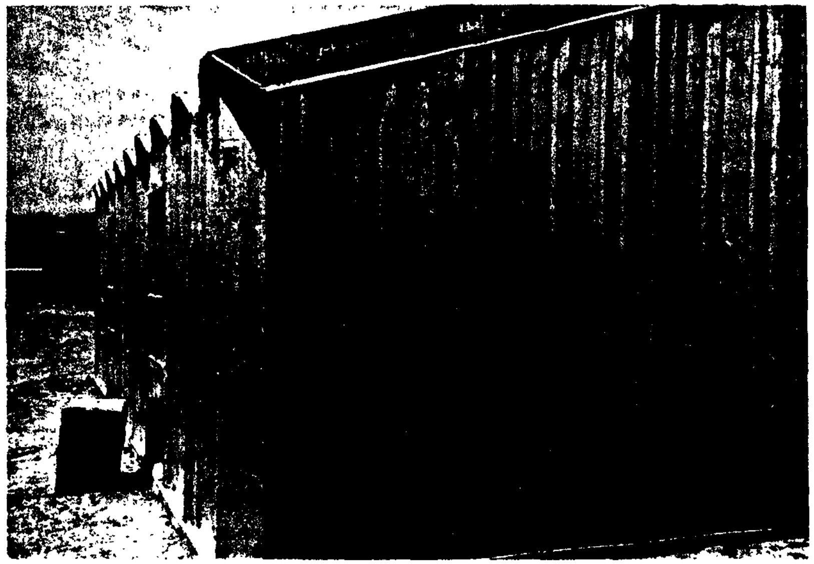

**Figure 4.69. Self-framing corrugated steel panel building before a nuclear explosion, Nevada Test Site.**

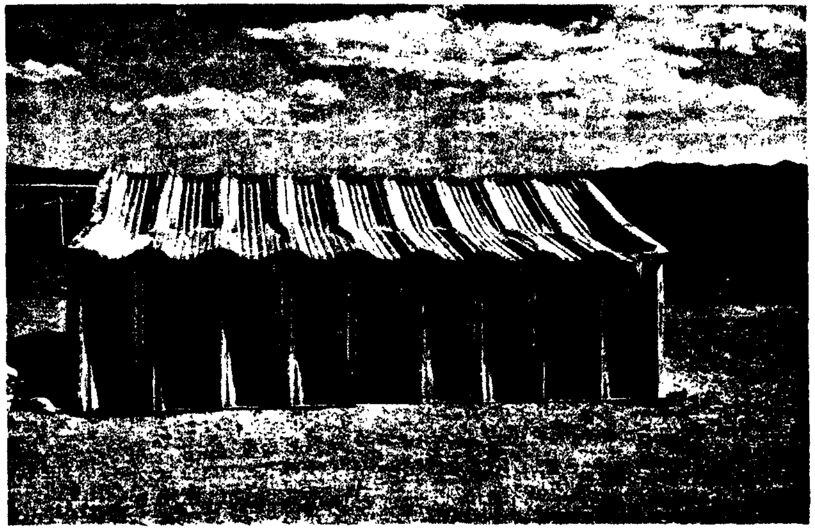

**Figure 4.70. Self-framing corrugated steel panel building after the nuclear explosion (3.1 psi overpressure).**

### OIL STORAGE TANKS

4.74 Large oil storage tanks (around 50,000 barrels capacity) were not in the damage areas of the Japanese cities and have not been tested in Nevada. However, in the Texas City disaster of April 1947, several tank farms were seriously damaged by blast, missiles, and fire. Oil storage tanks, particularly empty ones, received severe blast damage out to the overpressure region estimated to be 3 to 4 pounds per square inch, on the basis that the explosion had blast waves comparable to that of 2- to 4-kiloton nuclear weapons. The serious fire hazard represented by the fuel stored in such tanks is obvious from Fig. 4.74a which shows both blast and fire destruction. Fig. 4.74b indicates minor blast damage and some missile damage to the storage tank walls.

Figure 4.74a. General blast and fire damage at Texas City April 16–17, 1947; distance of foreground from detonation 0.65 mile.

Figure 4.74b. Light missile and blast damage to oil tanks, 0.70 mile from detonation at Texas City April 16–17, 1947.

### HEAVY-DUTY MACHINE TOOLS

4.75 Some reference has been made above (§4.59) to the damage suffered by machine tools in Japan. However, in the Nevada tests of 1955, the vulnerability of heavy-duty machine tools and their components to nuclear blast was investigated in order to provide information of particular interest to the defense mobilization program. With this objective, a number of machine tools were anchored on a reinforced-concrete slab in such a manner as to duplicate good industrial practice. Two engine lathes (weighing approximately 7,000 and 12,000 pounds, respectively), and two horizontal milling machines (7,000 and 10,000 pounds, respectively), were exposed to a peak overpressure of 10 pounds per square inch. A concrete-block wall, 8 inches thick and 64 inches high, was constructed immediately in front of the machines, i. e., between the machines and ground zero (Fig. 4.75). The purpose of this wall was to simulate the exterior wall of the average industrial plant and to provide a substantial amount of debris and missiles.

4.76 Of the four machines, the three lighter ones were moved from their foundations and suffered quite badly (Fig. 4.76a). The fourth, weighing 12,000 pounds, which was considered as the only one to be actually of the heavy-duty type, survived (Fig. 4.76b). From the observation it was concluded that a properly anchored machine tool of the true heavy-duty type would be able to withstand overpressures of 10 pounds per square inch or more without substantial damage.

4.77 In addition to the direct effects of blast, considerable destruction was caused by debris and missiles, much of which resulted from the expected complete demolition of the concrete-block wall. Delicate mechanisms and appendages, which are usually on the exterior and

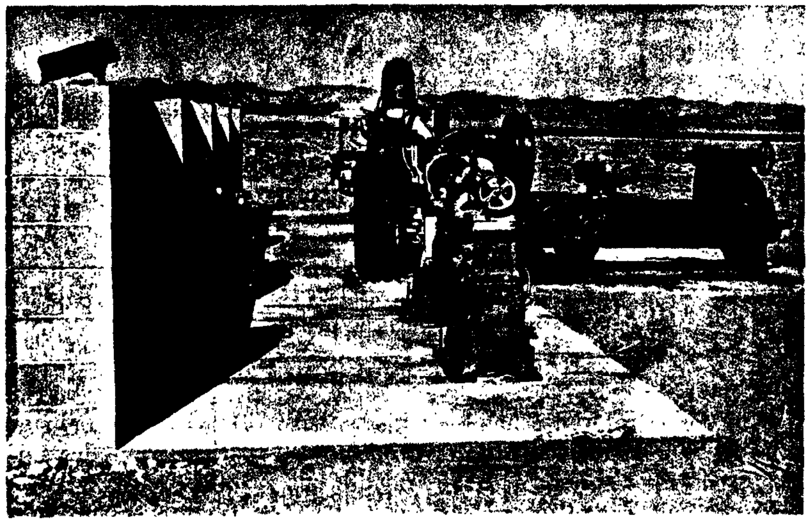

Figure 4.75. Machine tools behind masonry wall before a nuclear explosion, Nevada Test Site.

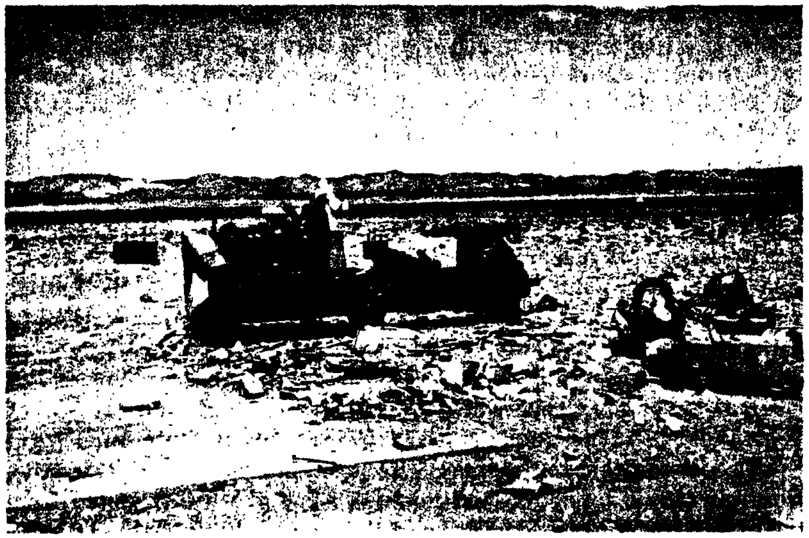

Figure 4.76a. Machine tools after the nuclear explosion (10 psi overpressure).

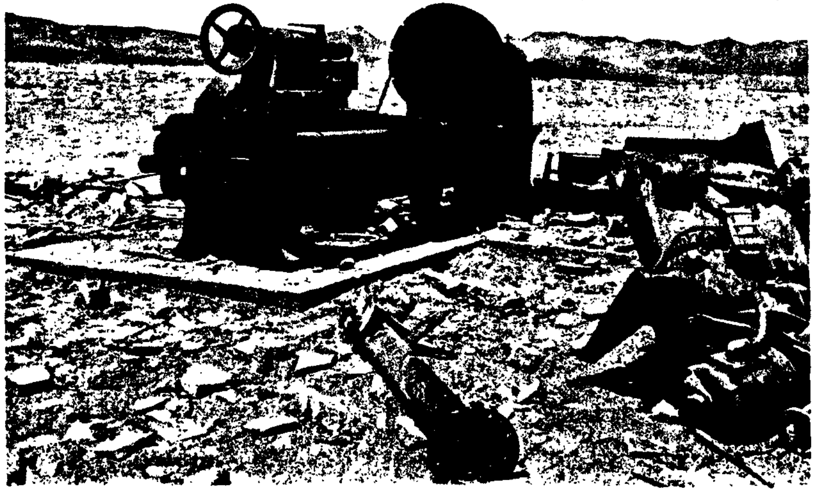

Figure 4.76b. Heavy-duty lathe after the nuclear explosion (10 psi overpressure).

unprotected, suffered especially severely. Gears and gear cases were damaged, hand valves and control levers were broken off, and drive belts were broken. It appears, however, that most of the missile damage could be easily repaired, if replacement parts were available, since major dismantling would not be required.

4.78 Behind the two-story brick house in the overpressure region of 5 pounds per square inch (§4.30) was erected a 200-ton capacity hydraulic press weighing some 49,000 pounds. The location was chosen as being the best to simulate actual factory conditions. This unusually tall (19 feet high) and slim piece of equipment showed little evidence of blast damage, even though the brick house was demolished. It is probable that the house provided some shielding from the blast wave. Further, at the existing blast pressure, missiles did not have high velocities. Such minor damage as was suffered by the machine was probably due to falling debris from the house.

4.79 At the 3-pounds per square inch overpressure location, there were two light, industrial buildings of standard type, described earlier. In each of these was placed a vertical milling machine weighing about 3,000 pounds, a 50-gallon capacity, stainless steel, pressure vessel weighing roughly 4,100 pounds, and a steel steam oven, approximately

2½ feet wide, 5 feet high, and 9 feet long. Both buildings suffered extensively from blast (§4.62), but the equipment experienced little or no operational damage. In one case, the collapsing structure fell on and broke off an exposed part of the milling machine.

4.80 It should be noted that the damage sustained by machines in the 1955 tests was probably less than that suffered in Japan at the same blast pressures (§4.59). Certain destructive factors, present in the latter case, were absent in the Nevada tests. First, the conditions were such that there was no damage by fire; and, second, there was no exposure to the elements after the explosion. In addition, the total amount of debris produced in the tests was probably less than in the industrial buildings in Japan.

## COMMERCIAL AND ADMINISTRATIVE STRUCTURES

4.81 Buildings used for commercial and administrative purposes, such as banks, offices, hospitals, hotels, and large apartment houses, are generally of more substantial construction than ordinary residences and industrial-type buildings. Essentially all the empirical information concerning the effects of nuclear blast on these multistory structures has been obtained from the observations made at Hiroshima and Nagasaki. The descriptions given below are for three general types, namely, *reinforced-concrete frame buildings*, *steel-frame buildings*, and *buildings with load-bearing walls*.

### Multistory, Reinforced-Concrete Frame Buildings

4.82 There were many such buildings of several types in Hiroshima and a smaller number in Nagasaki. They varied in resistance to blast according to design and construction, but they generally suffered remarkedly little damage externally. Close to ground zero, however, there was considerable destruction of the interior and contents due to the entry of blast through doors and window openings and to subsequent fires. An exceptionally strong structure of earthquake-resistant (aseismic) design, located some 720 feet from ground zero in Hiroshima, is seen in Fig. 4.82a. Although the exterior walls were hardly damaged, the roof was depressed and the interior was destroyed. More typical of reinforced-concrete frame construction in the United States was the building shown in Fig. 4.82b, at about the same distance from ground zero. This suffered more severely than the one of aseismic design.

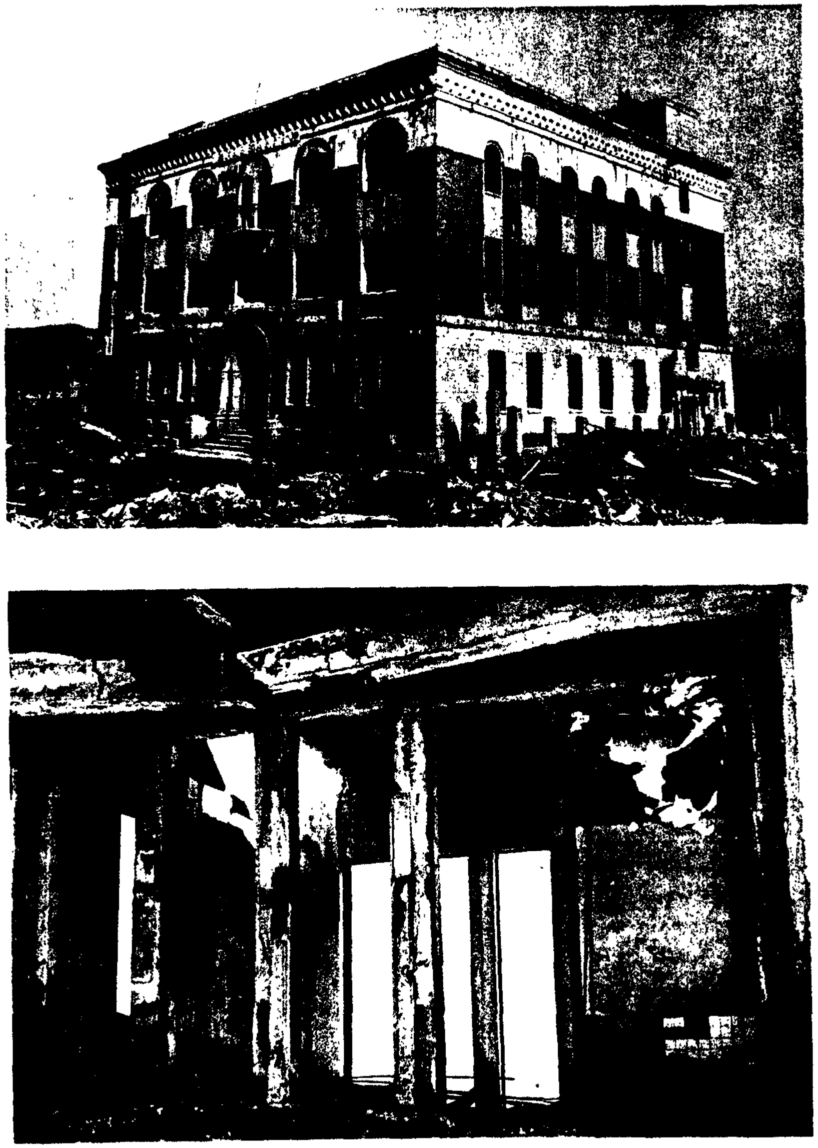

Figure 4.82a. *Upper photo*: Reinforced-concrete, aseismic structure; window fire shutters were blown in by blast and the interior gutted by fire (0.12 mile from ground zero at Hiroshima). *Lower photo:* Burned out interior of similar structure.

Figure 4.82b. Three story, reinforced-concrete frame building; walls were 13-inch thick brick panel with large window openings (0.13 mile from ground zero at Hiroshima).

4.83 A factor contributing to the blast resistance of many reinforced-concrete buildings in Japan was the construction code established after the severe earthquake of 1923. The height of new buildings was limited to 100 feet and they were designed to withstand a lateral force equal to 10 percent of the vertical load. In addition, the recognized principles of stiffening by diaphragms and improved framing to provide continuity were specified. The more important buildings were well designed and constructed according to the code. However, some were built without regard to the earthquake-resistant requirements, and these were less able to withstand the blast wave from the nuclear explosion.

4.84 Close to ground zero the vertical component of the blast was more significant and so greater damage to the roof resulted from the downward force (Fig. 4.84a) than appeared farther away. Depending upon its strength, the roof was pushed down and left sagging or it failed completely. The remainder of the structure was less damaged than similar buildings farther from the explosion because of the smaller horizontal (lateral) forces. Farther from ground zero, especially in the region of Mach reflection, the consequences of horizontal loading were apparent (Fig. 4.84b and c).

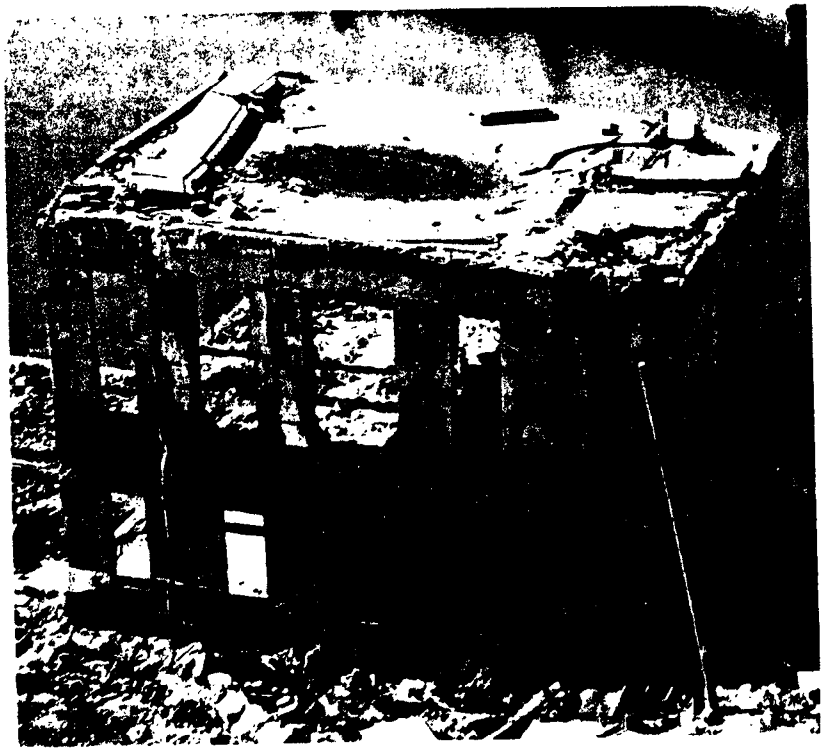

Figure 4.84a. Depressed roof of reinforced-concrete building (0.10 mile from ground zero at Hiroshima).

Figure 4.84b. Effects of horizontal loading on wall facing explosion (0.4 mile from ground zero at Nagaski).

Figure 4.84c. One story, reinforced-concrete building with steel roof trusses (0.26 mile from ground zero at Nagasaki). Note the resistance offered by end interior walls when acting as shear walls.

4.85 In addition to the failure of roof slabs and the lateral displacement of walls, numerous other blast effects were observed. These included bending and fracture of beams, failure of columns, crushing of exterior wall panels, and failure of floor slabs (Figs. 4.85a, b, c, and d). Heavy damage to false ceilings, plaster, and partitions occurred as far out as 9,000 feet (1.7 miles) from ground zero, and glass windows were generally broken out to a distance of 3¾ miles and in a few instances out to 8 miles.

4.86 The various effects just described have referred especially to reinforced-concrete structures. This is because the buildings as a whole did not collapse, so that other consequences of the blast loading could be observed. It should be pointed out, however, that damage of a similar nature also occurred in structures of the other types described below.

## MULTISTORY, STEEL-FRAME BUILDINGS

4.87 There was apparently only one steel-frame structure having more than two stories in the Japanese cities exposed to nuclear explosions. This was a five-story structure in Nagasaki at a distance of 4,500 feet (0.85 mile) from ground zero (Fig. 4.87). The only part of the building that was not regarded as being of heavy construction was the roof, which was of 4-inch thick reinforced concrete supported by unusually light steel trusses. The downward failure of the roof, which was dished 3 feet, was the only important structural damage suffered.

Figure 4.85a. Buckling and cracking of beams in reinforced-concrete building (0.32 mile from ground zero at Nagasaki).

Figure 4.85b. Multistory reinforced-concrete frame building showing the failure of columns and girders (0.36 mile from ground zero at Nagasaki).

Figure 4.85c. Reinforced-concrete frame building showing crushed concrete panel walls on side facing explosion (0.68 mile from ground zero at Nagasaki).

Figure 4.85d. Reinforced-concrete building showing collapsed roof and floor slabs (0.10 mile from ground zero at Hiroshima).

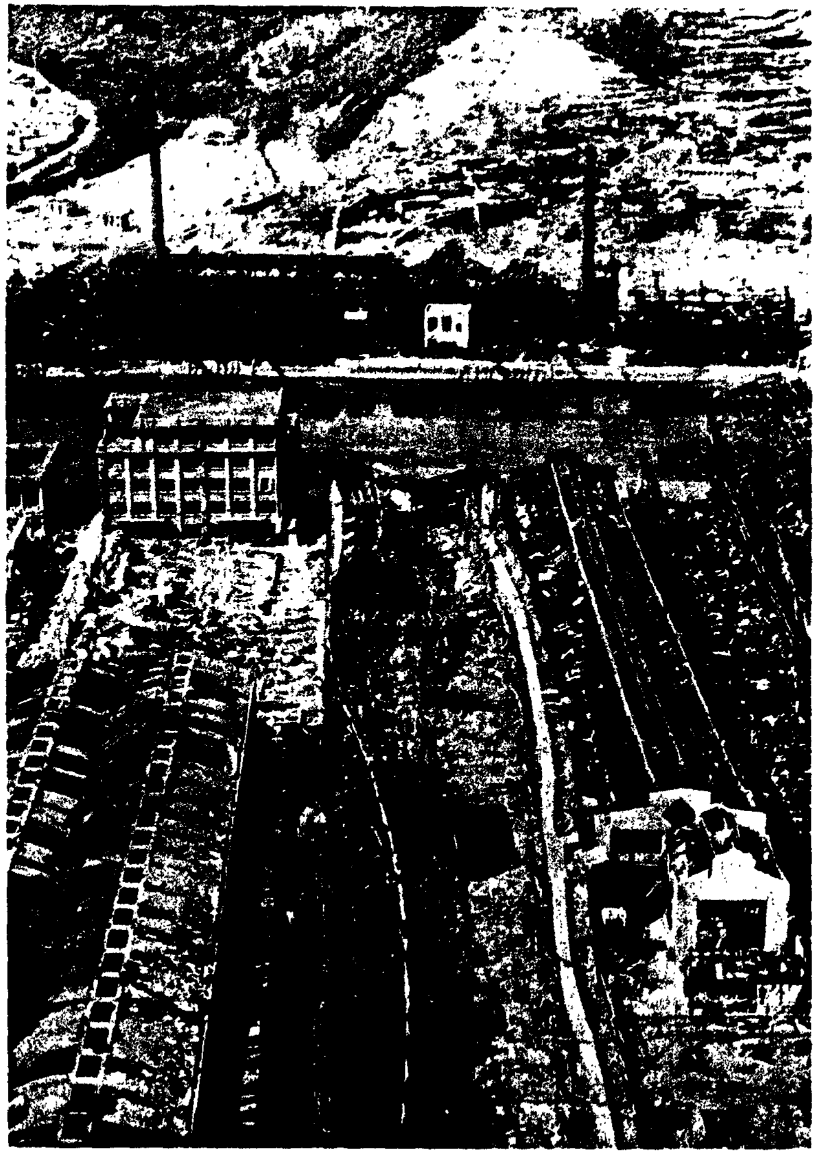

Figure 4.87. At left and back of center is a multistory, steel-frame building (0.85 mile from ground zero at Nagasaki).

Figure 4.88 Two story steel-frame building with 7-inch reinforced-concrete wall panels (0.40 mile from ground zero at Hiroshima). The first story columns buckled away from ground zero dropping the second story to the ground.

4.88 Reinforced-concrete frame buildings at the same distance from the explosion were also undamaged, and so there is insufficient evidence to permit any conclusions to be drawn as to the relative resistance of the two types of construction. An example of damage to a two-story, steel-frame structure is shown in Fig. 4.88. The heavy walls of the structure transmitted their loads to the steel frame, the columns of which collapsed.

### Buildings with Load-Bearing Walls

4.89 Small structures with light load-bearing walls offered little resistance to the nuclear blast and, in general, collapsed completely. Large buildings of the same type, but with cross walls and of somewhat heavier construction, were more resistant but failed at distances up to 6,300 feet (1.2 miles) from ground zero (Figs. 4.89a and b). Cracks were observed at the junctions of cross walls and sidewalls when the building remained standing. It is apparent that structures with load-bearing walls possess few of the characteristics that would make them resistant to collapse when subjected to large lateral loads.

### Bridges

4.90 There were a number of different kinds of bridges exposed to the nuclear explosions in Hiroshima and Nagasaki. Those of wood were burned in most cases, but steel-girder bridges suffered relatively little destruction (Figs. 4.90a, b, and c). One bridge, only 270 feet from ground zero, i. e., about 2,100 feet from the point of explosion,

Figure 4.89a. Interior of two-story, brick wall-bearing building; the walls were 19 inches thick (0.80 mile from ground zero at Hiroshima). Blast collapsed the roof and second story and part of the first story, but much of the damage was due to fire.

Figure 4.89b. Heavy wall-bearing structure; the 28-inch thick exterior walls of brick with buttresses were shattered (0.34 mile from ground zero at Nagasaki).

which was of a girder type with a reinforced-concrete deck, showed no sign of any structural damage. It had, apparently, been deflected downward by the blast force and had rebounded, causing only a slight net displacement. Other bridges, at greater distances from ground zero, suffered more lateral shifting. A reinforced-concrete deck was lifted from the supporting steel girder of one bridge, due apparently to the blast wave reflected from the surface of the water below.

Figure 4.90a. Bridge with deck of reinforced concrete on steel-plate girders: outer girder had concrete facing (270 feet from ground zero at Hiroshima). The railing was blown down but the deck received little damage so that traffic continued.

Figure 4.90b. A steel-plate girder, double-track railway bridge (0.16 mile from ground zero at Nagasaki). The plate girders were moved about 3 feet by the blast; the railroad tracks were bent out of shape and trolley cars were demolished, but the poles were left standing.

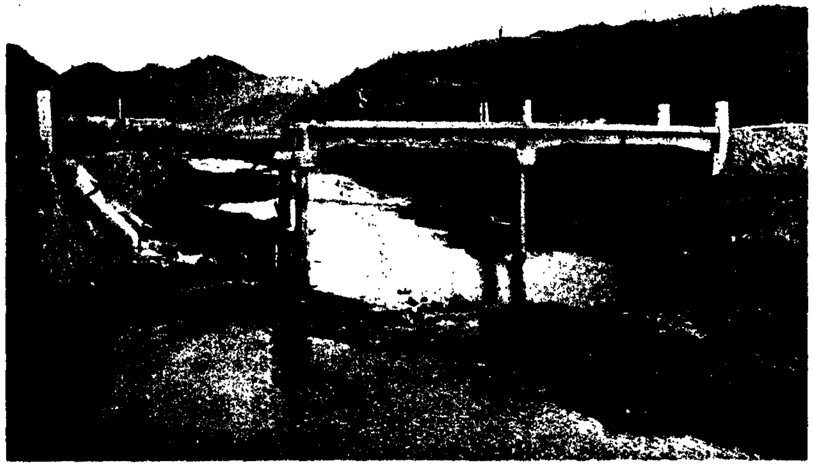

**Figure 4.90c.** A reinforced-concrete bridge with T-beam deck (0.44 mile from ground zero at Nagasaki). Part of deck was knocked off the pier and abutment by the blast, causing one span, 35 feet long, to drop into the river. The remainder of the bridge was almost undamaged.

## TRANSPORTATION

### Streetcars and Automobiles

4.91 In Japan, trolley-car equipment was heavily damaged by both blast and fire, although the poles were frequently left standing (Fig. 4.90b). Buses and automobiles were, in general, rendered inoperable by blast and fire as well as by damage caused by flying missiles. However, at a distance from the explosion they appeared to stand up fairly well. Thus, an American made automobile was badly damaged and burned at 3,000 feet (0.57 mile) from ground zero (Fig. 4.91), but a similar car at 6,000 feet (1.14 miles) suffered only minor damage.

4.92 Automobiles and buses have been exposed to several of the nuclear test explosions in Nevada, where the conditions, especially as regards damage by fire and missiles, were somewhat different from those in Japan. In the descriptions that follow, distance is related to peak overpressure. It must be remembered, however, that in most cases it was not primarily overpressure, but drag forces, which produced the damage. Hence, the damage radii cannot be determined from overpressure alone, but require the use of the chart given in Chapter VI (Fig. 6.41c), which takes these facts into account. Some illustrations of the effects of a nuclear explosion on motorized vehicles are shown in Figs. 4.92a, b, c, and d. At a peak overpressure of 5 pounds per square inch motor vehicles were badly battered, with their tops and sides pushed in, windows broken, and hoods blown open. However, the engines were still operable and the vehicles could be driven away after the explosion. Even at higher blast pressures, when the over-all damage was greater, the motors appeared to be intact.

**Figure 4.91.** General view at Nagasaki showing wrecked automobile in foreground (0.57 mile from ground zero).

### Emergency Vehicles

4.93 During the 1955 explosions in Nevada, tests were made to determine the extent to which various emergency vehicles and their equipment would be available for use immediately following a nuclear attack. The vehicles used included a rescue truck, gas and electric utility service or repair trucks, telephone service trucks, and fire pumpers and ladder trucks. One vehicle was exposed to an over-

Figure 4.92a. Effect of nuclear explosion on automobiles in simulated parking lot, Nevada Test Site. Much of the damage to glass, paint, and interiors was due to fires caused by thermal radiation.

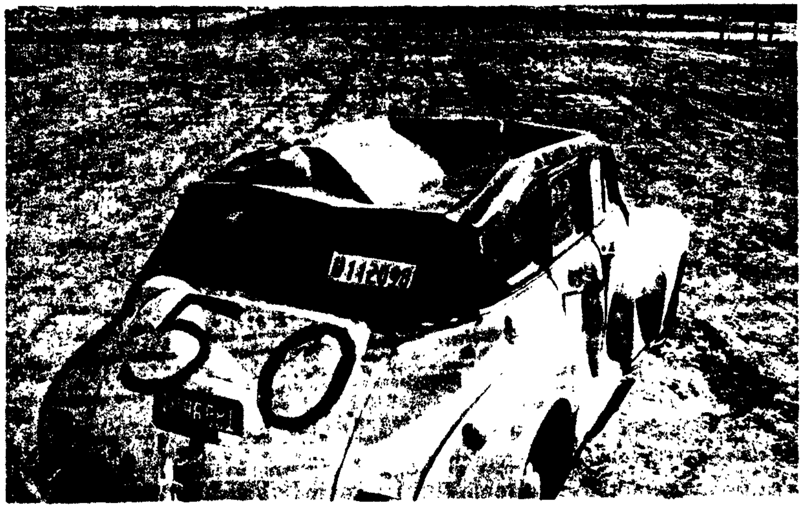

Figure 4.92b. Damage to automobile originally located behind wood-frame house (5 psi overpressure); the front of this car can be seen in Fig. 4.14. Although badly damaged, the car could still be driven after the explosion.

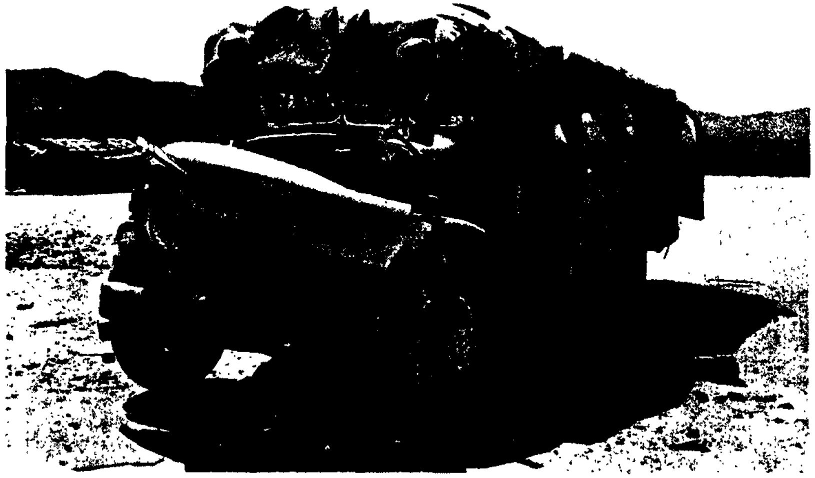

Figure 4.92c. Typical public bus damaged by a nuclear explosion, Nevada Test Site; this bus, like the one in the left background, was overturned, coming to rest as shown after a displacement of 50 feet.

Figure 4.92d. Interior damage to bus shown above, caused by blast, displacement, and incipient fire.

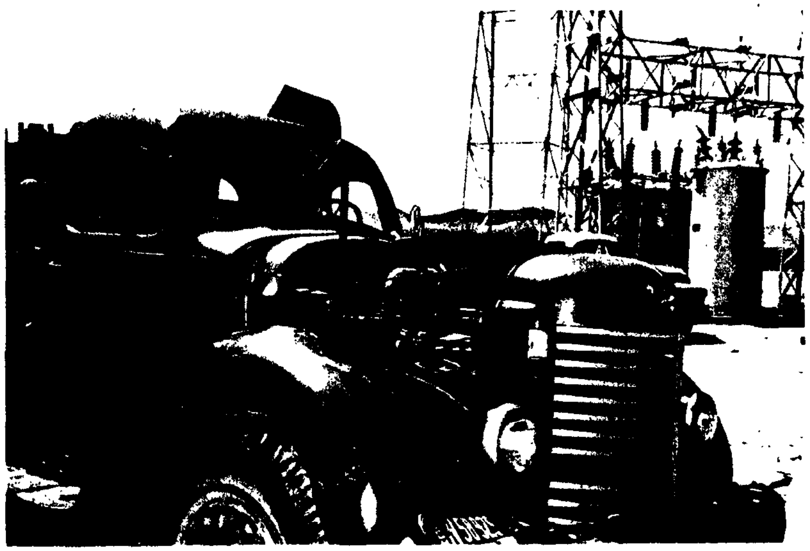

Figure 4.94. Light damage to heavy-duty electric utility truck (5 psi overpressure).

pressure of about 30 pounds per square inch, two at 5 pounds per square inch, two at 1.7 pounds per square inch, and six at about 1 pound per square inch. It should be pointed out, however, that, as for automobiles, the overpressure is not the sole criterion of damage (see Fig. 6.41c).

4.94 The rescue truck at the 30-pound per square inch location was completely destroyed, and only one wheel and part of the axle were found after the blast. At 5 pounds per square inch overpressure, a heavy-duty electric utility truck, facing head-on to the blast, had the windshield shattered, both doors and cab dished in, the hood partly blown off, and one tool-compartment door dished (Fig. 4.94). There was, however, no damage to tools or equipment and the truck was driven away without any repairs being required. At the same location, a truck with an earth-boring machine bolted to the bed, was broadside to the blast. This truck was overturned and somewhat damaged, but still operable. The earth-boring machine was knocked loose and was on its side, leaking gasoline and water.

4.95 At the 1.7 pounds per square inch location, a light-duty electric utility truck and a fire department 75-foot aerial ladder truck sustained minor exterior damage, such as broken windows and dished-in panels. There was no damage to equipment in either case, and both vehicles would have been available for immediate use after an attack. Two telephone trucks, two gas utility trucks, a fire department pumper, and a jeep firetruck, exposed to a blast overpressure of 1 pound per square inch, were largely unharmed.

4.96 It may be concluded that vehicles designed for disaster and emergency operation are substantially constructed, so that they can withstand blast overpressure of about 5 pounds per square inch and the associated dynamic pressure and still be capable of operation. Tools and equipment are protected from the blast by the design of the truck body or when housed in compartments with strong doors.

### Railroad Equipment

4.97 Railroad equipment suffered blast damage in Japan and also in one of the tests in Nevada. Like motor vehicles, these targets are primarily drag sensitive and damage cannot be directly related to overpressure. At a peak overpressure of 2 pounds per square inch an empty wooden boxcar will receive relatively minor damage. At 4 pounds per square inch overpressure, the damage to a loaded wooden boxcar was more severe (Fig. 4.97a). At a peak overpressure of 6 pounds per square inch, the body of an empty wooden boxcar, weighing about 20 tons, was lifted off its trucks and landed about 6 feet away. The trucks were themselves pulled off the rails, apparently by the brake rods connecting them to the car body. A similar boxcar, at the same location, loaded with 30 tons of sandbags remained upright (Fig. 4.97b). Although the sides were badly damaged and the roof demolished, the car was capable of being moved on its own wheels. At 7.5 pounds per square inch, a loaded boxcar of the same type was overturned, and at 9 pounds per square inch it was completely demolished.

4.98 A Diesel locomotive weighing 46 tons was exposed to a blast overpressure of 6 pounds per square inch while the engine was running. It continued to operate normally after the blast, in spite of damage to windows and compartment doors and panels. There was no damage to the track at this point.

### Parked Transport Aircraft

4.99 Transport-type aircraft are damaged by blast effects at levels of peak overpressure as low as 1 to 2 pounds per square inch. Complete destruction or damage beyond economical repair may be expected

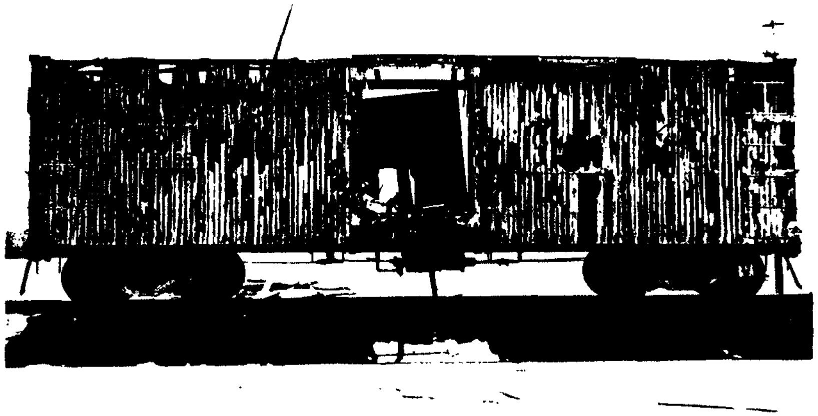

Figure 4.97a. Loaded wooden boxcar after a nuclear explosion (4 psi overpressure).

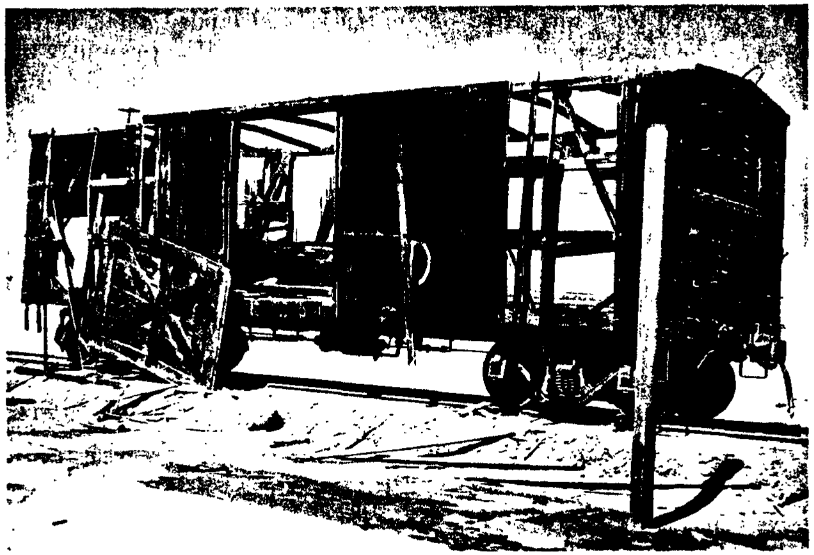

Figure 4.97b. Loaded wooden boxcar after a nuclear explosion (6 psi overpressure).

at peak overpressures of 4 to 6 pounds per square inch. Within this range, the peak overpressure appears to be the main criterion of damage. However, tests indicate that, at a given overpressure, damage to an aircraft oriented with the nose toward the burst will be less than damage to one with the tail or a side directed toward the explosion.

4.100 Damage to an aircraft exposed with its left side to the blast at a peak overpressure of 3.6 pounds per square inch is shown in Fig. 4.100a. The fuselage of this aircraft failed completely just aft of the wing. The skin of the fuselage, stabilizers, and engine cowling was severely buckled. Fig. 4.100b shows damage to an aircraft oriented with its tail toward the burst and exposed to a blast of 2.4 pounds per square inch peak overpressure. Skin was dished in on the vertical stabilizer, horizontal stabilizers, wing surface above the flaps, and outboard wing sections. Vertical stabilizer bulkheads and the fuselage frame near the cockpit were buckled.

Figure 4.100a. Aircraft after side exposed to nuclear explosion (3.6 psi overpressure).

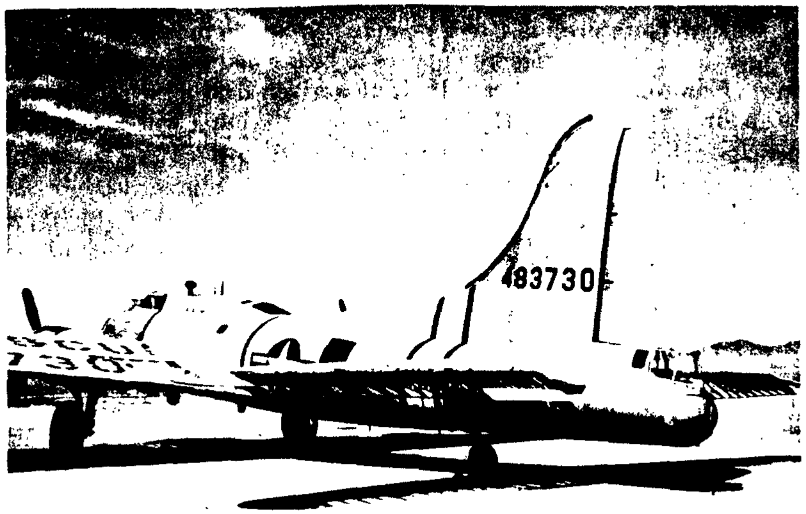

Figure 4.100b. Aircraft after tail exposed to nuclear explosion (2.4 psi overpressure).

## SHIPPING

4.101 Information concerning the effect of air blast on ships and their contents was obtained from the ABLE test (20-kiloton air burst) at Bikini in July 1946. From the results observed it appears that up to about 2,500 to 3,000 feet from surface zero, i. e., for peak overpressures of roughly 10 to 12 pounds per square inch, vessels of all types suffered serious damage or were sunk (Figs. 4.101a and b). Moderate damage was experienced out to 4,500 feet (6 pounds per square inch) and minor damage occurred within a radius of 6,000 feet (4 pounds per square inch).

4.102 Provided the ship survived, the machinery apparently remained intact. The principal exception was blast damage to boilers and uptakes, which accounted for most cases of immobilization. In general, boilers were badly damaged up to 2,700 feet, moderately damaged to 4,000 feet, while light damage extended out to 5,000 feet, corresponding to peak overpressures of approximately 11, 8, and 5 pounds per square inch, respectively.

4.103 With the closing of all exterior openings prior to exposure to a nuclear explosion, light structures and shock-sensitive equip-

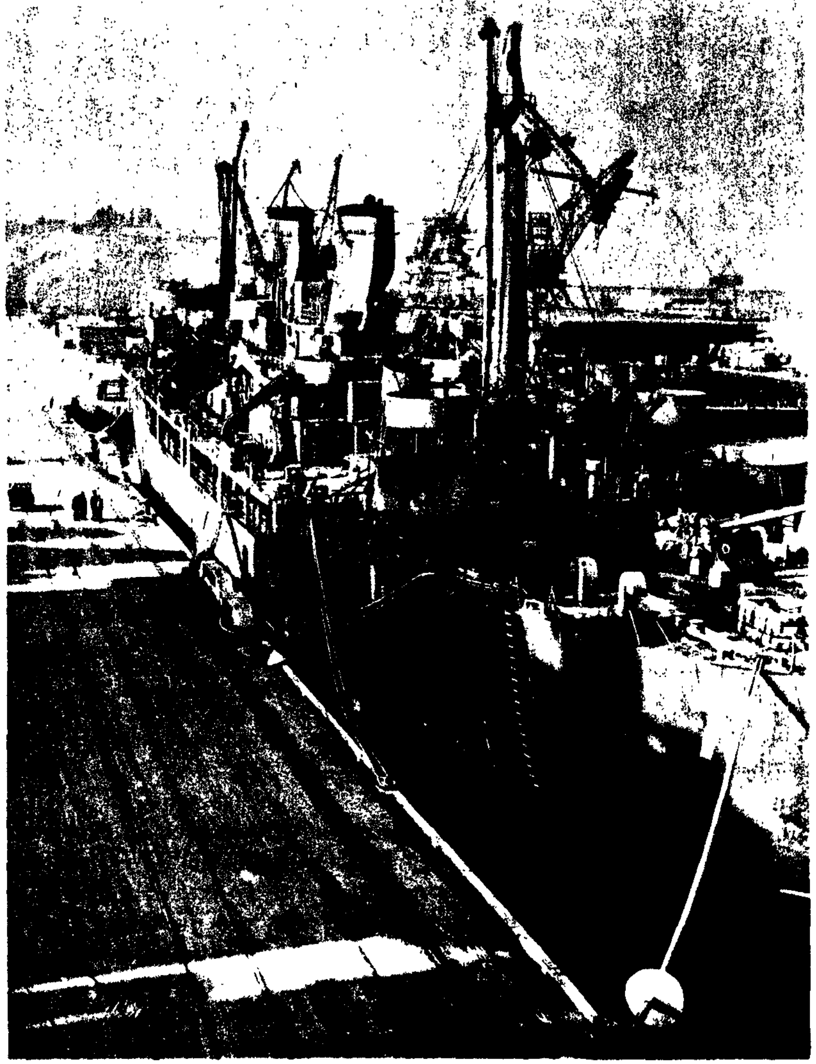

Figure 4.101a. The U. S. S. Crittenden after ABLE test; damage resulting was generally moderate (0.47 mile from surface zero).

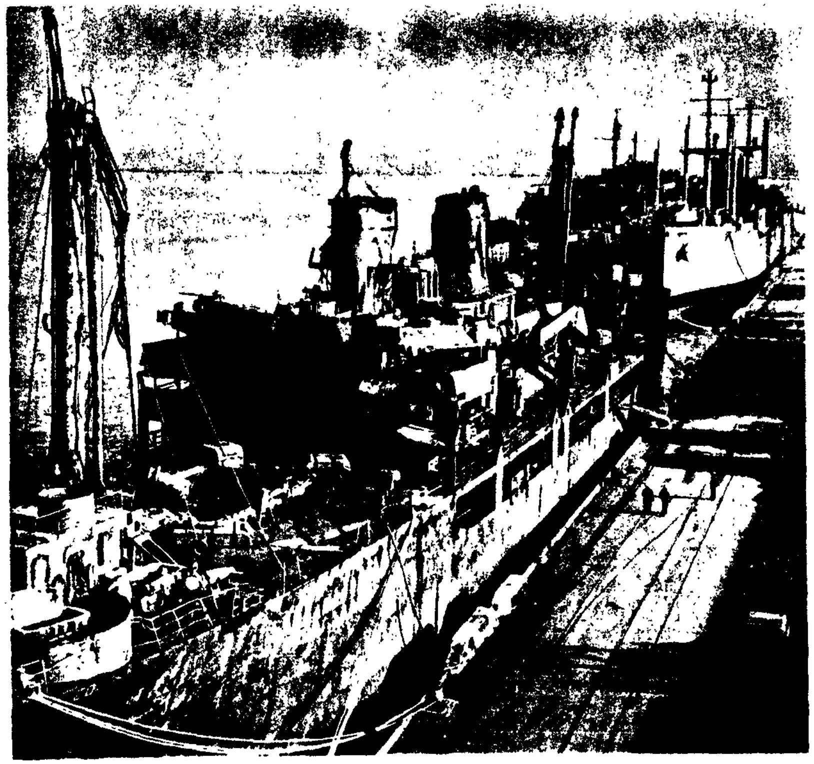

Figure 4.101b. Major visible superstructure damage to U. S. S. Crittenden, showing failure of the masting, crushing of the stacks, and damage to the bridge area.

ment (in the interior of the vessel) are not safeguarded from serious damage. A reduction in damage intensity may be achieved by shock mounting.

4.104 Structures on the ships' decks were not protected and so were severely damaged by the air blast (Figs. 4.104a and b). Light vehicles and aircraft also suffered badly when fairly close to surface zero. Masts, spars, and radar antennae are drag sensitive, and so the damage is determined mainly by the dynamic pressure and the duration of the positive phase of the blast wave. The effects may be expected to be similar to those experienced by analogous structures on land, as described below.

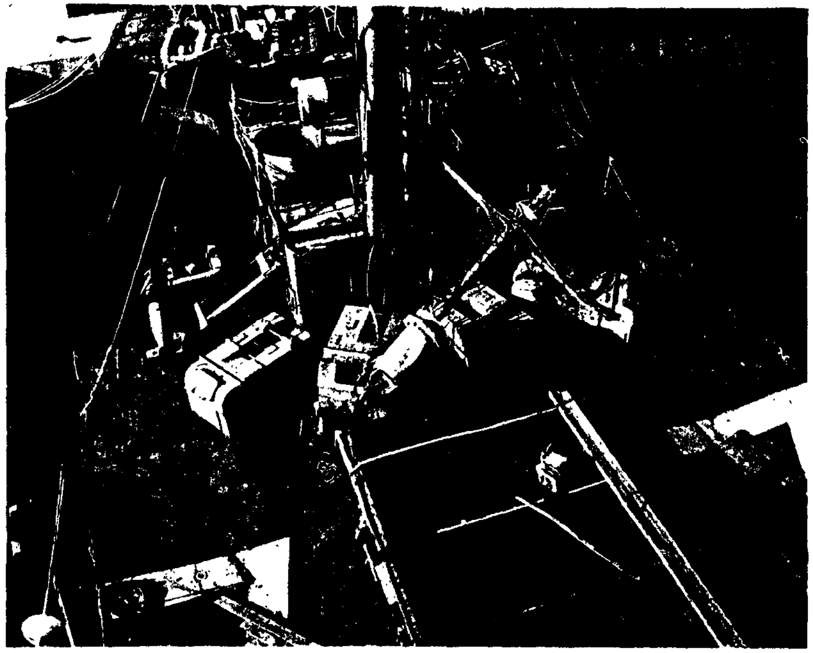

Figure 4.104a. Damage to the forecastle of the U. S. S. Crittenden at the ABLE test.

## UTILITIES AND COMMUNICATIONS

### Electrical Distribution Systems

4.105 Because of the extensive damage caused by the nuclear explosions to the cities in Japan, the electrical distribution systems suffered severely. Utility poles were destroyed by blast or fire, and overhead lines were heavily damaged at distances up to 9,000 feet (1.7 miles) from ground zero (Fig. 4.105). Underground electrical circuits were, however, little affected. Switch gear and transformers were not damaged so much directly by blast but rather by secondary effects, such as collapse of the structure in which they were located or by debris. Motors and generators were damaged by fire.

4.106 A fairly extensive study of the effects of a nuclear explosion on electric utilities was made in the Nevada tests in 1955. Among the purposes of these tests were the following: (1) to determine the

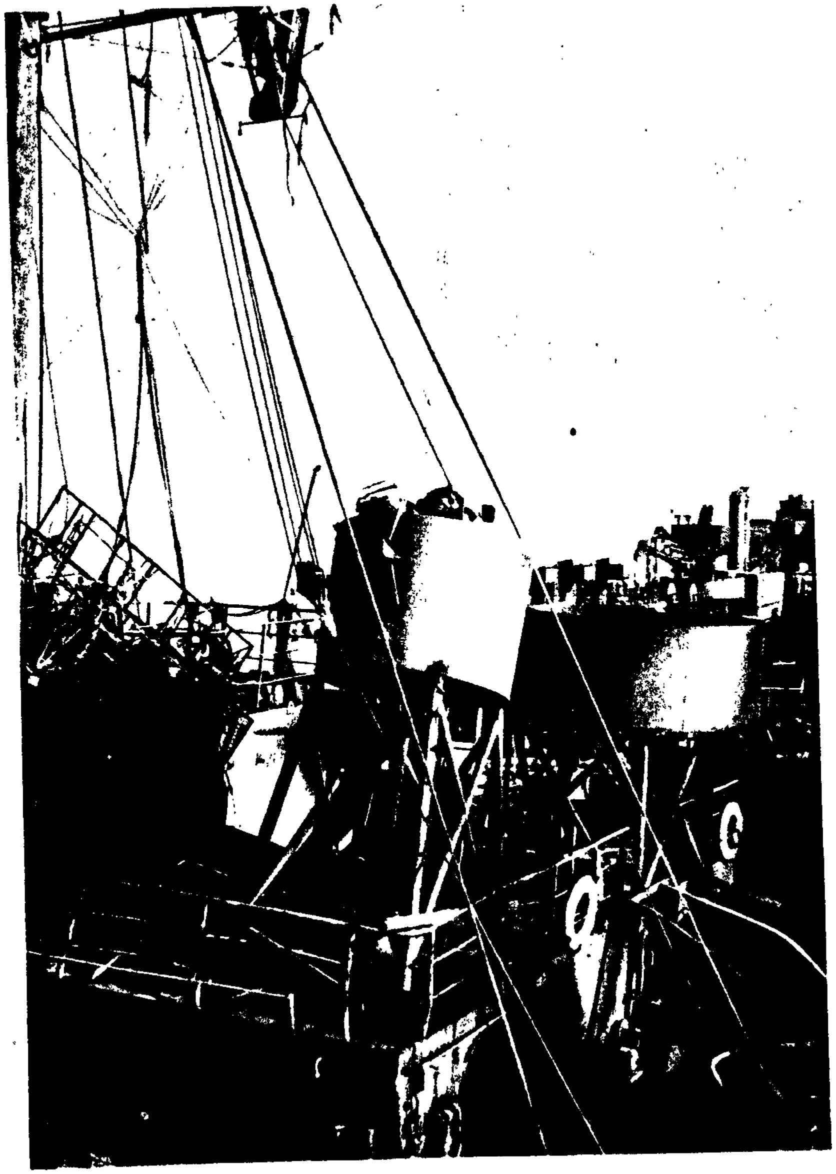

Figure 4.104b. Stern deck damage to U. S. S. Crittenden.

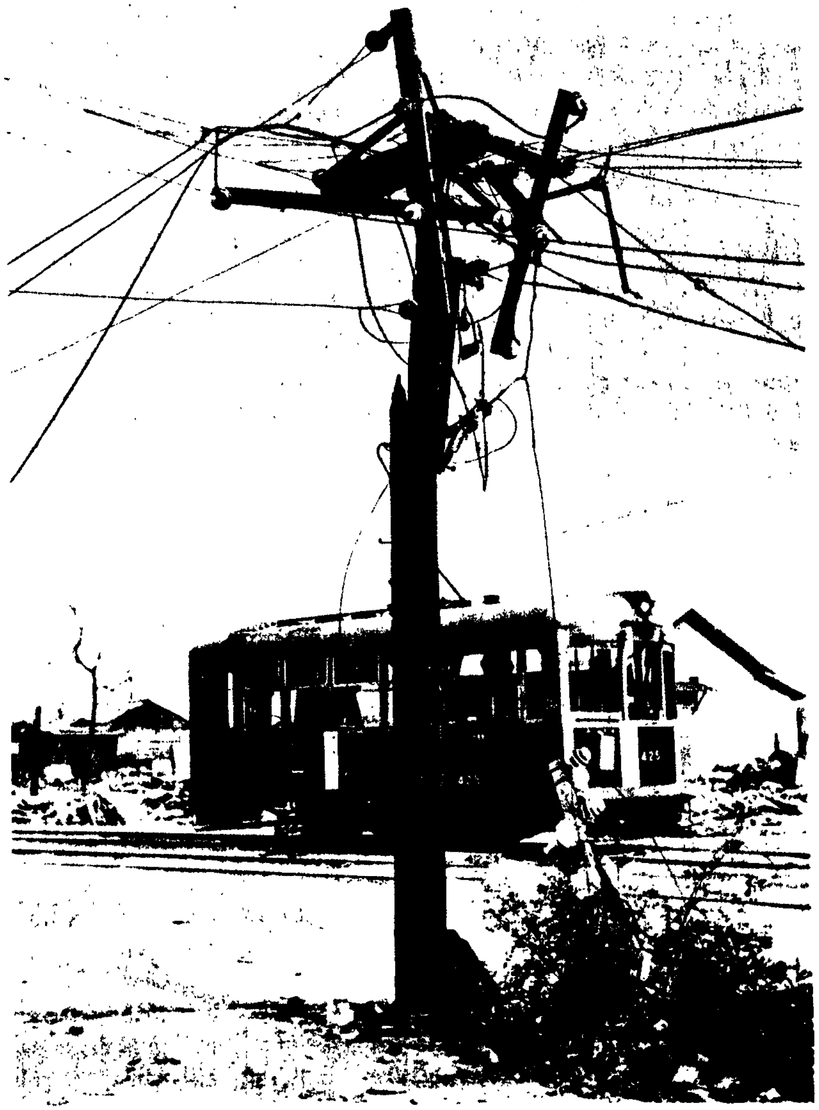

Figure 4.105. Damage to utility pole (0.80 mile from ground zero at Hiroshima).

blast pressure at which standard electrical equipment might be expected to suffer little or no damage; (2) to study the extent and character of the damage that might be sustained in a nuclear attack; and (3) to determine the nature of the repairs that would be needed to restore electrical service in those areas where homes and factories would survive sufficiently to permit their use after some repair. With these objectives in mind, two identical power systems were erected; one to be subjected to a blast overpressure of about 5 pounds per square inch and the other to 1.7 pounds per square inch. It will be recalled that at the lower overpressure, typical American residences would not be damaged beyond the possibility of further use.

4.107 Each power system consisted of a high-voltage (69 kv.) transmission line on steel towers connected to a conventional, outdoor transformer substation. From this proceeded typical overhead distribution lines on 15 wood poles; the latter were each 45 feet long and were set 6 feet in the ground. Service drops from the overhead lines supplied electricity to equipment placed in some of the houses used in the tests described above. These installations were typical of those serving an urban community. In addition, the 69-kv. transmission line, the 69-kv. switch rack with oil circuit-breakers, and the power transformer represented equipment of the kind that might supply electricity to large industrial plants.

4.108 At an overpressure of 5 pounds per square inch the power system suffered to some extent, but it was not seriously harmed. The type of damage appeared, on the whole, to be similar to that caused by severe wind storms. In addition to the direct effect of blast, some destruction was due to missiles.

4.109 The only damage suffered by the high-voltage transmission line was the collapse of the suspension tower, bringing down the distribution line with it (Fig. 4.109a). It may be noted that the dead-end tower, which was much stronger and heavier, and another suspension tower of somewhat stronger design, were only slightly affected (Fig. 4.109b). In some parts of the United States, the suspension towers are of similar heavy construction. However, structures of this type are sensitive to drag forces, so that the overpressure is not the important criterion of damage.

4.110 The transformer substation survived the blast with relatively minor damage to the essential components. The metal cubicle, which housed the meters, batteries, and relays, suffered badly, but this substation and its contents are not essential to the emergency operation of the power system. The 4-kv. regulators had been shifted on the

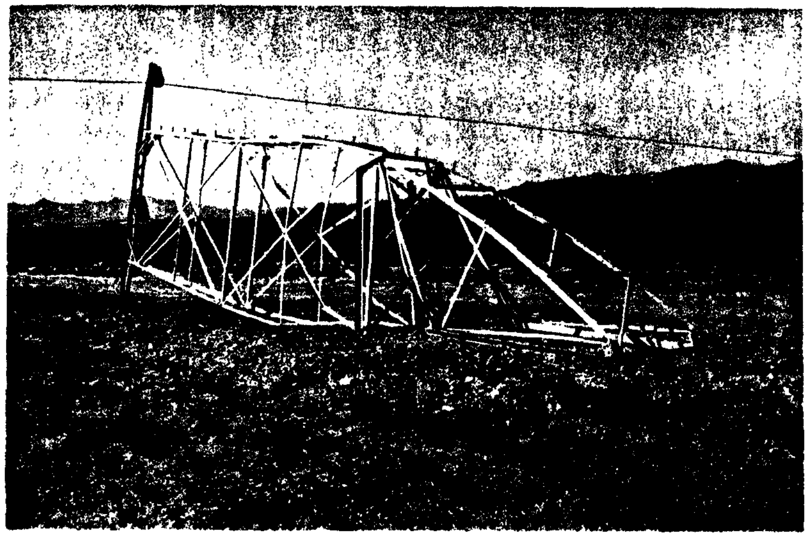

Figure 4.109a. Collapsed suspension tower (5 psi overpressure from 30-kiloton explosion, Nevada Test Site).

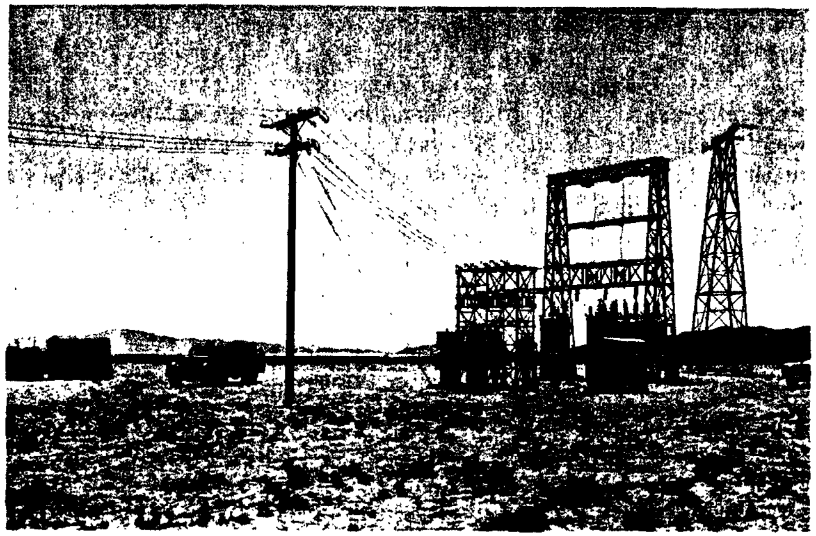

Figure 4.109b. Dead-end tower, suspension tower, and transformers (5 psi overpressure from 30-kiloton explosion, Nevada Test Site).

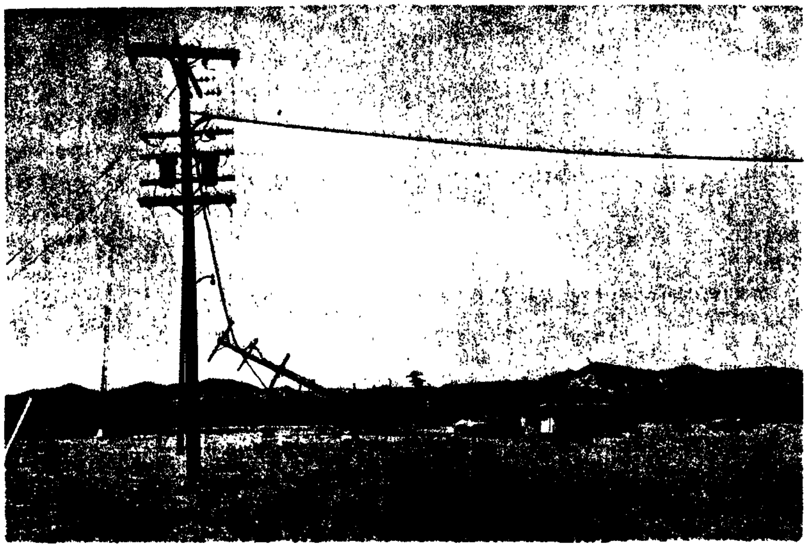

Figure 4.111. Collapse of utility poles on line (5 psi overpressure from 30-kiloton explosion, Nevada Test Site).

concrete pad, resulting in separation of the electrical connections to the bus. The glass cells of the batteries were broken and most of the plates were beyond repair. But relays, meters, and other instruments were undamaged, except for broken glass. The substation as a whole was in sufficiently sound condition to permit operation on a nonautomatic (manual) basis. By replacing the batteries, automatic operation could have been restored.

4.111 Of the 15 wood poles used to carry the lines from the substation to the houses, four were blown down completely and broken, and two others were extensively damaged. The collapse of the poles was attributed partly to the weight and resistance of the aerial cable (Fig. 4.111). Other damage was believed to be due to missiles.

4.112 Several distributor transformers had fallen from the poles, and secondary wires and service drops were down. Nevertheless, the transformers, pot heads, arresters, cut-outs, primary conductors of both aluminum and copper, and the aerial cables were unharmed. Although the pole line would have required some rebuilding, the general damage was such that it could have been repaired within a day or so with materials normally carried in stock by electric utility companies.

## GAS, WATER, AND SEWERAGE SYSTEMS

4.113 The public utility system in Nagasaki was similar to that of a somewhat smaller town in the United States, except that open sewers were used. The most significant damage was that suffered by the water-supply system, so that it became almost impossible to extinguish fires. Except for a special case, described below, loss of water pressure resulted from breakage of pipes inside and at entrances to buildings or on structures, rather than from the disruption of underground mains (Figs. 4.113a and b). The exceptional case was one in which the 12-inch cast iron water pipes were 8 feet below grade in a filled-in area. A number of depressions, up to 1 foot in depth, were produced

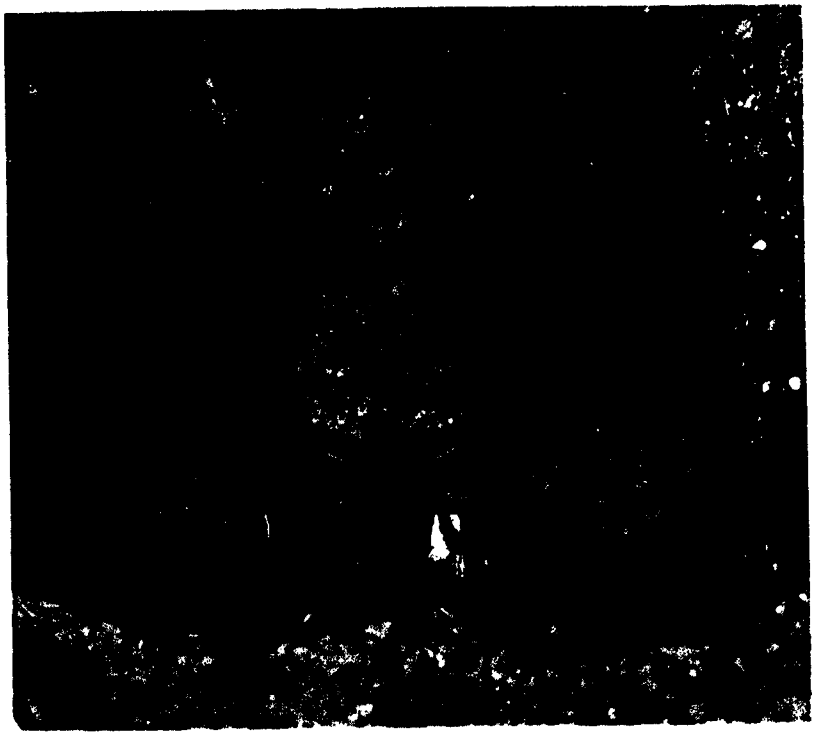

Figure 4.113a. Four-inch gate valve in water main broken by debris from brick wall (0.23 mile from ground zero at Hiroshima).

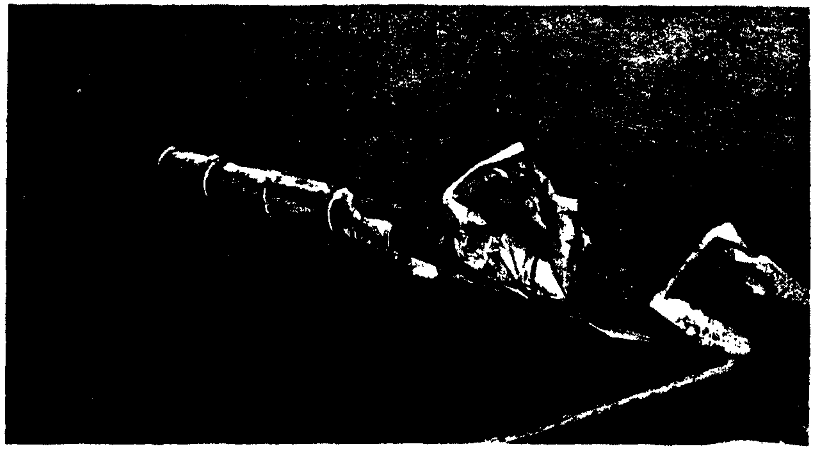

Figure 4.113b. Broken portion of 16-inch water main carried on bridge (0.23 mile from ground zero at Hiroshima).

Figure 4.115. Gas holder destroyed by nuclear explosion (0.63 mile from ground zero at Nagasaki).

in the fill, and these caused failure of the underground pipes, presumably due to unequal displacements.

4.114 There was no appreciable damage to reservoirs and water-treatment plants in Japan. As is generally the case, these were located outside the cities, and so were at too great a distance from the explosions to be damaged in any way.

4.115 Gas holders suffered heavily from blast up to 6,000 feet (1.1 miles) from ground zero and the escaping gas was ignited, but there was no explosion (Fig. 4.115). Underground gas mains appear to have been little affected by the blast.

## Natural and Manufactured Gas Installations

4.116 One of the objectives of the tests made in Nevada in 1955 was to determine the extent to which natural and manufactured gas utility installations might be disrupted by a nuclear explosion. The test was intended, in particular, to provide information concerning the effect of blast on critical underground units of a typical gas-distribution system.

4.117 The installations tested were of two kinds, each in duplicate. The first represented a typical underground gas-transmission and distribution main of 6-inch steel and cast iron pipe, at a depth of 3 feet, with its associated service pipes and attachments. Valve pits of either brick or concrete blocks contained 6-inch valves with piping and protective casings. A street regulator-vault held a 6-inch, low-pressure, pilot-loaded regulator, attached to steel piping projecting through the walls. One of these underground systems was installed where the blast overpressure was about 30 pounds per square inch and the other at 5 pounds per square inch. It should be noted that no domestic or ordinary industrial structures at the surface would survive the higher of these pressures.

4.118 The second type of installation consisted of typical service lines of steel, copper, and plastic materials connected to 20-foot lengths of 6-inch steel main. Each service pipe rose out of the ground at the side of a house, and was joined to a pressure regulator and meter. The pipe then entered the wall of the house about 2 feet above floor level. The copper and plastic services terminated inside the wall, so that they would be subject to strain if the house moved on its foundation. The steel service similarly terminated inside the wall, but it was also attached outside to piping that ran around the back of the house at ground level to connect to the house piping. This latter connection was made with flexible seamless bronze tubing, passing through a sleeve in the wall of the building. Typical domestic gas appliances, some attached to the interior piping, were located in several houses. Duplicate installations were located at overpressures of 5 and 1.7 pounds per square inch, respectively.

4.119 Neither of the underground installations was greatly affected by the blast. At the 30 pounds per square inch location a 1½-inch pipe pressure-test riser was bent to the ground, and the valve handle, stem, and bonnet had blown off. At the same place two 4-inch ventilating pipes of the street-regulator-vaults were sheared off just below ground level. A few minor leaks developed in jute and lead caulked cast iron bell and spigot joints, because of ground motion, presumably due to ground shock induced by air blast. Otherwise the blast effects were negligible.

4.120 At the overpressure of 1.7 pounds per square inch, where the houses did not suffer severe damage, the service piping both inside and outside the houses was unharmed, as also were pressure regulators and meters. In the two-story, brick house at 5 pounds per square inch overpressure, which was demolished beyond repair (§4.30), the piping in the basement was displaced and bent due to the collapse of the first floor. The meter also became detached from the fittings and fell to the ground, but the meter itself and the regulator were undamaged and still operable. All other service piping and equipment were essentially intact.

4.121 Domestic gas appliances, such as refrigerators, ranges, room heaters, clothes dryers, and water heaters suffered to a moderate extent only. There was some displacement of the appliances and connections which was related to the damage suffered by the house. However, even in the collapsed two-story, brick house, the upset rerefrigerator and range were probably still usable, although largely buried in debris. The general conclusion is, therefore, that domestic gas (and also electric) appliances would be operable in all houses that did not suffer major structural damage.

4.122 It would appear that little can be (or needs to be) done to make gas installations more blast resistant. Clamping or replacement of lead-caulked joints would be advantageous in decreasing the leaks caused by ground motion. Distribution piping, valves, regulators, and control equipment should be installed beneath the surface, as far as possible, to minimize blast and missile damage.

## Liquid Petroleum (LP) Gas Installations

4.123 In the 1955 tests, various LP-gas installations were exposed to the blast in order to determine the effect of a nuclear explosion on typical gas containers and supply systems such as are found at suburban and farm homes and at storage, industrial, and utility plants. In addition, it was of interest to see what reliance might be placed upon LP-gas as an emergency fuel after a nuclear attack.

4.124 Two kinds of typical home (or small commercial) LP-gas installations were tested: (1) a system consisting of two replaceable ICC-approved cylinders each of 100-pound capacity; and (2) a 500-gallon bulk storage type system filled from a tank truck. Some of these installations were in the open and others were attached, in the usual manner, by means of either copper tubing or steel pipe service line, to the houses exposed to overpressures of 5 and 1.7 pounds per square inch. Others were located where the overpressures were about 25 and 10 pounds per square inch. In these cases, piping from the gas containers passed through a concrete wall, simulating the wall of a house.

4.125 In addition to the foregoing, a complete bulk storage plant was erected at a point where the blast overpressure was 5 pounds per square inch. This consisted of an 18,000-gallon tank (containing 15,400 gallons of propane), pump compressor, cylinder-filling building, cylinder dock, and all necessary valves, fittings, hose, accessories, and interconnecting piping.

4.126 The dual-cylinder installation, exposed to 25 pounds per square inch overpressure, suffered most; the regulators were torn loose from their mountings and the cylinders displaced. One cylinder came to rest about 2,000 feet from its original position; it was badly dented, but was still usable. At both 25 and 10 pounds per square inch overpressure the components, although often separated, could generally be salvaged and used again. The cylinder installations at 5 pounds per square inch overpressure were mostly damaged by missiles and falling debris from the houses to which they were attached. The component parts, except for the copper tubing, suffered little and were usable. At 1.7 pounds per square inch, there was no damage to nor dislocation of LP gas cylinders. Of those tested, only one cylinder developed a leak, and this was a small puncture resulting from impact with a sharp object.

4.127 The 500-gallon bulk gas tanks also proved very durable and experienced little damage. The tank closest to the explosion was bounced end-over-end for a distance of some 700 feet; nevertheless, it suffered only superficially and its strength and serviceability were not impaired. The filler valve was damaged, but the internal check valve prevented escape of the contents. The tank exposed at 10 pounds per square inch overpressure was moved about 5 feet, but it sustained little or no damage. All the other tanks, at 5 or 1.7 pounds per square inch, including those at houses piped for service, were unmoved and undamaged (Fig. 4.38).

4.128 The equipment of the 18,000-gallon bulk storage and filling plant received only superficial damage from the blast at 5 pounds per square inch overpressure. The cylinder-filling building was completely demolished; the scale used for weighing the cylinders was wrecked, and a filling line was broken at the point where it entered the building (Fig. 4.128). The major operating services of the plant would, however, not be affected because the transfer facilities were outside and undamaged. All valves and nearly all piping in the plant were intact and there was no leakage of gas. The plant could have been readily put back into operation if power (electricity or a gasoline engine) were restored. If not, liquid propane in the storage tank could have been made available by taking advantage of gravity flow in conjunction with the inherent pressure of the gas in the tank.

4.129 The general conclusion to be drawn from the tests is that standard LP-gas equipment is very rugged, except for copper tubing connections. Disruption of the service as a result of a nuclear attack would probably be localized and perhaps negligible, so that LP-gas might prove to be a very useful emergency fuel. Where LP-gas is mainly used for domestic purposes, it appears that the gas supply will not be affected under such conditions that the house remains habitable.

## Communications Equipment

4.130 The importance of having communications equipment in operating condition after a nuclear attack is evident and so a variety of such equipment was tested in Nevada in 1955. Among the items exposed were mobile radio-communication systems and units, a standard broadcasting transmitter, antenna towers, home radio and television receivers, telephone equipment (including a small telephone exchange), public address sound systems, and sirens. Some of these were located where the peak overpressure was 5 pounds per square inch, and in most cases there were duplicates at 1.7 pounds per square inch. The damage at the latter location was of such a minor character

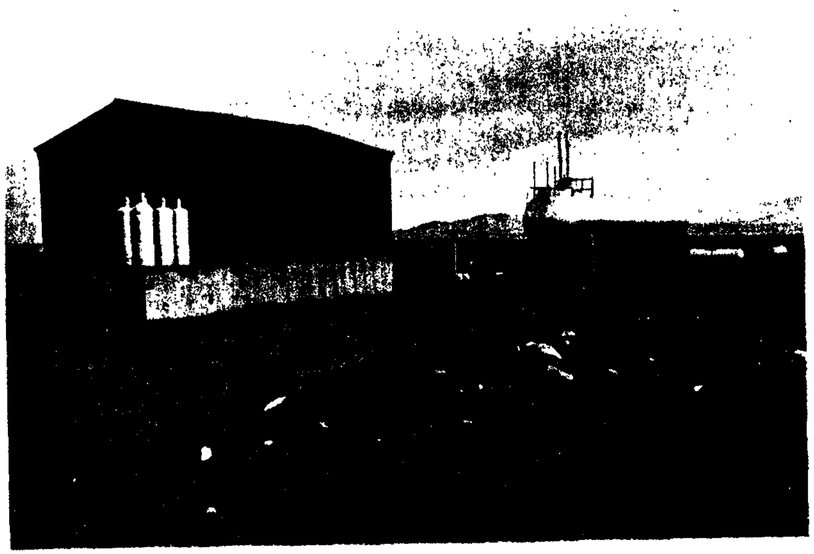

Figure 4.128. *Upper photo:* LP-Gas bulk storage and filling plant before a nuclear explosion. *Lower photo:* The plant after the explosion (5 psi overpressure).

that it need not be considered here. Damage radii for this type of equipment cannot be directly related to overpressure but should be obtained from the charts in Chapter VI.

4.131 At the higher overpressure region, where typical houses were damaged beyond repair, the communications equipment proved to be very resistant to blast. Standard broadcast and television receivers, and mobile radio base stations were found to be in working condition, even though they were covered in debris and had, in some cases, been damaged by missiles, or by being thrown or dropped several feet. No vacuum or picture tubes were broken. The only mobile radio station to be seriously affected was one in an automobile which was completely crushed by a falling chimney.

4.132 A guyed 150-foot antenna tower was unharmed, but an unguyed 120-foot tower, of lighter construction, close by, broke off at a height of about 40 feet and fell to the ground (Fig. 4.132). This represented the only serious damage to any of the equipment tested.

4.133 The base station antennas, which were on the towers, appeared to withstand blast reasonably well, although those attached to the unguyed tower, referred to above, suffered when the tower collapsed. As would have been expected from their lighter construction, television antennas for home receivers were more easily damaged. Several were bent both by the blast and the collapse of the houses upon which they were mounted. Since the houses were generally damaged beyond repair at an overpressure of 5 pounds per square inch, the failure of the television antennas is not of great significance.

4.134 It should be mentioned that representative items, such as power lines and telephone service equipment, were frequently attached to utility-line poles. When the poles failed, as they did in some cases (see §4.111), the communications systems suffered accordingly. Although the equipment operated satisfactorily, after repairs were made to the wire line, it appears that the power supply represents a weak link in the communications chain.

## SUMMARY

4.135 Although more complete data will be given in Chapter VI concerning damage-distance relationships for explosions of various energy yields and structures of different kinds, the simplified summaries in Tables 4.135a and b are presented for rapid reference. They apply to so-called typical air bursts, as defined in §2.47, with energy yields of 20 kilotons and 1 megaton, respectively. The information has been obtained from observations made in Japan and at several nuclear test explosions as well as from calculations. Since there are always substantial variations, due to differences in design and construction, among buildings of apparently the same type, the data in the tables may be regarded as applying to "average" structures. Some structures will be weaker and others will be stronger than the average. This limitation as well as possible variations due to a change in the height of burst must be kept in mind when using the tables. In order to make the information more complete, some of the characteristic properties of the blast waves at various distances are included. The dynamic pressures quoted are the horizontal components only (see § 3.95).

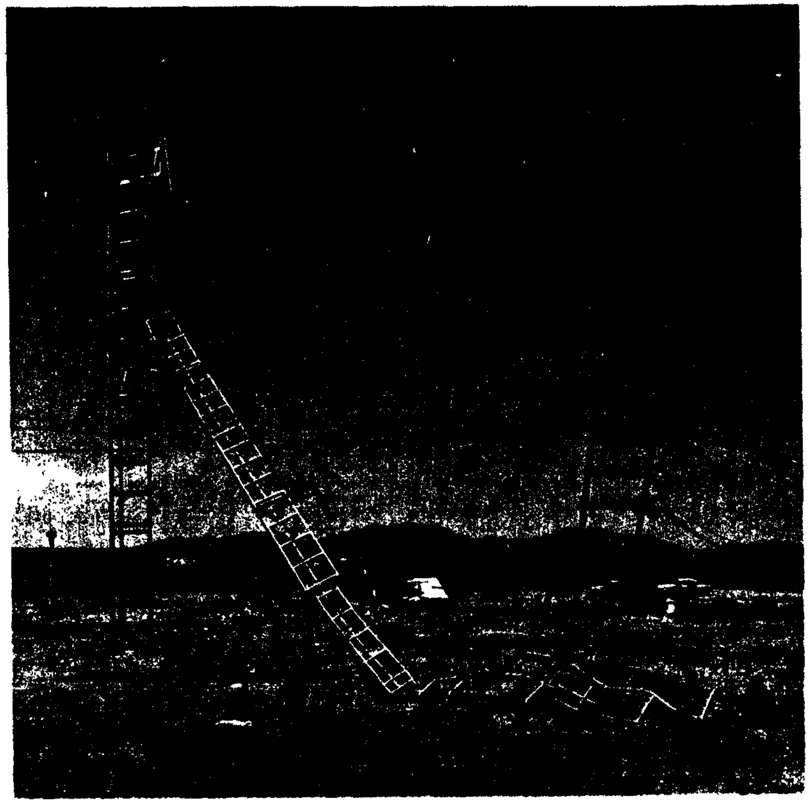

**Figure 4.132** Unguyed lightweight 120-foot antenna tower (5 psi overpressure from 30-kiloton explosion, Nevada Test Site).

Table 4.135a Damage Ranges for 20–Kiloton Typical Air Burst

| Peak Wind Velocity (mph) | Positive Phase Duration (sec) | Peak Dynamic Pressure (psi) | Peak Over-Pressure (psi) | Miles from Ground Zero | |
|---|---|---|---|---|---|
| | | | | | Light damage to window frames and doors, moderate plaster damage out to about 4 miles; glass breakage possible out to 8 miles. |
| 40 | 1.27 | – | 1.1 | 2.6 | Oil storage tanks, filled : slight damage. |
| 46 | 1.22 | – | 1.3 | 2.4 | |
| 53 | 1.17 | – | 1.5 | 2.2 | |
| 60 | 1.11 | – | 1.7 | 2.0 | Wood frame houses : moderate damage. |
| 70 | 1.06 | 0.09 | 2.0 | 1.8 | Fine kindling fuels : ignited. |
| | | | | | Radio and TV transmitting towers : slight damage.<br>Smokestacks : slight damage. |
| 86 | 1.00 | 0.15 | 2.5 | 1.6 | |
| | | | | | Light steel frame industrial buildings, light walls : moderate damage. |
| 105 | 0.96 | 0.23 | 3.1 | 1.4 | *Wood frame houses : severe damage.*<br>Motor vehicles : slight damage.<br>Radio and TV transmitting towers : moderate damage. |
| 133 | 0.91 | 0.39 | 4.0 | 1.2 | Medium steel frame industrial buildings, light walls : moderate damage.<br>Telephone and power lines : limit of significant damage. |
| | | | | | Wood frame houses : destroyed.<br>Highway and R.R. truss bridges : slight damage.<br>Wall bearing, brick (apartment house type) buildings : moderate damage. |
| 153 | 0.85 | 0.70 | 5.4 | 1.0 | Steel frame, light walls (office type) buildings : moderate damage. |
| | | | | | Reinforced concrete frame and walls, multistory structures : moderate damage.<br>*Wall bearing, brick (apartment house type) buildings : severe damage.* |
| 234 | 0.78 | 1.2 | 7.6 | 0.8 | Reinforced concrete frame building, light walls : moderate damage.<br>Highway and R. R. truss bridges : moderate damage. |
| | | | | | Medium steel frame industrial buildings, light walls : severe damage.<br>Reinforced concrete frame and walls, multistory structures : severe damage. |
| 294 | 0.71 | 2.2 | 10 | 0.6 | Massive wall bearing, multistory structures : moderate damage.<br>Motor vehicles : moderate damage. |
| | | | | | Steel frame, light walls (office type) buildings : severe damage.<br>Oil storage tanks, filled : severe damage. |
| 384 | 0.64 | 3.5 | 14 | 0.4 | |
| | | | | | Motor vehicles : severe damage.<br>Reinforced concrete, blast resistant, windowless structures : moderate damage.<br>All other (above ground) structures : severely damaged or destroyed. |
| 306 | 0.55 | 2.5 | 24 | 0.2 | |
| | | | | 0 | Ground zero for 20–kiloton air burst. |

Table 4.135b Damage Ranges for 1–Megaton Typical Air Burst

| Peak Wind Velocity (mph) | Positive Phase Duration (sec) | Peak Dynamic Pressure (psi) | Peak Over-Pressure (psi) | Miles from Ground Zero | |
|---|---|---|---|---|---|
| 36 | 4.8 | – | 1.0 | 10 | Light damage to window frames and doors, moderate plaster damage out to about 15 miles; glass breakage possible out to 30 miles. |
| | | | | | Oil storage tanks, filled : slight damage. |
| 43 | 4.6 | – | 1.2 | 9 | |
| | | | | | Fine kindling fuels : ignited. |
| 53 | 4.3 | – | 1.5 | 8 | |
| 63 | 4.0 | 0.08 | 1.8 | 7 | Wood frame houses : moderate damage.<br>Radio and TV transmitting towers : slight damage.<br>Smokestacks : slight damage |
| 83 | 3.8 | 0.13 | 2.4 | 6 | |
| | | | | | Light steel frame industrial buildings, light walls : moderate damage.<br>Motor vehicles : slight damage.<br>*Radio and TV transmitting towers : moderate damage.*<br>Wood frame houses : severe damage. |
| 109 | 3.5 | 0.26 | 3.2 | 5 | |
| | | | | | Medium steel frame industrial buildings, light walls : moderate damage.<br>Telephone and power lines : limit of significant damage. |
| | | | | | Highway and R. R. truss bridges : slight damage.<br>Steel frame, light walls (office type) buildings : moderate damage. |
| 142 | 3.2 | 0.55 | 4.7 | 4 | Wood frame houses : destroyed.<br>Wall bearing, brick (apartment house type) buildings : moderate damage. |
| | | | | | Reinforced concrete frame and walls, multistory structures : moderate damage.<br>*Wall bearing, brick (apartment house type)* buildings : severe damage. |
| 228 | 2.9 | 1.2 | 7.4 | 3 | Reinforced concrete frame buildings, light walls : moderate damage.<br>Highway and R. R. truss bridges : moderate damage.<br>Medium steel frame industrial buildings, light walls : severe damage. |
| | | | | | Reinforced concrete frame and walls, multistory structures : severe damage.<br>Massive wall bearing, multistory structures : moderate damage.<br>*Steel frame, light walls (office type)* buildings : severe damage.<br>Motor vehicles : moderate damage. |
| 317 | 2.6 | 2.6 | 11 | 2 | Oil storage tanks, filled : severe damage. |
| | | | | | Motor vehicles : severe damage. |
| 347 | 2.1 | 3.2 | 20 | 1 | |
| | | | | | Reinforced concrete, blast resistant, windowless structures : moderate damage.<br>All other (above ground) structures : severely damaged or destroyed. |
| | | | | 0 | Ground zero for 1–megaton air burst. |

## *CHAPTER V*

# EFFECTS OF SURFACE AND SUBSURFACE BURSTS

## CHARACTERISTICS OF A SURFACE BURST

### Air Blast Wave

5.1 In the present chapter there will be described some of the effects of nuclear explosions occurring at or near the surface of the ground, under the ground, and under water. The particular aspects considered will be those associated with the shock (or blast) wave produced as a result of the rapid expansion of the intensely hot gases at extremly high pressures in the ball of fire formed by the explosion (see Chapter II).

5.2 The first case to be discussed is that of a surface burst, i. e., one in which the explosion occurs either at the actual surface (contact burst) or at a height above the surface where the fireball (at maximum brilliance) touches or intersects the ground. Although some of the energy of the explosion may be spent in producing a crater, as will be seen shortly, a considerable proportion appears as air blast energy. Because the detonation occurs fairly close to the surface, fusion of incident and reflected blast waves occurs close to ground zero. In fact, as explained in Chapter III, in the event of a true surface (or contact) burst, i. e., when the weapon is exploded on the surface, the incident and reflected waves coincide immediately forming a hemispherical shock front as shown in Fig. 3.29.

5.3 The characteristic properties of the blast wave accompanying a reference (1-kiloton) surface burst, as functions of the distance from ground zero, have been given at the end of Chapter III. The cube root scaling law described there can be used to calculate the blast wave properties for a surface burst of any specified energy yield.

### Formation of Crater

5.4 It was mentioned in Chapter II that in a surface burst a considerable quantity of material is vaporized due to the extremely high temperature. This material is sucked upward by the ascending air currents resulting from the rising ball of fire and eventually condenses in the atomic cloud. As far as crater formation is concerned, a much more important contributory factor is the displacement of soil and other material due to the pressure produced by the rapid expansion of the hot gas bubble. The removal of material by being pushed, thrown, and scoured out is largely responsible for the crater formed as a result of the explosion. Because of the outward motion of the gases, very little of the earth falls back into the hole, although a considerable amount is deposited around the edges to form the upper layers of a lip.

5.5 Assuming, for simplicity, that the ground under the explosion consists of dry soil, then two more-or-less distinct zones immediately beneath the crater may be distinguished. First, there is the "rupture zone" in which there are innumerable cracks of various sizes due to the rupture of the soil. Below this is the "plastic zone" in which there is no visible rupture although the soil is permanently deformed. Plastic deformation and shear of soil around the edges of the crater contribute to the production of the lip referred to above (Fig. 5.5).

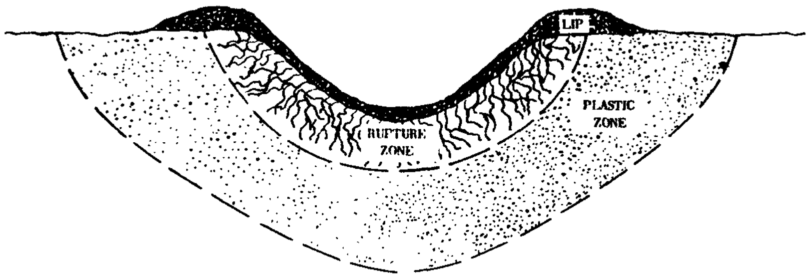

**Figure 5.5.** Plastic and rupture zone formation in a surface burst.

5.6 The thicknesses of the rupture and plastic zones depend on the nature of the soil, as well as upon the energy yield of the explosion and location of the point of burst. If the earth below the burst consists of rock, then there will be a rupture zone but little or no plastic zone. Except for damage to weak buried structures and some utilities, the undeground effects of a surface burst do not extend appreciably beyond the rupture zone, the radius of which is roughly one and one-half times that of the crater.

### CRATER DIMENSIONS

5.7 It has been estimated that for a 1-kiloton nuclear contact surface burst, the diameter of the crater, i. e., of the hole, will be about 125 feet in dry soil, the lip will extend a further 60 feet or so all around. The depth of the crater is expected to be about 25 feet. In hard rock, consisting of granite and sandstone, the dimensions will be somewhat less. The diameter will be appreciably greater in soil saturated with water, and so also will be the initial depth, to which the structural damage is related. The final depth, however, will be less due to "hydraulic fill", i. e., the slumping back of wet material and the seepage of water carrying loose soil.

5.8 The diameter (or radius) of the crater increases roughly in proportion to the cube root of the energy of the explosion. Hence, for an explosion of $W$ kilotons yield, the diameter will be $W^{1/3}$ times the value quoted above for a 1-kiloton burst. The depth scales approximately according to the fourth root of the energy, for most soils, which means that it increases by a factor of $W^{1/4}$. For example, for a 100-kiloton contact surface burst in dry soil, the diameter of the crater may be expected to be $125 \times (100)^{1/3} = 580$ feet, and the depth $25 \times (100)^{1/4} = 80$ feet. Curves showing the variation with energy yield of the diameter and depth of the crater from a contact surfact burst in dry soil, together with correction factors for other soil types, are given toward the end of this chapter (see Fig. 5.46).

5.9 The results quoted above apply to a burst on the surface. As the height of burst increases, the dimensions of the crater vary in a rather complicated manner, due to changes in the mechanism of crater formation. As a rough guide, it may be stated that both the radius and, especially, the depth of the hole decrease rapidly with increasing height of burst. Long before a height of burst at which the fireball just touches the ground, the cratering becomes insignificant. In fact, for an appreciable crater to be formed, the height of burst should be not more than about one-tenth of the fireball radius.

### GROUND SHOCK

5.10 In a nuclear surface burst a small proportion of the explosion energy is expended in producing a shock (or pressure) wave in the ground, of which only the general features are known at present. This pressure wave differs from the blast wave in air in having a much less sudden increase of pressure at the front; the ground shock wave also decays less sharply. Close to the explosion the pressure or shock gradient is large enough to destroy the cohesive forces in the soil. The magnitude of the pressure wave attenuates fairly rapidly with distance from the explosion, and at large distances it becomes similar to an acoustic (or seismic) wave.

5.11 The effects of underground shock have been described as being somewhat similar to those of an earthquake of moderate intensity, although, as pointed out in § 2.69, there are significant differences between an underground nuclear burst and an earthquake. The pressure in the ground shock waves falls off more rapidly with distance in the case of the nuclear explosion, and the radius of damage in a surface burst due to the ground shock (or "earthquake effect") is small in comparison with that due to air blast.

5.12 The shock waves in the ground are complex, but their general characteristics may be summarized briefly. At the surface of the ground a series of waves move outward in a manner somewhat similar to waves in water. These ground surface waves radiating out from the center produce what is called "ground roll," which, at any given location, is felt as an oscillation of the surface as the waves pass by. In addition, a pulse traveling outward from the expanding gas bubble, along a roughly hemispherical wave front of ever increasing size, produces compression and shear waves below the surface of the ground.

5.13 The effect of ground shock pressure on an underground structure is somewhat different in character from that of air blast on a structure above the ground. In the latter case, as explained in Chapter III, the structure experiences something like a sudden blow, followed by drag due to the blast wind. This type of behavior is not associated with underground shock. Due to the similarity in density of the medium through which a ground shock wave travels and that of the underground structure, the response of the ground and the structure are closely related. In other words, the movement (acceleration, velocity, and displacement) of the underground structure by the shock wave is largely determined by the motion of the ground itself. This fact has an important influence on the damage criteria associated with both surface and underground explosions. These criteria will be outlined below and are discussed more fully in Chapter VI.

## CHARACTERISTICS OF AN UNDERGROUND BURST

### AIR BLAST

5.14 An underground burst is defined in general terms as one in which the center of the explosion is below the surface of the ground

(§ 1.29). Practical considerations, however, would suggest that an explosion occurring at a depth greater than 50 or 100 feet is rather improbable. This means that the only underground nuclear explosions that need be given serious consideration are those in which the ball of fire or the sphere of hot, high-pressure gases breaks through the earth's surface. A burst of this kind will evidently have many features in common with a surface burst.

5.15 The proportion of the bomb energy appearing as air blast will be greatly dependent on circumstances, particularly the depth of burst. If the explosion occurs a few feet below the earth's surface, the situation will not be very different from that in a true (or contact) surface burst. As the depth of burst increases, the air blast energy decreases and the attenuation of peak overpressure with distance is more rapid. Consequently, the blast overpressure at a given range will be somewhat less for deeper bursts.

### Crater Formation and Ground Shock

5.16 The size of the crater produced by an underground burst just below the surface will be essentially the same as for a contact burst, as given above. With increasing depth of the burst, a decreasing fraction of the explosion energy appears as air blast, while an increasing proportion is spent in producing ground shock and in crater formation. Hence, up to a point, the diameter and radius of the crater increase with increasing depth of the explosion. Further information on this subject will be found in the technical section of this chapter (see Fig. 5.46).

5.17 The characteristic properties of the ground shock wave accompanying an underground explosion are quite similar to those described earlier in connection with a surface burst. The energy fraction going into the ground shock is not precisely known, but it will increase up to a limiting value with increasing depth of burst.

## DAMAGE CRITERIA

### Ground Surface Bursts

5.18 For a surface burst at a moderate height above the ground, the crater or depression formed will not be very deep. Shallow buried structures near ground zero will be damaged by this depression of the earth, but those at greater depths will hardly be affected. As indicated in § 5.6, the damage to underground structures and utility pipes will probably not extend to distances beyond one and one-half times the crater radius. As far as structures above ground are concerned, the range of damage will depend upon the characteristics of the blast wave in air, just as for an air burst (see Chapter III). The area affected by air blast will greatly exceed that in which damage is caused by motion of (or shock waves in) the ground. In the event of a contact or near surface burst, the situation is similar to that in an underground burst, as described below.

### Underground Bursts

5.19 The damage criteria associated with underground (and contact surface) bursts, especially in connection with buried structures, are difficult to define. A simple and practical approach is to consider three regions around "surface zero," i. e., around the point on the surface directly above the underground explosion. The first region is that of the crater itself. Within this region there is practically complete destruction of everything both above and below the surface, and so there is nothing further to be discussed.

5.20 The second region extends roughly out to the end of the plastic zone, i. e., as far as the actual displacement of the ground (see Fig. 5.5). In some soils the radius of this zone may be roughly two and one-half times the radius of the crater itself. Within this region, heavy and well-designed underground structures are probably affected only to a minor extent by the air blast, and damage is caused by the effects of ground shock and ground movement. The actual mechanism of damage from these causes depends upon several more-or-less independent factors, such as size, shape, and flexibility of the structure, its orientation with respect to the explosion, and the soil characteristics. Some of these factors will be considered in more detail in Chapter VI.

5.21 Along with underground structures, mention may be made of buried utility pipes and tunnels and subways. Long pipes are damaged primarily as a result of differential motion at the joints and at points where the line enters a building. Failure is especially likely to occur if the utility connections are made of brittle material and are rigidly attached to the structure. Although tunnels and subways would probably be destroyed within the crater region and would suffer some damage in the (plastic zone) region under consideration, it appears that these structures, particularly when bored through solid rock and lined to minimize spalling, are very resistant to underground shock.

5.22 In the third region, beyond the plastic zone, the effects of ground shock are relatively unimportant and then air blast loading becomes the significant criterion of structural damage. Strong or deeply buried underground structures will not be greatly affected, but damage to moderately light, shallow buried structures and some utility pipes will be determined, to a great extent, by the downward pressure, i. e., by the peak overpressure of the air blast accompanying the surface or subsurface burst. Structures which are partly above and partly below ground will, of course, also be affected by the direct air blast.

## CHARACTERISTICS OF AN UNDERWATER BURST

### Shock Wave in Water

5.23 The rapid expansion of the gas bubble formed by a nuclear explosion under water results in a shock wave being sent out through the water in all directions. The shock wave is similar in general form to that in air, although it differs in detail. Just as in air, there is a sharp rise in overpressure at the shock front. In water, however, the peak overpressure does not fall off as rapidly with distance as it does in air. Hence, the peak values in water are much higher than at the same distance from an equal explosion in air. For example, the peak overpressure at 3,000 feet from a 100-kiloton burst in deep water is about 2,700 pounds per square inch, compared with a few pounds per square inch for an air burst. On the other hand, the duration of the shock wave in water is shorter than in air. In water it is of the order of a few hundredths of a second, compared with something like a second or so in air.

5.24 The velocity of sound in water under normal conditions is nearly a mile per second, almost five times as great as in air. When the peak pressure is high, the velocity of the shock wave is greater than the normal velocity of sound. The rate of motion of the shock front becomes less at lower overpressures and ultimately approaches that of sound, just as it does in air.

5.25 When the shock wave in water strikes a rigid, submerged surface, such as the hull of a ship or the sea bottom, reflection occurs as in air. The direct and reflected waves may even fuse in certain circumstances to produce a shock front of enhanced pressure. However, when the water shock wave reaches the upper (air) surface, an entirely different reflection phenomenon occurs.

5.26 At the surface between the water and the air, the shock wave moving through the water meets a much less rigid medium, namely the air. As a result a reflected wave is sent back into the water, but this is a rarefaction (or suction) wave. At a point below the surface the combination of the reflected suction wave with the direct wave produces a sharp decrease in the water shock pressure. This is referred to as the "surface cutoff."

5.27 The variation at a given location of the shock overpressure with time after the explosion at a point under water, not too far from the air surface, is shown in Fig. 5.27. After the lapse of a short interval, which is the time required for the shock wave to travel from the explosion to the given location, the overpressure rises suddenly due to the arrival of the shock front. Then, for a period of time, the pressure decreases steadily, as in air. Soon thereafter, the arrival of the reflected suction wave from the surface causes the pressure to drop sharply, even below the normal (hydrostatic) pressure of the water. This negative pressure phase is of short duration.

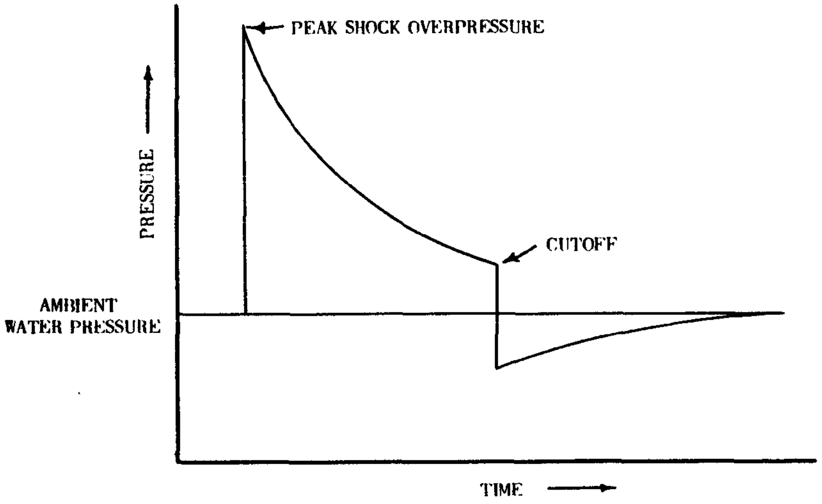

**Figure 5.27.** Variation of water pressure with time in an underwater explosion at a point near the air surface.

5.28 The time interval between the arrival of the direct shock wave at a particular location (or target) in the water and that of the cutoff, signalling the arrival of the reflected wave, depends upon the depth of burst, the depth of the target, and the distance from the burst point to the target. As may be seen from Fig. 5.28, these three distances will determine the lengths of the paths traveled by the direct and reflected shock waves in reaching the target. If the underwater target is close to the surface, e. g., a ship bottom, then the time elapsing between the arrival of the two shock fronts will be small and the cutoff will occur soon after the arrival of the shock front. This can result in a decrease in the extent of damage sustained by the target.

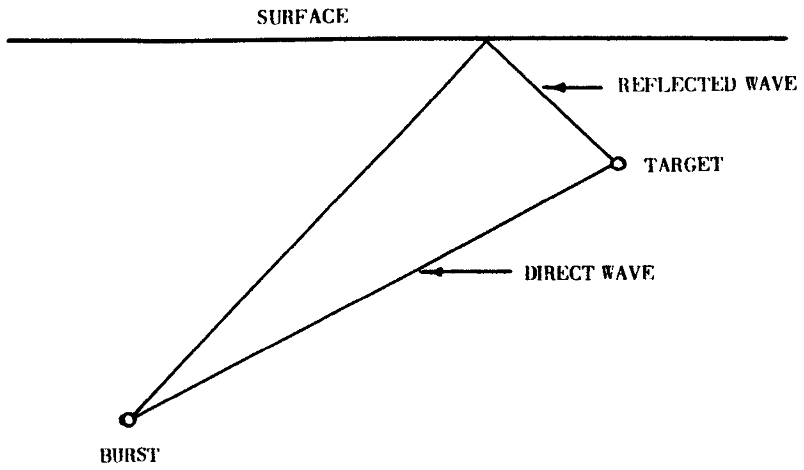

Figure 5.28. Direct and reflected waves reaching an underwater target.

### UNDERWATER SHOCK DAMAGE: GENERAL CHARACTERISTICS

5.29 The impact of a shock wave on a ship or structure, such as a breakwater or dam, is a sudden blow. Shocks of this kind have been experienced in connection with underwater detonations of TNT and other chemical explosives. But, whereas the shock produced by such an explosion is localized, that resulting from a nuclear explosion acts over a large area, e. g., the whole of a ship, almost instantaneously.

5.30 It appears that the effects of an underwater nuclear burst on a ship may be expected to be of two general types. First, there will be the direct effect of the shock on the vessel's hull; and, second, the indirect effects due to components within the ship being set in motion by the shock. An underwater shock acting on the hull of a ship tends to cause distortion of the hull below the water line, and rupture of the shell plating, thus producing leaks as well as severely stressing the ship's framing. The underwater shock also causes a rapid movement in both horizontal and vertical directions. This motion causes damage by shock to components and equipment within the ship.

5.31 Main feed lines, main steam lines, shafting, and boiler brickwork within the ship are especially sensitive to shock. Due to the effect of inertia, the supporting members or foundations of heavy components, such as engines and boilers, are likely to collapse or become distorted. Lighter or inadequately fastened articles will be thrown about with great violence, causing damage to themselves, to bulkheads, and to other equipment. Equipment which has been properly mounted against shock will probably not suffer as seriously.

5.32 The damage to the component plates of a ship is dependent mainly on the peak pressure of the underwater shock wave. The same is probably true for the gate structure of canal locks and drydock caissons. Within the range of very high pressures at the shock front, such structures may be expected to sustain appreciable damage. On the other hand, damage to large, rigid subsurface structures, such as harbor installations, is more nearly dependent upon the shock wave impulse. The impulse is dependent upon the duration of the shock wave as well as its pressure.

### UNDERWATER SHOCK DAMAGE: BIKINI EXPERIENCE

5.33 In the shallow, underwater (BAKER) nuclear test at Bikini in July 1946, which was described in Chapter II, some 70 ships of various types were anchored around the point of burst. Although, the explosion was accompanied by an air blast wave of considerable energy, the major damage to the ships in the lagoon was caused by the shock wave transmitted through the water. From the observations made after the shot, certain general conclusions were drawn, and these will be outlined here. It should be noted, however, that the nature and extent of the damage sustained by a surface vessel from underwater shock will depend upon the depth of the burst, the ship type, whether it is operating or riding at anchor, and its orientation with respect to the position of the explosion.

5.34 The lethal or sinking shock overpressure in water for all types of ships of fairly substantial construction is expected to be very much the same, probably about 3,000 or 4,000 pounds per square inch, for a shallow underwater burst similar to the BAKER test. Some ships may be expected to sink as a result of an overpressure of 2,000 pounds per square inch, and those which survive will be damaged to such an extent as to render them almost useless. Most vessels will be immobilized at peak pressures down to 1,000 pounds per square inch. At lower pressures most of the damage will be to equipment rather than to the ship plates.

5.35 With a shallow underwater burst, boilers and main propulsive machinery will suffer heavy damage due to motion caused by the water shock at locations where the water shock overpressures are about 2,500 pounds per square inch; at locations where pressures are down to 2,000 pounds per square inch the damage will be moderate, and light damage will extend to somewhat beyond the 1,000-pound per square inch location. Auxiliary machinery associated with propulsion of the ship will not suffer as severely, but light interior equipment will be affected down to water shock pressures of 500 pounds per square inch. Vessels underway will perhaps suffer somewhat more damage to machinery than those at anchor.

### Air Blast from Underwater Explosion

5.36 Although the major portion of the shock energy due to a shallow underwater explosion is propagated through the water, a considerable amount is transmitted through the surface as a shock (or blast) wave in air (§ 5.15). Air blast undoubtedly caused some damage to the superstructures of the ships at the Bikini BAKER test, but this was insignificant in comparison to the damage done by the underwater shock. The main effect of the air blast wave would probably be to targets on land, if the bomb were exploded not too far from shore. The damage criteria are then the same as for an air burst over land, at the appropriate overpressures and dynamic pressures.

### Water Waves in Underwater Explosion

5.37 A brief account of the water wave phenomena observed at the Bikini BAKER test was given in Chapter II. Some further details, with particular reference to the destructive action of these waves, will be added here. The first wave to form after the underwater explosion consisted of a crest followed by a trough which descended as far below the still water as the crest rose above it. After this came a train of waves, the number increasing as the wave system moved outward from the point of the explosion. The appearance of the water when the waves reached the beach 11 miles distant is shown in Fig. 5.37.

5.38 Observation of the properties of the waves indicated that the first wave behaved differently from the succeeding ones in that it was apparently a long, solitary wave, generated directly by the explosion, receiving its initial energy from the high-velocity outward motion of the water accompanying the expansion of the gas bubble. The subsequent waves were probably formed by the venting of the gas bubble and refilling of the void created in the water.

Figure 5.37. Waves from the BAKER underwater explosion reaching the beach at Bikini, 11 miles from surface zero.

5.39 Near the explosion the first crest was somewhat higher than the succeeding ones, both above the undisturbed water level and in total height above the following trough. At greater distances from the burst point the highest wave was usually one of those in the succeeding train. The maximum height of this train appeared to pass backward to later and later waves as the distance from the center increased.

5.40 The maximum heights and arrival times (not always of the first wave), at various distances from surface zero, of the water waves accompanying a 20-kiloton shallow underwater explosion are given in Table 5.40. These results are based on observations made at the

Bikini BAKER test. A more generalized treatment of wave heights, which can be adapted to shallow underwater explosions of any specified energy, is given later in this chapter.

TABLE 5.40

MAXIMUM HEIGHTS (CREST TO TROUGH) AND ARRIVAL TIMES OF WATER WAVES AT BIKINI BAKER TEST

| Distance (yards) | 330 | 660 | 1, 330 | 2, 000 | 2, 700 | 3, 300 | 4, 000 |
|---|---|---|---|---|---|---|---|
| Wave height (feet) | 94 | 47 | 24 | 16 | 13 | 11 | 9 |
| Time (seconds) | 11 | 23 | 48 | 74 | 101 | 127 | 154 |

5.41 It appears probable that the large waves were responsible for some of the ship damage which occurred in the BAKER test. Fairly definite evidence of the destruction caused by water waves to the carrier U. S. S. Saratoga, anchored with its stern 400 yards from surface zero, was obtained from a series of photographs taken at 3-second intervals. A photograph taken before any visible shock effect had reached the Saratoga shows the island structure and the radar mast undamaged. In a photograph taken 9 seconds later, the radar mast is seen to be bent over by the blast wave, but the island structure is yet unaffected. This photograph shows the stern of the vessel rising on the first wave crest, at least 43 feet above its previous position, but shortly thereafter it was obscured from view by the base surge.

5.42 When the Saratoga was again visible, after the major waves and other effects had subsided, the central part of the island structure was observed to be folded down on the deck of the carrier (Fig. 5.42). It appears highly probable that shortly after the rise on the first wave crest, the Saratoga fell into the succeeding trough and was badly hit by the second wave crest, causing the damage to the island structure.

### CHANGE IN THE LAGOON BOTTOM

5.43 The explosion of the Bikini BAKER bomb caused a measurable increase in depth of the bottom of the lagoon over an area roughly 2,000 feet across. The greatest apparent change in depth was 32 feet, but this represents the removal of an elevated region rather than an excavation in a previously flat surface. Before the test, samples of sediment collected from the bottom of the lagoon consisted of coarse-grained algal debris mixed with less than 10 percent of sand and mud. Samples taken after the explosion were, however, quite different. Instead of algal debris, layers of mud, up to 10 feet thick, were found on the bottom near the burst point. Further information on cratering in underwater explosions is given at the end of the chapter.

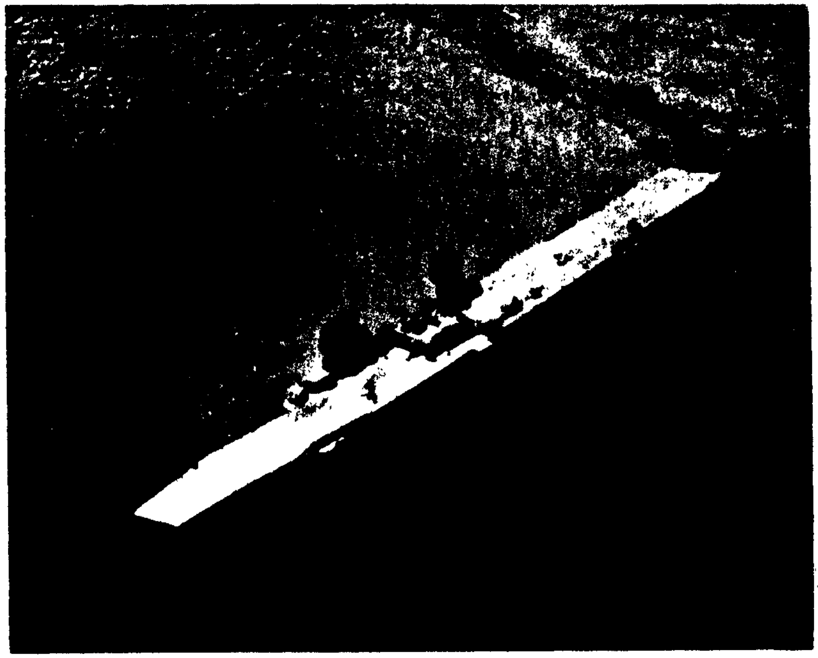

Figure 5.42. The aircraft carrier U. S. S. Saratoga after the BAKER explosion.

## TECHNICAL ASPECTS OF SURFACE AND UNDERGROUND BURSTS[1]

### CRATER DIMENSIONS IN SURFACE BURST

5.44 In addition to the rupture and plastic zones, defined earlier, two other features of a crater may be defined; these are the "apparent crater" and the "true crater." The apparent crater, which has a diameter $D_a$ and a depth $H_a$, as shown in Fig. 5.44, is the surface of the depression or hole left in the ground after the explosion. The true crater, diameter $D_t$, on the other hand, is the surface extending beyond the apparent crater where a definite shear has occurred. The volume

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[1] The remaining sections of this chapter may be omitted without loss of continuity.

of the (apparent) crater assumed to be roughly paraboloid, is given approximately by

$$\text{Volume of crater} = \frac{\pi D_a^2 H_a}{8}.$$

Using the data given in § 5.7, the crater volume for a 1-kiloton burst at at the surface in dry soil is found to be about 150,000 cubic feet, weighing close to 7,500 tons.

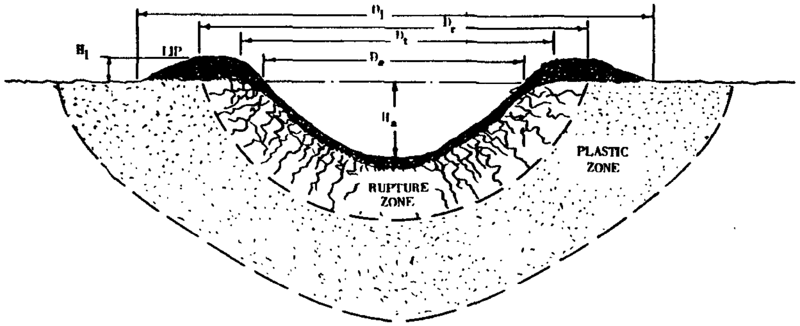

Figure 5.44. Characteristic dimensions of crater in a surface burst.

5.45 The diameter of the rupture zone, indicated by $D_r$ in Fig. 5.44, is roughly one and one-half times the crater diameter, i. e.,

$$D_r \approx 1.5\ D_a.$$

The overall diameter, including the lip, i. e., $D_l$, is about twice the crater diameter, so that

$$D_l \approx 2\ D_a,$$

and the height of the lip, $H_l$, is approximately one-fourth of the depth of the crater, i. e.,

$$H_l \approx 0.25\ H_a.$$

5.46 The (apparent) depth and diameter of the crater formed in a surface burst in dry soil of a weapon of energy yield $W$ kilotons, ranging from 1 kiloton to 20,000 kilotons (20 megatons), can be obtained from Fig. 5.46. The plots are based on the scaling laws given in § 5.8, namely, that the crater diameter scales according to $W^{1/3}$ and the depth according to $W^{1/4}$. Various soil characteristics, particularly, the moisture content, affect the dimensions of the crater. Approximate "soil factors" are therefore used to obtain the values in other soils when those in dry soil are known. These factors, together with an example of their application, are given on the page facing Fig. 5.46.

### Crater Radius in Underground Burst

5.47 The dependence of the crater radius upon the depth of burst in the case of the underground explosion of a 1-kiloton weapon in dry soil is shown by the curve in Fig. 5.47. In order to determine the crater radius for an explosion of $W$ kilotons yield at a specified depth, it is first necessary to determine the scaled depth of burst by dividing the actual depth by $W^{1/3}$. The crater radius for this depth in the case of a 1-kiloton explosion is then read from Fig. 5.47. Upon multiplying the result by $W^{1/3}$ the required crater radius is obtained. The correction factors for hard rock and saturated soil are given in connection with the example facing Fig. 5.47.

## TECHNICAL ASPECTS OF UNDERWATER EXPLOSIONS

### Shock Wave Properties

5.48 By combining a theoretical treatment with measurements made in connection with detonations of TNT charges under water, some characteristic properties of the underwater shock from a nuclear explosion have been calculated. The peak pressure, the impulse per unit area, and the energy per unit area of the shock wave at various distances from a deep underwater explosion of 1-kiloton energy, are recorded in Fig. 5.48. An explosion at a considerable depth in deep water is postulated, so as to eliminate the effects of surfaces. Consequently, the values of impulse given in Fig. 5.48 are independent of the cutoff effect. For an explosion and target near the surface, the impulse and energy would be greatly decreased.

5.49 The scaling procedures for calculating water shock wave properties for an explosion of $W$ kilotons yield are similar to those described in Chapter III for an air burst. Thus, if $D_0$ is the slant distance from a 1-kiloton explosion under water at which a certain shock pressure occurs, then for a $W$-kiloton burst the same pressure will be attained at a slant distance $D$, where

$$D = D_0 \times W^{1/3},$$

as in equation (3.86.2) for an air burst. The underwater impulse and energy scale in the same manner as impulse for an explosion in the air, as given in § 3.88. Thus,

$$I = I_0 \times W^{1/3} \text{ at a distance } D = D_0 \times W^{1/3},$$

$$E = E_0 \times W^{1/3} \text{ at a distance } D = D_0 \times W^{1/3},$$

(Text continued on page 216.)

The curves give the values of apparent crater diameter and depth as a function of weapon yield for a contact surface burst in dry soil. Average values of soil factors to be used as multipliers for estimating crater dimensions in other soil types are as follows:

| *Soil Type* | *Diameter* | *Depth* |
|---|---|---|
| Hard rock (granite or sandstone) | 0.8 | 0.8 |
| Saturated soil | 1.7 | 0.7 |

*Example*

*Given:* A 20 KT contact burst over a sandy loam soil where the water table is within a few feet of the surface.

*Find:* The crater dimensions.

*Solution:* From Figure 5.46, the crater diameter and depth in dry soil are 340 feet and 53 feet, respectively. By applying the soil factors listed above for saturated soil, the estimated (approximate) crater dimensions for a 20 KT surface burst over saturated soil are as follows:

Crater Diameter $(D_a) = 340 \times 1.7 = 580$ feet.

Crater Depth $(H_a) = 53 \times 0.7 = 37$ feet.

Diameter of Rupture Zone $= 1.5\ D_a = 1.5 \times 580 = 870$ feet.

Height of Lip $= 0.25\ H_a = 0.25 \times 37 = 9$ feet. *Answer.*

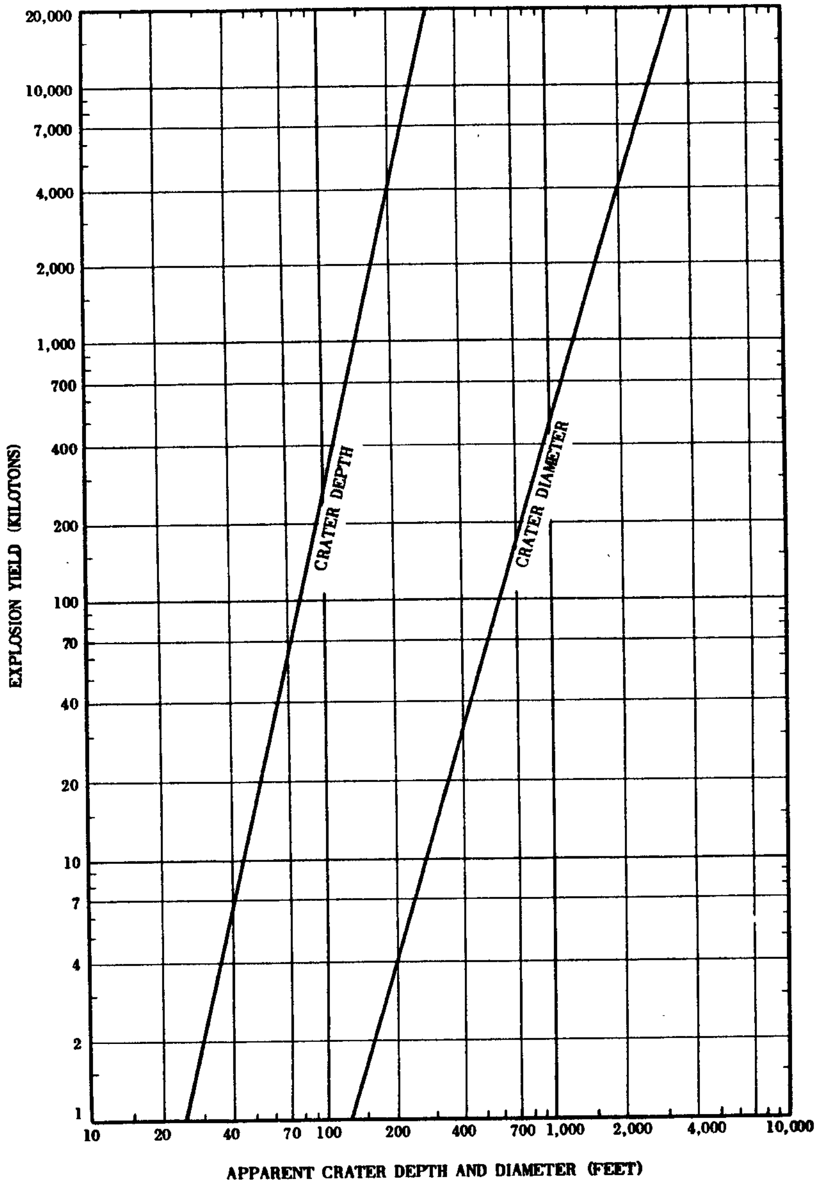

**Figure 5.46.** Apparent crater depth and diameter for a contact surface burst in dry soil.

The curve gives the estimated crater radius as a function of depth of burst for 1 KT explosions in dry soil. For other soils, multiplication factors should be used as follows:

| *Soil Type* | *Relative Crater Radius* |
|---|---|
| Hard rock (granite and sandstone) | 0.8 |
| Saturated soil | 1.7 |

*Scaling.* To determine the crater radius for a $W$ KT yield, the actual burst depth is divided by $W^{1/3}$ to obtain the scaled depth. The radius for 1 KT at this depth of burst, read from Fig. 5.47, is then multiplied by $W^{1/3}$

*Example*

*Given:* A 20 KT burst at a depth of 50 feet in saturated soil.

*Find:* The crater radius.

*Solution:* The scaled burst depth is $50/20^{1/3}=50/2.7=18$ feet. From Fig. 5.47, the crater radius for a 1 KT explosion at this depth is 88 feet. Hence, crater radius for the 20 KT burst at a depth of 50 feet in dry soil is

$$88\times 20^{1/3}=88\times 2.7=240 \text{ feet.}$$

Crater radius in saturated soil is, therefore,

$$240\times 1.7=410 \text{ feet. } \textit{Answer}$$

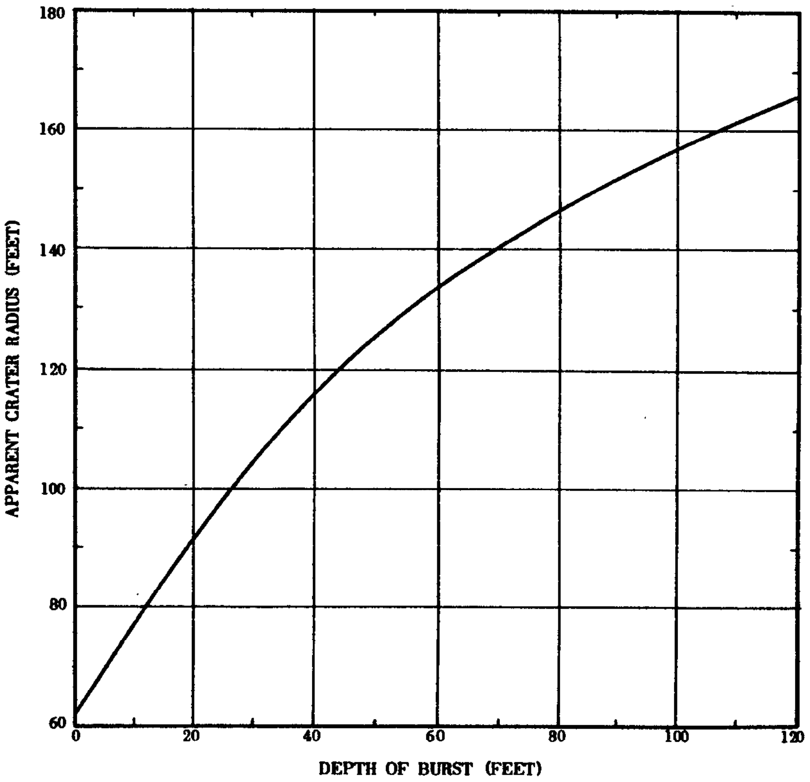

**Figure 5.47.** Relation of apparent crater radius to depth of burst for 1-kiloton explosion in dry soil.

The curves show the peak water overpressure, the energy per unit area, the impulse per unit area, and the time constant (defined in § 5.50) as functions of distance (slant range) from a 1-kiloton explosion in deep water.

*Scaling.* For yields other than 1 KT, the range to which a given pressure extends is given by

$$D = D_0 \times W^{1/3},$$

where $D_0$ is the distance from the explosion for 1 KT,
and $D$ is the distance from the explosion for $W$ KT.

For the impulse, energy, and time constant the appropriate scaling equations are as follows:

$$I = I_0 \times W^{1/3} \text{ at } D = D_0 \times W^{1/3},$$
$$E = E_0 \times W^{1/3} \text{ at } D = D_0 \times W^{1/3},$$

and

$$\theta = \theta_0 \times W^{1/3} \text{ at } D = D_0 \times W^{1/3},$$

where $I_0$, $E_0$, and $\theta_0$ are impulse, energy, and time constant for 1 KT at distance $D_0$,
and $I$, $E$, and $\theta$ are impulse, energy, and time constant for $W$ KT at distance $D$.

*Example*

*Given:* A 30 KT bomb detonated in deep water.

*Find:* The peak overpressure, impulse, energy, and time constant at a slant range of 3.1 miles.

*Solution:* The distance $D_0$ for 1 KT, corresponding to $D = 3.1$ miles for 30 KT, is $3.1/30^{1/3} = 3.1/3.1 = 1$ mile. From Figure 5.48, the peak overpressure at 1 mile from a 1 KT burst is 330 psi. By the scaling law, the same pressure occurs at a distance $1 \times 30^{1/3} = 3.1$ miles from a 30 KT explosion; hence, the required value of the peak overpressure is 330 psi. *Answer*

At 1 mile from the 1 KT explosion, the impulse, energy, and time constant from Fig. 5.48 are as follows:

Impulse = 6.5 lb-sec/in$^2$.
Energy = 12.5 lb-ft/in$^2$.
Time constant = 17.3 millisec.

Therefore, at 3.1 miles from the 30 KT burst, the corresponding values will be

Impulse $= 6.5 \times 30^{1/3} = 20.2$ lb-sec/in$^2$.
Energy $= 12.5 \times 30^{1/3} = 39$ lb-ft/in$^2$.
Time constant $= 17.5 \times 30^{1/3} = 54$ millisec. *Answer*

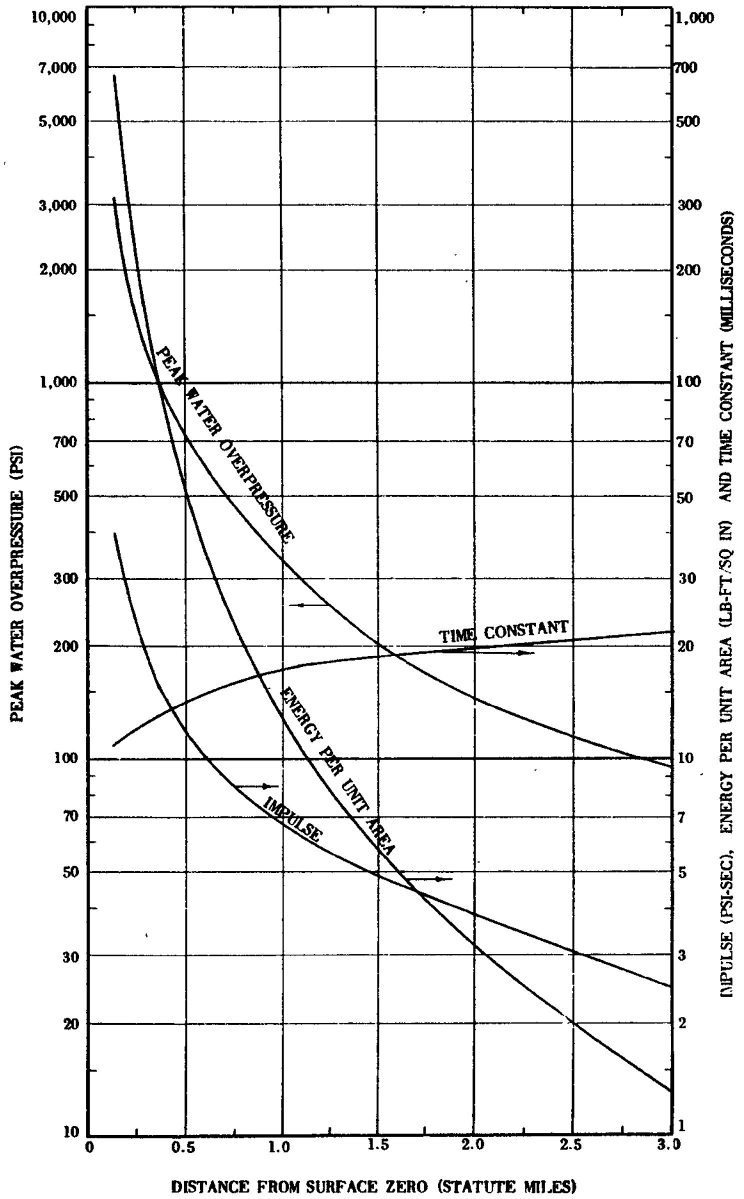

**Figure 5.48.** Water shock wave properties for a 1-kiloton explosion in deep water.

(Text continued from page 211.)

where $I$ and $E$ are the impulse and energy, respectively, at a distance $D$ from an explosion of $W$ kilotons, and $I_0$ and $E_0$ are the values at a distance $D_0$ from a 1-kiloton explosion. These scaling laws are illustrated in connection with the example based on the use of Fig. 5.48.

5.50 The rate at which the shock pressure, at a fixed distance from the explosion, falls off with time can be represented by

$$p(t) = pe^{-t/\theta}, \qquad (5.50.1)$$

where $p(t)$ is the pressure at a time $t$ after the arrival of the shock front at the point of observation, $p$ is the peak value at the time of arrival, and $\theta$ is a parameter called the "time constant." Physically, $\theta$ is the time at which the pressure has decayed to $p/e$. The time constant varies with the distance from the explosion, and some calculated values for a deep underwater explosion of 1-kiloton energy are included in Fig. 5.48. The time constant for an explosion of $W$-kilotons energy may be obtained by the scaling method given above for energy and impulse.

5.51 It is apparent from equation (5.50.1) that $\theta$ determines the rate at which the shock pressure decreases with time and, consequently, provides a relative indication of the duration of the shock wave. As $\theta$ increases with increasing distance from the explosion, the duration of the shock wave increases correspondingly.

5.52 The peak pressure and duration of the water shock wave from a burst in shallow water will be less than those given above for an explosion in deep water, because of the influence of the air and bottom boundaries. The peak water pressures versus distance from surface zero for a 1-kiloton burst at mid-depth, as derived from measurements made at the Bikini BAKER test, are shown in Fig. 5.52. The results are applicable, in general, to a burst at mid-depth in water having a scaled total depth, i. e., actual depth divided by $W^{1/3}$, of 66 feet. The distance at which a given peak pressure occurs is then obtained upon multiplying by the usual scaling factor of $W^{1/3}$.

## AIR BLAST FROM UNDERWATER EXPLOSIONS

5.53 As seen earlier, a certain amount of the shock energy accompanying a shallow underwater explosion is transmitted as a blast wave in the air. The proportion of the energy so transmitted depends upon the depth of burst, but in order to give some indication of the overpressures in the air, the data obtained at the Bikini BAKER test have been used as a basis. From these, with the aid of the familiar $W^{1/3}$ scaling law, the curve in Fig. 5.53 has been derived for a 1-kiloton underwater explosion. The overpressures obtained from this curve will be lower than observed from a surface burst, but greater than those from a deeper burst in water. As a rough approximation, this overpressure-distance curve may be used, together with the usual scaling law for blast overpressure, for any shallow burst in moderately deep water.

## WAVE HEIGHT IN UNDERWATER EXPLOSIONS

5.54 By appropriate scaling of the wave heights observed at the BAKER test (Table 5.40), the results given in Fig. 5.54 have been obtained for the approximate maximum wave heights (crest to trough) at various distances from a 1-kiloton burst under water. The results apply to an explosion of $W$-kilotons energy yield in water having a scaled depth, defined in this case as actual depth divided by $W^{1/4}$, of 85 feet. The wave height at any given distance from surface zero for a $W$-kiloton burst can be obtained upon multiplying the result for 1-kiloton yield in Fig. 5.54 by the scaling factor $W^{1/2}$. If the scaled depth of the water is less than 85 feet, the wave height decreases linearly with the actual depth. It should be noted that the data in Fig. 5.54 are for a constant depth of water and do not allow for peaking that may occur as the waves reach shallow water.

## UNDERWATER CRATER FORMATION

5.55 The dimensions of the crater formed on the bottom as the result of an underwater explosion for a range of energy yields are represented by the curves in Fig. 5.55. The values are for a burst less than 20 feet deep in 60 feet of water for a sand, sand and gravel, or soft rock bottom. The correction factors for other bottom materials are given on the page facing Fig. 5.55.

The curve shows the dependence of the peak water overpressure on the range for a 1 KT burst at mid-depth in water that is 66 feet deep.

*Scaling.* For a $W$ KT burst, the distance at which a given pressure occurs in a scaled depth of 66 ft of water is obtained by multiplying the distance for a 1 KT explosion by $W^{1/3}$.

*Example*

*Given:* A 30 KT bomb detonated at mid-depth in 200 feet of water.

*Find:* The distance at which a peak overpressure of 300 psi will occur.

*Solution:* The scaled depth corresponding to the actual depth of 200 feet is $200/30^{1/3}=200/3.1=65$ feet. This is close enough to 66 feet for Fig. 5.52 to be used.

From the curve, it is found that 300 psi occurs at 0.39 mile from a 1 KT explosion. Therefore, for a 30 KT bomb, the peak overpressure of 300 psi occurs at

$$0.39\times30^{1/3}=0.39\times3.1=1.2 \text{ miles.}$$ *Answer*

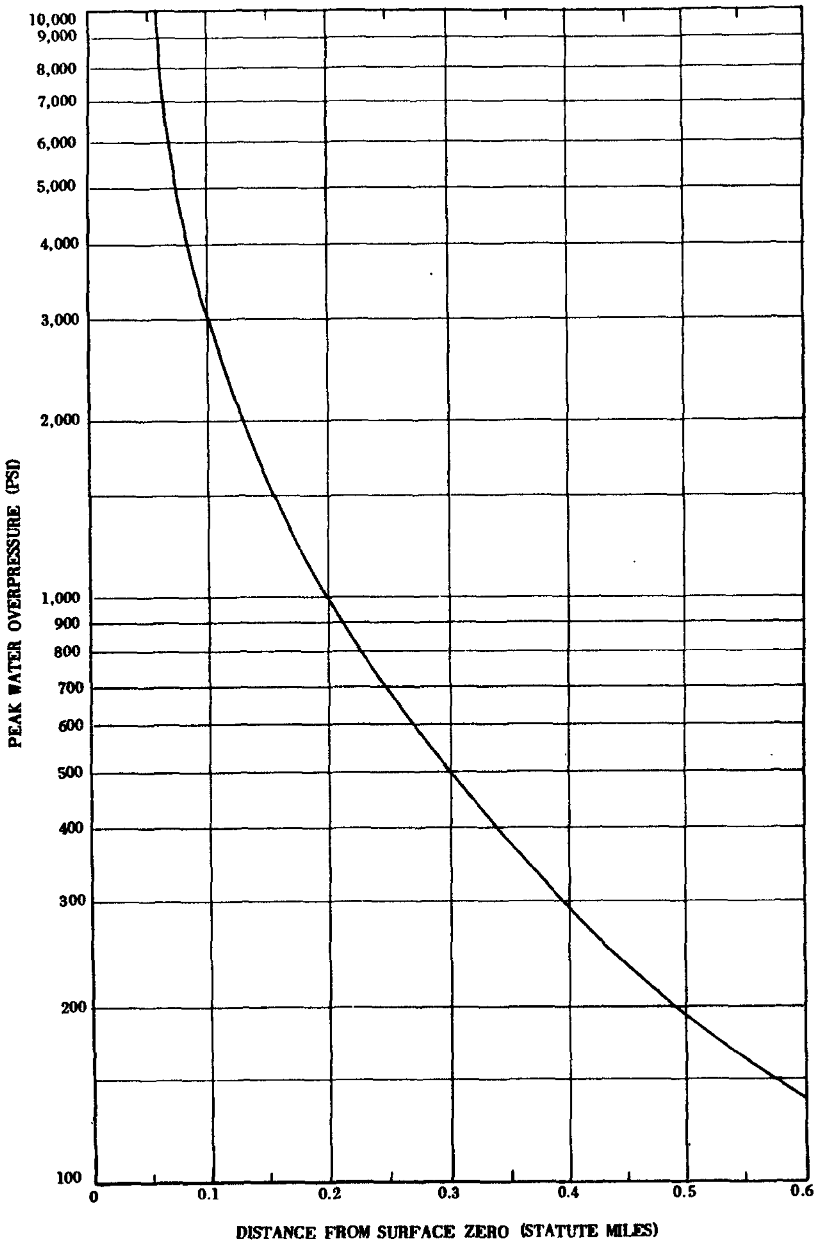

**Figure 5.52.** Peak water overpressure for a 1-kiloton explosion at mid-depth in water 66 feet deep.

The curve gives the peak air overpressure at the surface for a 1 KT explosion in shallow water as a function of the distance from surface zero.

*Scaling.* The distance at which a given peak air overpressure occurs for a $W$ KT explosion is obtained by multiplying the distance for the same overpressure in the case of a 1 KT burst by the scaling factor $W^{1/3}$.

*Example*

*Given:* A 30 KT bomb detonated in 100 feet of water.

*Find:* The distance at which the air overpressure at the surface is 5 psi.

*Solution:* From Fig. 5.53, the air overpressure of 5 psi will occur at a distance of 0.2 mile from surface zero for a 1 KT burst. Hence, the surface zero distance from a 30 KT explosion for the same overpressure is

$$0.2 \times 30^{1/3} = 0.62 \text{ mile.} \quad \textit{Answer}$$

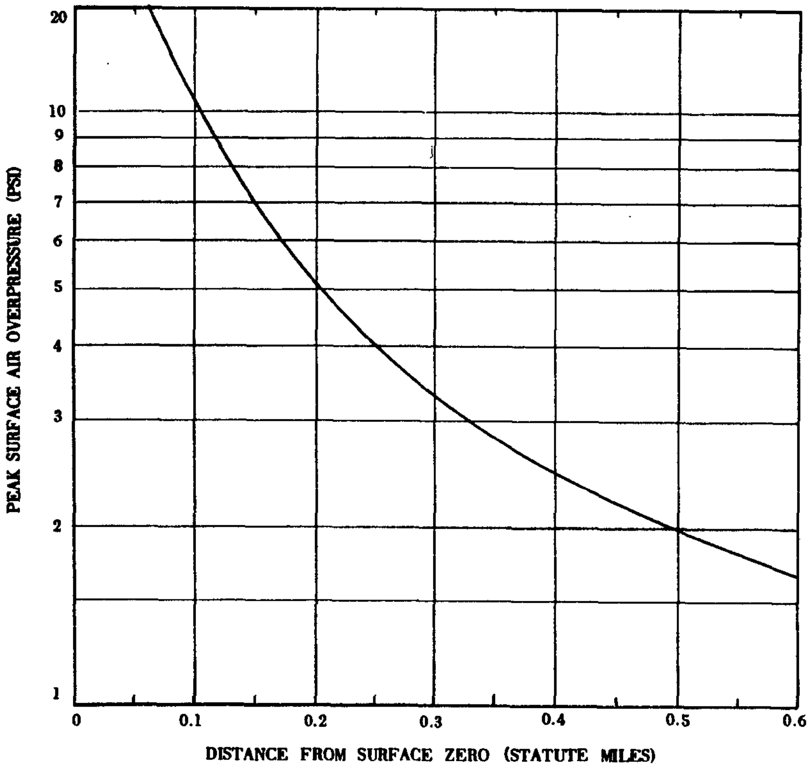

Figure 5.53. Peak air overpressure at surface for a 1-kiloton shallow underwater explosion.

The curve shows the approximate maximum crest-to-trough wave height versus horizontal distance for a 1 KT burst in water having a depth of 85 feet. (This corresponds to the scaled depth at the Bikini BAKER test.)

*Scaling.* At a given distance from surface zero, the wave height for a $W$ KT explosion is $W^{1/2}$ times the wave height at this distance in the case of a 1 KT burst in water of the same scaled depth. For water shallower than 85 $W^{1/4}$ feet, the wave height decreases linearly with the depth of the water.

*Example*

*Given:* (*a*) A 30 KT bomb detonated in 200 feet of water.
(*b*) A 30 KT bomb detonated in 100 feet of water.

*Find:* The expected maximum wave height in each case at 4 miles from surface zero.

*Solution:* (*a*) The scaled depth of the water is

$$200/30^{1/4}=200/2.34=85 \text{ feet};$$

consequently, Fig. 5.54 is applicable to this case. From the curve, the maximum wave height at 4 miles from the 1 KT explosion is 1.0 feet. Therefore, for a 30 KT bomb in 200 feet of water, the wave height at 4 miles is

$$1.0\times 30^{1/2}=1.0\times 5.5=5.5 \text{ feet, crest to trough.} \quad \textit{Answer}$$

(*b*) Since 100 feet is less than 85 $W^{1/4}$ when $W$ is 30 KT, the wave height will now be proportional to the actual depth of the water. When the depth is 200 feet, the wave height at 4 miles from the 30 KT burst is 5.5 feet; hence, for a water depth of 100 feet the wave height at the same distance is

$$5.5\times\frac{100}{200}=2.7 \text{ feet, crest to trough.} \quad \textit{Answer}$$

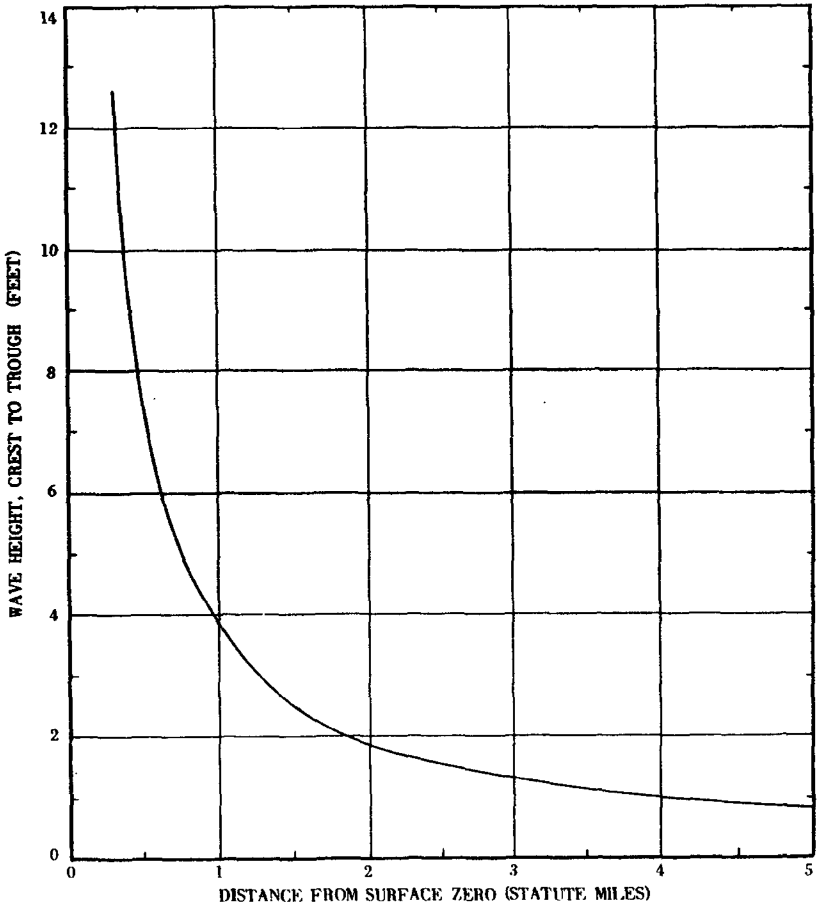

Figure 5.54. Maximum wave height (crest to trough) for a 1-kiloton explosion in water 85 feet deep.

The curves give the depth, diameter, and lip height of the underwater crater as functions of yield. The results are for a burst less than 20 feet deep in 60 feet of water for a sand, sand and gravel, or soft rock bottom.

For other bottom materials the crater dimensions can be estimated by multiplying the values from Fig. 5.55 by the following factors:

| *Material* | *Diameter* | *Depth* | *Lip Height* |
|---|---|---|---|
| Loess | 1.0 | 1.7 | 0.7 |
| Clay | 1.0 | 2.3 | 2.3 |
| Hard Rock | 0.7 | 0.5 | 0.4 |
| Mud or Muck | 0.7 | 0.4 | 0.2 |

*Example*

*Given:* A 200 KT bomb detonated just below the surface of 60 feet of water; the bottom is predominantly clay.

*Find:* The crater dimensions.

*Solution:* The dimensions from Fig. 5.55 for this burst are

Diameter = 1,100 feet
Depth = 37 feet
Lip Height = 3.3 feet.

The dimensions for a clay bottom are then

Diameter = 1,100 × 1.0 = 1,100 feet
Depth = 37 × 2.3 = 85 feet
Lip Height = 3.3 × 2.3 = 7.6 feet. *Answer*

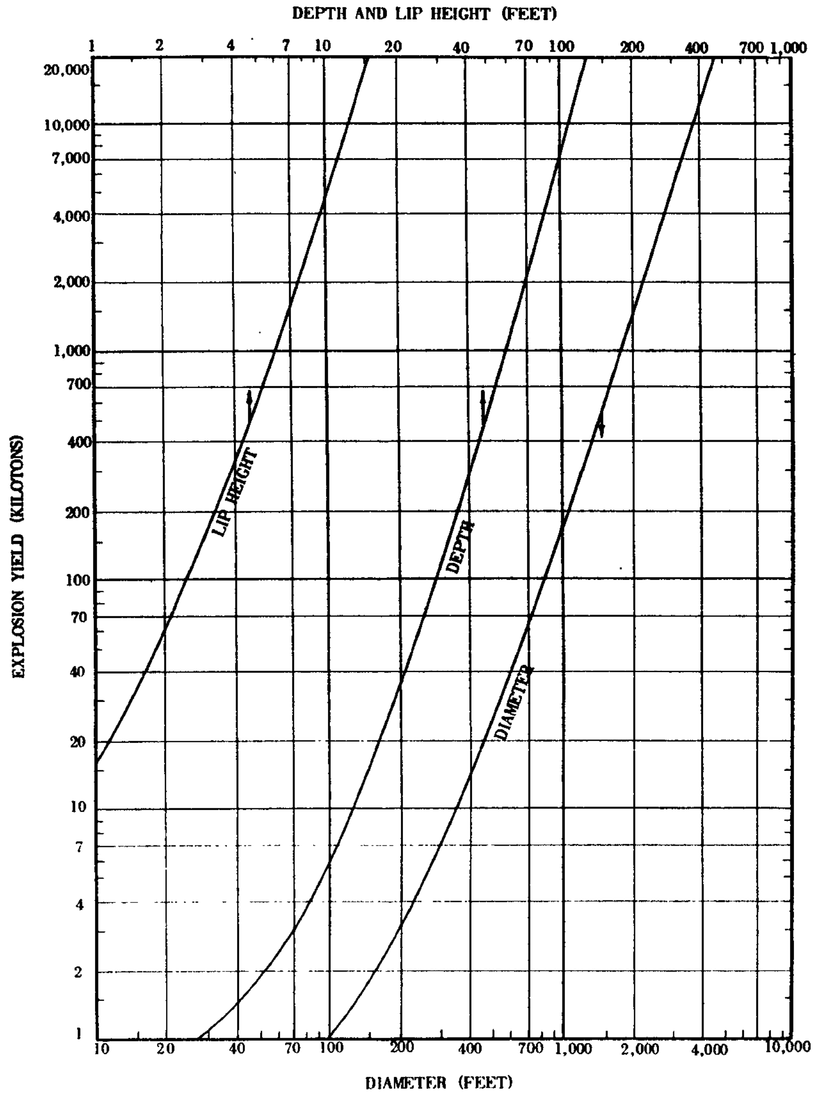

Figure 5.55. Dimensions of crater from underwater burst.

*CHAPTER VI*

# DAMAGE FROM AIR BLAST, UNDERGROUND SHOCK, AND UNDERWATER SHOCK

## INTRODUCTION

6.1 In the three preceding chapters the basic phenomena of air blast and ground and water shock have been presented, with a general description of the damage produced by these effects of nuclear explosions on various targets. The purpose of this chapter is to present an overall discussion of damage criteria and to consider damage-distance relationships, as functions of the energy yield of the explosion, for a number of specific structural types. In addition, a method is outlined for making a detailed analysis of the factors which determine the damage suffered by particular structures exposed to the action of air blast.

6.2 The general conclusions concerning the expected effects of nuclear explosions on various structures are summarized in the form of three charts (Figs. 6.41a, b, and c). These are based on a combination of theoretical analysis with data obtained from actual nuclear explosions, both in Japan and at various tests, as well as from laboratory studies. However, the nature of any target complex, especially a city, is such that no exact prediction of the effect of blast on structures can be made. Nor is it possible to indicate the reliability of the prediction for any particular situation. Nevertheless, by the application of proper judgment to the available information, it is believed that results of practical value can be obtained. The conclusions to be presented here are considered to be the most representative for the average situation that might be encountered in actual target complexes.

## DAMAGE FROM AIR BLAST

### Damage Classification

6.3 In describing or classifying the damage to a city complex, the Federal Civil Defense Administration (FCDA) uses a system based on four zones. In the A-zone, all buildings are almost completely destroyed by the blast; in the B-zone, most buildings are damaged beyond repair; in the C-zone, moderately damaged buildings must be vacated during repairs; and in the D-zone, partially damaged buildings need not be vacated during repairs. This system classifies damage to average buildings in a city, and is of particular value for gross planning purposes. Since it refers to average conditions, it is not recommended for describing damage suffered by a structure which may be stronger or weaker than the average. Further, certain targets, such as aircraft and ships, do not fit the concept of zones as established for a city complex.

6.4 In order to describe damage to particular targets, the average zone system of the FCDA has been modified. Because of the variation in the blast response, even among related structures, the A-zone for one building will not necessarily be the same as the A-zone for another, and similarly for the other zones. Hence, instead of being used to describe average damage zones, the letters A, B, C, and D will here refer to degrees of damage to a particular structure or object. The definitions are then as follows:

A: The structure is virtually completely destroyed.

B: The damage is so severe that complete reconstruction is required prior to re-use.

C: The structural damage is such that major repairs are required before the object (or structure) can be used for its intended purpose.

D: The object (or structure) receives light damage, so that only minor makeshift repairs (or no repairs at all) are required to maintain its usefulness.

A more detailed description of the application of this classification to specific targets will be given below. Charts for estimating the class of damage that might be expected for various structures at specified distances from explosions of prescribed energy yield will be presented later.

## DAMAGE TO ABOVE GROUND STRUCTURES

6.5 The nature of the damage in the B, C, and D classes to various structures are given in Tables 6.5a and b. Since A damage represents virtually complete destruction, it has not been included. For convenience, the structures in the first table are those damaged by forces acting primarily during the diffraction process; these forces are closely related to the reflected overpressure. The second table is concerned with buildings which are affected mainly by drag (dynamic pressure) forces. It will be noted that there is no mention in the tables of high buildings, such as are common in many large cities in the United States. This is because information concerning such buildings is lacking. There were no structures of this type in Hiroshima and Nagasaki, and there have been none exposed at the nuclear test explosions.

### TABLE 6.5a

### STRUCTURAL TYPES PRIMARILY AFFECTED BY BLAST WAVE DURING THE DIFFRACTION PROCESS

| Description of structure | Description of damage | | |
|---|---|---|---|
| | B | C | D |
| Multistory reinforced-concrete building,* with reinforced-concrete walls, blast resistant design, no windows, three stories. | Walls shattered, structure frame severely distorted, first floor columns collapse or near collapse. | Walls cracked, building slightly distorted, entranceways damaged, doors blown in or jammed: some spalling of concrete (Fig. 4.82a). | Designed to prevent light damage. |
| Multistory, reinforced-concrete building, with concrete walls, small window area, five stories. | Walls shattered, severe frame distortion, incipient collapse of first floor columns. | Exterior walls badly cracked, interior partitions badly cracked or blown down, structure frame permanently distorted; spalling of concrete. | Windows and doors blown in, interior partitions cracked. |
| *Multistory*, wall-bearing building, brick apartment house type, up to three stories. | Bearing walls collapse resulting in total collapse of structure (Fig. 4.89a). | Exterior walls badly cracked, interior partitions badly cracked or blown down. | Windows and doors blown in, interior partitions cracked. |
| Multistory, wall-bearing building, massive type, four stories. Large structure (over 200 ft x 200 ft plan dimensions). In this case the side facing the blast may be severely damaged while the interior remains relatively undamaged. | Bearing walls collapse resulting in collapse of structure supported by these walls. Some bearing walls may be shielded enough by intervening walls so that part of structure may receive only moderate damage (Fig. 4.89b). | Exterior walls facing blast badly cracked, interior partitions badly cracked, although toward far end of building damage may be reduced. | Windows and doors blown in, interior partitions cracked. |
| Wood-frame building, house type, one or two stories. | Frame shattered so that structure is for the most part collapsed (Fig. 4.14). | Wall framing cracked, roof badly damaged, interior partitions blown down (Fig. 4.8). | Windows and doors blown in, interior partitions cracked (Fig. 4.16). |
| Oil tanks, 30,000 to 100,000 bbl, *cone roof*; tanks considered full (more vulnerable if empty). Floating roof tanks are less vulnerable. | Large distortions of sides, *seams split, so* that most of contents are lost (Fig. 4.74a). | Roof collapsed, sides above liquid buckled, some distortion below liquid level. | Roof badly damaged (Fig. 4.74b). |

*Designed to withstand 20 psi overpressure in the Mach region from a 20-kiloton weapon without any impairment of facilities.

### TABLE 6.5b

### STRUCTURAL TYPES PRIMARILY AFFECTED BY DRAG LOADING

| Description of structure | Description of damage | | |
|---|---|---|---|
| | B | C | D |
| Light steel-frame industrial building, single story with up to 5 ton crane capacity. Light weight, low strength walls fail quickly. | Severe frame distortion (half column height deflection), (Fig. 4.55a and b). | Some distortion of frame; cranes (if any) cannot operate until repairs made (Fig. 4.62b). | Windows and doors blown in, light siding ripped off or buckled. |
| Medium steel-frame industrial building, single story with a 20-ton capacity crane. Light weight, low strength walls fail quickly. | Severe frame distortion (half column height deflection). | Some distortion of frame; cranes (if any) cannot operate until repairs made. | Windows and doors blown in, light siding ripped off or buckled. |
| Heavy steel-frame industrial building, single story with 50 ton crane capacity. Light weight, low strength walls fail quickly. | Severe frame distortion (half column height deflection). | Some distortion of frame; cranes (if any) cannot operate until repairs made. | Windows and doors blown in, light siding ripped off or buckled. |
| Multistory, steel-frame office type building, five stories. Light weight, low strength walls fail quickly. | Severe frame distortion. Incipient collapse of lower floor columns. | Frame distorted moderately. Interior partitions blown down. | Windows and doors blown in, light siding ripped off, interior partitions cracked or buckled. |
| Multistory, reinforced-concrete frame office-type building, five stories. Light weight, low strength walls fail quickly. | Severe frame distortion. Incipient collapse of lower floor columns (Fig. 4.82b). | Frame distorted moderately. Interior partitions blown down; some spalling of concrete (Fig. 4.85b). | Windows and doors blown in, light siding ripped off, interior partitions cracked or buckled. |
| Highway and railroad truss bridges. | Total failure of lateral bracing, collapse of bridge. | Some failure of lateral bracing such that bridge capacity is reduced about 50 percent. | Capacity of bridge unchanged. Barely noticeable distortion of lateral bracing. |

6.6 For certain structural elements, with short periods of vibration (up to about 0.05 second) and small plastic deformation at failure, the conditions for failure can be expressed as a peak overpressure without consideration for the duration of the blast wave. The failure conditions for elements of this type are given in Table 6.6. Some of these elements fail in a brittle fashion, and thus there is only a small difference between the pressures that cause no damage and those that produce complete failure. Other elements may fail in a moderately ductile manner, but still with little difference between the pressures for light damage and complete failure. The pressures are incident blast overpressures for panels that face ground zero. For panels that are oriented so that there are no reflected pressures thereon, the incident pressures must be doubled.

TABLE 6.6

CONDITIONS OF FAILURE OF PEAK OVERPRESSURE-SENSITIVE ELEMENTS

| Structural Element | Failure | Approximate Incident Blast Overpressure (psi) |
|---|---|---|
| Glass windows, large and small. | Shattering usually, occasional frame failure. | 0. 5–1. 0 |
| Corrugated asbestos siding. | Shattering. | 1. 0–2. 0 |
| Corrugated steel or aluminum paneling. | Connection failure followed by buckling. | 1. 0–2. 0 |
| Brick wall panel, 8″ or 12″ thick (not reinforced). | Shearing and flexure failures. | 7. 0–8. 0 |
| Wood siding panels, standard house construction. | Usually failure occurs at the main connections allowing a whole panel to be blown in. | 1. 0–2. 0 |
| Concrete or cinder-block wall panels, 8″ or 12″ thick (not reinforced). | Shattering of the wall. | 2. 0–3. 0 |

## DAMAGE TO LIGHT-WEIGHT EARTH COVERED AND BURIED STRUCTURES

6.7 Air blast is the controlling factor for damage to light-weight earth covered structures and shallow buried underground structures. The earth cover provides surface structures with substantial protection against air blast and also some protection against missiles. The depth of earth cover above the structure would usually be determined by the degree of protection from nuclear radiation required at the design overpressure or dynamic pressure (see Chapter VIII).

6.8 The usual method of providing earth cover for surface or "cut-and-cover" structures is to build an earth mound over the portion of the structure that is above the normal ground level. The earth mound reduces the blast reflection factor (see Fig. 6.82a) and improves the aerodynamic shape of the structure. This results in a considerable reduction in the applied translational forces. An additional benefit of the earth cover is the stiffening or resistance to motion that the earth provides to flexible structures by the buttressing action of the soil.

6.9 Light-weight, shallow buried underground structures are those constructed deep enough for the top of the earth cover to be flush with the original grade. However, they are not sufficiently deep for the ratio of span to depth of burial to be large enough for any benefit to be derived from soil arching (see § 6.11). For depths of cover up to about 10 feet in most soils, there is little attenuation of the air blast pressure applied to the top surface of a shallow buried underground structure. The results of full scale nuclear tests in Nevada indicate that there is apparently no increase in pressure exerted on the structure due to ground shock reflection at the interface between the earth and the top of the structure.

6.10 The lateral pressures exerted on the vertical faces of a buried structure have been found to be as low as 15 percent of the pressure on the roof in dry, well-compacted, silty soils. For most soils, however, this lateral pressure is likely to be somewhat higher and may approach 100 percent of the roof pressure in porous saturated soil. The pressures on the bottom of a buried structure, in which the bottom slab is a structural unit integral with the walls, may range from 75 to 100 percent of the pressure exerted on the roof.

6.11 Underground structures, buried at such a depth that the ratio of the burial depth to the span approaches (or exceeds) unity, will obtain some benefit from the arching effect of the soil surrounding the structure. Limited experience at the Nevada Test Site has indicated that the arching action of the soil effectively reduces the loading on flexible structures, although the exact extent is at present uncertain.

6.12 The damage that might be suffered by a shallow buried structure will depend on a number of variables, including the structural characteristics, the nature of the soil, the depth of burial, and the downward pressure, i. e., the peak overpressure of the air blast wave. In Table 6.12 are given the limiting values of the peak overpressure required to cause various degrees of damage to two types of earth-covered structures. The range of pressures is intended to allow for differences in structural design, soil conditions, shape of earth mound, and orientation with respect to the incident blast wave. The damage-distance relationships for these structural types are summarized in Fig. 6.41a.

TABLE 6.12

DAMAGE CRITERIA FOR SHALLOW BURIED OR EARTH COVERED SURFACE STRUCTURES

| Type of structure | Damage class | Peak overpressure (psi) | Nature of damage |
|---|---|---|---|
| Light, corrugated steel arch, surface structure (10-gage corrugated steel with a span of 20 to 25 feet) with 3 feet of earth cover over the crown. | A | 35–40 | Complete collapse. |
| | B | 30–35 | Collapse of portion of arch facing blast. |
| | C | 20–25 | Deformation of end walls and arch, possible entrance door damage. |
| | D | 10–15 | Possible damage to ventilation system and entrance door. |
| Light, reinforced-concrete surface or underground shelter with 3 feet minimum earth cover. (Panels 2 to 3 inches thick, with beams spaced on 4-foot centers.) | A | 30–35 | Collapse. |
| | B | 25–30 | Partial collapse. |
| | C | 15–25 | Deformation, severe cracking and spalling of panels. |
| | D | 10–15 | Cracking of panels, possible entrance door damage. |

6.13 An illustration of B-type damage to a 10-gage corrugated steel-arch, earth-covered, surface structure is shown in Fig. 6.13. It will be noted that about half of the arch has collapsed. This failure was attributed primarily to the dynamic pressure acting on the forward slope of the earth mound.

6.14 The peak overpressure for the complete collapse of the corrugated steel-arch structure, with 3 feet of earth cover, is given in Table 6.12 as 35 to 40 pounds per square inch. However, it has been estimated that if this structure had been completely buried, so that no earth mound was required, an overpressure of 40 to 50 pounds per square inch would have been necessary to cause it to collapse. This increase in the required overpressure is due to the fact that the dynamic pressure is minimized under these conditions. It may be mentioned that, using standard engineering techniques, it is possible to design underground structures which will withstand blast overpressures in excess of 100 pounds per square inch at the surface (see Chapter XII).

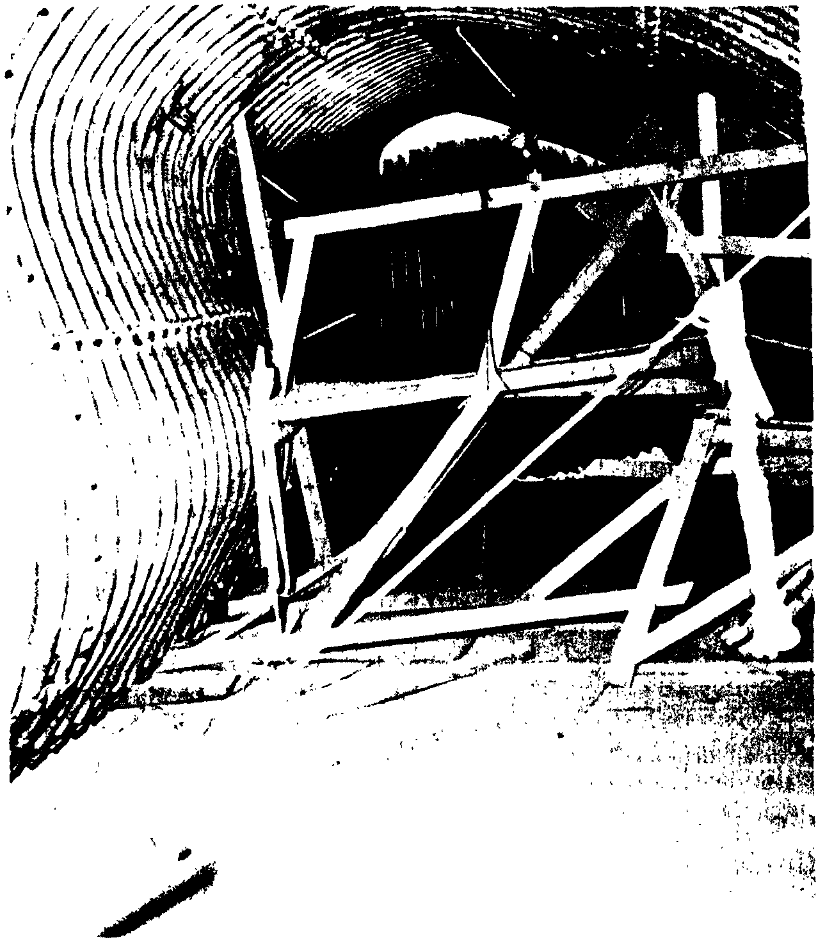

Figure 6.13. B-type damage to earth-covered 10-gage corrugated steel structure.

## DAMAGE TO LAND TRANSPORTATION EQUIPMENT

6.15 The general types of land transportation equipment considered here include civilian motor-driven vehicles (cars, trucks) and earth-moving equipment (bulldozers, graders, scrapers), and railroad rolling stock (locomotives and box, tank, and gondola cars). These items are primarily drag sensitive, i. e., they respond chiefly to the dynamic pressure, rather than to the air blast overpressure. The descriptions of the various degrees of damage are given in Table 6.15. The corresponding ranges as a function of explosion yield are included in a chart (see Fig. 6.41c). For civilian motor equipment, the ranges apply, specifically, to heavy trucks. For passenger cars and light trucks, the respective distances would be somewhat greater, whereas for heavy earthmoving and construction equipment, they would be less than those derived from the chart.

Table 6.15

DAMAGE CRITERIA FOR LAND TRANSPORTATION EQUIPMENT

| Description of equipment | Damage class | Nature of damage |
|---|---|---|
| Civilian motor equipment (cars, trucks, bulldozers, and graders). | A | Completely demolished and parts scattered. |
| | B | Large displacements, outside appurtenances (doors and hoods) torn off, need rebuilding before use. |
| | C | Turned over and displaced, badly dented, frames sprung, need major repairs. |
| | D | Glass broken, dents in body, possibly turned over, immediately usable. |
| Railroad rolling stock (box, tank, and gondola cars). | A | Completely demolished and parts scattered. |
| | B | Car blown from tracks and badly smashed, some parts usable. |
| | C | Doors demolished, body damaged, could roll to repair shop (Fig. 4.97a). |
| | D | Some door and body damage, car can continue in use. |
| Railroad locomotives (Diesel or steam). | A | Twisted and generally demolished. |
| | B | Overturned, parts blown off, sprung and twisted so that major overhaul required. |
| | C | Probably overturned, can be towed to repair shop after being righted and need major repairs. |
| | D | Glass breakage and minor damage to parts, immediately usable. |

## Damage to Parked Transport Aircraft

6.16 Aircraft are relatively vulnerable to air blast effects and, as stated in Chapter IV, the peak overpressure is the significant parameter for estimating damage. The forces developed by overpressures of 1 to 2 pounds per square inch are sufficient to dish in panels and buckle stiffeners and stringers. At higher overpressures, the material (or wind) velocity behind the shock front develops drag forces which tend to rotate, translate, overturn, or lift a parked aircraft, so that damage may then result from collision with other aircraft, structures, or the ground. Aircraft are also very susceptible to damage from flying debris carried by the blast wave.

6.17 Several factors influence the degree of damage that may be expected for an aircraft of a given type at a specified range from a nuclear detonation. Aircraft that are parked with the nose pointed toward the burst will suffer less damage than those with the tail or either side directed toward the oncoming blast wave. Shielding of one aircraft by another or by structures or terrain features may reduce damage, especially that caused by flying missiles. Standard tiedown of aircraft, as used when high winds are expected, will also minimize the extent of damage at ranges where destruction might otherwise occur.

6.18 The various damage categories of aircraft are outlined in Table 6.18, together with the approximate overpressures at which they

Table 6.18

DAMAGE CRITERIA FOR PARKED AIRCRAFT

| Damage class | Nature of damage | Overpressure (psi) |
|---|---|---|
| A | Complete destruction. | 6 |
| B | Damage beyond economical repair. | 4 |
| C | Major shop repair required prior to flight (Figs. 4.100a and b). | 3 |
| D | Minor or no repair or replacement required prior to flight. | 1 |

may be expected. The corresponding damage ranges, as related to the energy yield of the nuclear explosion, are given later (see Fig. 6.41a). They are applicable to transport aircraft, of the type utilized by commercial air carriers, parked in the open at random orientation with respect to the point of burst. It should be noted that these ranges are based on tests in which military aircraft were exposed to detonations having yields in the kiloton energy range. For megaton yield detonations the longer duration of the blast exposure may influence the results. However, as no data are available to define this effect, no attempt has been made to adjust the damage ranges.

6.19 Aircraft with fabric-covered control surfaces or other exposed ignitable materials may, under certain conditions, be damaged by thermal radiation at distances beyond those at which equivalent damage would result from blast effects (see Fig. 6.41c). The vulnerability to thermal radiation may be decreased by protecting ignitable materials from exposure to direct radiation or by painting them with protective (light colored) coatings which reflect, rather than absorb, most of the thermal radiation (see Chapter VII).

## DAMAGE TO SHIPPING

6.20 Damage to ships from an air or surface burst will be due primarily to the air blast, since little pressure is transmitted through the water. For this reason, the exposed portion of the ship above water, will suffer the greatest. A brief description of the observations made at the Bikini ABLE test was given in Chapter IV, and the general conclusion may be summarized here. Masts, spars, radar antennae, stacks, electrical equipment, and other light objects are especially sensitive to air blast. Ship machinery would probably remain intact at the range within which the ship survives. Boilers and uptakes are the principal exceptions, and blast damage to these components will account for many cases of immobilization.

6.21 The degrees of damage to merchant type vessels are described in Table 6.21. The A and B classifications are combined because it is difficult to make a reasonably clear distinction between them. The damage-distance relationships for various types of damage are included in Fig. 6.41a. Illustrations of the destruction caused to ships by air blast from a nuclear explosion were given in Chapter IV.

TABLE 6.21

DAMAGE CRITERIA FOR SHIPPING FROM AIR BLAST

| Damage class | Nature of damage |
|---|---|
| A and B | Severe damage, with probable sinking.<br>(The ship is sunk or is damaged to the extent of requiring rebuilding.) |
| C | Moderate damage, with immobilization.<br>(The ship requires extensive repairs, especially to shock-sensitive components or their foundations, e. g., propulsive machinery, boilers, and interior equipment.) |
| D | Light damage.<br>(The ship may still be able to operate, although there will be damage to electronic, electrical, and mechanical equipment.) |

## DAMAGE TO UTILITIES

6.22 The treatment given here applies to damage caused to utility power lines, telephone and telegraph lines above the surface, and transmitting towers. Buried utility pipes will be considered later (§ 6.31). Damage to structures, such as power stations, pumping stations, and storage tanks may be inferred from the information given earlier in the section on above-ground structures (§ 6.5, *et seq.*). Essentially, power lines are damaged if some (or all) of the poles are blown down, but they are otherwise undamaged. Lines radial to the direction of propagation of the blast wave are less susceptible to damage than those running in a transverse direction. The results may be interpolated to give the damage-distance relationships for lines of intermediate orientations. For utility lines, A damage signifies that most of the poles will be blown down and wires broken (see Fig. 4.111). There is, however, essentially no B, C or D damage, since outside the A zone, the damage may be expected to be light and easily repaired.

6.23 For radio and television transmitting towers, about 200 to 500 feet in height, the various types of damage are as described in Table 6.23. The corresponding ranges as a function of energy yield of the explosion are given in Fig. 6.41c.

TABLE 6.23

DAMAGE CRITERIA FOR TRANSMITTING TOWERS

| Damage class | Nature of damage |
|---|---|
| A and B | Towers demolished or flat on the ground (Fig. 4.109a). |
| C | Towers partially buckled, but held by guy lines; ineffective for transmission. |
| D | Guy lines somewhat slack, but tower able to transmit (Fig. 4.109b). |

## DAMAGE TO FORESTS

6.24 In considering damage to forests, the discussion will refer more specifically to naturally occurring broadleaf and coniferous stands averaging about 175 trees per acre. Because trees are primarily sensitive to drag forces, the zone in which the damage decreases from class A to class D is relatively narrow. In particular, the transition from A to B is difficult to delineate, and so these two types of damage are taken together. The different classifications are described in Table 6.24. Since the effect of air blast on forests is similar to that of strong

Figure 6.24a. Forest stand after a nuclear explosion, B damage (3.8 psi overpressure).

Figure 6.24b. Forest stand after a nuclear explosion, C damage (2.4 psi overpressure).

TABLE 6.24

DAMAGE CRITERIA FOR FORESTS

| Damage class | Nature of damage | Equivalent hurricane wind velocity (miles per hour) |
|---|---|---|
| A & B | Up to 90 percent of trees blown down; remainder denuded of branches and leaves (Fig. 6.24a). (Area impassable to vehicles and very difficult on foot.) | 130–140 |
| C | About 30 percent of trees blown down; remainder have some branches and leaves blown off (Fig. 6.24b). (Area passable to vehicles only after extensive clearing.) | 90–100 |
| D | Very few trees blown down; some leaves and branches blown off. (Area passable to vehicles.) | 60–80 |

winds, the velocities of steady winds which would produce comparable damage are included in the table.

6.25 The damage-distance relationship for average forest stands are given in Fig. 6.41c. The distances for broadleaf stands are somewhat greater than the average, whereas those for coniferous stands are slightly less.

## DAMAGE FROM GROUND AND WATER SHOCK

### UNDERGROUND STRUCTURES

6.26 An underground structure can be designed so as to be practically immune to air blast (§6.14), but such structures can be damaged or destroyed by cratering or by ground shock due to a near surface, true surface, or underground burst. The average density of an underground structure will usually be less than that of the displaced soil. In addition, it is known that the pressure pulse in the soil from a contact surface burst or an underground burst is relatively long compared to the dimensions of the structure, and the pressure at the shock front does not increase abruptly.

6.27 On the basis of these facts, it is to be expected that underground structures of relatively small size will "roll with the blow." This expectation has been borne out by actual experience. The movement of the structure is intimately connected with the movement of the soil as the shock wave passes. In other words, if the particle acceleration in the soil has certain peak horizontal and vertical components, then the small underground structure may be expected to have almost the same peak acceleration components.

6.28 As stated in § 5.18, *et seq.*, the criteria for damage caused by cratering and ground shock may be described in terms of three regions, namely (1) the crater itself; (2) the region extending roughly out to the limit of the plastic zone, i. e., to approximately two and one-half times the crater radius; and (3) the zone in which transient earth movements occur without permanent measurable deformation, there being no appreciable ground shock damage in this region.

6.29 The shock parameter mainly responsible for damage has not been defined either theoretically or empirically. However, there is considerable evidence that the degrees of damage can be related, without serious error, to the crater radius. Some examples of this type of relationship are given in Table 6.29. There are certain minor variations in the distances due to the factors referred to in § 5.18, as well as

to the characteristics of the soil or rock in which the structure is buried. It will be seen that, as is to be anticipated, there is no appreciable damage from ground shock beyond the plastic zone, i. e., farther than about two and one-half crater radii from surface zero.

TABLE 6.29

GROUND SHOCK DAMAGE CRITERIA FOR MODERATELY DEEP UNDERGROUND STRUCTURES

| Type of structure | Damage class | Distance from surface zero | Nature of damage |
|---|---|---|---|
| Relatively small, heavy, blast-resistant design (shelters). | A & B | 1¼ crater radii. | Collapse or severe displacement. |
| | C | 1¼ to 2 crater radii. | Shock damage to interior equipment. |
| | D | 2 to 2½ crater radii. | Severance of brittle connections, slight cracking at structural discontinuities. |
| Relatively long, flexible (pipelines). | A | 1½ crater radii. | Deformation and rupture. |
| | B | 1½ to 2 crater radii. | Slight deformation with some rupture. |
| | C | 2 to 3 crater radii. | Failure of connections. |

6.30 A heavy, reinforced-concrete underground shelter is an example of the first type of structure referred to in Table 6.29. This may be expected to survive just beyond the crater region. But, attention should be called to the fact that the structure would be covered with the highly radioactive earth (see § 9.58) of the crater lip out to the limit of class C damage.

6.31 Buried utility pipes would be representative of the long, flexible structure in Table 6.29. The damage in zones A and B is primarily a result of permanent displacement of the soil, and in zone C it is due to permanent or transient strains. The actual distance to which type C damage will extend is dependent upon the orientation of the pipeline with respect to the explosion center. It is expected that a radial orientation will result in greater damage than a transverse orientation at a given range. Failure is most likely to occur at structural discontinuities, such as at lateral connections and entrances to buildings. This will particularly be the case if brittle materials are involved.

6.32 Although tunnels and subways would be destroyed within the crater region and would suffer damage outside this area, these structures, especially when bored through solid rock and lined to minimize spalling, are very resistant to ground shock. The rock, being an elastic medium, will transmit the pressure (compression) wave very well, and when this wave strikes the wall of the tunnel, a tensile (negative pressure) wave is reflected from the rock-air interface.[1]

6.33 Under certain circumstances, failure of the rock at the tunnel wall will result in spalling when the reflected tensile stress exceeds the tensile strength of the rock. The thickness of spalling is dependent upon the magnitude, duration, and shape of the pressure wave, upon the size and shape of the tunnel, and upon the physical properties of the rock.

6.34 When structures are partly above and partly below ground, the damage to the underground portion will be very much as indicated in Table 6.29, if the walls are sufficiently strong. However, as a general rule, for surface and subsurface bursts, destruction due to air blast will extend well beyond the plastic zone, the third region referred to above. The over-all damage is then determined by the air blast, and is in accordance with the discussion in the earlier parts of this chapter.

### Damage to Ships From Underwater Shock

6.35 A description of the interaction of underwater shock with ships, based on experience at the Bikini BAKER tests, was given in Chapter V. For most cases of underwater explosions, the water shock will be the important factor in determining damage. Exceptions to this rule may occur if the underwater burst is very near the surface or a weapon of very high yield is detonated in shallow water. In these cases, the air blast would be more significant than water shock.

6.36 The various types of damage to ships from underwater shock are defined in the same manner as for air blast. Thus, the general descriptions in Table 6.21 are applicable, irrespective of whether water shock or air blast is the main cause of damage. The relationships between various degrees of damage to merchant-type ships and distance from an underwater harbor burst, as a function of the energy yield, are given in Fig. 6.41c.

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[1] The formation of a negative pressure wave upon reflection of a compression wave at the surface of a less dense medium (air) is discussed more fully in the treatment of shock waves in water (§ 5.23).

### Damage to Hydraulic Structures

6.37 As is the case with air blast, it is to be expected that the damage to an underwater structure resulting from water shock will depend upon the dimensions of the structure and certain characteristic times. The particular times which appear to be significant are, on the one hand, the time constant of the shock wave (§ 5.50) and, on the other hand, the natural response (or plastic) time and the diffraction time of the structure, i. e., the time required for the diffracted pressure (shock) wave to be propagated distances of the order of magnitude of the dimensions of the structure. In the event that the underwater structure is near the surface, the cutoff time (§ 5.26) would be significant in certain cases.

6.38 If the time constant of the pressure wave is large compared to the times which are characteristic of the structure, that is to say, if the water shock wave is one of relatively long duration, the effect of the shock is similar to that of an applied steady (or static) pressure. In these circumstances, the peak pressure is the appropriate criterion of damage. Such would be the case for small, rigid underwater structures, since they can be expected to have short characteristic times.

6.39 For large, rigid underwater structures, where the duration of the shock wave is short in comparison with the characteristic times of the structure, the impulse of the shock wave will be significant in determining the damage (Fig. 5.48). It should be remembered, in this connection, that the magnitude of the impulse and damage will be greatly decreased if the reflected wave from the air-water surface reaches the target soon after the arrival of the primary shock wave.

6.40 If the large underwater structure can accept a substantial amount of permanent (plastic) deformation, as a result of impact with the shock front, it appears that the damage depends essentially on the energy of the shock wave (Fig. 5.48). If the structure is near the surface, the cutoff effect will decrease the amount of shock energy available for causing damage.

## DAMAGE EVALUATION

### Damage-Distance Relationships

6.41 By combining the information collected after the explosions in Japan and the data obtained at various nuclear tests with a theoretical analysis of loading and response of structures, as described below, in the technical section of this chapter, relationships have been developed between the yield of the explosion, the distance from ground zero, and the degree of damage that would be expected for a variety of structures. The results for a typical air burst (AB) and a contact surface burst (SB) are summarized in the charts in Fig. 6.41a, b, and c. For convenience, Fig. 6.41a is concerned with the effects of air blast on structures which are essentially of the diffraction type, whereas the structures to which Fig. 6.41b and c refer are primarily drag sensitive. Damage to ships from an underwater harbor burst and thermal damage to aircraft are also included in Fig. 6.41c. Examples showing how these charts are used are given on the explanatory pages preceding the respective figures.

6.42 As explained in § 6.4, the system used for classifying damage is a modification of the zone system adopted by the Federal Civil Defense Administration to describe damage to an average city complex. In the present treatment, however, the letters A, B, C, and D refer to degrees of damage, of decreasing severity, to individual structures or objects. Detailed descriptions of these damage classes have been given above in various tables but, in simple terms, they are as follows: type A damage means virtually complete destruction; type B damage refers to destruction severe enough to need very extensive (perhaps prohibitive) repair; type C damage would require major repairs before the object or structure could be used for its intended purpose; and type D damage would involve minor repairs or even further use without repair.

6.43 The data presented in Figs. 6.41a, b, and c are for certain average target conditions. These include the assumptions that (1) the target is at sea level (no correction is necessary if the target altitude is less than 5,000 feet): (2) the terrain is fairly flat (rugged terrain would provide some local shielding and protection); and (3) the structures have average characteristics (that is, they are of average size and strength). In applying the results to conditions which depart appreciably from the average, any modifications that may be necessary must be left to the judgment of the analyst.

6.44 Since the structures in Fig. 6.41a are of the diffraction type, the peak overpressure is the significant damage criterion. Consequently, the distances from ground zero for a specific damage are related to the explosion energy yield by the familiar cube root law (§ 3.86, *et seq.*). For the drag-type structures in Fig. 6.41b and c, however, this scaling law does not apply (§ 3.66). Nevertheless, if it is required to extend the results to explosions of energy yields in excess of 20 megatons, which is the maximum value in the charts, the

(Text continued on page 250.)

From the nomogram and bar chart in Fig. 6.41a the nature of the damage to various diffraction-sensitive structures can be determined at any given distance from ground zero for an explosion of specified energy yield. The symbols A, B, C, and D in the bars refer to degrees of damage of decreasing severity, as described in the text. The abbreviations "SB" and "AB" at the head of each set of bars indicates a surface burst and an air burst, respectively.

*Scaling.* The chart can be used directly for energy yields in the range from 1 KT to 20 MT. For yields $W$ MT, in excess of 20 MT, the scaling law is

$$d=\frac{W^{1/3}}{2.71}d_0 \text{ for } W>20 \text{ MT},$$

where

$d$=distance from ground zero for a $W$ MT (>20 MT) explosion to cause a specific damage,

and

$d_0$=distance from ground zero for a 20 MT explosion to cause the same damage.

*Example*

*Given:* A 1 MT air burst.

*Find:* The nature of the damage suffered by (*a*) a blast-resistant, reinforced-concrete structure, (*b*) a conventional reinforced-concrete structure, and (*c*) a wood-frame house, at 2 miles from ground zero.

*Solution:* Find the point indicating 1 megaton on the left scale of the nomogram and the one representing 2 miles on the center scale; draw a straight line through these points until it cuts the line at the right ("construction line"). From the point of intersection draw a horizontal line through the bars showing degrees of damage.

(*a*) A blast-resistant, reinforced-concrete building will suffer essentially no structural damage.

(*b*) A conventional reinforced-concrete structure will suffer B damage.

(*c*) A wood-frame house will suffer A damage, i. e., essentially complete destruction. *Answer.*

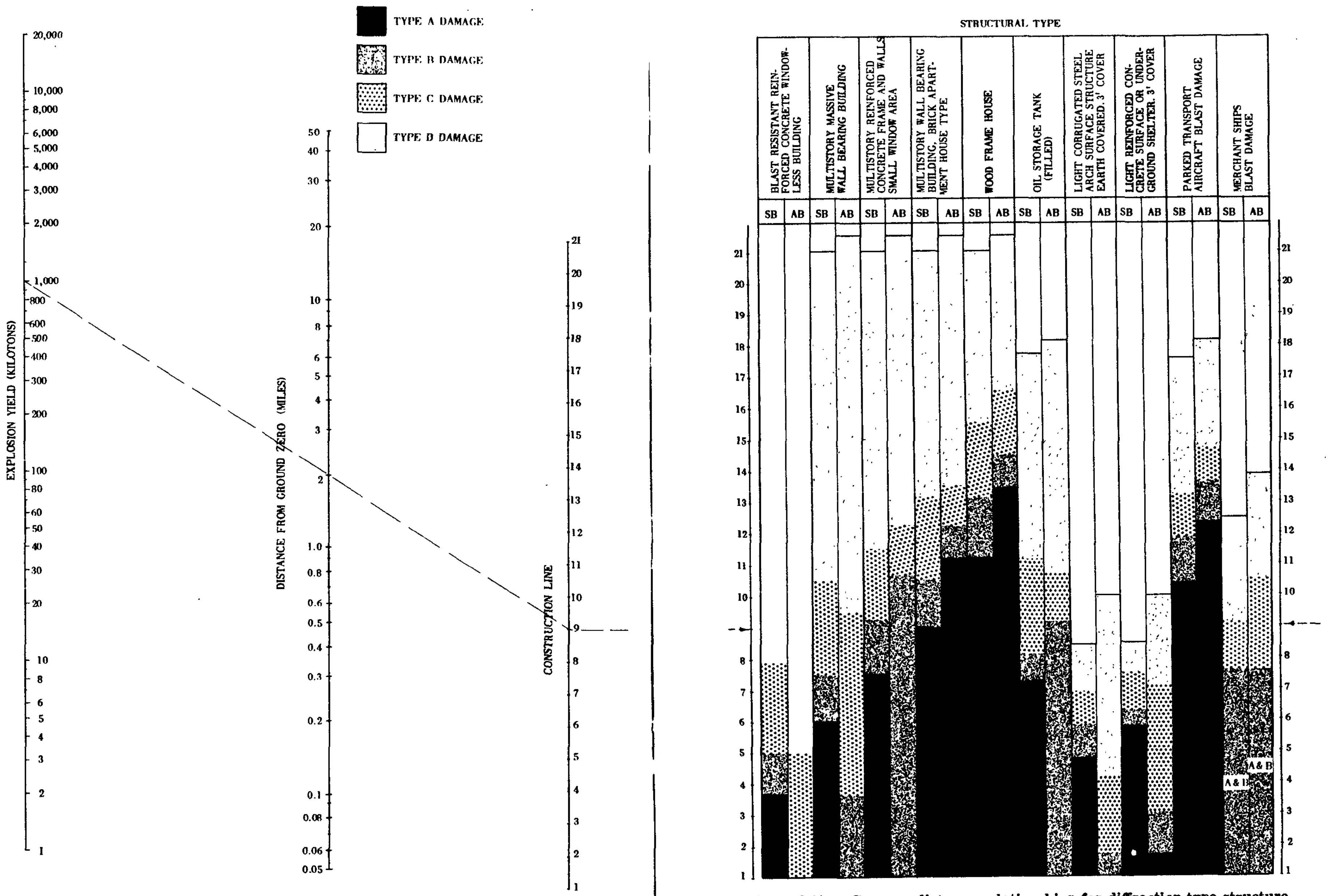

Figure 6.41a. Damage-distance relationships for diffraction-type structure.

(Text continued from page 246.)

cube root law may be used for both diffraction and drag type targets, provided the reference explosion is taken as 20 megatons. Thus, if $d$ is the distance from ground zero for an explosion of $W$ (which is greater than 20) megatons, where a certain degree of damage is expected, and $d_0$ is the distance for the same damage for a 20-megaton explosion, then

$$\frac{d}{d_0}=\left(\frac{W}{20}\right)^{1/3} \text{ or } d=\frac{W^{1/3}}{2.71}d_0.$$

Since $d_0$ can be obtained from the charts, the value of $d$ for an explosion yield of $W$ (which is in excess of 20) megatons can be readily evaluated.

6.45 In conclusion, it should be mentioned that the damage charts do not take into consideration the possibility of fire. Generally speaking, except for fabric surfaces of aircraft, for which data are included, the direct effects of thermal radiation on structures and other targets under consideration are inconsequential. However, thermal radiation may initiate fires, and in structures with A, B, or C damage fires may start because of disrupted gas and electric utilities. In some cases, as in Hiroshima (§ 7.100), the individual fires may develop into a fire storm which may exist throughout a city, even beyond the range of significant blast damage. The spread of such a fire depends to a great extent on local weather (and other) conditions and is therefore difficult to predict. This limitation must be kept in mind when Figs. 6.41a, b, and c are used to make a damage analysis of a particular city or target area.

## INTERACTION OF OBJECTS WITH AIR BLAST[2]

### Development of Blast Loading

6.46 Because precise information concerning the effects of blast from nuclear explosions on structures is somewhat limited, the usual procedure for predicting blast damage is by an analysis, supported by such laboratory and full-scale empirical data as may be available. The first stage in this analysis is the determination of the air blast loading on the particular structure, followed by an evaluation of the response to this loading. Since actual structures are generally complex, the treatment presented here will refer to a number of idealized targets of simple shape.

(Text continued on page 256.)

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[2] The remaining sections of this chapter may be omitted without loss of continuity.

From the nomograms and bar charts in Fig. 6.41b and c the nature of the damage to various drag-sensitive structures can be determined at any given distance from ground zero for an explosion of specified energy yield. The symbols A, B, C, and D in the bars refer to degrees of damage of decreasing severity, as described in the text. The abbreviations "SB" and "AB" at the head of each set of bars indicate a surface burst and an air burst, respectively.

*Scaling.* For energy yields above 20 MT, the same cube root scaling law may be applied as that given on the page preceding Fig. 6.41a, for diffraction-sensitive structures.

*Example*

*Given:* A 1 MT air burst.

*Find:* The nature of the damage suffered by (*a*) a truss bridge, (*b*) a steel-frame industrial-type structure of medium strength, and (*c*) public utility (above ground power and telephone) lines, at 2 miles from ground zero.

*Solution:* Find the point indicating 1 megaton on the left scale of the nomogram and the one representing 2 miles on the center scale; draw a straight line through these points until it cuts the line at the right ("construction line"). From the point of intersection draw a horizontal line through the bars showing degrees of damage.

(*a*) A truss bridge, more or less irrespective of its length, will suffer C damage.

(*b*) A medium strength, steel-frame industrial building will suffer A damage from an air burst.

(*c*) Public utility (above ground power and telephone) lines will suffer A damage, irrespective of whether they are oriented radially or transversely to the direction of the blast wave. *Answer.*

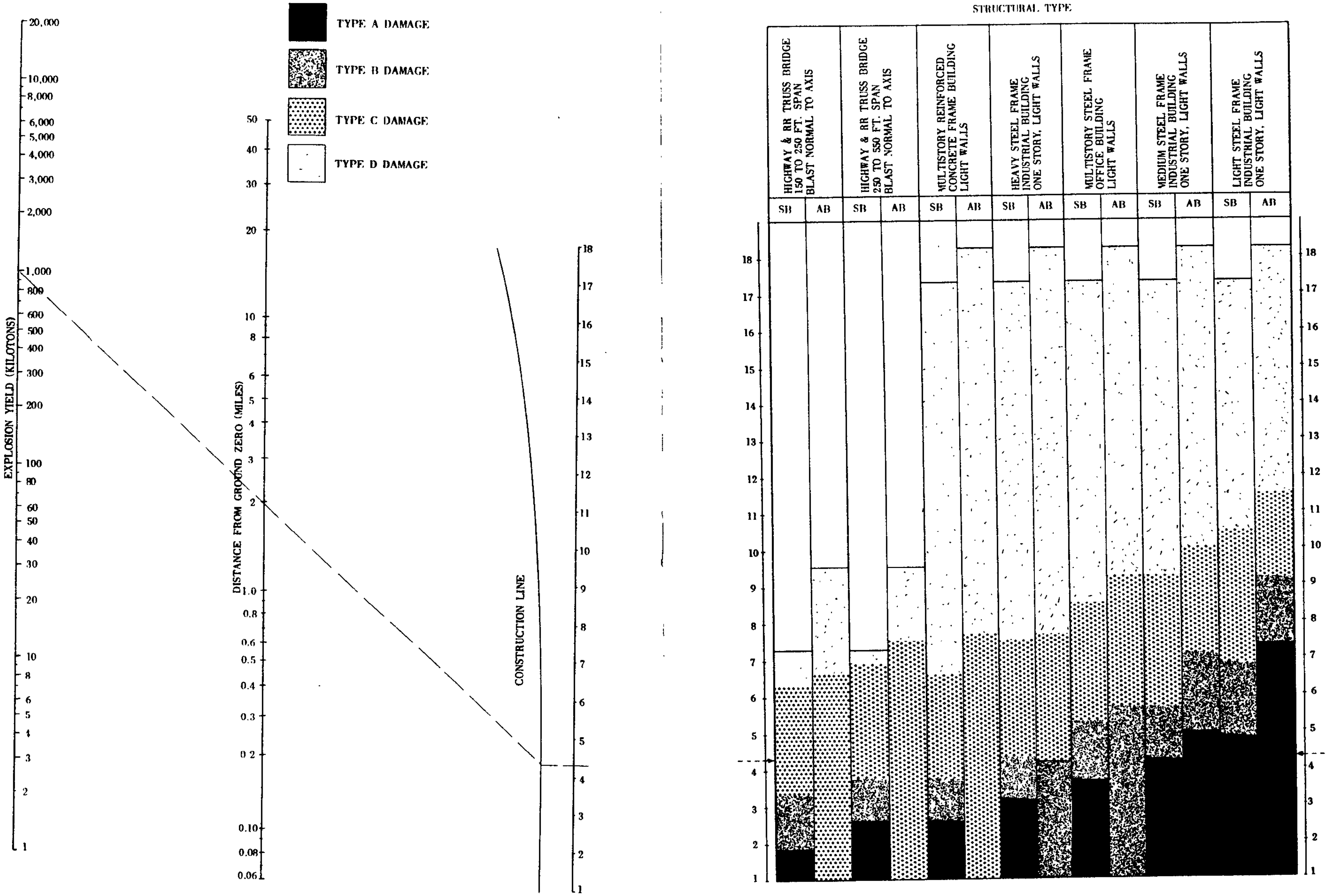

Figure 6.41b. Damage-distance relationships for drag-type structures (buildings).

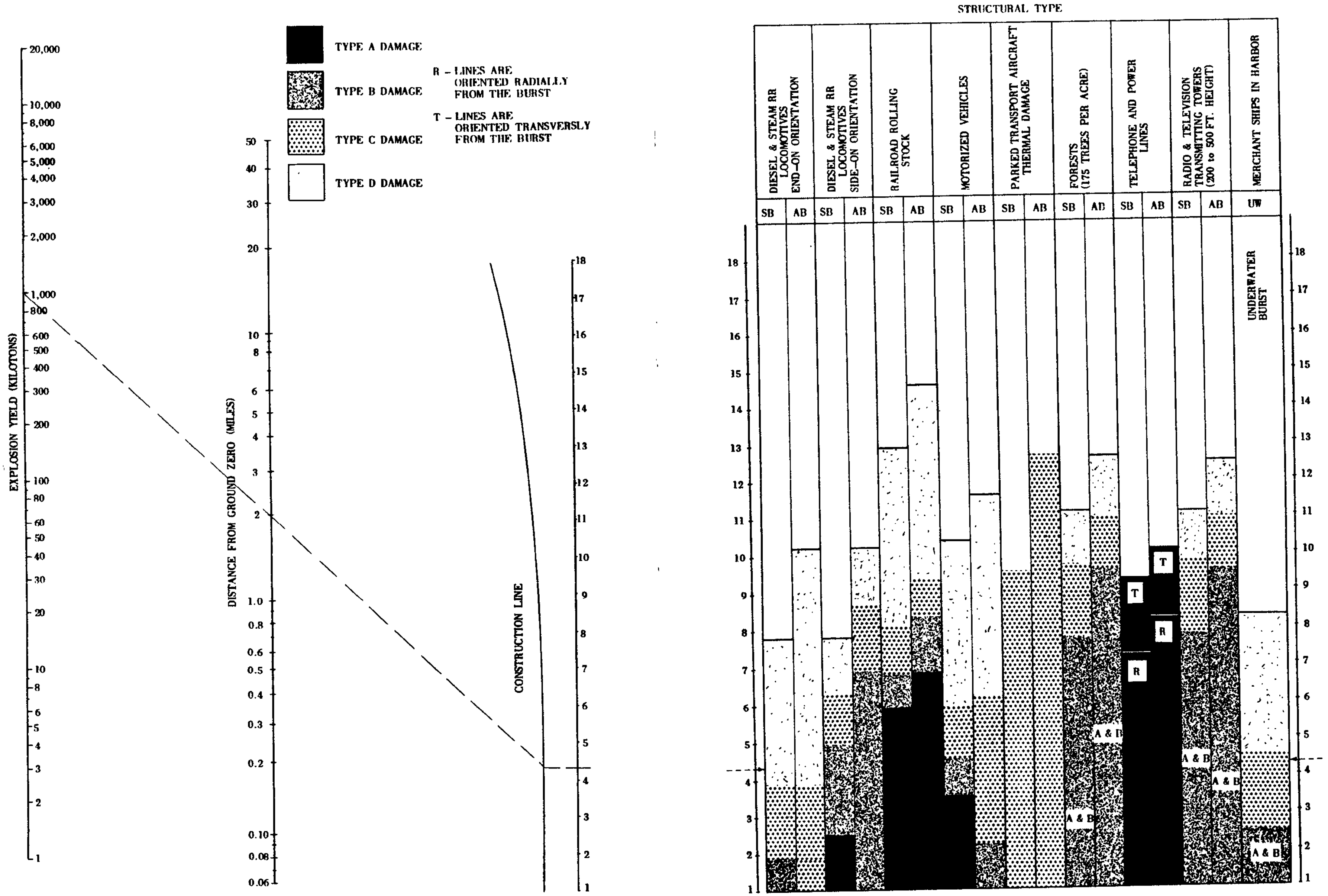

Figure 6.41c. Damage-distance relationships for drag-type structures (other than buildings).

(Text continued from page 250.)

6.47 The blast loading on an object is a function of both the incident blast wave characteristics, i. e., the peak overpressure, dynamic pressure, decay, and duration, as described in Chapter III, and the size, shape, orientation, and response of the object. The interaction of the incident blast wave with an object is a complicated process, for which a theory, supported primarily by empirical data from shock tubes and wind tunnels, has been developed. To reduce the complex problem of blast loading to reasonable terms, it will be assumed, for the present purpose, that (1) the overpressures of interest are less than 50 pounds per square inch, and (2) the object being loaded is in the region of Mach reflection.

6.48 To obtain a general idea of the blast loading process, a simple object, namely, a cube with one side facing toward the explosion, will be selected as an example. It will be postulated, further, that the cube is rigidly attached to the ground surface and remains motionless when subjected to the loading. The blast wave front is taken to be of such size compared to the cube that it can be considered to be a plane wave striking the cube. The pressures referred to below are then the average pressures on a particular face. Since the object is in the region of Mach reflection, the blast front is perpendicular to the surface of the ground. The front of the cube, i. e., the side facing toward the explosion, is normal to the direction of propagation of the blast wave (Fig. 6.48).

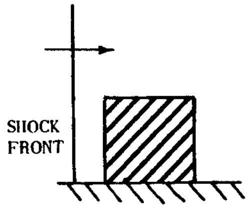

Figure 6.48. Blast wave approaching cube rigidly attached to ground.

6.49 As the blast wave strikes the front face of the cube, a reflection occurs producing (reflected) overpressures which may be from twice to eight times as great as the incident overpressure (§3.81). The blast wave then bends (or diffracts) around the cube exerting pressures on the sides and top of the object, and then on its rear face. The object is thus engulfed in the high pressure of the blast wave and this decays with time, eventually returning to ambient conditions. Because the reflected pressure on the front face is greater than the pressure in the blast wave above and to the sides, the reflected pressure cannot be maintained and soon decays to a "stagnation pressure," which is the sum of the incident overpressure and the dynamic (drag) pressure. The decay time is roughly that required for a rarefaction wave to sweep from the edges of the front face to the center of this face and back to the edges.

6.50 The pressures on the sides and top of the cube build up to the incident overpressure when the blast front arrives at the points in question. This is followed by a short period of low pressure caused by a vortex formed at the front edge during the diffraction process and which travels along or near the surface behind the blast front (Fig. 6.50). After the vortex has passed, the pressure returns essentially to that in the incident blast wave which decays with time. The air flow causes some reduction in the loading to the sides and top, because, as will be seen later, the drag coefficient has here a negative value.

6.51 When the blast wave reaches the rear of the cube, it diffracts around the edges, and travels down the back surface (Fig. 6.51). The pressure takes a certain time ("rise time") to reach a more-or-less steady state value equal to the algebraic sum of the overpressure and the drag pressure, the latter having a negative value in this case also. The finite rise time results from a weakening of the blast front as it

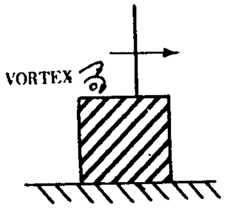

Figure 6.50. Blast wave moving over sides and top of cube.

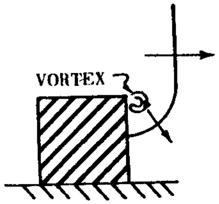

Figure 6.51. Blast wave moving down rear of cube.

diffracts around the back edges, accompanied by a temporary vortex action, and the time of transit of the blast wave from the edges to the center of the rear face.

6.52 When the overpressure at the rear of the cube attains the value of the overpressure in the blast wave, the diffraction process may be considered to have terminated. Subsequently, more-or-less steady state conditions may be assumed to exist until the pressures have returned to the ambient value prevailing prior to the arrival of the blast wave.

6.53 The total loading on any given face of the cube is equal to the algebraic sum of the respective overpressure, $p(t)$, and the drag pressure. The latter is related to the dynamic pressure, $q(t)$, by the expression,

$$\text{Drag pressure} = C_d q(t),$$

where $C_d$, called the "drag coefficient," has a value dependent upon the orientation of the particular face to the blast front and may be positive or negative. The quantities $p(t)$ and $q(t)$ represent the overpressure and dynamic pressure, respectively, at any time, $t$, after the arrival of the shock front (§§3.82, 3.83).

6.54 The foregoing discussion has referred to the loading on the various surfaces in a general manner. For a particular point on a surface, the loading depends also on the distance from the point to the various edges and a more detailed treatment is necessary. It should be noted that only the gross characteristics of the development of the loading have been described here. There are, in actual fact, several cycles of reflected and rarefaction waves traveling across the surfaces before damping out, but these fluctuations are considered to be of minor significance, as far as damage to the structure is concerned.

## EFFECT OF SIZE ON LOADING DEVELOPMENT

6.55 The loading on each surface may not be as important as the net horizontal loading on the entire object. Hence, it is necessary to study the net loading, which is the loading on the front face minus that on the back face of the cube. The net horizontal loading during the diffraction process is high because the pressure on the front face is initially the reflected pressure before the blast wave has reached the back face.

6.56 When the diffraction process is completed, the overpressure loadings on the front and back faces are essentially equal. The net horizontal loading is then relatively small. At this time the net loading consists primarily of the difference between front and back loadings resulting from the dynamic pressure loading. Because the time required for the completion of the diffraction process depends on the size of the object, rather than on the duration of the incident blast wave, the loading impulse per unit area during the diffraction process is greater for long objects than for short ones.

6.57 The magnitude of the dynamic pressure (or drag) loading, on the other hand, is affected by the shape of the object and the duration of the blast wave. It is the latter, and not the size of the object, which determines the time duration of application (and impulse per unit area) of the drag loading.

6.58 It may be concluded, therefore, that, for large objects struck by blast waves of short duration, the net horizontal loading during the diffraction process is more important than the dynamic pressure loading. As the object becomes smaller, or as the blast wave duration becomes longer, e. g., with weapons of larger yield, the drag (dynamic pressure) loading becomes increasingly important. For classification purposes, objects are often described as "diffraction targets" or "drag targets," as mentioned in Chapter III, to indicate the loading mainly responsible for damage. Actually, all objects are damaged by the total loading, which is a combination of overpressure and dynamic pressure loadings, rather than by any one component of the blast loading.

## EFFECT OF SHAPE ON LOADING DEVELOPMENT

6.59 The description given above for the interaction of a blast wave with a cube may be generalized to apply to the loading on an object of any other shape. The reflection coefficient, i. e., the ratio of the (instantaneous) reflected overpressure to the incident overpressure at the blast front, depends on the angle at which the blast wave strikes the object. For curved objects, e. g., a sphere (or part of a sphere), the reflection varies from point to point on the front surface. The time of decay from reflected to stagnation pressure then depends on the size of the object and the point in question on the front surface.

6.60 The drag coefficient, i. e., the ratio of the drag pressure to the dynamic pressure (§ 6.53), varies with the shape of the object. In many cases an overall (or average) drag coefficient is given, so that the net force on the surface can be determined. In other instances, local coefficients are necessary to evaluate the pressures on various points on the surfaces. The time of build up (or rise time) of the average pressure on the back surface depends on the size and also, to some extent, on the shape of the object.

6.61 Some structures have frangible portions that are easily blown out by the initial impact of the blast wave, thus altering the shape of the object and the subsequent loading. When windows are blown out of an ordinary building, the blast wave enters and tends to equalize the interior and exterior pressures. In fact, a structure may be designed to have certain parts frangible to lessen damage to all other portions of the structure. Thus, the response of certain elements in such cases influences the blast loading on the structure as a whole. In general, the movement of a structural element is not considered to influence the blast loading on that element itself. However, an exception to this rule arises in the case of an aircraft in flight when struck by a blast wave.

## Blast Loading-Time Curves

6.62 The procedures whereby the curves showing the air blast loading as a function of time may be derived are given below. The methods presented are for the following four relatively simple shapes: (1) closed box-like structure; (2) partially open box-like structure; (3) open frame structure; and (4) cylindrical structure. These methods can be altered somewhat for objects having similar characteristics. For very irregularly shaped objects, however, the procedures to be given may provide no more than a rough guess of the blast loading to be expected.

6.63 The blast wave characteristics which need to be known and their symbols are summarized in Table 6.63. The locations in Chapter III where the data may be obtained, at a specified distance from ground zero for an explosion of given energy yield, are also indicated.

## Closed Box-Like Structure

6.64 A closed box-like structure may be represented simply by a parallelepiped, as in Fig. 6.64, having a length $L$, height $H$, and breadth $B$. In this category will fall structures with a flat roof and walls of approximately the same blast resistance as the frame. The walls have either no openings (doors and windows), or a small number of such openings, up to about 5 percent of the total area, so that the pressures on the interior of the structure remain near the preshock ambient value while the outside is subjected to blast loading. To simplify the treatment, it will be supposed, as above, that one side of the structure faces toward the explosion and is perpendicular to the direction of propagation of the blast wave. This side is called the front face. The loading diagrams are computed below for (*a*) the front face, (*b*) the side and top, and (*c*) the back face. By combining the data for (*a*) and (*c*), the net horizontal loading is obtained in (*d*).

Table 6.63

BLAST WAVE CHARACTERISTICS FOR DETERMINATION OF LOADING

| Property | Symbol | Source |
|---|---|---|
| Peak overpressure | $p$ | Fig. 3.94a and b |
| Time variation of overpressure | $p(t)$ | Fig. 3.82 |
| Peak dynamic pressure | $q$ | Fig. 3.95 |
| Time variation of dynamic pressure | $q(t)$ | Fig. 3.82 |
| Reflected pressure at normal incidence | $p_r$ | Fig. 3.80 or equation (3.81.1) |
| Duration of positive phase | $t_+$ | Fig. 3.96 |
| Blast front (shock) velocity | $U$ | Fig. 3.80 |

6.65 (*a*) *Average Loading on Front Face.*—The first step is to determine the reflected pressure, $p_r$; this gives the pressure at the time $t=0$, when the blast wave front strikes the front face (see Fig. 6.65). Next, the time $t_s$, is calculated at which the stagnation pressure, $p_s$, is first attained. It has been found, from laboratory studies, that $t_s$ can be represented, to a good approximation, by

$$t_s=\frac{3S}{U},$$

where $S$ is equal to $H$ or to $\frac{1}{2}B$, whichever is less. The drag coefficient for the front face is unity, so that the drag pressure is here equal to the dynamic pressure. The stagnation pressure is thus

$$p_s=p(t_s)+q(t_s),$$

where $p(t_s)$ and $q(t_s)$ are the overpressure and dynamic pressure at the time $t_s$. The pressure subsequently decays with time, so that,

$$\text{Pressure at time } t=p(t)+q(t),$$

where $t$ is any time between $t_s$ and $t_+$. The pressure-time curve for the front face can thus be determined, as in Fig. 6.65.

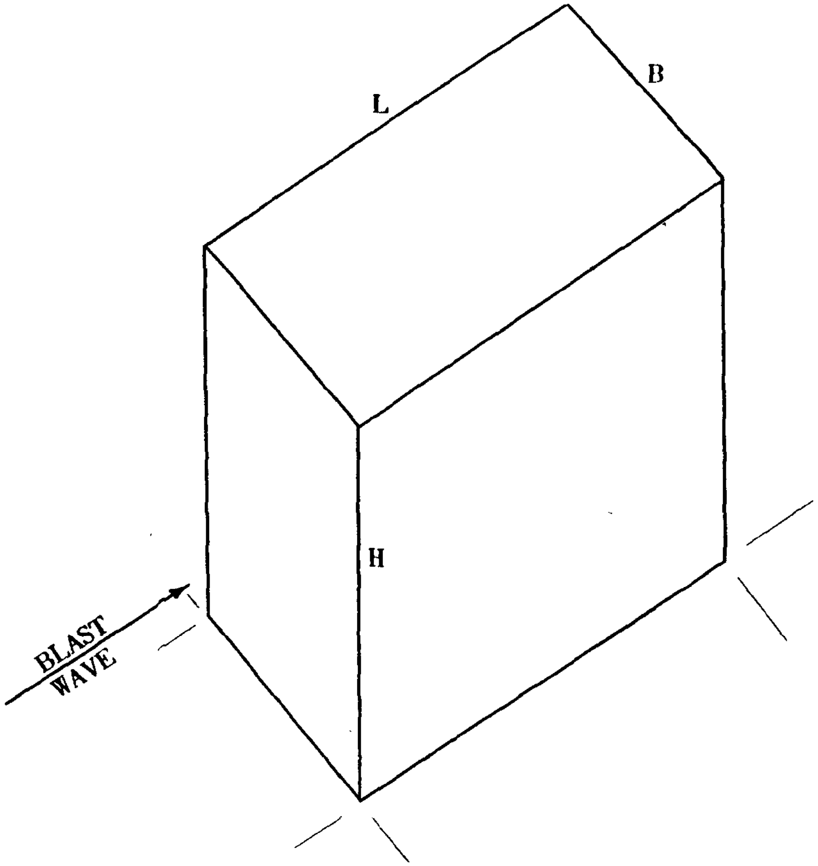

Figure 6.64. Representation of closed box-like structure.

6.66 *(b) Average Loading on Sides and Top.*—Although loading commences immediately after the blast wave strikes the front face, i. e., at $t=0$, the sides and top are not fully loaded until the wave has traveled the distance $L$, i. e., at time $t=L/U$. The average pressure, $p_a$, at this time is considered to be the overpressure plus the drag loading at the distance $L/2$ from the front of the structure, so that,

$$p_a=p\left(\frac{L}{2U}\right)-\frac{q}{2}\left(\frac{L}{2U}\right),$$

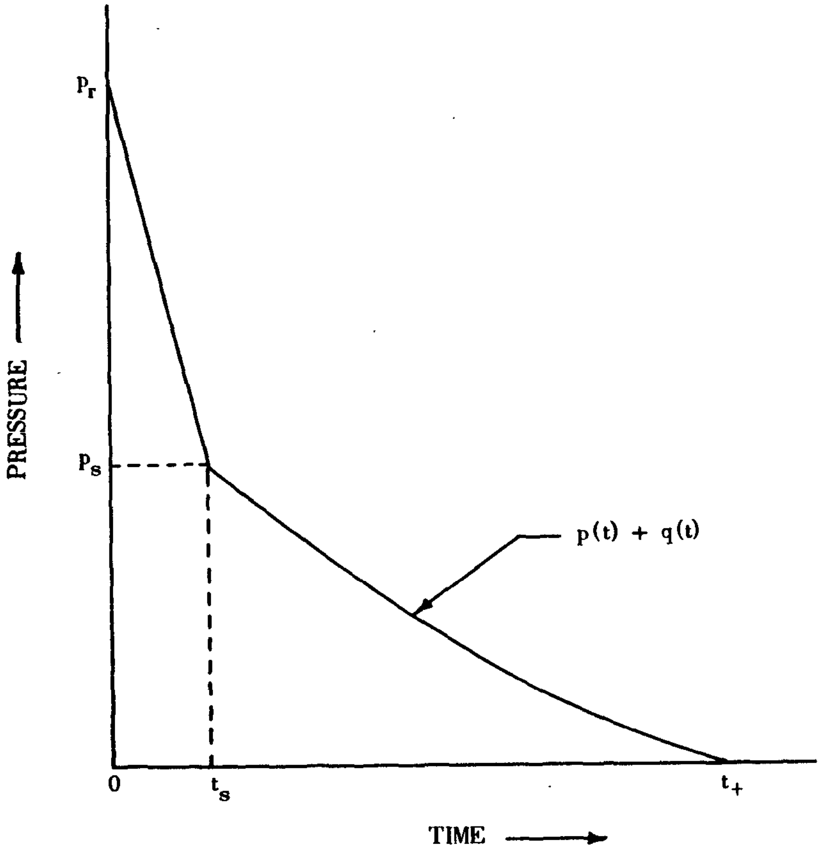

Figure 6.65. Average front face loading of closed box-like structure.

the drag coefficient on the sides and top of the structure being −½. The loading thus increases from zero at $t=0$ to the value $p_a$ at the time $L/U$, as shown in Fig. 6.66. After this time the pressure at any time $t$ is given by

$$\text{Pressure at time } t=p\left(t-\frac{L}{2U}\right)-\frac{q}{2}\left(t-\frac{L}{2U}\right),$$

where $t$ lies between $L/U$ and $t_+ + L/2U$, as shown in Fig. 6.66. The overpressure and dynamic pressure, respectively, are the values at the time $t-L/2U$.

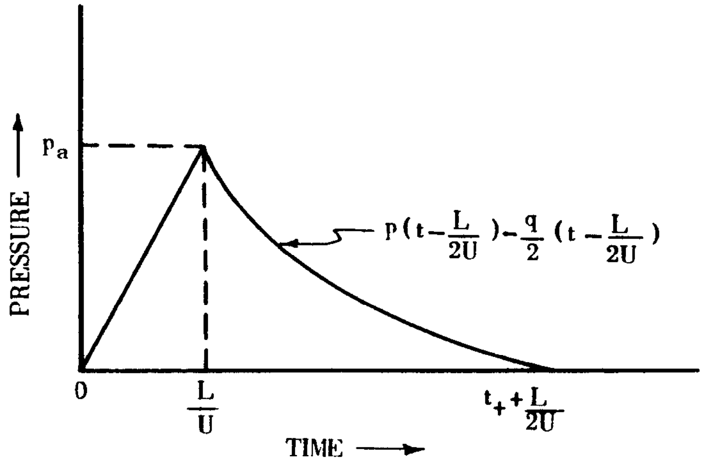

Figure 6.66. Average side and top loading of closed box-like structure.

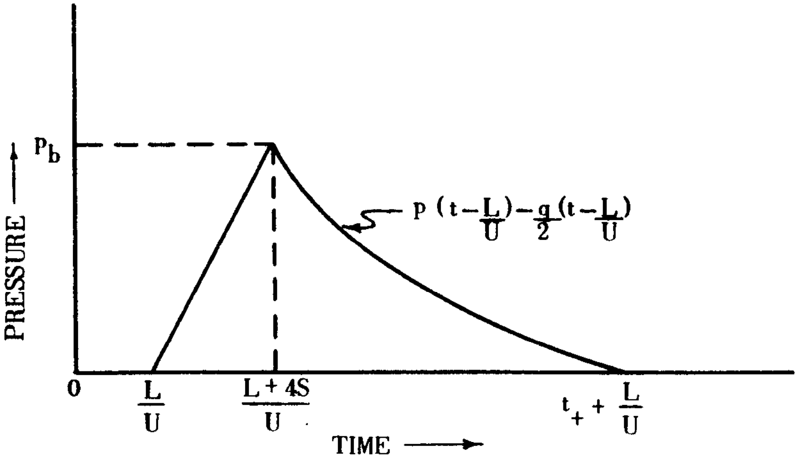

Figure 6.67. Average back face loading of closed box-like structure.

6.67 (*c*) *Average Loading on Back Face.*—The shock front arrives at the back face at time $L/U$, but it requires an additional time, $4S/U$, for the pressure to build up to the value $p_b$ (Fig. 6.67). Here, as before, $S$ is equal to $H$ or $\frac{1}{2}B$, whichever is the smaller. The drag coefficient on the back face is $-\frac{1}{2}$, and so the pressure at any time after $p_b$ is attained is represented by

$$\text{Pressure at time } t=p\left(t-\frac{L}{U}\right)-\frac{q}{2}\left(t-\frac{L}{U}\right),$$

where $t$ lies between $(L+4S)/U$ and $t_+ + L/U$, as seen in Fig. 6.67.

6.68 (*d*) *Net Horizontal Loading.*—The net loading is equal to the front loading minus the back loading. This subtraction is best performed graphically, as shown in Fig. 6.68. The left-hand diagram gives the individual front and back loading curves, as derived from Figs. 6.65 and 6.67, respectively. The difference indicated by the shaded region is then transferred to the right-hand diagram to give the net pressure. The net loading is necessary for determining the frame response, whereas the wall actions are governed primarily by the loadings on the individual faces.

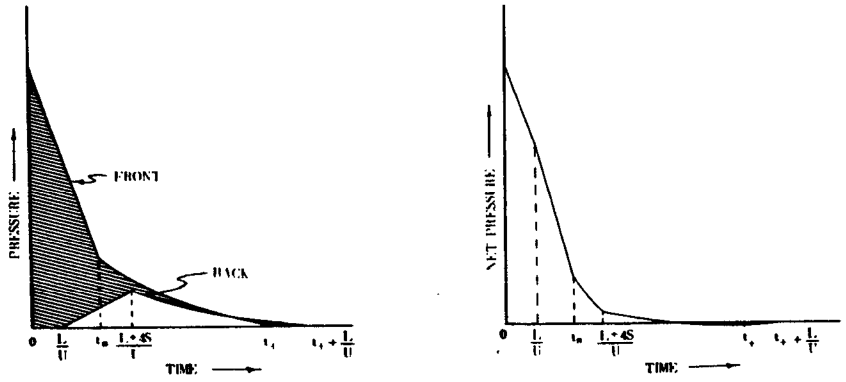

Figure 6.68. Net horizontal loading of closed box-like structure.

### PARTIALLY OPEN BOX-LIKE STRUCTURE

6.69 Such a structure is one in which the front and back walls have about 30 percent of openings or window area. As in the previous case, the loading is derived for (*a*) the front face, (*b*) the sides and roof, (*c*) the back face, and (*d*) the net horizontal loading. Because the blast wave can now enter the inside of the structure, the loading-time curves must be considered for both the exterior and interior of the structure.

6.70 (*a*) *Average Loading on Front Face.*—The outside loading is computed in the same manner as that used for a closed structure, except that $S$ is replaced by $S'$. The quantity $S'$ is the average distance (for the entire front face) from the center of a wall section to an open edge of the wall. It represents the average distance which rarefaction waves must travel on the front face to reduce the reflected pressures to the stagnation pressure.

6.71 The pressure on the inside of the front face starts rising at zero time, because the blast wave immediately enters through the openings, but it takes a time $2L/U$ to reach the blast wave overpressure value. Subsequently, the inside pressure at any time $t$ is given by $p(t)$. The dynamic pressures are assumed to be negligible on the interior of the structure. The variations of the inside and the outside pressures with time are as represented in Fig. 6.71.

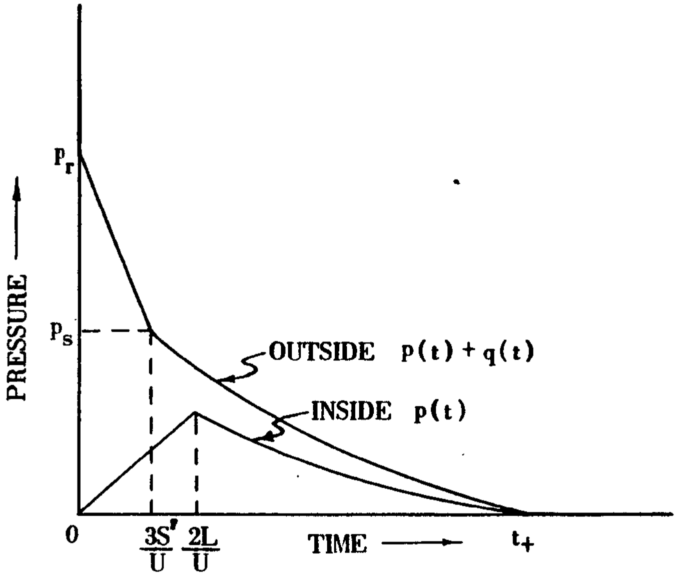

Figure 6.71. Average front face loading of partially open box-like structure.

6.72 (*b*) *Average Loading on Sides and Top.*—The outside pressures are obtained as for a closed structure, but the inside pressures, as for the front face, require a time $2L/U$ to attain the overpressure in the blast wave. Here also, the dynamic pressures on the interior are neglected, and side wall openings are ignored because their effect on the loading is uncertain. The loading curves are depicted in Fig. 6.72.

6.73 (*c*) *Average Loading on Back Face.*—The outside pressures are the same as for a closed structure, with the exception that $S$ is replaced by $S'$, as described above. The inside pressure, reflected from the inside of the back face, reaches the same value as the blast overpressure at a time $L/U$ and then decays as $p(t-L/U)$; as before, the dynamic pressure is regarded as being negligible (Fig. 6.73). These results are based on the assumption that there are no partitions to influence the passage of the blast wave through the structure.

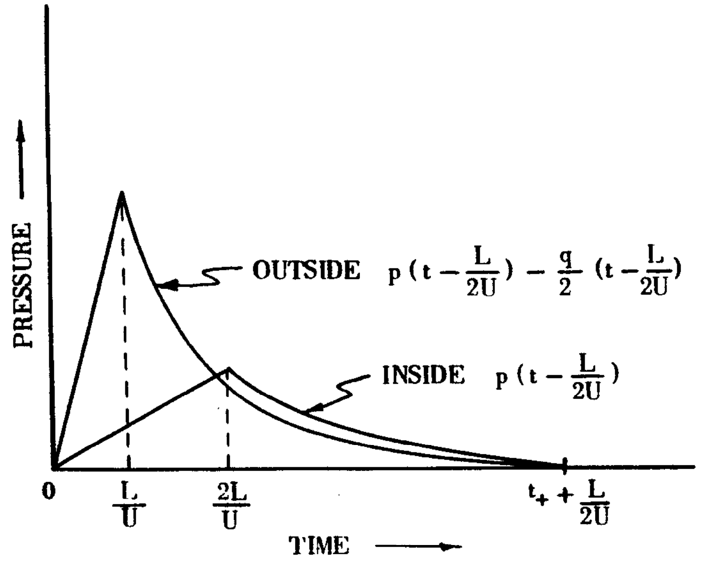

Figure 6.72. Average side and top loading of partially open box-like structure.

6.74 (*d*) *Net Horizontal Loading.*—The net horizontal loading is equal to the net front loading, i. e., outside minus inside, minus the net back face loading.

## Open Frame Structure

6.75 A structure in which small separate elements are exposed to a blast wave, e. g., a truss bridge, may be regarded as an open frame structure. Steel-frame office buildings, with a majority of the wall area of glass, or industrial buildings, with asbestos, light steel, or aluminum panels, quickly become open frame structures after the initial impact of the blast wave.

6.76 It is difficult to determine the magnitude of the loading that the frangible wall material transmits to the frame before failing. For glass, the load transmitted is assumed to be negligible if the loading is sufficient to fracture the glass. For asbestos, transite, corrugated steel, or aluminum paneling, an approximate value of the load transmitted to the frame is an impulse of 0.04 pound-second per square inch. Depending on the span lengths and panel strength, the panels are not likely to fail when the peak overpressure is less than about 2 pounds per square inch. In this event, the full blast load is transmitted to the frame.

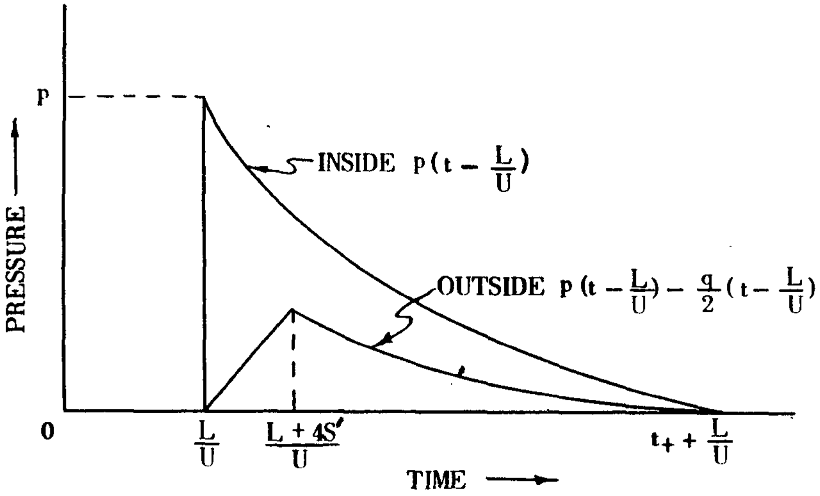

Figure 6.73. Average back face loading of partially open box-like structure.

6.77 Another difficulty in the treatment of open frame structures arises in the computation of the overpressure loading on each individual member during the diffraction process. Because this process occurs at different times for various members and is affected by shielding of one member by adjacent members, the problem must be simplified. A recommended simplification is to treat the loading as an impulse, the value of which is obtained in the following manner. The overpressure loading impulse is determined for an average member treated as a closed structure and this is multiplied by the number of members. The resulting impulse is considered as being delivered at the time the shock front first strikes the structure, or it can be separated into two impulses for front and back walls where the majority of the elements are located and applied, as shown below in Fig. 6.79.

6.78 The major portion of the loading on an open frame structure consists of the drag (dynamic pressure) loading. For an individual member in the open, the drag coefficient for I-beams, channels, angles, and for members with rectangular cross section is approximately 2.0. However, because in a frame the various members shield one another to some extent from the full blast loading, the average drag coefficient when the whole frame is considered is reduced to 1.0. The force $F$, i. e., pressure multiplied by area, on an individual member is thus given by

$$F\text{ (member)}=C_d q(t) A_i,$$

where $C_d$ is 2.0 and $A_i$ is the member area projected perpendicular to the direction of blast propagation. For the loading on the frame, however, the force is

$$F\text{ (frame)}=C_d q(t)\Sigma A_i,$$

where $C_d$ is 1.0 and $\Sigma A_i$ is the sum of the projected areas of all the members. The result may thus be written in the form,

$$F\text{ (frame)}=q(t)A,$$

where $A=\Sigma A_i$.

6.79 The loading (force) versus time for a frame of length $L$, having major areas in the planes of the front and rear walls, is shown in Fig. 6.79. The symbols $A_{fw}$ and $A_{bw}$ represent the areas of the front and back walls, respectively, which transmit loads before failure, and $I_{fm}$ and $I_{bm}$ are the overpressure loading impulses on front and back members, respectively. It is seen that the drag force does not attain its full value of $q(L/2U)$ until the time $L/U$, i. e., when the blast wave reaches the end of the structure.

## CYLINDRICAL STRUCTURE

6.80 The following treatment, which is limited to peak overpressures of less than 30 pounds per square inch, is applicable to structures having a circular cross section, such as telephone poles and smokestacks. It can also be applied to structures with semicircular cross

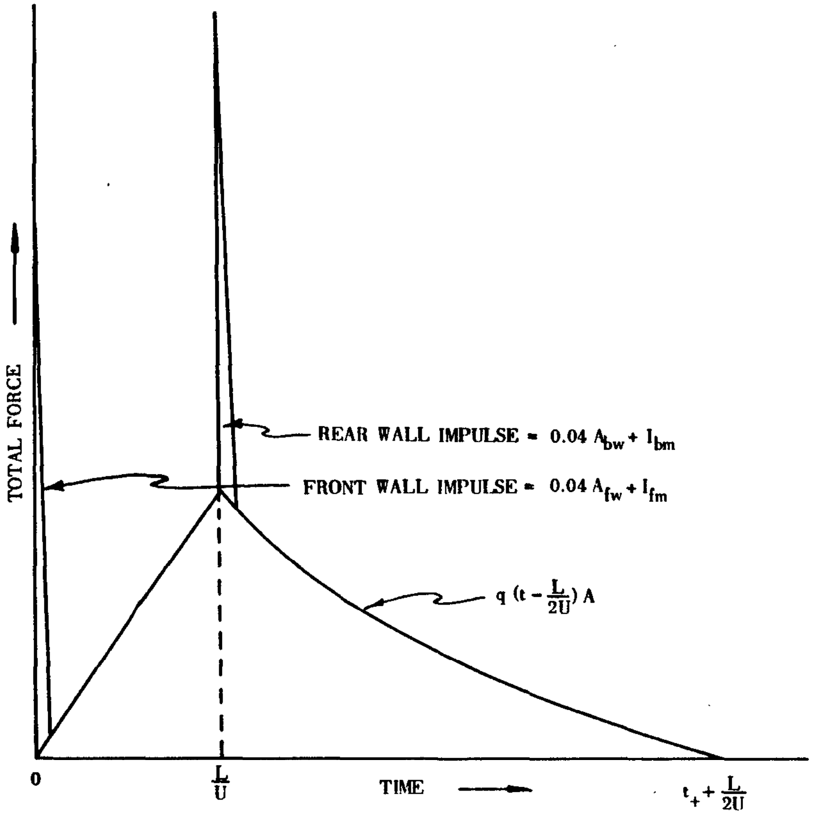

Figure 6.79. Net horizontal loading of an open frame structure.

sections, such as quonset huts and, as a rough approximation, to dome-shaped or spherical structures.

6.81 The discussion presented here is for a cylinder with the direction of propagation of the blast perpendicular to the axis of the cylinder. The pressure-time curves to be developed are, however, those for a semicircular cross section, since a cylinder consists of two such semicylinders with identical loading in each case. The general situation is then as depicted in Fig. 6.81; $r$ is the radius of the cylinder and $z$ represents any point on the surface.

6.82 The reflection coefficient at $z$ varies with the angle $\alpha$, and for the front part of the structure, i. e., for $\alpha$ between 0° and 90°, the dependence of the reflected overpressure on the angle $\alpha$ is given in Fig. 6.82a. Here, $p$ is the incident overpressure, $p_r$ is the reflected overpressure at the base, where $\alpha$ is 0°, obtained from Fig. 3.80, and $p_{rz}$ is the value at any arbitrary point $z$. The drag coefficient also varies with $\alpha$ as shown in Fig. 6.82b, where $C_{dz}$ represents this coefficient at any point $z$ on either the front or back of the semicylindrical structure, i. e., for values of $\alpha$ from 0° to 180°.

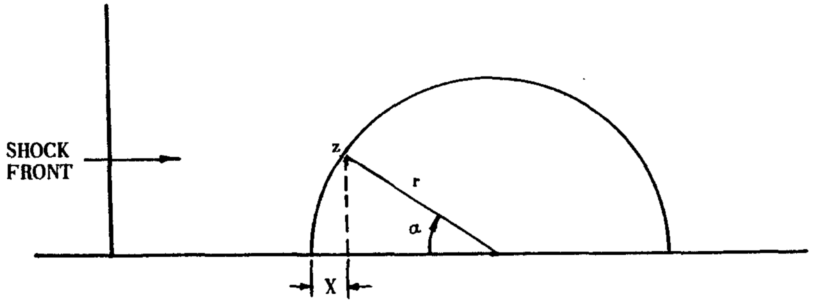

Figure 6.81. Representation of semicylindrical structure.

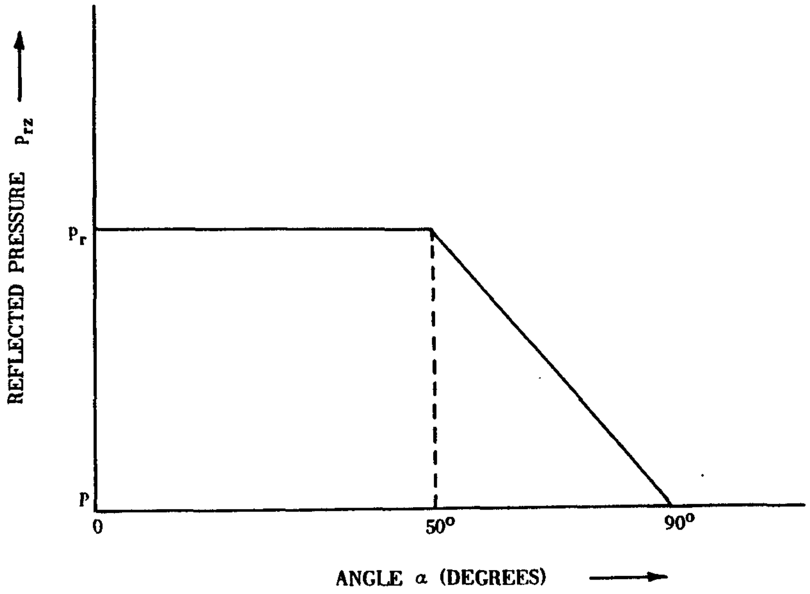

Figure 6.82a. Reflected overpressure versus angle for semicylindrical structure.

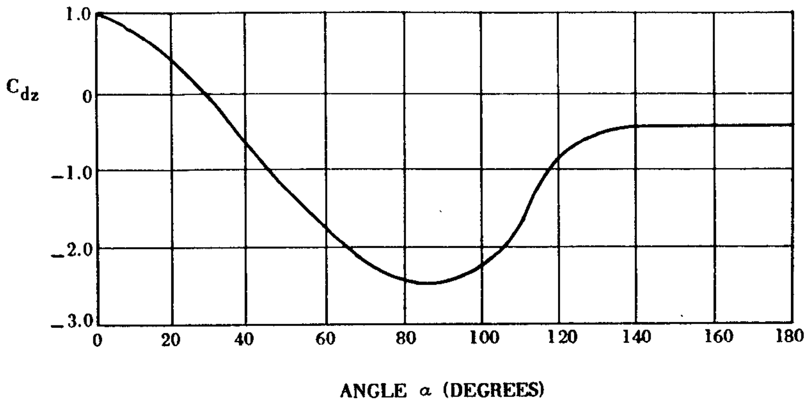

Figure 6.82b. Drag coefficient versus angle for semicylindrical structure.

6.83 Using the information now available, the development of the loading will be considered for (*a*) the front half, (*b*) the back half, and (*c*) the net horizontal force.

6.84 (*a*) *Loading on Front Half* ($\alpha=0°$ *to* $90°$).—The shock front strikes the base of the structure at time $t=0$, and the time of arrival at any point $z$ on the front half is $X/U$, where,

$$X=r(1-\cos\alpha),$$

as may be seen from Fig. 6.81. The value of the reflected pressure (normal to the surface) at this point is obtained from Fig. 6.82a. The decay time, $t_s$ is $3r/U$ when $\alpha$ is 0° and decreases linearly to zero when $\alpha$ is 90°, as seen in Fig. 6.84a. After time $t_s$, the pressure (normal to the surface) at any time, $t$, is given by,

$$\text{Pressure at time } t=p\left(t-\frac{X}{U}\right)+C_{dz}q\left(t-\frac{X}{U}\right).$$

The pressure-time curve at any point $z$ on the front half of the structure is thus of the form shown in Fig. 6.84b.

6.85 (*b*) *Pressure on Back Half* ($\alpha=90°$ *to* $180°$).—The time of arrival of the blast at a point $z$ on the back half is here also equal to $X/U$, where $X=r(1-\cos\alpha)$. But, instead of the pressure rising sharply, as it does on the front half, there is a finite rise time, $t_r$, which is zero when $\alpha=90°$ and increases in a linear manner to $2r/U$ when $\alpha=180°$, as seen in Fig. 6.85a. The maximum pressure is thus attained at the time $X/U+t_r$. Subsequently, the decrease in pressure with time is given by,

$$\text{Pressure at time } t=p\left(t-\frac{X}{U}\right)+C_{dz}q\left(t-\frac{X}{U}\right).$$

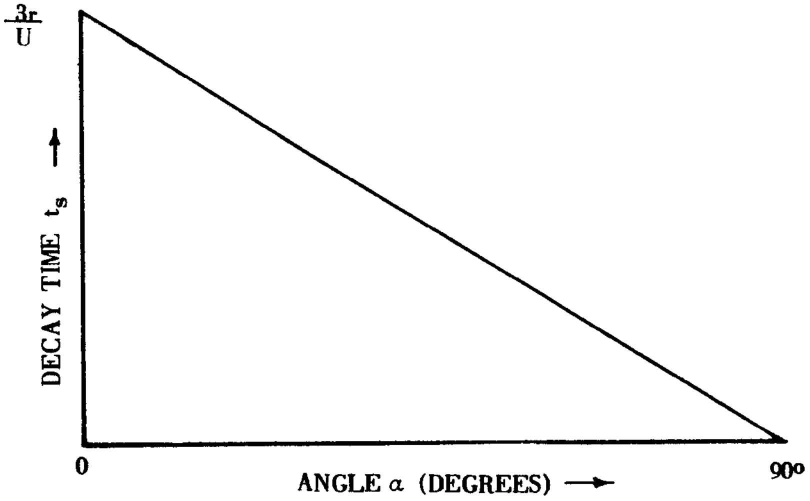

Figure 6.84a. Decay time versus angle for semicylindrical structure.

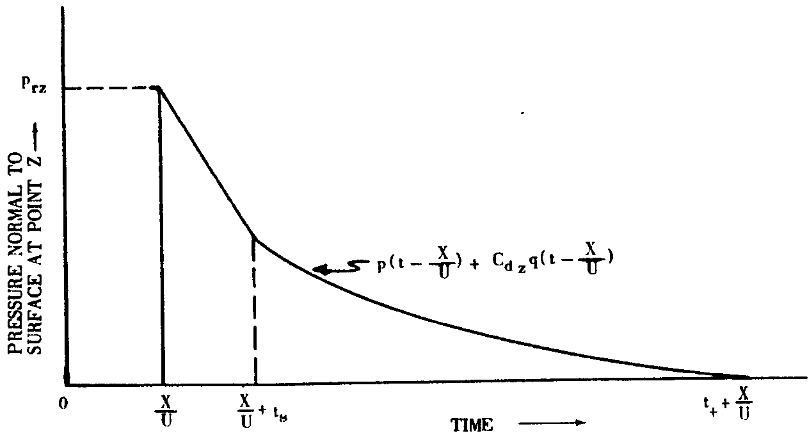

Figure 6.84b. Loading at point on front half of semicylindrical structure.

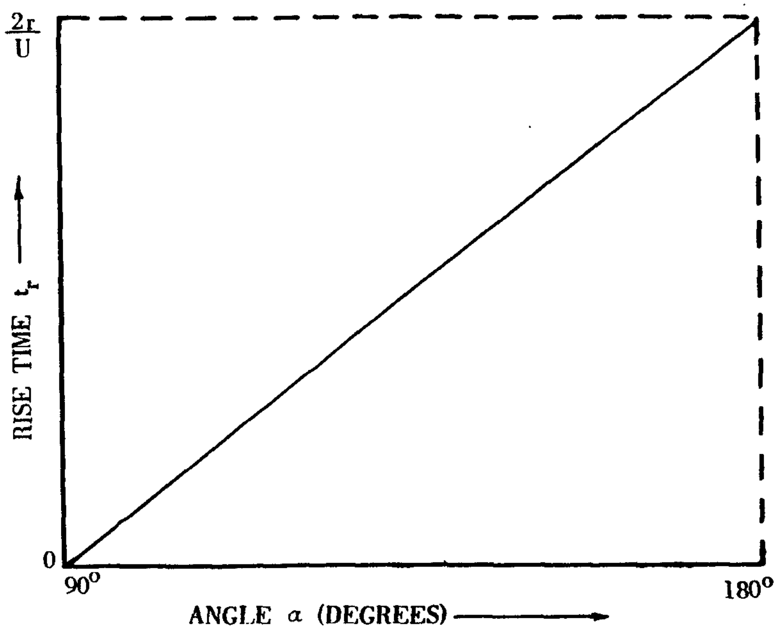

Figure 6.85a. Rise time versus angle for back half of semicylindrical structure.

The development of the loading, as represented by the pressure normal to the surface at any point *z* on the back half, is indicated in Fig. 6.85b.

6.86 (*c*) *Net Horizontal Force.*—Since the procedures described above give the loads normal to the surface at any arbitrary point *z*, the net horizontal loading is not determined by the simple process of subtracting the back loading from that on the front. To obtain the net horizontal loading, it is necessary to sum the horizontal components of the loads over the two areas and then subtract them. In practice, an approximation may be used to obtain the required result, in such cases where the net horizontal loading is considered to be important. It may be pointed out that, in certain instances, especially for large structures, it is the local loading, rather than the net loading, which is the significant criterion of damage.

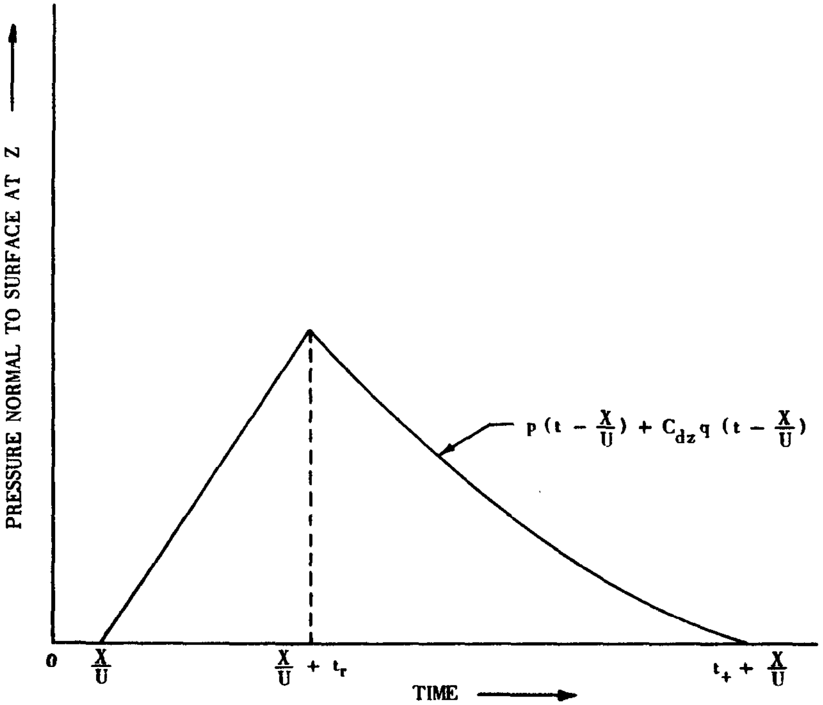

Figure 6.85b. Loading at point on back half of semicylindrical structure.

6.87 In the approximate procedure for determining the net loading, the overpressure loading during the diffraction process is considered to be equivalent to an initial impulse equal to $p_r A 2r/U$, where $A$ is the projected area normal to the direction of the blast propagation. It will be noted that $2r/U$ is the time taken for the blast front to traverse the structure. The drag coefficient for a single cylinder is about 0.4 in the region of interest, i. e., for overpressures of less than 30 pounds per square inch, postulated earlier. Hence, in addition to the initial impulse, the remainder of the net horizontal loading may be represented by the force $0.4\ q(t)A$, as seen in Fig. 6.87, which applies to a single structure. When a frame is made up of a number of circular elements, the methods used are similar to those for an open frame structure (§ 6.78, *et seq.*) with $C_d$ equal to 0.2.

## RESPONSE OF OBJECTS TO AIR BLAST LOADING

### DAMAGE TO FIXED AND MOVABLE OBJECTS

6.88 The response of an object is the motion or deflection it suffers when subjected to loading (§ 3.46). For objects that are fixed to the ground, the response is the movement of one portion of the structure

## ANALYSIS OF STRUCTURAL RESPONSE

6.94 Once the loading on a structure has been determined, the response can be predicted in principle. But, in many cases, this is not a simple matter because of the extensive mathematics involved. Hence, in order to permit a structural analysis to be made in a reasonable time, some simplification is necessary. For a structure in which the deflection of one point can be related to that of the structure as a whole, the response analysis can be reduced to a relatively simple procedure. If this point may be considered to be free to deflect in one direction only, then a one degree of freedom mass-spring system can be used to represent the response of the structure arising from a single mode of vibration. As a general rule, most of the motion is contributed by the mode corresponding to the lowest (or fundamental) vibration frequency of the structure.

6.95 The major assumption in the following presentation is, therefore, that a system with one degree of freedom will adequately duplicate the given structure. The latter may be treated as a mass-spring system, where the columns of the structure are considered to be springs on which the roof mass rests (Fig. 6.95a). In accordance with the postulate of one degree of freedom, the mass is permitted to deflect in the $x$-direction only. Thus, under the influence of a force $F$ acting on the roof, the mass is deflected by an amount $X$ (Fig. 6.95b).

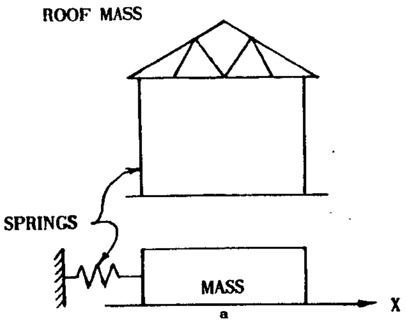

**Figure 6.95a.** Structure as mass-spring system before deflection.

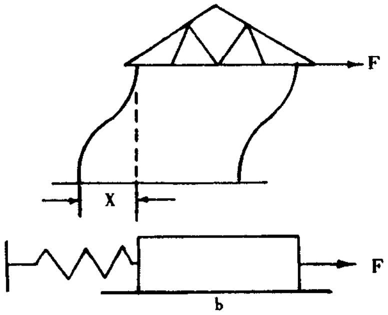

**Figure 6.95b.** Structure as mass-spring system when deflected.

6.96 In addition to the structure as a whole, a structural beam or a one-way slab (actually an infinite degree of freedom system) can also be represented as a system of one degree of freedom, by using an equivalent mass and load. The present discussion is somewhat limited since the methods presented cannot be applied directly to all multidegree of freedom systems, e. g., a multistory building.

6.97 Another limitation is the assumption that structural materials are deflected beyond the yield point or, in other words, that only large deflections are of interest in connection with the response of structures to blast loads. The methods presented therefore are not intended for use in computing elastic deflections, but rather large plastic deflections.

6.98 A treatment has been developed for calculating the deflection produced in a system of one degree of freedom by a given peak load or, alternatively, of estimating the peak load that will cause a prescribed deflection. For this purpose, three basic data are required, namely, (1) the dynamic resistance-deflection curve of the structure, (2) the fundamental period of vibration, and (3) the blast loading.

## DYNAMIC RESISTANCE-DEFLECTION CURVE

6.99 Idealized curves are shown in Fig. 6.99, for the deflection, as a function of the dynamic resistance, of a selected point of the structure (usually the point having the maximum deflection) when subjected to a concentrated load at that point. When the deflection exceeds the yield value, $X_e$, where the dynamic resistance is $Q_e$, the curve

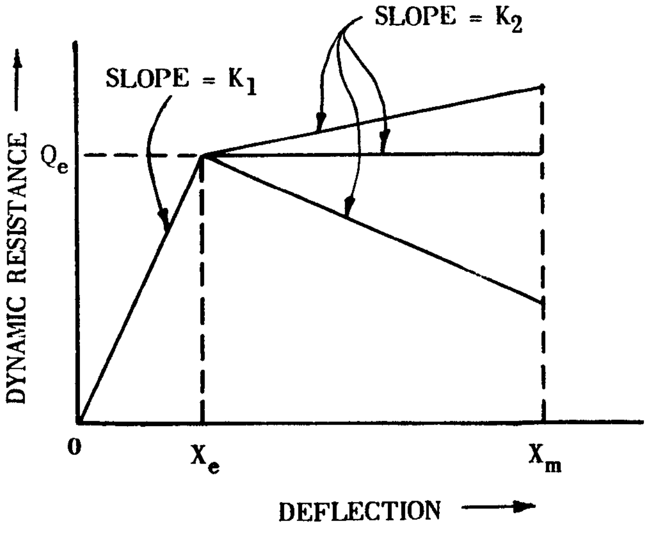

**Figure 6.99.** Idealized dynamic resistance-deflection curves.

may have one of the three forms indicated, according to the nature of the structure. The slope of the resistance-deflection curve in the elastic region is represented by $K_1$, whereas in the plastic region it is $K_2$. The maximum deflection to failure (or deflection prescribed for analysis) is indicated by $X_m$.

6.100 For reinforced-concrete or steel structures the dynamic resistance curve is derived from the static resistance-deflection curve by adding 20 percent to the values of the dynamic resistance at both $X_e$ and $X_m$, i. e., at the points representing the yield and maximum deflections, respectively. For structures of masonry, wood, or metal, other than steel, the static resistance curve may be used. If the true static resistance curve is found to be of the form shown by the full curve in Fig. 6.100, it may be approximated by two (dashed) straight lines, the area under the "approximate curve" being equal to that under the "true curve."

### FUNDAMENTAL PERIOD OF VIBRATION

6.101 The fundamental period of vibration, $T$, of a structure is expressed by

$$T=2\pi\sqrt{\frac{M_e}{K_1}}, \qquad (6.101.1)$$

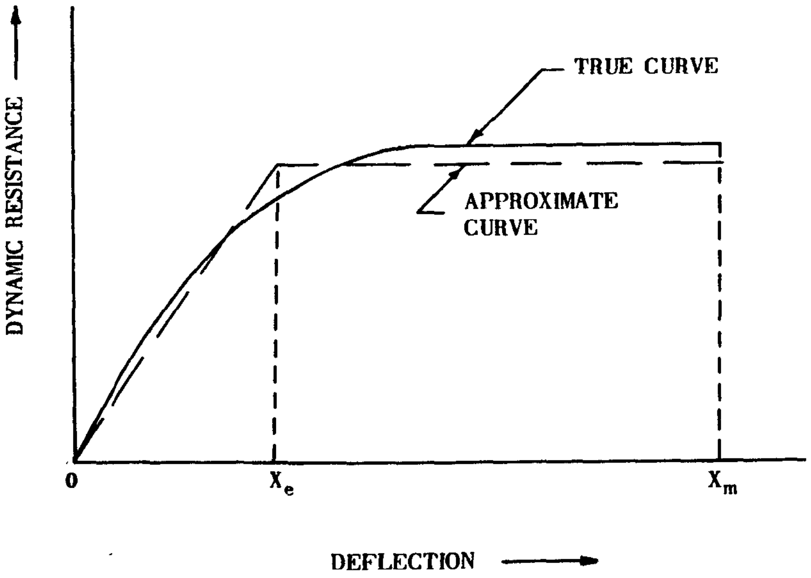

Figure 6.100. True and approximate dynamic resistance-deflection curve.

where $K_1$ is the slope in the elastic region defined above, and $M_e$ is the equivalent mass of the structure. For a structure consisting of a roof mass supported by columns, as shown in simple form in Fig. 6.95, the equivalent mass, concentrated at the column tops, may be taken as the actual roof mass plus one-half of the mass of the columns, assuming the columns to be fixed at both ends. For structural beams or one-way slabs the equivalent mass is obtained from the total mass by multiplying by the appropriate mass factor given in Table 6.101.

TABLE 6.101

MASS AND LOAD FACTORS

| Structure | Mass factor | | Load factor |
|---|---|---|---|
| Simply supported beam, uniformly distributed load. | Equivalent mass at center of beam (one degree of freedom). | 0.50 | 0.50 |
| Simply supported beam, concentrated center load. | do | 0.49 | 1.00 |
| Fixed ended beam, uniform load | do | 0.41 | 0.50 |
| Fixed ended beam, concentrated center load. | do | 0.37 | 1.00 |
| Cantilever beam, uniformly distributed load. | Equivalent mass at end of beam (one degree of freedom). | 0.24 | 0.40 |
| Cantilever beam, end concentrated load. | do | 0.26 | 1.00 |

### BLAST LOADING

6.102 For the present purpose, the actual blast loading curve, as developed earlier in this chapter, is replaced by an equivalent force-time curve of the form shown in Fig. 6.102. This consists of an initial impulse, $I$, plus a linear force-time loading function applied to the point where the mass is assumed to be concentrated. The initial (or peak) force is $F$, and $t_1$ is the duration of the equivalent linear load, as indicated in the figure. The peak force in the triangular diagram of Fig. 6.102 is the same as the peak force in the computed distributed loading diagram, and the area of the triangle must be equal to that under the actual loading (force-time) curve. For beams and one-way

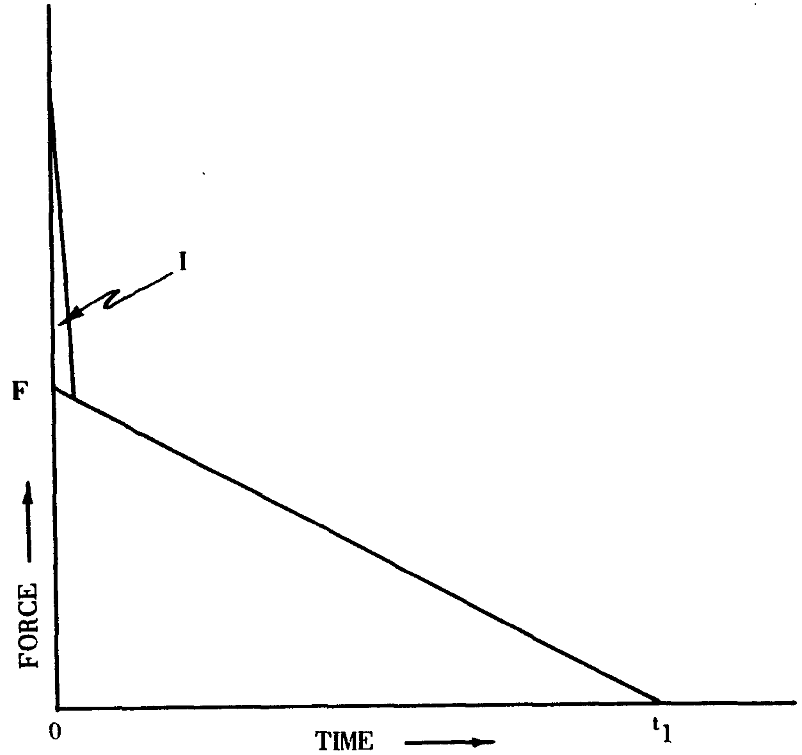

Figure 6.102. Triangular force-time and impulse loading diagram.

slabs, $F$ is equal to the peak force multiplied by the appropriate load factor given in Table 6.101.

6.103 The value of the initial impulse, where it is appropriate, is derived by the methods given above. In many cases, e. g., for large closed or partially open structures, an initial impulse contribution is not computed. For relatively small or open structures, the value of the initial impulse should be determined, although it may turn out to be negligible in magnitude.

6.104 Both the impulse and the linear force function must be changed from distributed loads to concentrated loads at the points where the mass is assumed concentrated. Where buildings have their mass concentrated primarily at floor levels, one-half of the remaining column or wall masses can be carried to each floor level. The distributed blast loads can be concentrated at connections as end reactions computed in the usual manner.

### Peak Force-Deflection Relationship

6.105 With the necessary data secured in the manner described above, the solution of the structural response problem is obtained from the equation,

$$\frac{F}{Q_e}=\frac{T}{\pi t_1}(\sqrt{A}-\sqrt{D})+\frac{A-D}{2\frac{X_m}{X_e}\left(1+0.7\frac{T}{t_1}\right)}, \qquad (6.105.1)$$

where

$$A=2\frac{X_m}{X_e}-1+\frac{K_2}{K_1}\left(\frac{X_m}{X_e}-1\right)^2$$

and

$$D=\left(\frac{2\pi I}{Q_e T}\right)^2 \text{ or } D=0 \text{ if } I \text{ is not computed.}$$

For convenience in the application of equation (6.105.1), the various symbols involved, all of which have been defined previously, are given below, together with their usual units:

$F$=peak force in pounds (see Fig. 6.102)

$t_1$=duration of equivalent linear loading in seconds (see Fig. 6.102)

$Q_e$=yield resistance in pounds (see Fig. 6.99)

$T$=fundamental period of vibration in seconds (see equation (6.101.1))

$I$=initial impulse in pound-seconds (see Figs. 6.79, 6.87, and 6.102)

$X_e$=yield deflection in any units (see Fig. 6.99)

$X_m$=maximum (or prescribed) deflection in same units as $X_e$ (see Fig. 6.99)

$K_1$=slope of dynamic resistance-deflection curve in elastic region (see Fig. 6.99)

$K_2$=slope of dynamic resistance-deflection curve in plastic region (see Fig. 6.99).

6.106 There are two general types of problems which may be solved with the aid of equation (6.105.1). If the load is prescribed, e. g., a given distance from an explosion of a specified yield, so that $F$ may be regarded as known, the corresponding deflection, $X_m$, can be determined. Alternatively, if the maximum (or prescribed) deflection,

$X_m$, is given, the corresponding value of $F$ can be calculated. In either case, the solution must be approached by a series of approximations.

6.107 If the load is specified, so that $F$ and $t_1$ may both be regarded as known, a provisional value of $X_m$ must first be estimated and then checked by means of equation (6.105.1). A new value is then tried, and so on, until agreement of the two sides is obtained. On the other hand, if a particular deflection, $X_m$, is decided upon to represent the degree of damage that can be tolerated or that is not to be exceeded, the calculation of $F$ is somewhat more difficult, since $t_1$ is also unknown and this is dependent upon $F$. It is necessary, therefore, to guess a linear function for the variation of the force with time, so as to give $t_1$. With this, an approximate value of $F$ is determined from equation (6.105.1), and a check of the guessed function is then made. This permits a new estimate of $t_1$, and the process is repeated until a satisfactory solution is obtained.

6.108 The use of the procedure just described can involve an error when the dynamic resistance curve shows the structure to be unstable, i. e., when $K_2$ is negative. The solution to a problem of determining the value of $F$ to produce a deflection $X_m$ may then imply that a greater force $F$ is required for a smaller value of $X_m$. It is necessary, therefore, to check this possibility. For cases in which $K_2$ is negative, $F$ is first determined for a certain $X_m$, say 2 feet, then $F$ is redetermined for a somewhat smaller value of $X_m$, say 1.8 feet, which is greater than $X_e$ but close to the original $X_m$. If the second value of $F$ is greater than the first, the calculations must be continued to determine the maximum value of $F$, called $F_m$, which is associated with $X_m$. For any greater value of the deflection $X_m$, the force $F_m$ is still required.

## *CHAPTER VII*

# THERMAL RADIATION AND ITS EFFECTS

## RADIATION FROM THE BALL OF FIRE

### General Characteristics of Thermal Radiation

7.1 One of the important differences between a nuclear and a conventional (TNT) bomb, which was mentioned in Chapter I, is the large proportion of the energy of a nuclear explosion which is released in the form of thermal (or heat) radiation. Because of the enormous amount of energy liberated per unit mass in a nuclear bomb, very high temperatures are attained. These may be of the order of several million degrees, compared with a few thousand degrees in the case of a TNT explosion. As a consequence of the high temperatures in the ball of fire, similar to those in the center of the sun, a considerable fraction of the nuclear energy appears as thermal radiation.

7.2 From the standpoint of this radiation, the fireball in a nuclear explosion resembles the sun in many respects. The radiation in each case is made up of ultraviolet rays of short wave length, visible light of longer wave length, and infrared radiation of still longer wave length. Thermal radiation travels with the speed of light, i. e., 186,000 miles per second, so that the time elapsing between its emission from the ball of fire and its arrival at a target a few miles away, is quite insignificant.

7.3 The radiations from the ball of fire, like the sun's rays, are attenuated as they pass through the air. The amount of thermal radiation from a particular nuclear explosion that will reach a given point depends upon the distance from the burst and upon the condition of the intervening atmosphere. Just as with sunlight, much of the ultraviolet radiation is absorbed in the air, so that the thermal radiation received, at distances of interest from a nuclear explosion, lies mainly in the longer wave length, i. e., visible and infrared, regions of the spectrum.

7.4 Of the total energy of nuclear explosion, one third is emitted in the form of thermal radiation. This means that for every 1-kiloton energy of the nuclear explosion, something like $3.3\times10^{11}$ calories, which is equivalent to nearly 400,000 kilowatt hours, is released as radiation thermal energy within a few seconds (or less) of the detonation.[1] This large amount of energy has important consequences.

7.5 Although blast is responsible for most of the destruction caused by a nuclear air burst, thermal radiation will contribute to the overall damage by igniting combustible materials, e. g., finely divided or thin fuels such as dried leaves and newspapers, and thus starting fires in buildings or forests. These fires may spread rapidly among the debris produced by the blast. In addition, thermal radiation is capable of causing skin burns on exposed individuals at such distances from the nuclear explosion that the effects of blast and of the initial nuclear radiation are not significant. This difference between the injury ranges of thermal radiation and of the other effects mentioned becomes more marked with increasing energy yield of the explosion. The hazard due to delayed nuclear radiations from fallout accompanying a surface burst may extend over a greater range than significant thermal radiation, but even then the latter would be an important cause of personnel injuries.

## ATTENUATION OF THERMAL RADIATION

7.6 The extent of injury or damage caused by thermal radiation or the chances of igniting combustible material depend to a large extent upon the amount of thermal radiation energy received by a unit area of skin, fabric, or other exposed material. The thermal energy falling upon a given area from a specified explosion will be less the farther from the explosion, for two reasons: (1) the spread of the radiation over an ever increasing area as it travels away from the fireball, and (2) attenuation of the radiation in its passage through the air. These factors will be considered in turn.

7.7 If the radiation is distributed evenly in all directions, then at a distance $D$ from the explosion the same amount of energy will fall upon each unit area of the surface of a sphere of radius $D$. The total area of this sphere is $4\pi D^2$, and if $E$ is the thermal radiation energy produced in the explosion, the energy received per unit area at a distance $D$ would be $E/4\pi D^2$, provided there were no attenuation by the atmosphere. Obviously, this quantity varies inversely as the square of the distance from the explosion. At 2 miles, from a given explosion, for example, the thermal energy received per unit area would be one-fourth of that received at half the distance, i. e., at 1 mile, from the same explosion.

7.8 In order to esimate the amount of thermal energy actually reaching the unit area, allowance must also be made for the attenuation of the radiation by the atmosphere. This attenuation is due to two main causes, namely, absorption and scattering. Atoms and molecules present in the air are capable of absorbing, and thus removing, certain radiations. Absorption is most effective for the short wave length (or ultraviolet) rays. In this connection, oxygen molecules and ozone play an important part. Although the proportion of ozone in the air is usually quite small, appreciable amounts of this substance are produced by the interaction of gamma radiation from the nuclear explosion with atmospheric oxygen.

7.9 Because of absorption, the amount of ultraviolet present in thermal radiation decreases markedly within a short distance from the explosion. At such distances that thermal radiation effects are significant, compared with others (blast and initial nuclear radiation), the proportion of ultraviolet radiation is quite small.

7.10 Attenuation as a result of scattering, i. e., by the diversion of rays from their original paths, occurs with radiation of all wave lengths. Scattering can be caused by molecules, such as oxygen and nitrogen, present in the air. This is, however, not as important as scattering resulting from the reflection and diffraction (or bending) of light rays by particles, e. g., of dust, smoke, or fog, present in the atmosphere. The diversion of the radiation path due to scattering interactions leads to a somewhat diffuse, rather than a direct, transmission of the thermal radiation.

## EFFECT OF ATMOSPHERIC CONDITIONS

7.11 The decrease in energy of thermal radiation due to scattering by particles present in the air depends upon the atmospheric conditions, such as the concentration and size of the particles, and also upon the wave length of the radiation. This means that radiations of different wave lengths, namely, ultraviolet, visible, and infrared, will suffer energy attenuation to different extents. For most practical purposes, however, it is more convenient and reasonably satisfactory, although less precise, to postulate a mean attenuation averaged over all the wave lengths present in the thermal radiation.

7.12 The state of the atmosphere as far as scattering is concerned will be represented by what is known as the "visibility range" or, in brief, as the "visibility." This is defined as the horizontal distance

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[1] The thermal radiation energy emitted per kiloton of nuclear explosion energy could convert over a million pounds of water, at ordinary temperature, completely into steam.

at which a large dark object can be seen against the horizon sky in daylight. A rough correlation between the visibility and the clarity of the atmosphere is given in Table 7.12.

TABLE 7.12

VISIBILITY AND ATMOSPHERIC CLARITY

| *Atmospheric Condition* | *Visibility (miles)* |
|---|---|
| Exceptionally clear | More than 30 |
| Very clear | 12–30 |
| Moderately clear | 6–12 |
| Light haze | 2.5–6 |
| Haze | 1.2–2.5 |
| Dense haze or fog | Less than 1.2 |

7.13 At one time it was thought the amount of thermal radiation received per unit area of exposed material, at a specified distance from a nuclear explosion, depended markedly on the atmospheric visibility. It appears, however, that, within wide limits, such is not the case. The attenuation is believed to increase continuously with increasing distance from the explosion, although not as rapidly as was previously supposed. Further, at any given distance the degree of attenuation does not vary appreciably with the visibility within the range of visibility of from 2 to 50 miles, i. e., for atmospheric conditions ranging from light haze to exceptionally clear, provided the distance is half the visibility range or less.

7.14 The reason for this—at first sight unexpected—effect is that the thermal radiation received at a given point at a distance from a nuclear explosion is made up of both directly transmitted (unscattered) and scattered radiations. If the air is clear, and there are very few suspended particles, the extent of scattering is small, and only a minor proportion of the scattered radiation reaches the observation point. In this case, the radiation received is essentially only that which has been transmitted directly from the exploding bomb without scattering.

7.15 If the air contains a moderately large number of particles, the amount of radiation transmitted directly will be less than in a clear atmosphere. However, this decrease is largely compensated by an increase in the scattered radiation reaching the point under consideration. Multiple scattering, i. e., subsequent scattering of already scattered radiation, which is very probable when the concentration of particles is high, will frequently result in the return of the radiation to its original direction.

7.16 It is because of the compensation due to multiple scattering, therefore, that the total amount of energy from a nuclear explosion falling upon unit area at a given distance may not be greatly dependent upon the visibility range, within certain limits. It should be noted that this general conclusion will apply only if the atmosphere is reasonably clear, that is, in the absence of rain, fog, or dense industrial haze. If these special conditions exist, however, only a small proportion of the thermal radiation escapes scattering. The considerable loss in the directly transmitted radiation cannot now be compensated by multiple scattering. There is consequently a definite decrease in the radiant energy received at a specified distance from the explosion. Another exceptional case, considered below, is when the explosion occurs below a cloud layer.

7.17 Attention should also be drawn to the limitation concerning distance mentioned at the end of § 7.13, namely, that the thermal radiation attenuation is somewhat independent of the atmospheric conditions only at distances from the explosion less than half the visibility range. At greater distances, more of the radiant energy is lost as the atmospheric visibility becomes less. In these circumstances, therefore, the supposition that the energy attenuation is independent of the visibility leads to estimates of the thermal energy that are too high. From the standpoint of protection, such estimates are preferable to those which err in being too low.

### EFFECT OF SMOKE AND FOG

7.18 In the event of an air burst occurring above a layer of dense cloud, smoke, or fog, an appreciable portion of the thermal radiation will be scattered upward from the top of the layer. This scattered radiation may be regarded as lost, as far as a point on the ground is concerned. In addition, most of the radiation which penetrates the layer will be scattered, and very little will reach the given point by direct transmission. These two effects will result in a substantial decrease in the amount of thermal energy reaching a ground target covered by fog or smoke, from a nuclear explosion above the layer.

7.19 Artificial white (chemical) smoke acts just like fog in attenuating thermal radiation. A dense smoke screen between the point of burst and a given target can reduce the thermal radiation energy to as little as one-tenth of the amount which would otherwise be received at the target. Smoke screens would thus appear to provide the possi-

*bility of protection against thermal radiation from a nuclear explosion.*

7.20 It is important to understand that the decrease in thermal radiation by fog and smoke, will be realized only if the burst point is above or, to a lesser extent, within the fog (or similar) layer. If the explosion should occur in moderately clear air beneath a layer of cloud, or fog, some of the radiation which would normally proceed outward into space will be scattered back to earth. As a result, the thermal energy received will actually be greater than for the same atmospheric transmission conditions without a cloud or fog cover.

### Effect of Shielding

7.21 Unless scattered, thermal radiation from a nuclear explosion, like ordinary light in general, travels in straight lines from its source, the ball of fire. Any solid, opaque material, such as a wall, a hill, or a tree, between a given object and the fireball will thus act as a shield and provide protection from thermal radiation. Some instances of such shielding, many of which were observed after the nuclear explosions in Japan, will be described later. Transparent materials, on the other hand, such as glass or plastics, allow thermal radiation to pass through only slightly attenuated.

7.22 A shield which merely intervenes between a given target and the ball of fire, but does not surround the target, may not be entirely effective under hazy atmospheric conditions. A large proportion of the thermal radiation received, especially at considerable distances from the explosion, has undergone scattering and will arrive from all directions, not merely that from the point of burst. This situation should be borne in mind in connection with the problem of thermal radiation shielding.

### Type of Burst

7.23 The foregoing discussion has referred in particular to thermal radiation from a nuclear air burst. For other types of burst the general effects are the same, although they differ in degree. For a surface burst, when the ball of fire actually touches the earth or water, the proportion of the explosion energy appearing as thermal radiation will be less than for an air burst. This is due partly to the fact that a portion of the thermal radiation is absorbed by the earth (or water). Less of the thermal energy is lost in this manner as the height of burst is increased.

7.24 Another significant fact is that in the event of a surface burst, most of the thermal radiation reaching a given target on the ground will have traveled through the air near the earth's surface. In this part of the atmosphere there is considerable absorption by molecules of water vapor and of carbon dioxide and the extent of scattering by dust particles is greater than at higher altitudes. Consequently, in addition to the smaller fraction of the total energy emitted as thermal energy in the case of a surface burst, a smaller proportion of this energy reaches the target at a specified distance from the explosion. The thermal effects of a surface burst will thus be significantly less than for an air burst of the same total energy yield.

7.25 In subsurface bursts, either in the earth or under water, nearly all the thermal radiation is absorbed, provided there is no appreciable penetration of the surface by the ball of fire. The thermal (heat) energy is then used up in vaporizing the soil or water, as the case may be. Normal thermal radiation effects, such as accompany an air burst, are thus absent.

## THERMAL RADIATION EFFECTS

### Absorption of Thermal Radiation

7.26 As already stated, because of the high temperatures attained in a nuclear explosion, the ball of fire resembles the sun in the respect that a large amount of energy is emitted as thermal radiation. With conventional high explosive bombs, not only is the total energy yield much smaller, but the temperatures are much lower so that the proportion of energy that appears as thermal radiation is very much less than for a nuclear bomb. Consequently, the thermal radiation effects of a conventional bomb are insignificant, except perhaps quite close to the explosion. On the other hand, for a nuclear air burst, in particular, the thermal energy can be appreciable even at considerable distances. The phenomena associated with thermal radiation, particularly skin burns and incendiary effects on a large scale, are therefore novel as far as bomb explosions are concerned.

7.27 The amount of thermal energy falling upon a unit area exposed to a nuclear explosion depends upon the total energy yield, the distance from the explosion, and, to some extent, upon the state of the atmosphere. Although the thermal radiation leaving the ball of fire covers a wide range of wave lengths, from the short ultraviolet, through the visible, to the infrared region of the spectrum, much of the ultraviolet radiation is absorbed or scattered in its passage through the atmosphere.

7.28 Of the two thermal radiation pulses emitted by the ball of fire, as described in Chapter II, the first contains a larger proportion of ultraviolet rays, because of the very high temperatures existing during this period.[2] However, the first pulse lasts only a fraction of a second, even for explosions in the megaton energy range, and the amount of thermal energy emitted is a negligible proportion of the total. At distances from the detonation at which thermal radiation effects are important, the ultraviolet portion of the radiation is small because of the short time that the fireball surface temperature is very high and the strong atmospheric absorption of the ultraviolet rays. Nevertheless, since these radiations have a greater capability for causing biological damage than visible or infrared rays, they may contribute to thermal injury in some circumstances.

7.29 When thermal radiation falls upon any material or object, part may be reflected, part will be absorbed, and the remainder, if any, will pass through and ultimately fall upon other materials. It is the radiation absorbed by a particular material that produces heat and so determines the damage suffered by that material. The extent or fraction of the incident radiation that is absorbed depends upon the nature and color of the material or object. Highly reflecting and transparent substances do not absorb much of the thermal radiation and so they are relatively resistant to its effects. A thin material will often transmit a large proportion of the radiation falling upon it and thus escape serious damage.

7.30 A black fabric will absorb a much larger proportion of the incident thermal radiation than will the same fabric when white in color. The former will thus be more affected than the latter. A light-colored material will then not char as readily as a dark piece of the same material. However, a material which blackens (or chars) readily in the early stages of exposure to thermal radiation behaves essentially as black, i. e., as a strong absorber irrespective of its original color. On the other hand, if smoke is formed it will partially shield the underlying material from the subsequent radiation.

7.31 Essentially all of the thermal radiation absorbed is immediately converted into heat. In other words, the temperature of the absorbing material rises and it is the high temperature which can cause injury or damage, or even ignition of combustible materials. An important point about the thermal radiation from a nuclear explosion is not only that the amount of energy is considerable, but also that it is emitted in a very short time. This means that the intensity of the radiation, i. e., the rate at which it falls upon a particular surface, is very high. Because of this high intensity, the heat accompanying the absorption of the thermal radiation is produced with great rapidity.

7.32 Since only a small proportion of the heat is dissipated by conduction in the short time during which the radiation falls upon the material—except perhaps in good heat conductors such as metals—the absorbed energy is largely confined to a shallow depth of the material. Consequently, very high temperatures are attained at the surface. It has been estimated, for example, that in the nuclear explosions in Japan, which took place at a height of some 1,850 feet, the temperature on the ground immediately below the burst was probably from 3,000 to 4,000° C (5,400 to 7,200° F.). It is true that the temperature fell off rapidly with increasing distance from the explosion, but there is some evidence that it exceeded 1,600° C. (2,900° F.) even 4,000 feet away (see § 7.83).

7.33 The most important physical effects of the high temperatures resulting from the absorption of thermal radiation are burning of the skin, and scorching, charring, and possibly ignition of combustible organic substances, e. g., wood, fabrics, and paper (Fig. 7.33). Thin or porous materials, such as lightweight fabrics, newspaper, dried grass and leaves, and dry rotted wood, may flame when exposed to thermal radiation. On the other hand, thick organic materials, for example, wood (more than ½ inch thick), plastics, and heavy fabrics, char but do not burn. Dense smoke, and even jets of flame, may be emitted, but the material does not sustain ignition.

7.34 This behavior is illustrated in the photographs taken of one of the wood-frame houses exposed in the 1953 Nevada tests. As mentioned earlier (§ 4.12), the houses were given a white exterior finish in order to reflect the thermal radiation and minimize the chances of fire. Virtually at the instant of the burst, the house front became covered with a thick black smoke, as shown in Fig. 7.34a. There was, however, no sign of flame. Very shortly thereafter, but before the arrival of the blast wave, i. e., within less than 2 seconds from the explosion, the smoke ceased, as is apparent from Fig. 7.34b. Presumably, because the heat was partially conducted away from the surface, the temperature was not high enough, during the short ef-

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[2] It is known, from theoretical studies and experimental measurements, that the wave length corresponding to the maximum energy density of radiation from an ideal (or "black body") radiator, to which the nuclear fireball is a good approximation, decreases with increasing temperature of the radiation. At temperatures above 7,6000° K. (13,700° F.), *this maximum lies in the ultraviolet region of the spectrum* (see § 7.106).

Figure 7.33. Thermal radiation from a nuclear explosion ignited the upholstery and caused fire to spread in an automobile, Nevada Test Site.

fective period of the radiation pulse, for ignition of the wood to occur. As will be seen later (§ 7.65), thin combustible material would probably have burst into flame at the same location.

7.35 The ignition of materials by thermal radiation depends upon a number of factors, the two most important, apart from the nature of the material itself, being the thickness and the moisture content. A thin piece of a given material, for example, will ignite more easily than a thick one, and a dry sample will be more readily damaged than one that is damp. The temperature may also be important, since ignition will be more difficult if the material is cold than if it were hot.

7.36 An important consideration in connection with charring and ignition of various materials and with the production of skin burns by thermal radiation is the rate at which the thermal energy is delivered. For a given total amount of thermal energy received by each unit area of exposed material, the damage will be greater if the energy is delivered rapidly than if it were delivered slowly. This means that, in order to produce the same thermal effect in a given material, the total amount of thermal energy (per unit area) received must be larger for a nuclear explosion of high yield than for one of lower yield, because the energy is delivered over a longer period of time, i. e., more slowly, in the former case.

Figure 7.34a. Thermal effects on wood frame house almost immediately after explosion (about 25 cal/sq cm).

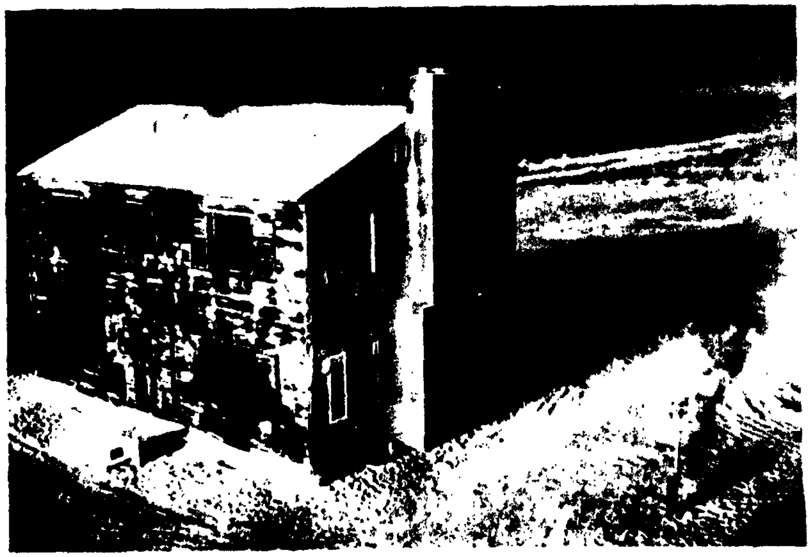

Figure 7.34b. Thermal effects on wood frame house 2 seconds later.

## SKIN BURNS DUE TO THERMAL RADIATION

### CLASSIFICATION OF BURNS

7.37 Thermal radiation can cause burn injuries either directly, i. e., by absorption of the radiant energy by the skin, or indirectly, as a result of fires started by the radiation. The direct burns are often called "flash burns," since they are produced by the flash of thermal radiation from the ball of fire. The indirect (or secondary) burns are referred to as "flame burns"; they are identical with skin burns that would accompany (or are caused by) any large fire no matter what its origin.

7.38 A highly significant aspect of a nuclear explosion is the very large number of flash burns (see § 7.69), as a consequence of the considerable emission of thermal radiation energy. Due to the very rapid heating of the skin, flash burns differ to some extent, in their physical and physiological aspects, from the more familiar flame burns. However, from the view point of their over-all effects on the body and their treatment, both types of burns appear to be similar. They also resemble burns produced in other ways, e. g., by contact with hot metal.

7.39 Burns, irrespective of their cause, are generally classified according to their severity, in terms of the degree (or depth) of the injury. In first-degree burns, of which moderate sunburn is an example, there is only redness of the skin. Healing should occur without special treatment and there will be no scar formation. Second-degree burns are deeper and more severe, and are characterized by the formation of blisters. Severe sunburn with blistering is an example of a second-degree burn. In third-degree burns, the full thickness of the skin is destroyed. Unless skin grafting techniques are employed, there will be scar formation at the site of the injury.

7.40 The distribution of burns into three groups obviously has certain limitations since it is not possible to draw a sharp line of demarcation between first- and second-degree, or between second- and third-degree burns. Within each class the burn may be mild, moderate, or severe, so that upon preliminary examination it may be difficult to distinguish between a severe burn of the second degree and a mild third-degree burn. Subsequent pathology of the injury, however, will usually make a distinction possible. In the following discussion, reference to a particular degree of burn should be taken to imply a moderate burn of that type.

7.41 The depth of the burn is not the only factor in determining its effect on the individual. The extent of the area of the skin which has been affected is also important. Thus, a first-degree burn over the entire body may be more serious than a third-degree burn at one spot. The larger the area burned, the more likely is the appearance of symptoms involving the whole body. Further, there are certain critical, local regions, such as the hands, where almost any degree of burn will incapacitate the individual.

### BURN INJURY ENERGIES AND RANGES

7.42 A first-degree burn over a large area of the body may produce a casualty, and an extensive second-degree burn will usually incapacitate the victim. In other words, all persons exposed to thermal radiation from a nuclear explosion within a range in which the energy received is sufficient to cause second-degree flash burns (at least) will be potential casualties. Not all will be incapacitated, since many individuals will be protected to some extent from the thermal radiation, but, within the specified area, there will be the possibility of serious burn injury.

7.43 In order to estimate the potential casualty range due to thermal burns from a nuclear explosion, two kinds of data are needed. First, it is required to know the amount of thermal radiation energy received from an explosion of given yield at various distances from the point of burst (or from ground zero). This depends upon a number of atmospheric and environmental conditions.

7.44 Second, information must be available concerning the thermal energy necessary to cause burns of various types at different rates of delivery of the energy, i. e., for explosions of different yields and different effective emission times. These aspects of the problem will be considered more fully in the final part of this chapter, but for the present it may be stated that the necessary data for air and surface bursts have been obtained by combining theoretical calculations with experimental observations made in the laboratory and at various nuclear test explosions.

7.45 The approximate thermal radiation energy required to produce moderate first-, second-, or third-degree burns as a result of exposure to nuclear explosions (in the air or at the surface) with total energy yields of 1 kiloton, 100 kilotons, and 10,000 kilotons (10 megatons) are given in Table 7.45.[3] This energy is expressed in

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[3] For further information on the dependence of the thermal energy requirements on the energy yield of the explosion, see Fig. 7.120.

TABLE 7.45

APPROXIMATE THERMAL ENERGIES REQUIRED TO CAUSE SKIN BURNS IN AIR OR SURFACE BURST

| Total energy yield | Thermal energy (cal/sq cm) | | |
|---|---|---|---|
| | First degree | Second degree | Third degree |
| 1 kiloton | 2 | 4 | 6 |
| 100 kilotons | 2½ | 5½ | 8 |
| 10 megatons | 3½ | 7 | 11 |

calories, and the unit area is taken as 1 square centimeter, so that the energies are given in calories per square centimeter (cal/sq cm) of skin area. There are some variations from the quoted energy values because of differences in skin sensitivity, pigmentation, and other factors affecting the severity of the burn.

7.46 It will be seen from Table 7.45 that the amount of thermal radiation energy required to produce a burn of any particular degree of severity increases with the total energy yield of the explosion. Thus, 4 calories per square centimeter will cause a second-degree burn in the case of a 1-kiloton explosion, but for a 10-megaton burst, 7 calories per square centimeter would be necessary. The reason for this difference lies in the fact that in the former case the thermal energy is received in a very short time, e. g., not more than a few tenths of a second, but in the latter case, the effective delivery time may extend to several seconds. As explained earlier (§7.35), the greater the exposure time, the larger, in general, is the amount of thermal energy required to produce a particular effect.

7.47 Taking into consideration the variation of the heat energy requirement with the energy yield of the explosion, Fig. 7.47 has been prepared to show the ranges for moderate first-, second-, and third-degree burns for nuclear explosions from 1 kiloton to 20 megatons energy yield. In deriving the curves, two particular assumptions have been made. First, it is supposed that the explosion occurs in the air at the same height as that to which the results on blast phenomena in Chapter III are applicable. For a surface burst, the distances would be scaled down to about 60 percent of those in the figure. Second, it is assumed that reasonably clear atmospheric conditions prevail, so that the attenuation is essentially independent of the visibility range as far out as 10 miles or more from ground zero. If the atmosphere is

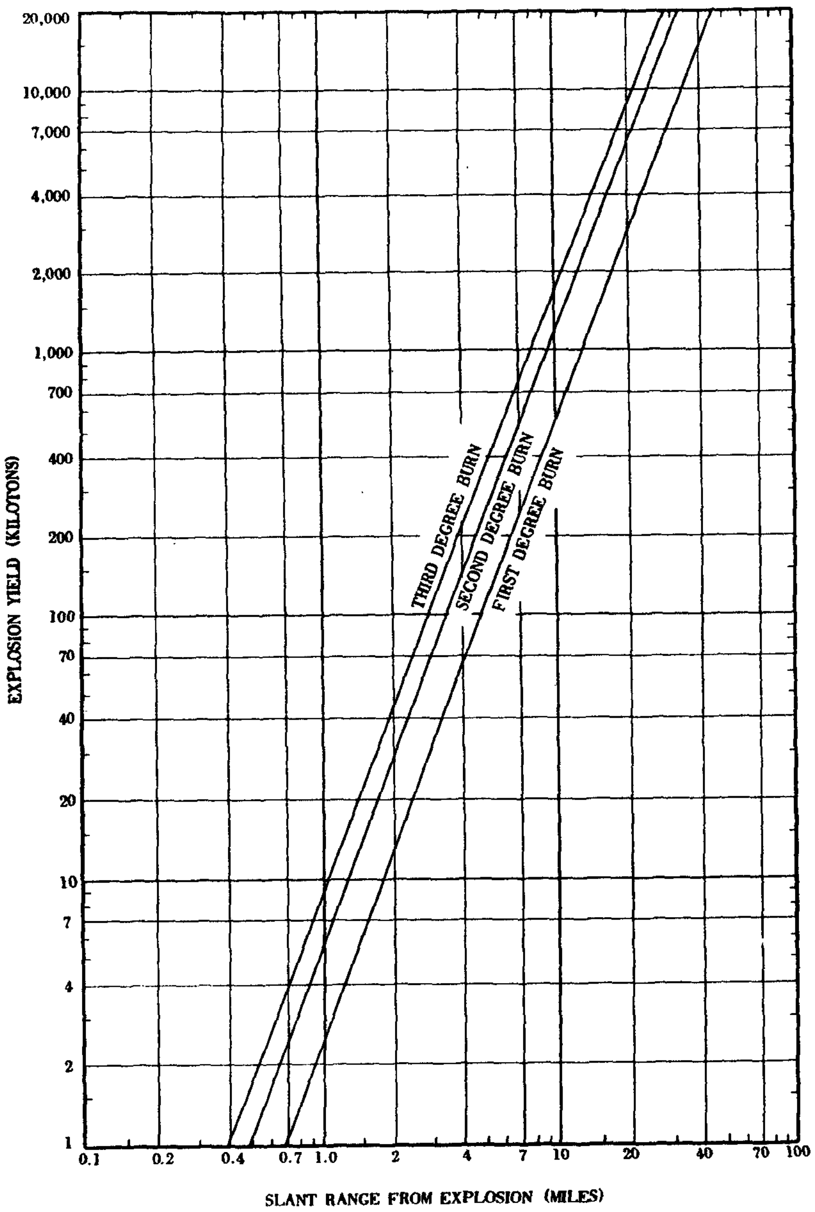

Figure 7.47. Distances at which burns occur on bare skin.

hazy, the distances predicted in Fig. 7.47, especially for the higher energy yields, may be somewhat in excess of the actual distances. They will certainly be too large if there is a substantial layer of cloud or smoke below the point of burst (§ 7.19, *et seq.*).

7.48 The application of Fig. 7.47 may be illustrated by using it to estimate the approximate limiting range for burns of the second degree in the event of an air burst of 100 kilotons energy. The figure is entered at the point where the vertical scale indicates 100 kilotons; the horizontal line is followed until it encounters the second curve, representing second-degree burn formation. The value on the horizontal (distance) scale corresponding to this point is seen to be 3.4 miles. Hence, it may be expected that, for a 100 kiloton explosion, moderate second-degree (or more severe) burns will be experienced as far out as 3.4 miles from the burst, under average atmospheric conditions.

## EFFECTIVENESS OF SECOND RADIATION PULSE

7.49 An important point to consider, especially from the standpoint of protection from thermal radiation, is the period during which the radiation is most effective in causing skin burns. It has been established, as already mentioned, that the proportion of the total thermal energy contained in the first radiation pulse, emitted while the surface temperature of the fireball is dropping toward the first minimum (Fig. 2.92), is small. However, it is still desirable to know whether the radiation emitted during the whole of the second pulse, from the minimum through the maximum and down to the second minimum, is significant.

7.50 Due to the decrease in thermal energy received per unit area at increasing distances from the fireball, more distant objects will receive less energy than those closer in. As objects are located farther and farther away from the explosion, the thermal energy received from all portions of the pulse is proportionately reduced, so that when the separation is great enough, no damage will be sustained. The part of the thermal pulse which can be most easily decreased to insignificance is toward the end, when the intensity of the ball of fire has become relatively low. Hence, at some distance from the explosion, the tail end of the thermal pulse may be ineffective in causing damage, although the high-intensity part, especially that around the temperature maximum, is still capable of inflicting injury. Closer to the fireball, the tail of the pulse will also be dangerous and the high-intensity region will be even more so.

7.51 At all distances from the explosion, the most dangerous part of the thermal pulse is that around the time of the second temperature maximum of the fireball. It is here that the thermal radiation intensity of (or the rate of energy emission from) the ball of fire is greatest. Consequently, the rate at which energy is delivered to objects at any distance from the explosion is also greatest. In other words, from a given explosion, more thermal energy will be received in a certain period of time around the temperature maximum than at any other equal period during the thermal pulse.

7.52 These facts are important in relation to the efficacy of evasive action that might be taken by individuals to reduce injuries due to thermal radiation. From what has been stated above, it is apparent that it is desirable to take such action before the temperature maximum in the second thermal pulse is reached.

7.53 In the case of an explosion in the kiloton range, it would be necessary to take shelter within a small fraction of a second if an appreciable decrease in thermal injury is to be realized. The time appears to be too short for evasive action to be possible. On the other hand, for explosions in the megaton range, shelter taken within a second or two of the appearance of the ball of fire could reduce the severity of injury due to thermal radiation in many cases and may even prevent injury in others. The problem of evasive action will be considered more fully in Chapter XII.

## PROTECTION AGAINST FLASH BURNS

7.54 As indicated in §7.21, the intervention of any shadow-producing object will decrease the extent of injury from thermal radiation. In a building, emergency shelter may be taken anywhere, away from windows, of course. Outdoors, some protection may be obtained in a ditch or behind a tree or utility pole. Probably the best instinctive action in any emergency situation is to drop to the ground in a prone position, behind the best available shelter, using the clothed parts of the body to protect the hands, face, and neck (see §12.60, *et seq.*).

7.55 Clothing can also provide protection against flash burns. Most common, light-colored clothing reflects a large fraction of the incident thermal radiation, so that appreciable protection is usually afforded. For example, two layers of cotton clothing—one a light-green oxford outer garment and the other a knitted undergarment—in contact were found to increase the energy required to cause a second-degree burn from 4 to 7.5 calories per square centimeter. If the layers of clothing are spaced from one another and from the skin, the required energy is even higher. However, since a moderately large amount of thermal energy may cause clothing to ignite (see Table 7.61), flame burns may occur even though there is no flash burn.

7.56 Dark fabrics are more effective in absorbing radiation than are those of light color. But as a result of absorbing the thermal radiation the material may become very hot. Heat will then be transferred, either by conduction or by radiation, to the skin. Conduction is the more likely mechanism and this will be particularly significant when the fabric is in contact with the skin. Thus, contact burns, which are neither flash burns nor flame burns, can result from dark colored clothing which actually touches the body. Flame burns will, of course, occur if the fabric gets hot enough to ignite.

7.57 White clothing materials of substantial weight reflect much of the thermal radiation, so that a relatively small amount is transmitted to the skin. However, white fabrics that are not very heavy may allow enough radiant energy to pass through to cause skin burns without being affected themselves.

7.58 As a general rule, at least two layers of clothing are desirable to provide reasonable protection against thermal injury. The outer garment should preferably be of a light color and the clothing should be loosely draped, to provide adequate air spaces between the layers and between the undergarment and the skin. Suitable treatment of fabrics, especially dark-colored materials, to render them flame retardant, would be very advantageous.

## THERMAL RADIATION DAMAGE TO MATERIALS

### Fabrics, Wood, and Plastics

7.59 Mention has been made earlier in this chapter of the specific damage caused to fabrics by the high surface temperatures accompanying the absorption of thermal radiation. Natural fibers, e. g., cotton and wool, and some synthetic materials, e. g., rayon, will scorch, char, and perhaps burn; nylon, on the other hand, melts when heated to a sufficient extent. The heat energy required to produce a particular change in a fabric depends on a variety of circumstances, as indicated in §7.35. The following generalizations, however, appear to hold in most instances.

7.60 Dark-colored fabrics absorb the radiation, and hence suffer damage more readily than do the same fabrics if light in color. Even in this connection there are variations according to the method of dyeing and the particular fiber involved. Wool is more resistant to radiant energy than cotton or rayon, and these are less easily affected than nylon. Orlon appears to be appreciably more resistant than nylon. Materials of light weight require less thermal energy to cause specific damage than do those of heavy weight. The energy required, for the same exposure time, is roughly proportional to the fabric weight per unit area. The moisture content is also an important factor; the larger the amount of moisture in the fabric, the greater is the energy required to damage it.

7.61 Although extensive studies have been made of the effects of thermal radiation on a large number of individual fabrics, it is difficult to summarize the results because of the many variables that have a significant influence. Some attempt is nevertheless made in Table 7.61 to give an indication of the magnitude of the energy needed to ignite various fabric materials due to the absorption of thermal radiation. The results are presented for total explosion (air or surface burst) energies of 20 kilotons and 10,000 kilotons (10 megatons), respectively. As in the case of skin burns, and for the same reason (§ 7.35), the thermal energy required is greater for explosions of higher yield.

7.62 Wood is charred by exposure to thermal radiation, the depth of the char being closely proportional to the energy received. For sufficiently large amounts of energy, wood in some massive forms may exhibit transient flaming but persistent ignition is improbable under the conditions of a nuclear explosion. However, the transitory flame may ignite adjacent combustible material which is not directly exposed to the radiation. In a more-or-less finely divided form, such as sawdust, shavings, or excelsior, or in a decayed, spongy (punk) state, wood can be ignited fairly readily by the thermal radiation from a nuclear explosion, as will be seen below.

7.63 Roughly speaking, something like 10 to 15 calories per square centimeter of thermal energy are required to produce visible charring of unpainted and unstained pine, douglas fir, redwood, and maple. Dark staining increases the tendency of the wood to char, but light-colored paints and hard varnishes provide protection.[4]

7.64 Glass is highly resistant to heat, but as it is very brittle it is sometimes replaced by transparent or translucent plastic materials or combined with layers of plastic, as in automobile windshields, to

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[4] The thermal radiation energy incident on the front of the house referred to in § 7.34 was about 25 calories per square centimeter.

TABLE 7.61

APPROXIMATE THERMAL ENERGIES FOR IGNITION OF FABRICS

| Material | Weight (oz/sq yd) | Ignition energy (cal/sq cm) | |
|---|---|---|---|
| | | 20 kilotons | 10 megatons |
| Rayon-acetate taffeta (wine) | 3 | 2 | 3 |
| Cotton chenille bedspread (light blue) | — | 4 | 8 |
| Doped fabric, aluminized cellulose acetate | — | 18 | 35 |
| Cotton muslin, oiled window shade (green) | 8 | 5 | 11 |
| Cotton awning canvas (green) | 12 | 5 | 9 |
| Cotton corduroy (brown) | 8 | 6 | 11 |
| Rayon twill lining (black) | 3 | 1 | 2 |
| Cotton venetian blind tape, dirty (white) | — | 7 | 12 |
| Cotton sheeting, unbleached, washed (cream) | 3 | 15 | 30 |
| Rayon twill lining (beige) | 3 | 8 | 16 |
| Rayon gabardine (black) | 6 | 3 | 6 |
| Cotton shirting (tan) | 5 | 7 | 13 |
| Cotton denim, used (blue) | 10 | 8 | 13 |
| Cotton and rayon auto seat cover (dark blue) | 9 | 8 | 13 |
| Acetate shantung (black) | 3 | 9 | 15 |
| Rayon-acetate drapery (wine) | 5 | 9 | 16 |
| Rayon marquisette curtain (ivory) | 2 | 9 | 14 |
| Cotton denim, new, washed (blue) | 10 | 9 | 14 |
| Cotton auto seat upholstery (green, brown, white) | 10 | 9 | 16 |
| Rayon gabardine (gold) | 7 | 9 | 20 |
| Cotton venetian blind strap (white) | — | 16 | 30 |
| Wool flannel, new, washed (black) | 7 | 8 | 16 |
| Cotton tapestry, tight weave (brown shades) | 12 | 16 | 30 |
| Wool surface, cotton base, auto seat upholstery (gray) | 13 | *16 | *35 |
| Wool, broadloom rug (gray) | 7 | *16 | *35 |
| Wool pile chair upholstery (wine) | 16 | *16 | *35 |
| Wool pile frieze chair upholstery (light brown) | 14 | *16 | *35 |
| Nylon hosiery (tan) | — | *5 | *10 |
| Cotton mattress stuffing (gray) | — | 8 | 16 |
| Burlap, heavy, woven (brown) | 18 | 8 | 16 |
| Rubberized canvas auto top (gray) | 20 | *16 | *28 |

*In these cases the material was not ignited to sustained burning by the incident thermal energy indicated.

make it shatterproof. These plastics are organic compounds and so are subject to decomposition by heat. Nevertheless, many plastic materials, such as Bakelite, cellulose acetate, Lucite, Plexiglass, polyethylene, and Teflon, have been found to withstand thermal radiation remarkably well. At least 60 to 70 calories per square centimeter of thermal energy are required to produce surface melting or darkening.

### THERMAL ENERGIES FOR IGNITION OF VARIOUS MATERIALS

7.65 In connection with the initiation of fires, the thermal energies required for the ignition of various common household and other materials are of great interest. Studies have been made both in the laboratory and at nuclear tests, and although the results are by no means definitive, they do provide a general indication of the amount of thermal energy that would be needed to cause a particular material to ignite. The data in Table 7.65 have been divided into two sections: one contains household materials and the other combustible substances which might start forest fires. It is evident that there are combustible materials around many homes which could be ignited by an exposure to 3 calories per square centimeter of thermal radiation. Almost any thin, flammable household fabric would ignite if exposed to 10 calories per square centimeter.

7.66 As far as the forest fuels are concerned, in particular, the ignition energies are greatly dependent upon the amount of moisture they contain. For the present purpose, it has been assumed that the leaves and grass were fairly dry, so that the energies are essentially minimum values. In the presence of some dry fuel, thermal radiation may start a fire; it will then spread among combustible materials of higher moisture content which could not be directly ignited by the radiation.

### THERMAL ENERGY-DISTANCE RELATIONSHIPS

7.67 In order to utilize the data in Tables 7.61 and 7.65 to determine how far from the burst point, for an explosion of given energy yield, ignition of a particular material would be observed, it is required to know how the thermal energy varies with distance for the particular yield. A convenient way of representing this information is shown in Fig. 7.67, assuming a reasonably clear state of the atmosphere.

7.68 Suppose it is required to determine the range over which fires may be expected to be initiated by thermal radiation as a result of a 1,000 kiloton (1 megaton) air burst. The thermal energy required for

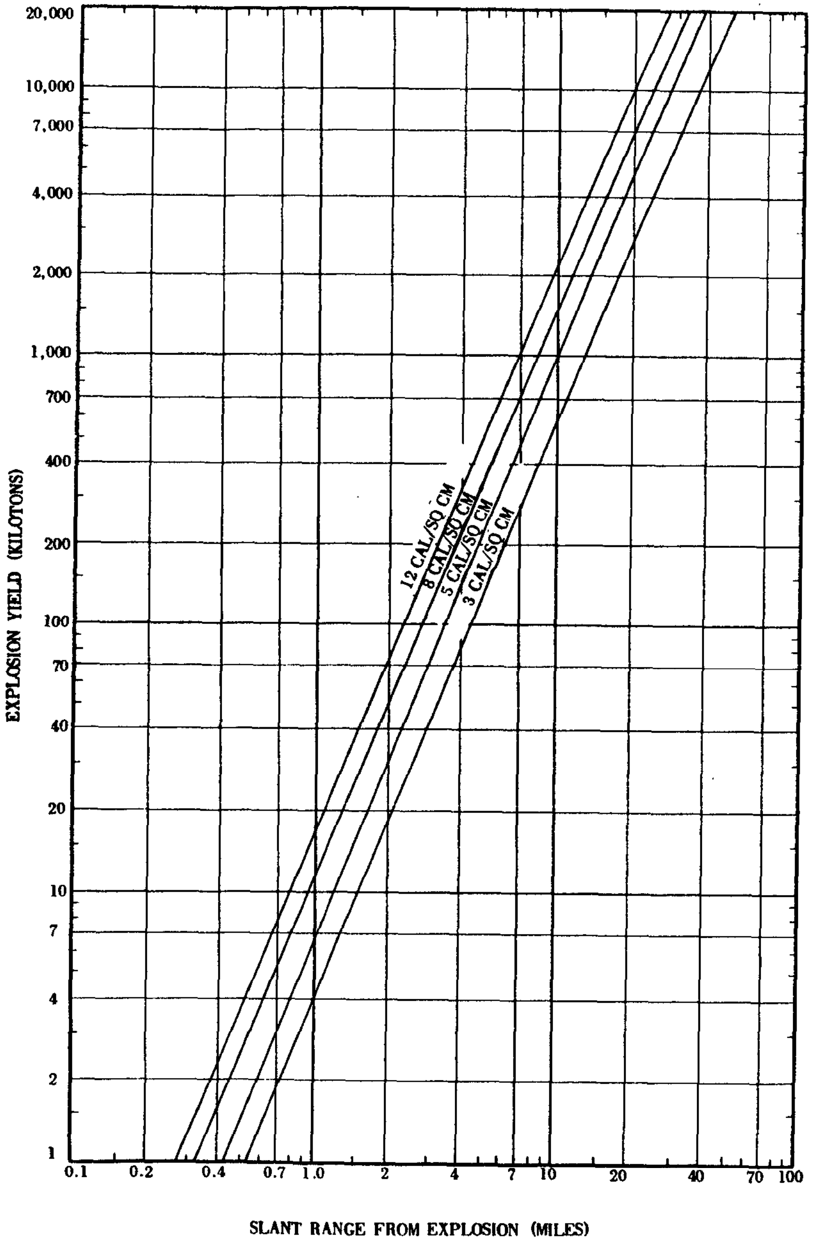

Figure 7.67. Thermal energy received at various slant ranges.

TABLE 7.65

THERMAL ENERGIES FOR IGNITION OF HOUSEHOLD MATERIALS

| Material | Weight (oz/sq yd) | Ignition energy (cal/sq cm) | |
|---|---|---|---|
| | | 20 kilotons | 10 megatons |
| Dust mop (oily gray) | — | 3 | 5 |
| Newspaper, shredded | 2 | 2 | 4 |
| Paper, crepe (green) | 1 | 4 | 8 |
| Newspaper, single sheet | 2 | 3 | 6 |
| Newspapers piled flat, surface exposed | — | 3 | 6 |
| Newspapers, weathered, crumpled | 1 | 3 | 6 |
| Newspaper, crumpled | 2 | 4 | 8 |
| Cotton waste (oily gray) | — | 5 | 8 |
| Paper, bond typing, new (white) | 2 | 15 | 30 |
| Paper, Kraft, single sheet (tan) | 2 | 7 | 14 |
| Matches, paper book, blue heads exposed | — | 5 | 9 |
| Cotton string scrubbing mop, used (gray) | — | 6 | 10 |
| Cellulose sponge, new (pink) | 39 | 6 | 10 |
| Cotton string mop, weathered (cream) | — | 7 | 13 |
| Paper bristol board, 3 ply (dark) | 10 | 8 | 15 |
| Paper bristol board, 3 ply (white) | 10 | 12 | 25 |
| Kraft paper carton, flat side, used (brown) | 16 | 8 | 15 |
| Kraft paper carton, corrugated edges exposed, used (brown) | — | 12 | 25 |
| Straw broom (yellow) | — | 8 | 17 |
| Excelsior, Ponderosa pine (light yellow) | 2 lb/cu ft | 5 | 12 |
| Tampico fiber scrub brush, used (dirty yellow) | — | 10 | 20 |
| Palmetto fiber scrub brush, used (rust) | — | 12 | 25 |
| Twisted paper, auto seat cover, used (multicolor) | 13 | 12 | 25 |
| Leather, thin (brown) | 6 | *15 | *30 |
| Vinyl plastic auto seat cover | 10 | *16 | *27 |
| Woven straw, old (yellow) | 13 | *16 | *33 |

*Indicates material was not ignited to sustained burning by the incident thermal energy indicated.

ignition to occur, under average conditions, may be estimated from the results in Table 7.65 to be about 5 calories per square centimeter. Entering Fig. 7.67 at the point on the vertical axis corresponding to 1,000 kilotons, the horizontal line is followed across until it intersects the

Figure 7.71. The skin under the areas of contact with clothing is burned. The protective effect of thicker layers can be seen on the shoulders and across the back.

as described in § 7.57, rather than to the direct effect of radiation. Areas over which the clothing fitted loosely, so that an air space separated it from the skin, were generally unharmed by the radiation (Fig. 7.71).

7.72 There were many instances in which burns occurred through black clothing, but not through white material worn by the same individuals (Fig. 7.72). This was attributed to the reflection of thermal radiation by white or other light-colored fabrics, whereas materials of dark color absorbed radiation, became hot, and so caused contact burns. In some cases black outer clothing actually burst into flame and ignited the undergarments, so that flame burns resulted. It should be recalled, however, as mentioned in § 7.57, that white clothing does not always necessarily provide protection against thermal radiation. Some materials of this kind transmit enough radiation to permit flash burning of the skin to occur.

Figure 7.72. The patient's skin is burned in a pattern corresponding to the dark portions of a kimono worn at the time of the explosion.

## OTHER EFFECTS OF THERMAL RADIATION

7.73 Apart from the actual ignition of combustible materials resulting in fires being started, which will be referred to later, a number of other phenomena observed in Japan testified to the intense heat due

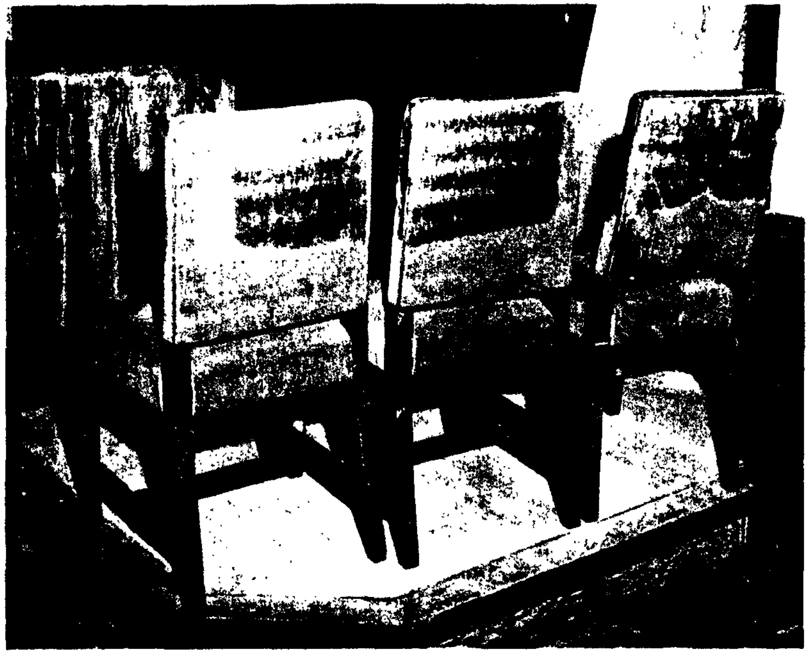

**Figure 7.73a.** *Flash burns on upholstery of chairs exposed to bomb flash at window* (1 mile from ground zero at Hiroshima).

to the absorption of thermal radiation. Fabrics (Fig. 7.73a), utility poles (Fig. 7.73b), trees, and wooden posts, up to a radius of 11,000 feet (2.1 miles) from ground zero at Nagasaki, and 9,000 feet (1.7 miles) at Hiroshima (3 to 4 calories per square centimeter), if not destroyed in the general conflagration, were charred and blackened, but only on the side facing the point of burst. Where there was protection by buildings, walls, hills, and other objects there was no evidence of thermal radiation effects.

7.74 An interesting case of shadowing of this kind was recorded at Nagasaki. The tops and upper parts of a row of wooden posts were heavily charred, but the charred area was sharply limited by the shadow of a wall. The wall was, however, completely demolished by the blast wave which arrived after the thermal radiation. As stated earlier, this radiation travels with the speed of light, whereas the blast wave advances much more slowly (§ 3.14).

7.75 From observations of the shadows left by intervening objects where they shielded otherwise exposed surfaces (Figs. 7.75a and b), the direction of the center of the explosion was located with con-

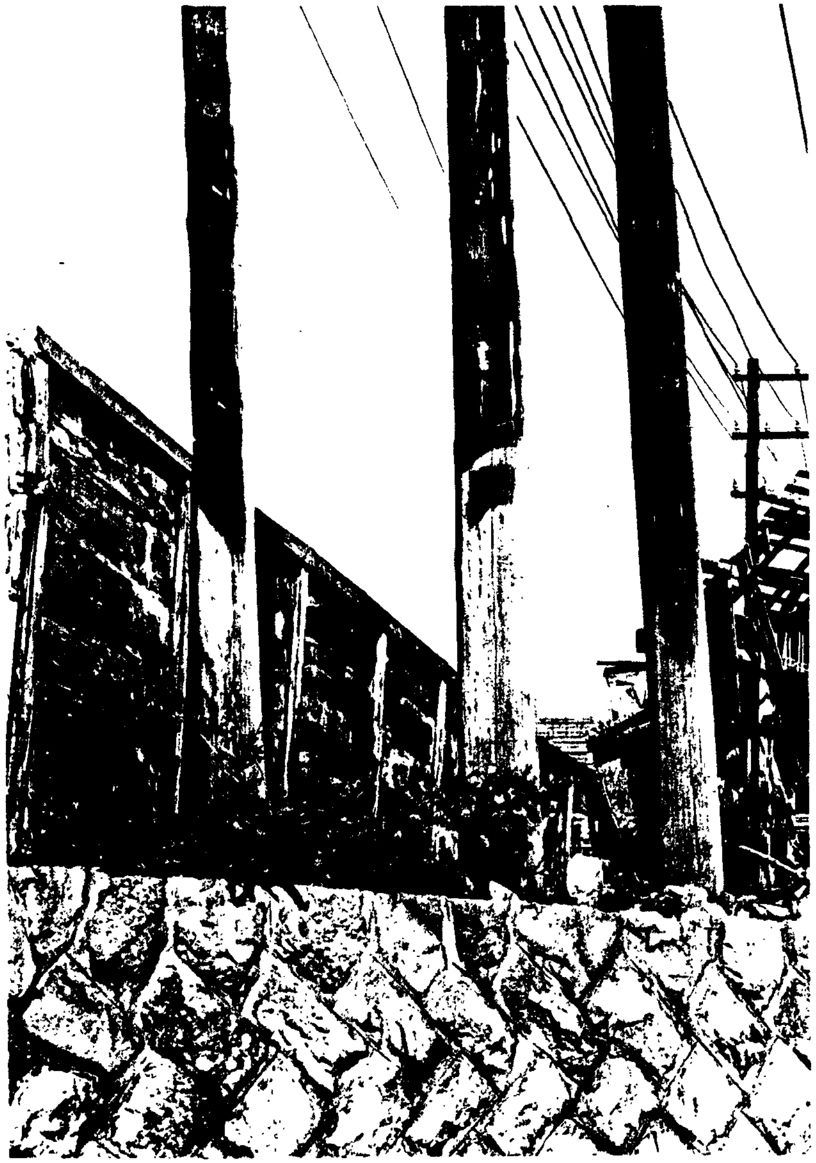

**Figure 7.73b.** Flash burns on wooden poles (1.17 miles from ground zero at Nagasaki). *The uncharred portions were protected from thermal radiation by a fence.*

Figure 7.75a. Flash marks produced by thermal radiation on asphalt of bridge in Hiroshima. Where the railings served as a protection from the radiation, there were no marks; the length and direction of the "shadows" indicate the point of the bomb explosion.

siderable accuracy. Further, by examining the shadow effects at various places around the explosion, a good indication was obtained of the height of burst. Occasionally, a distinct penumbra was found, and from this it was possible to calculate the diameter of the ball of fire at the time the thermal radiation intensity was at a maximum.

7.76 One of the striking effects of the radiation was the roughening of the surface of polished granite where there was direct exposure. This roughening was attributed to the unequal expansion of the constituent crystals of the stone, and it is estimated that a temperature of at least 600° C. (1,100° F.) was necessary to produce the observed results. From the depth of the roughening and ultimate flaking of the granite surface, the depth to which this temperature was attained could be determined. These observations were used to calculate the maximum ground temperatures at the time of the explosion. As seen in § 7.32, they were extremely high, especially near ground zero.

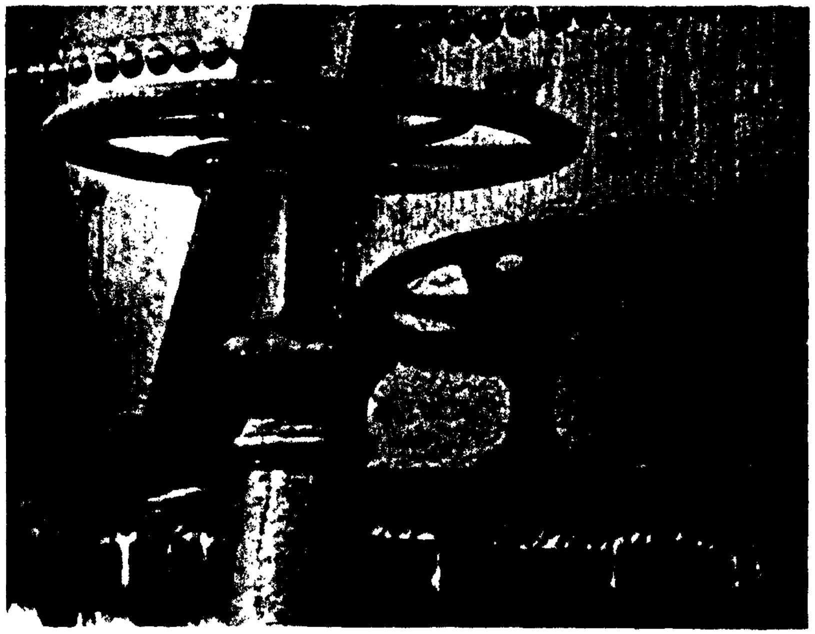

Figure 7.75b. Paint on gas holder scorched by the thermal radiation, except where protected by the valve (1.33 miles from ground zero at Hiroshima).

7.77 Another thermal effect, which proved to be valuable in subsequent studies, was the bubbling or blistering of the dark green (almost black) tile with a porous surface which is widely used for roofing in Japan (Fig. 7.77). The phenomenon was observed out to 3,900 feet (0.76 mile) from the explosion center, where the thermal energy was about 40 calories per square centimeter. The size of the bubbles and their extent increased with proximity to ground zero, and also with the directness with which the tile itself faced the explosion. In a laboratory test, using undamaged tile of the same kind, it was found that similar blistering could be obtained by heating to 1,800° C. (3,270° F.) for a period of 4 seconds, although the effect extended deeper into the tile than it did in Japan. From this result, it was concluded that in the nuclear explosion a temperature of more than

Figure 7.77. Blistered surface of roof tile; left portion of the tile was shielded by an overlapping one (0.37 mile from the explosion at Hiroshima).

1,800° C. (3,270° F.) was attained for a period of less than 4 seconds.

7.78 The difference in behavior of light and dark fabrics exposed to thermal radiation in Japan is also of considerable interest. Light-colored fabrics either reflect or transmit most of the thermal radiation and absorb very little. Consequently, they will not reach such a high temperature, and so will suffer less damage than dark fabrics which absorb a large proportion of the radiation. In one case, a shirt consisting of alternate narrow light and dark gray stripes had the dark stripes burned out, whereas the light-colored stripes were undamaged (Fig. 7.78). Similarly, a piece of paper, which had been exposed about 7,800 feet (1.5 miles) from ground zero (5 calories per square centimeter), had the characters, written in black ink, burned out, but the rest of the paper was not greatly affected.

## INCENDIARY EFFECTS

### Origin of Fires

7.79 There are two general ways in which fires can originate in a nuclear explosion. First, by the ignition of paper, trash, window curtains, awnings, excelsior, dry grass, and leaves, as a direct result of the absorption of thermal radiation. And second, as an indirect effect of the destruction caused by the blast wave, fires can be started by upset stoves and furnaces, electrical short-circuits, and broken gas lines. No matter how the fire originates, its subsequent spread will be determined by the amount and distribution of combustible materials in the vicinity. It is seen, therefore, that the problem of the development of fires accompanying a nuclear explosion falls into two distinct categories: (1) the number of points at which fires originate, and (2) the character of the surrounding area.

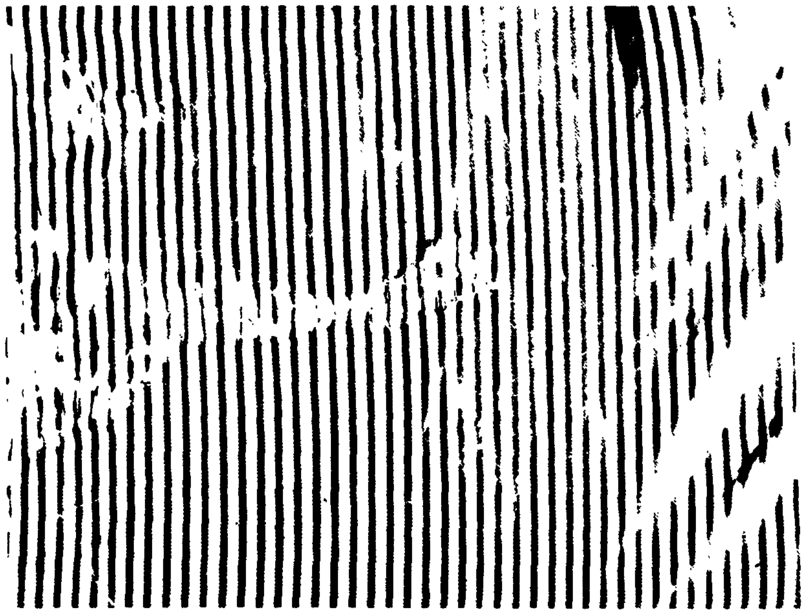

Figure 7.78. The light-colored portions of the material are intact, but some of the dark-colored stripes have been destroyed by the heat from the thermal radiation.

7.80 The initiation of secondary (or indirect) fires is difficult to analyze, but there are some aspects of direct ignition by thermal radiation which are reasonably clear. The most important appears to be what has been called the "density of ignition points." This is the number of points in a given area, e. g., an acre, where exterior combustible materials, such as those mentioned in the preceding paragraph, might be found. In general, these materials might be expected to ignite when exposed to from 3 to 5 calories per square centimeter of radiant energy. The data in Fig. 7.80 are based on surveys made in a

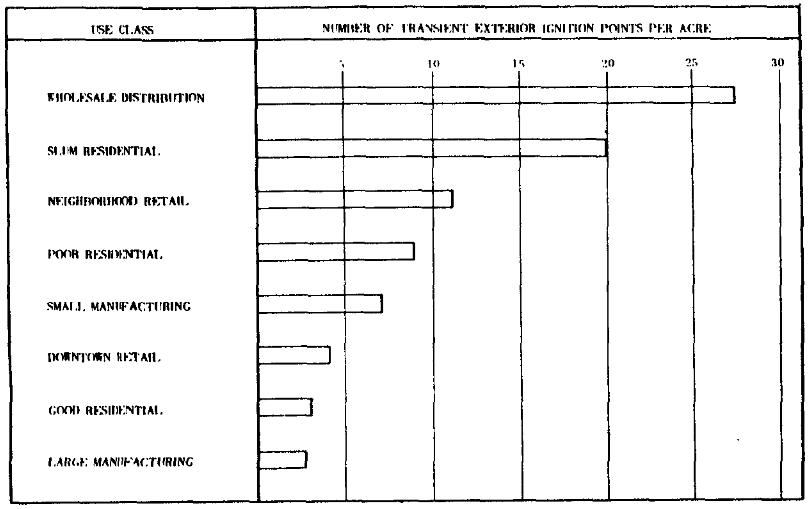

**Figure 7.80.** Frequency of exterior ignition points for various areas in a city.

number of large cities in the United States. It is seen that the density of ignition points is greatest in wholesale distribution and slum residential areas, and is least in good residential and large manufacturing areas.[5] Paper was the commonest ignitable material found everywhere except in downtown retail areas where awnings represented the major source of fire.

7.81 The density of ignition points provides some indication of the chance of fires being started under ideal weather conditions. But the results in Fig. 7.80 are by themselves not sufficient to permit an estimate to be made of the number of significant fires that will actually result. In the first place, at locations closer to ground zero, where the thermal energy exceeds about 12 calories per square centimeter, almost all the ignitable materials will actually flame (Table 7.65). On the other hand, at greater distances, only those most easily ignitable will catch fire. Further, the formation of a significant fire, capable of spreading, will require appreciable quantities of combustible material close by, and this may not always be available.

7.82 The fact that accumulations of ignitable trash close to a wooden structure represent a real fire hazard was demonstrated at the nuclear tests carried out in Nevada in 1953. In these tests, three miniature wooden houses, each having a yard enclosed with a wooden fence, were exposed to 12 calories per square centimeter of thermal radiation. One house, at the left of Fig. 7.82, had weathered siding showing considerable decay, but the yard was free from trash. The next house also had a clean yard and, further, the exterior siding was well maintained and painted. In the third house, at the right of the photograph, the siding, which was poorly maintained, was weathered, and the yard was littered with trash.

7.83. The state of the three houses after the explosion is seen in Fig. 7.83. The third house, at the right, soon burst into flame and was burned to the ground. The first house, on the left, did ignite but it did not burst into flame for 15 minutes. The well maintained house in the center with the clean yard suffered scorching only. It is of interest to recall that the wood of a newly erected white-painted house exposed to about 25 calories per square centimeter was badly charred but did not ignite (Fig. 7.34b).

7.84 The value of fire-resistive furnishing in decreasing the number of ignition points was also demonstrated in the 1953 tests. Two identical, sturdily constructed houses, each having a window 4 feet by 6 feet facing the point of burst, were erected where the thermal radiation exposure was 17 calories per square centimeter. One of the houses contained rayon drapery, cotton rugs, and clothing, and, as was expected, it burst into flame immediately after the explosion and burned completely. In the other house, the draperies were of vinyl plastic, and rugs and clothing were made of wool. Although more ignition occurred, the recovery party, entering an hour after the explosion, was able to extinguish fires.

7.85 There is another point in connection with the initiation of fires by thermal radiation that needs consideration. This is the possibility that the flame resulting from the ignition of a combustible material may be subsequently extinguished by the blast wind. It was thought that there was evidence for such an effect from an observation made in Japan (§ 7.92), but this may have been an exceptional case. The matter has been studied, both in connection with the effects in Japan and at various nuclear tests, and the general conclusion is that the blast wind has no significant effect in extinguishing fires (see § 7.93).

### SPREAD OF FIRES

7.86 The spread of fires in a city, depends upon a variety of conditions, e. g., weather, terrain, and closeness and combustibility of the buildings. A detailed review of large-scale fires has shown, however, that if other circumstances are more-or-less the same, the most

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[5] The area types are in accordance with the classification used by the U. S. Bureau of Census.

Figure 7.82. Wooden test houses before exposure to a nuclear explosion, Nevada Test Site.

Figure 7.83. Wooden test houses after exposure to the nuclear explosion.

important criterion of the probability of fire spread is the distance between buildings. It is evident, from general considerations, that the lower the building density or "built-upness" of an area, the less will be the probability that fire will spread from one structure to another. Further, the larger the spaces between buildings the greater the chances that the fire can be extinguished.

7.87 The curve in Fig. 7.87 gives a rough idea of how the probability of fire spread, expressed as a percentage, depends upon the average distance between buildings in a city. The results will be dependent, to some extent, upon the types of structures involved, e. g., whether they are fire-resistive or not, as well as upon the damage caused by the blast wave (§ 7.79). It should be noted that Fig. 7.87 applies to fire spread accompanying a nuclear explosion, when a large number of small fires are started directly by thermal radiation and indirectly in other ways.

7.88 Another aspect of fire spread is the development of mass fires in a forest following primary ignition of dried leaves, grass, and rotten wood by the thermal radiation. Some of the factors which will influence the growth of such fires are the moisture content of the trees,

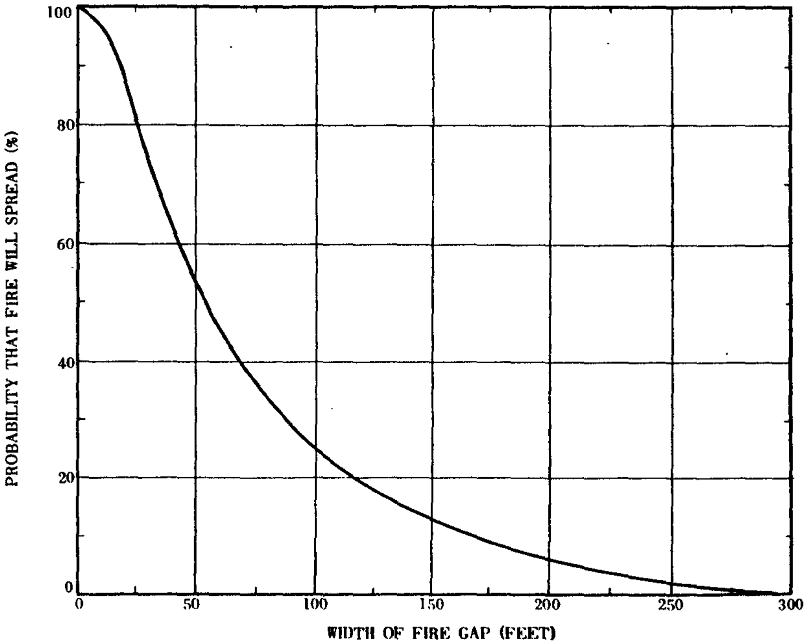

Figure 7.87. Width of gap and probability of fire spread.

topography, and meteorological conditions. Low atmospheric humidity, strong winds, and steep terrain favor the development of forest fires. In general, a deciduous forest, particularly when in leaf, may be expected to burn less rapidly and with less intensity than a forest of coniferous trees. Green leaves and the trunks of trees would act as shields against thermal radiation, so that the number of points at which ignition occurs in a forest may well be less than would appear at first sight.

## INCENDIARY EFFECTS IN JAPAN

### The Nuclear Bomb as an Incendiary Weapon

7.89 The incendiary effects of a nuclear explosion do not present any especially characteristic features. In principle, the same over-all result, as regards destruction by fire and blast, might be achieved by the use of conventional incendiary and high-explosive bombs. It has been estimated, for example, that the fire damage to buildings and other structures suffered at Hiroshima could have been produced by about 1,000 tons of incendiary bombs distributed over the city. It can be seen, however, that since this damage was caused by a single nuclear bomb of only 20 kilotons energy yield, nuclear weapons are capable of causing tremendous destruction by fire, as well as by blast.

7.90 Evidence was obtained from the nuclear explosions over Japan that the damage by fire is much more dependent upon local terrain and meteorological conditions than are blast effects. At both Hiroshima and Nagasaki the distances from ground zero at which particular types of blast damage were experienced were much the same. But the range of incendiary effects was quite different. In Hiroshima, for example, the total area severely damaged by fire, about 4.4 square miles, was roughly four times as great as in Nagasaki. One contributory cause was the irregular layout of Nagasaki as compared with Hiroshima; also greater destruction could probably have been achieved by a change in the point of burst. Nevertheless, an important factor was the difference in terrain, with its associated building density. Hiroshima was relatively flat and highly built up, whereas Nagasaki had hilly portions near ground zero that were bare of structures.

### Origin and Spread of Fires in Japan

7.91 Definite evidence was obtained from Japanese observers that the thermal radiation caused thin, dark cotton cloth, such as the

black-out curtains that were in common use during the war, thin paper, and dry, rotted wood to catch fire at distances up to 3,500 feet (0.66 mile) from ground zero (about 35 calories per square centimeter). It was reported that a cedar bark roof farther out was seen to burst into flame, apparently spontaneously, but this was not definitely confirmed. Abnormal enhanced amounts of radiation, due to reflection, scattering, and focusing effects, might have caused fires to originate at isolated points (Fig. 7.91).

7.92 Interesting evidence of the ignition of sound wood was found about a mile from ground zero at Nagasaki, where the thermal energy was approximately 15 calories per square centimeter. A light piece of wood, similar to the flat side of an orange crate, had its front surface charred. In addition, however, blackening was observed through cracks and nail holes, where the thermal radiation would not have penetrated, and also around the edges adjoining the charred surface. A possible explanation is that the exposed surface of the wood had actually ignited, due to the heat from the thermal radiation, and the flames had spread through the cracks and holes around the edges for several seconds, before they were extinguished by the blast wind.

7.93 From the evidence of charred wood found at both Hiroshima and Nagasaki, it was originally concluded that such wood had actually been ignited by thermal radiation and that the flames were subsequently extinguished by the blast. But it now seems more probable that, apart from some exceptional instances, such as that just described, there was no actual ignition of the wood. The absorption of the thermal radiation caused charring in sound wood but the temperatures were generally not high enough for ignition to occur (§ 7.34). Rotted and checked wood and excelsior, however, have been known to burn completely, and the flame is not greatly affected by the blast wave.

7.94 It is not known to what extent thermal radiation contributed to the initiation of fires in the nuclear bombings in Japan. It is possible that, up to a mile or so from ground zero, some fires may have originated from secondary causes, such as upsetting of stoves, electrical short-circuits, broken gas lines, and so on, which were a direct effect of the blast wave. A number of fires in industrial plants were initiated by furnaces and boilers being overturned, and by the collapse of buildings on them.

7.95 Once the fires had started, there were several factors, directly related to the destruction caused by the nuclear explosion, that influenced their spreading. By breaking windows and blowing in or

Figure 7.91. The top of a wood pole was reported as being ignited by the thermal radiation (1.25 miles from ground zero at Hiroshima). Note the unburned surroundings; the nearest burned building was 360 feet away.

damaging fire shutters (Fig. 7.95), by stripping wall and roof sheathing, and collapsing walls and roofs, the blast made many buildings more vulnerable to fire. Noncombustible (fire-resistive) structures were often left in a condition favorable to the internal spread of fires by damage at stairways, elevators, and in firewall openings, as well as by the rupture and collapse of floors and partitions (Fig. 4.85d).

Figure 7.95. Fire shutters in building blown in or damaged by the blast; shutter at center probably blown outward by blast passing through building (0.57 mile from ground zero at Hiroshima).

7.96 On the other hand, when combustible frame buildings were blown down, they did not burn as rapidly as they would have done had they remained standing. Further, the noncombustible debris produced by the blast frequently covered and prevented the burning of combustible material. There is some doubt, therefore, whether, on the whole, the effect of the blast was to facilitate or to hinder the development of fires at Hiroshima and Nagasaki.

7.97 Although there were firebreaks, both natural, e. g., rivers and open spaces, and artificial, e. g., roads and cleared areas, in the Japanese cities, they were not very effective in preventing the fires from spreading. The reason was that fires often started simultaneously on both sides of the firebreaks, so that they could not serve their intended purpose. In addition, combustible materials were frequently strewn across the firebreaks and open spaces, such as yards and street areas, by the blast, so that they could not prevent the spread of fires. Nevertheless, there were a few instances where firebreaks assisted in preventing the burn-out of some fire-resistive buildings.

7.98 One of the important aspects of the nuclear bomb attacks on Japan was that, in the large area that suffered simultaneous blast damage, the fire departments were completely overwhelmed. It is true that the fire-fighting services and equipment were poor by American standards, but it is doubtful if much could have been achieved, under the circumstances, by more efficient fire departments. At Hiroshima, for example, 70 percent of the fire-fighting equipment was crushed in the collapse of fire houses, and 80 percent of the personnel were unable to respond. Even if men and machines had survived the blast, many fires would have been inaccessible because of the streets being blocked with debris. For this reason, and also because of the fear of being trapped, a fire company from an area which had escaped destruction was unable to approach closer than 6,600 feet (1.25 miles) from ground zero at Nagasaki. It was almost inevitable, therefore, that all buildings within this range would be destroyed.

7.99 Another contributory factor to the destruction by fire was the failure of the water supply in both Hiroshima and Nagasaki. The pumping stations were not largely affected, but serious damage was sustained by distribution pipes and mains, with a resulting leakage and drop in available water pressure. Most of the lines above ground were broken by collapsing buildings and by heat from the fires which melted the pipes. Some buried water mains were fractured and others were broken due to the collapse or distortion of bridges upon which they were supported (§4.113).

### Fire Storm in Hiroshima

7.100 About 20 minutes after the detonation of the nuclear bomb at Hiroshima, there developed the phenomenon known as "fire storm." This consisted of a wind which blew toward the burning area of the city from all directions, reaching a maximum velocity of 30 to 40 miles per hour about 2 to 3 hours after the explosion, decreasing to light or moderate and variable in direction about 6 hours after. The wind was accompanied by intermittent rain, light over the center of the city and heavier about 3,500 to 5,000 feet (0.67 to 0.95 mile) to the north and west. Because of the strong inward draft at ground level, the fire storm was a decisive factor in limiting the spread of the fire beyond the initial ignited area. It accounts for the fact that the radius of the burned-out area was so uniform in Hiroshima and was not much greater than the range in which fires started soon after the explosion. However, virtually everything combustible within this region was destroyed.

7.101 It should be noted that the fire storm is by no means a special characteristic of the nuclear bomb. Similar fire storms have been reported as accompanying large forest fires in the United States, and especially after incendiary bomb attacks in both Germany and Japan during World War II. The high winds are produced largely by the updraft of the heated air over an extensive burning area. They are thus the equivalent, on a very large scale, of the draft of a chimney under which a fire is burning. The rain associated with a fire storm is apparently due to the condensation of moisture on particles from the fire when they reach a cooler area.

7.102 The incidence of fire storms is dependent on the conditions existing at the time of the fire. Thus, there was no such definite storm over Nagasaki, although the velocity of the southwest wind, blowing between the hills, increased to 35 miles an hour when the conflagration had become well established, perhaps about 2 hours after the explosion. This wind tended to carry the fire up the valley in a direction where there was nothing to burn. Some 7 hours later, the wind had shifted to the east and its velocity had dropped to 10 to 15 miles per hour. These winds undoubtedly restricted the spread of fire in the respective directions from which they were blowing. The small number of dwellings exposed in the long narrow valley running through Nagasaki probably did not furnish sufficient fuel for the development of a fire storm as compared to the many buildings on the flat terrain at Hiroshima.

## TECHNICAL ASPECTS OF THERMAL RADIATION[6]

### Spectral Distribution of Energy from Ball of Fire

7.103 If it can be assumed that the ball of fire in a nuclear explosion, like the sun, behaves rather like a black body, i. e., as a perfect radiator, the distribution of the thermal radiation energy over the

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[6] The remaining sections of this chapter may be omitted without loss of continuity.

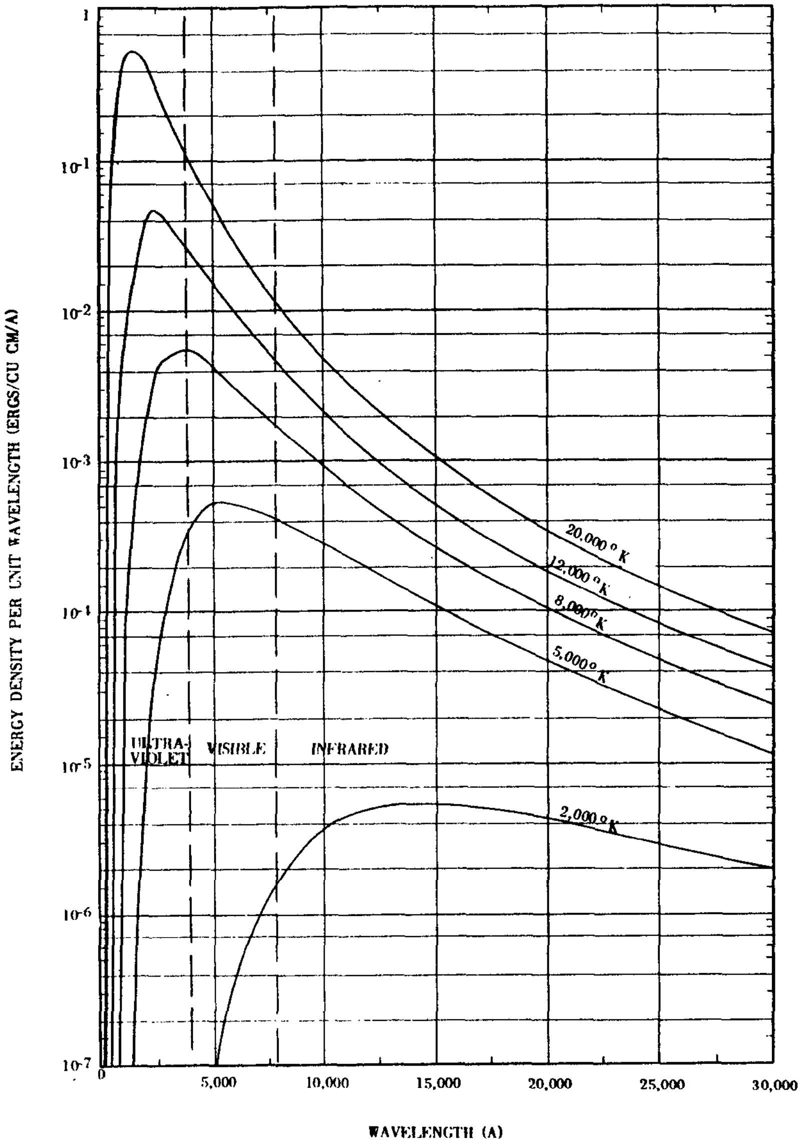

Figure 7.104. Energy density per unit wave length of radiations of various wave lengths.

spectrum can be related to the surface temperature by Planck's radiation equation. If $E_\lambda d\lambda$ denotes the energy density, i. e., energy per unit volume, in the wave length interval $\lambda$ to $\lambda+d\lambda$, then,

$$E_\lambda=\frac{8\pi hc}{\lambda^5}\cdot\frac{1}{e^{hc/\lambda kT}-1}, \tag{7.103.1}$$

where $c$ is the velocity of light, $h$ is Planck's quantum of action, $k$ is Boltzmann's constant, i. e., the gas constant per molecule, and $T$ is the absolute temperature.

7.104 From the Planck equation it is possible to calculate the energy density of the thermal radiation from a nuclear explosion over a range of wave lengths for any specified temperature. The results obtained for several temperatures are shown by the curves in Fig. 7.104. It will be apparent that at temperatures exceeding about 8,000° K., such as is the case during most of the first radiation pulse from the ball of fire, i. e., prior to the first temperature minimum, much of the thermal energy emitted lies in the short wave length (ultraviolet) region of the spectrum.

7.105 As the temperature of the black-body radiator decreases, the wave length at which the energy density is a maximum is seen to move to the right, i. e., to regions of higher wave length. An expression for the wave length for maximum energy density, $\lambda_m$, can be obtained by differentiating equation (7.103.1) with respect to wave length and equating the result to zero. It is then found that

$$\lambda_m=\frac{A}{T}, \tag{7.105.1}$$

where $A$ is a constant, equal to 0.2897 angstrom-degree K. Hence, the wave length for maximum energy density is inversely related to the absolute temperature.

7.106 From the known value of $A$, it can be calculated that the maximum energy density of thermal radiation just falls into the visible region of the spectrum at a temperature of about 7,600° K. This happens to be very close to the maximum surface temperature of the ball of fire after the minimum, i. e., during the second radiation pulse (Fig. 2.92). Since the temperature does not exceed 7,600° K. and the average is considerably less, it is evident that most of the radiant energy emitted in the second pulse consists of visible and infrared rays, with very little in the ultraviolet region of the spectrum.

## THERMAL ENERGY FROM BALL OF FIRE

7.107. For the present purpose, the total rate of emission of thermal radiation energy from the ball of fire is more significant than the distribution of radiation density. According to the Stefan-Boltzmann law for black-body radiation, the flux (or intensity) of radiant energy, $\phi$, i. e., the amount of energy passing through 1 square centimeter of surface of a black body per second, is related to the absolute temperature, $T$, by the equation,

$$\phi=\sigma T^4, \tag{7.107.1}$$

where $\sigma$ is a constant. The value of $\phi$ can also be obtained by integration of the Planck equation (7.103.1), at constant temperature, over the whole range of wave lengths, from zero to infinity. It is then found that

$$\begin{aligned}\sigma&=2\pi^5k^4/15h^3c^2\\&=1.38\times10^{-12}\text{cal/(cm}^2\text{) (sec) (deg}^4\text{)}.\end{aligned}$$

With $\sigma$ known, the total radiant energy intensity from the ball of fire behaving as a black body can be readily calculated for any required temperature.

7.108 According to equation (7.107.1), the intensity of the radiation emitted from the ball of fire at any temperature is proportional to the fourth power of that temperature on the absolute scale. Since the surface temperatures are very high during the first radiation pulse, the rate of energy emission (per unit area), mainly in the ultraviolet region, will also be high. However, because of the short duration of the initial pulse, the total *quantity* of energy emitted is relatively small. In any case, most of what is emitted is absorbed and scattered by the atmosphere before it travels any appreciable distance from the fireball.

7.109 In accordance with the definition of radiation flux, $\phi$, given in § 7.107, it follows that the total rate of emission of radiant energy from the ball of fire can be obtained upon multiplying the expression in equation (7.107.1) by the area. If $R$ is the radius of the fireball, its area is $4\pi R^2$, so that the rate of thermal energy emission is $\sigma T^4\times4\pi R^2$. This is the same as the thermal power, since power is defined as the rate of production (or expenditure) of energy. Representing this quantity by the symbol $P$, it follows that

$$\begin{aligned}P&=4\pi\sigma T^4R^2\\&=1.71\times10^{-11}T^4R^2 \text{ calories per second,}\end{aligned}$$

where $T$ is in degrees Kelvin and $R$ is in centimeters. Alternatively, if the radius, $R$, is expressed in feet, then,

$$P=1.59\times10^{-8}T^4R^2 \text{ calories per second.} \tag{7.109.1}$$

7.110 The results of numerous tests have shown that the ball of fire does not, in fact, behave as a perfect radiator. This is due to a number of factors. The surface temperature during the first radiation pulse is modified by the disturbed air immediately around the fireball and, at later times, the temperature is not that of the surface but the result of radiation some distance inside the fireball. The radius of the ball of fire during the second thermal pulse is very difficult to determine because the surface of the luminous ball of fire becomes very diffuse. Since the radii and surface temperatures will depend on the energy yield of the explosion, a different curve will be obtained for every value of the yield. However, it is possible to generalize the results, by means of scaling laws, so that a curve applicable to the second pulse for all energy yields can be obtained from a single set of calculations.

7.111 Actually the power, $P$, is measured directly as a function of time, $t$, for each explosion. However, instead of plotting $P$ versus $t$, a curve is drawn of the scaled power, i. e., $P/P_{\max}$, versus the scaled time, i. e., $t/t_{\max}$, where $P_{\max}$ is the maximum value of the thermal power, corresponding to the temperature maximum in the second pulse, and $t_{\max}$ is the time at which this maximum is attained. The resulting (left scale) curve, shown in Fig. 7.111 is then of general applicability, irrespective of the yield of the explosion.

7.112 In order to make the power-time curve specific for any particular explosion energy yield, it is necessary to know the appropriate values of $P_{\max}$ and $t_{\max}$. These are related to the yield, $W$ kilotons, in the following manner:

$$P_{\max}=4W^{1/2} \text{ kilotons per second,}$$

and

$$t_{\max}=0.032W^{1/2} \text{ seconds.}$$

The application of these equations is illustrated in the example facing Fig. 7.111.

7.113 The amount of thermal energy, $E$, emitted by the ball of fire up to any specified time can be obtained from the area under the curve of $P$ versus $t$ up to that time. The result, expressed in percent as $E/E_{\text{tot}}$ versus $t/t_{\max}$, is shown by the second curve (right scale) in Fig. 7.111. The quantity $E_{\text{tot}}$ is the total thermal energy emitted by the ball of fire; this is related to the total energy yield of the explosion, $W$ kilotons, by the expression,

$$E_{\text{tot}} \text{ (kilotons)}=\tfrac{1}{3}\,W, \tag{7.113.1}$$

derived from measurements made at a number of test explosions. This equation gives the thermal energy in terms of kilotons of TNT

(Text continued on page 334.)

The curves show the variation with the scaled time, $t/t_{\max}$, of the scaled fireball power, $P/P_{\max}$ (left ordinate) and of the percent of the total thermal energy emitted, $E/E_{\text{tot}}$ (right ordinate).

*Scaling.* In order to apply the data in Fig. 7.111 to an explosion of any energy, $W$ kilotons, the following expressions are used:

$$P_{\max}=4\ W^{1/2}\ \text{kilotons per second}$$

$$t_{\max}=0.032\ W^{1/2}\ \text{seconds.}$$

$$E_{\text{tot}}=\tfrac{1}{3}\ W\ \text{kilotons,}$$

where

$t_{\max}$=time after explosion for temperature maximum in second thermal pulse,

$P_{\max}$=maximum rate (at $t_{\max}$) of emission of thermal energy from fireball,

and

$E_{\text{tot}}$=total thermal energy emitted by fireball.

*Example*

*Given:* A 500 KT burst.

*Find:* (*a*) The rate of emission of thermal energy, (*b*) the amount of thermal energy emitted, at 2 seconds after the explosion.

*Solution:* Since $W$ is 500 KT, the value of $W^{1/2}$ is 22.4, so that $t_{\max}=0.032\times 22.4=0.72$ second, and the scaled time at 2 seconds after the explosion is

$$t/t_{\max}=2.0/0.72=2.8.$$

(*a*) From Fig. 7.111, the value of $P/P_{\max}$ at this scaled time is 0.26, and since $P_{\max}=4\times 22.4=90$ kilotons per second, it follows that,

$$P=0.26\times 90=23\ \text{kilotons per second}$$
$$=23\times 10^{12}\ \text{calories per second.}\quad \textit{Answer}$$

(*b*) At the scaled time of 2.8, the value of $E/E_{\text{tot}}$ from Fig. 7.111 is 58 percent, i. e., 0.58.

$$E_{\text{tot}}=\tfrac{1}{3}\times 500=167\ \text{kilotons}$$

Hence,

$$E=0.58\times 167=97\ \text{kilotons}$$
$$=97\times 10^{12}\ \text{calories.}\quad \textit{Answer}$$

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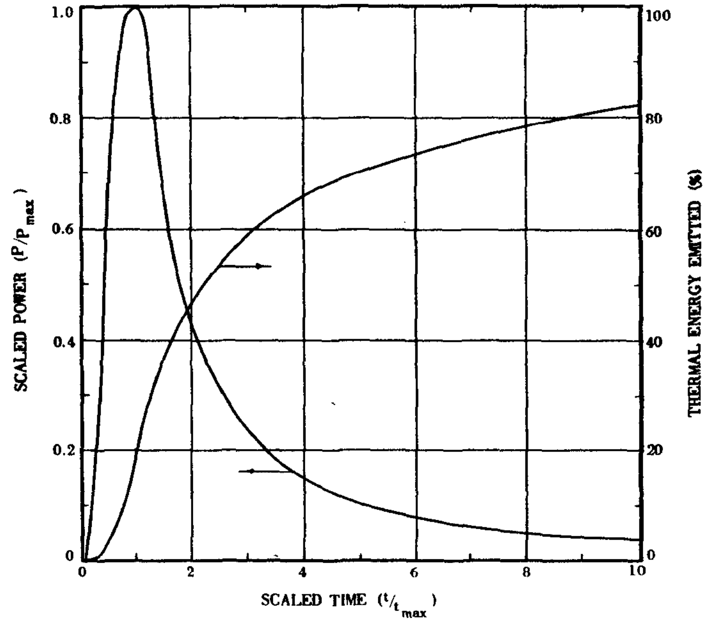

Figure 7.111. Scaled fireball power and fraction of thermal energy versus scaled time in second thermal pulse.

(Text continued from page 331.)

equivalent, but if it is required in calories the result is multiplied by $10^{12}$.

7.114 The curves in Fig. 7.111 present some features of special interest. As is to be expected, the thermal power (or rate of emission of radiant energy) of the fireball rises to a maximum, just as does the temperature in the second radiation pulse. However, since the thermal power is roughly proportional to $T^4$, it increases and decreases much more rapidly than does the temperature. This accounts for the sharp rise to the maximum in the $P/P_{\text{max}}$ curve, followed by a somewhat less sharp drop which tapers off as the ball of fire approaches its final stages.

7.115 From the standpoint of protection against skin burns, by taking evasive action, the important quantity is $t_{\text{max}}$, since the rate of emission of thermal radiation from the ball of fire is then a maximum. It is seen from the relationship in § 7.112 that this time increases in proportion to the square root of the energy yield of the explosion. Thus, $t_{\text{max}}$ is about 0.1 second for a 10-kiloton explosion, but it is over 3 seconds for a burst with 10 megatons energy yield. At such respective distances where severe burns might be experienced, evasive action would thus be expected to achieve greater relative success for explosions of high energy yield.

### THERMAL ENERGY-DISTANCE RELATIONSHIP

7.116 The next matter to consider is the variation with distance from the explosion of the total thermal energy (in calories) received per square centimeter of a target material. As seen earlier in this chapter, such information, combined with the data in Tables 7.45, 7.61, and 7.65, permits estimates to be made of the probable ranges for various thermal radiation effects.

7.117 If there is no atmospheric attenuation, the thermal energy, $E_{\text{tot}}$, at a distance $D$ from the explosion, may be regarded as being spread uniformly over the surface of a sphere of area $4\pi D^2$. If attenuation were due only to absorption, this quantity would be multiplied by the factor $e^{-kD}$, where $k$ is an absorption coefficient averaged over the whole spectrum of wave lengths. Hence, in these circumstances, using the symbol $Q$ to represent the thermal energy received per unit area at a distance $D$ from the explosion, it follows that

$$Q = \frac{E_{\text{tot}}}{4\pi D^2} e^{-kD}.$$

Since, according to the results given in § 7.112, $E_{\text{tot}}$ is equal to $\frac{1}{3} W \times 10^{12}$ calories, where $W$ is the explosion yield in kilotons, the appropriate expression would be

$$Q \text{ (cal/sq cm)} = \frac{10^{12} W e^{-kD}}{12\pi D^2},$$

where the distance $D$ is in centimeters.

7.118 When scattering of the radiation occurs, in addition to absorption, the coefficient $k$ is no longer a constant but is a function of distance, and it is then not convenient to express the attenuation by means of an exponential factor. A more useful formulation which has been developed is represented by

$$Q \text{(cal/sq cm)} = \frac{10^{12} W T}{12\pi D^2}, \tag{7.118.1}$$

where the transmittance, $T$, that is, the fraction of the radiation transmitted, is a complex function of the visibility (scattering), absorption, and distance. The variation of $T$ with distance from the explosion is shown by the curve in Fig. 7.118. This curve was actually computed for the case of a visibility of 10 miles and for air having a water vapor concentration, which determines the absorption, of 10 grams per cubic meter. Calculations for other reasonable atmospheric conditions have given results which do not differ very greatly from those in Fig. 7.118, and it appears that the same transmittance curve may be used in all cases without serious error, provided the distances are not greater than half the visibility.

7.119 In order to simplify the use of equation (7.118.1), the values of $Q$ for various distances, $D$, from the explosion, are plotted for $W=1$ kiloton in Fig. 7.119. The thermal energy received at any distance from an explosion of $W$ kilotons is then obtained upon multiplying the thermal energy for the same distance in Fig. 7.119 by $W$.

### FLASH BURN ENERGY AND TOTAL ENERGY YIELD

7.120 Since $t_{\text{max}}$ increases with the total energy yield, it is evident that a given quantity of thermal radiation energy will be received in a shorter time from an explosion of low yield than from one of higher yield. Hence, it is to be expected that the thermal energy required to produce flash burns of any given kind will increase with the energy yield of the explosion, as pointed out earlier. On the basis of labora-

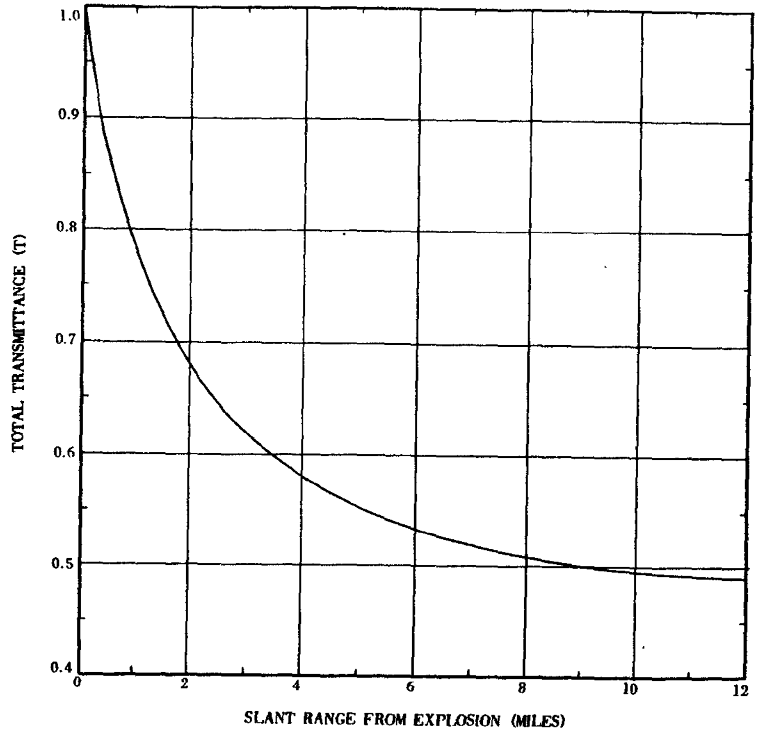

Figure 7.118. Total transmittance for 6000° K black body source (10 mile visibility, 10 gm/cubic meter water vapor concentration).

tory measurements, observations at nuclear tests, and theoretical calculations, estimates have been made of the amounts of thermal energy required to produce moderate first-, second-, and third-degree burns as a function of explosion yield. The results are given in Fig. 7.120.

7.121 It is by combining these data with those derived above for the variation of thermal energy received with distance from an explosion of given yield that the curves in Fig. 7.47 were obtained. Thus, in the example facing Fig. 7.119 it was found that at a distance of 3 miles from a 100-kiloton air burst the thermal energy received is 8 calories per square centimeter. From Fig. 7.120 it is seen that this amount of thermal energy from a 100-kiloton explosion may be expected to produce a third-degree burn.

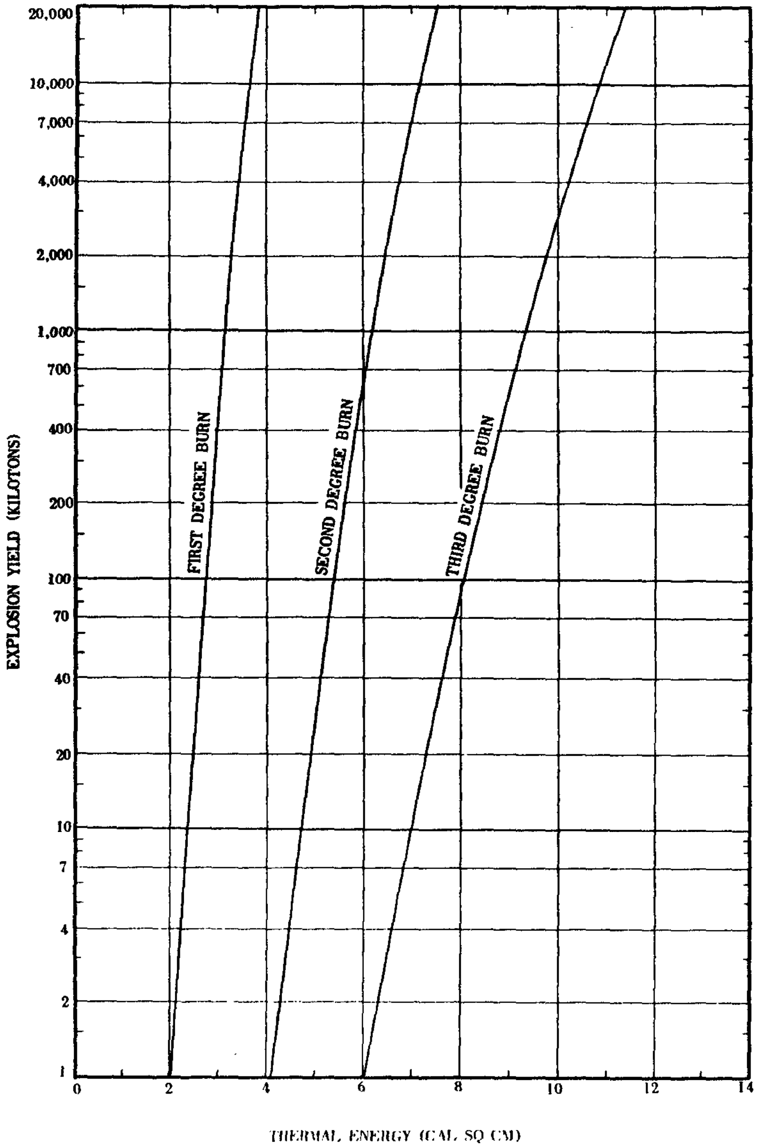

Figure 7.120. Thermal energy required for burns on bare skin.

The plot, which is in two parts for convenience of representation, shows the amount of thermal energy (in calories per square centimeter) received at various distances from a 1 KT air burst for atmospheric visibility in the range of 2 to 50 miles.

*Scaling.* The thermal energy received at any specified distance from a *W* KT explosion is *W* times the value for the same distance from a 1 KT burst.

*Example*

*Given:* A 100 KT air burst and a visibility of 10 miles.

*Find:* The amount of thermal energy received at a distance of 3 miles from the explosion.

*Solution:* From Fig. 7.119 the amount of thermal energy received at 3 miles from a 1 KT air burst is 0.08 calorie per square centimeter. Consequently, the thermal energy received at 3 miles from a 100 KT air burst is

100×0.08=8 calories per square centimeter. *Answer*

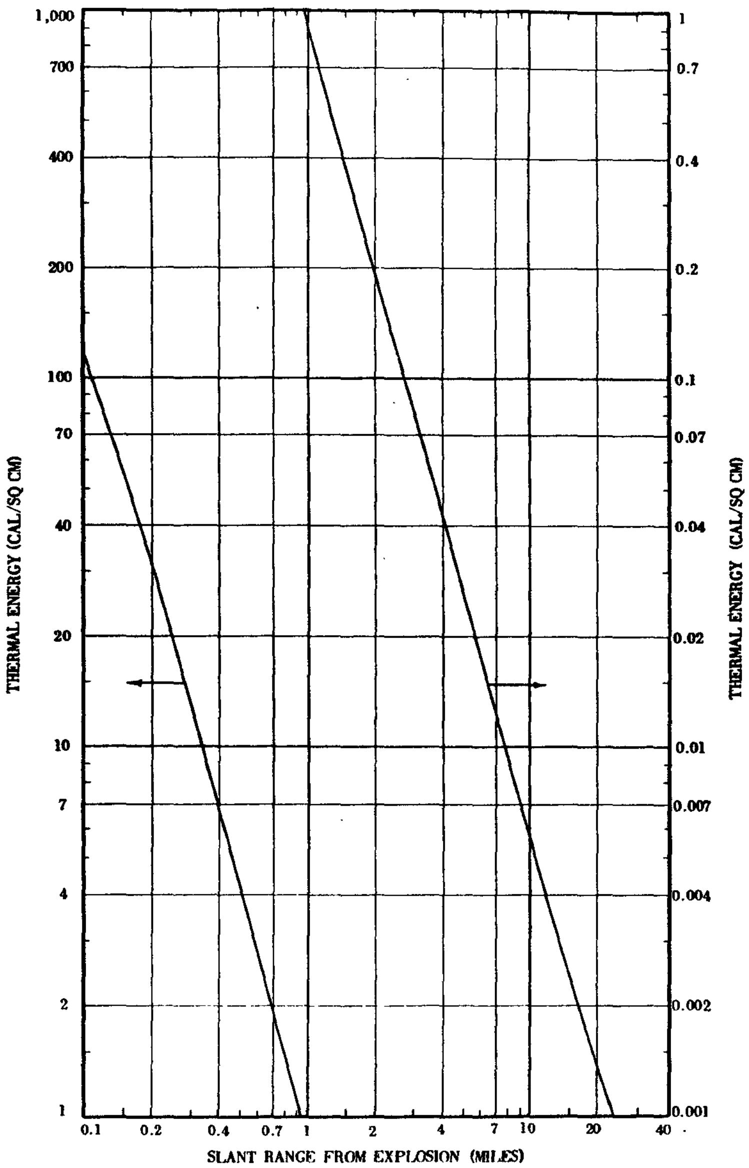

Figure 7.119. Thermal energy received at various slant ranges for a 1-kiloton air burst with visibility of 2 to 50 miles.

## *CHAPTER VIII*

# INITIAL NUCLEAR RADIATION

## NATURE OF NUCLEAR RADIATIONS

### Neutrons and Gamma Rays

8.1 It was stated in Chapter I that one of the unique features of a nuclear explosion is the fact that it is accompanied by the emission of nuclear radiation. These radiations, which are quite different from the thermal radiation discussed in the preceding chapter, consist of gamma rays, neutrons, beta particles, and a small proportion of alpha particles. Most of the neutrons and some of the gamma rays are emitted in the actual fission process, that is to say, simultaneously with the explosion, whereas the beta particles and the remainder of the gamma rays are liberated as the fission products decay. Some of the alpha particles result from the normal radioactive decay of the uranium or plutonium that has escaped fission in the bomb, and others (helium nuclei) are formed in hydrogen fusion reactions (§ 1.55).

8.2 Because of the nature of the phenomena associated with a nuclear explosion, either in the air or near the surface, it is convenient, for practical purposes, to consider the nuclear radiations as being divided into two categories, namely, initial and residual (§ 1.2). The line of demarcation is somewhat arbitrary, but it may be taken as about 1 minute after the explosion, for the reasons given in § 2.39. The initial nuclear radiation, with which the present chapter will be concerned, consequently refers to the radiation emitted within 1 minute of the detonation. For underground or underwater explosions, it is less meaningful to separate the initial from the residual nuclear radiation (§§ 2.64, 2.74), although the distinction may be made if desired.

8.3 The ranges of alpha and beta particles are comparatively short and they cannot reach the surface of the earth from an air burst. Even when the ball of fire touches the ground, the alpha and beta particles are not very important. The initial nuclear radiation may thus be regarded as consisting only of the gamma rays and neutrons produced during a period of 1 minute after the nuclear explosion. Both of these nuclear radiations, although different in character, can penetrate considerable distances through the air. Further, both gamma rays and neutrons can produce harmful effects in living organisms (see Chapter XI). It is the highly injurious nature of these nuclear radiations, combined with their long range, that makes them such a significant aspect of nuclear explosions.

8.4 Most of the gamma rays accompanying the actual fission process are absorbed by the bomb materials and are thereby converted into other forms of energy. Thus, only a small proportion (about 1 percent) of this gamma radiation succeeds in penetrating any great distance from the exploding bomb, but, as will be seen shortly, there are several other sources of gamma radiation that contribute to the initial nuclear radiation. Similarly, the neutrons produced in fission are to a great extent slowed down and captured by the bomb residues or by the air engulfed by the shock front. Nevertheless, a sufficient number of fast (fission) neutrons escape from the explosion region to represent a significant hazard at considerable distances away. Although the energy of the initial gamma rays and neutrons is only about 3 percent of the total explosion energy, compared with some 33 percent appearing as thermal radiation, the nuclear radiations can cause a considerable proportion of the bomb casualties.

### Comparison of Nuclear Bomb Radiations

8.5 As seen in Chapter VII, shielding from thermal radiation, at distances not too close to the point of the explosion of the bomb, is a fairly simple matter, but this is not true for gamma rays and neutrons. For example, at a distance of 1 mile from the explosion of a 1-megaton bomb, the initial nuclear radiation would probably prove fatal to about 50 percent of human beings even if sheltered by 24 inches of concrete, although a much lighter shield would provide complete protection from thermal radiation at the same location. The problems of shielding from thermal and nuclear radiations are thus quite distinct.

8.6 The effective injury ranges of these two kinds of nuclear bomb radiations may differ widely. For explosions of moderate and large energy yields, thermal radiation can have harmful consequences at appreciably greater distances than can the initial nuclear radiation. Beyond about 1¼ miles, the initial nuclear radiation from a 20-kiloton explosion, for instance, would not cause observable injury even without protective shielding. However, exposure to thermal radiation at this distance could produce serious skin burns. On the other hand, when the energy of the nuclear explosion is relatively small, e. g., a kiloton or less, the initial nuclear radiation has the greater effective range.

8.7 In the discussion of the characteristics of the initial nuclear radiation, it is desirable to consider the neutrons and the gamma rays separately. Although their ultimate effects on living organisms are much the same, the two kinds of nuclear radiations differ in many respects. The subject of gamma rays will be considered in the section which follows, and neutrons will be discussed later in this chapter.

## GAMMA RAYS

### Sources of Gamma Rays

8.8 In addition to the gamma rays which actually accompany the fission process, contributions to the initial nuclear radiations are made by gamma rays from other sources. Of the neutrons produced in fission, some serve to sustain the fission chain reaction and others escape, but a large proportion of the fission neutrons are inevitably captured by nonfissionable nuclei. As a result of neutron capture, the nucleus is converted into a new species known as a "compound nucleus," which is in a high energy (or excited) state. The excess energy may then be emitted, almost instantaneously, as gamma radiations. These are called "capture gamma rays," because they are the result of the capture of a neutron by a nucleus. The process is, correspondingly, referred to as "radiative capture."

8.9 Neutrons produced in fission can undergo radiative capture reactions with the nuclei of various materials present in the bomb, as well as with those of nitrogen in the surrounding atmosphere. These reactions are accompanied by gamma rays which form part of the initial nuclear radiation. The interaction with nitrogen nuclei is of particular importance, since some of the gamma rays thereby produced have very high energies and are, consequently, much less easily attenuated than the other components of the initial gamma radiation.

8.10 The interaction of fission neutrons with atomic nuclei provides another source of gamma rays. When a fast neutron, i. e., one having a large amount of kinetic energy, collides with a nucleus, the neutron may transfer some of its energy to the nucleus, leaving it in an excited (high-energy) state. The excited nucleus can then return to its normal energy (or ground) state by the emission of gamma rays.

8.11 The gamma rays produced in fission and as a result of other neutron reactions and nuclear excitation of the bomb materials all appear within a second (or less) after the nuclear explosion. For this reason, the radiations from these sources are known as the "prompt" or "instantaneous" gamma rays.

8.12 The fission fragments and many of their decay products are radioactive isotopes which emit gamma radiations (see Chapter I). The half lives of these radioactive species range from a millionth of a second (or less) to many years. Nevertheless, since the decay of the fission fragments commences at the instant of fission and since, in fact, their rate of decay is greatest at the beginning, there will be an appreciable liberation of gamma radiation from these radioisotopes during the first minute after the explosion. In other words, the gamma rays emitted by the fission products make a significant contribution to the initial nuclear radiation. However, since the radioactive decay process is a continuing (or gradual) one, spread over a period of time which is long compared to that in which the instantaneous radiation is produced, the resulting gamma radiations are referred to as the "delayed" gamma rays.

8.13 The instantaneous gamma rays and the portion of the delayed gamma rays, which are included in the initial radiation, are nearly equal in amount, but they are by no means equal fractions of the initial nuclear radiation transmitted from the exploding bomb. The instantaneous gamma rays are produced almost entirely before the bomb has completely blown apart. They are, therefore, strongly absorbed by the dense bomb materials, and only a small proportion actually emerges. The delayed gamma rays, on the other hand, are mostly emitted at a later stage in the explosion, after the bomb materials have vaporized and expanded to form a tenuous gas. These radiations thus suffer little or no absorption before emerging into the air. The net result is that the delayed gamma rays, together with those produced by the radiative capture of neutrons by the nitrogen in the atmosphere, contribute about a hundred times as much as do the prompt gamma rays to the total nuclear radiation received at a distance from an air (or surface) burst during the first minute after detonation.

8.14 There is another possible source of gamma rays which may be mentioned. If a nuclear explosion occurs near the earth's surface, the emitted neutrons can cause what is called "induced radioactivity" in the materials present in the ground. This may be accompanied by radiations which will be part of the delayed gamma rays. Since induced radioactivity is an aspect of the residual nuclear radiation, it will be treated more fully in the next chapter.

## MEASUREMENT OF GAMMA RADIATIONS

8.15 Thermal radiation from a nuclear explosion can be felt (as heat), and the portion in the visible region of the spectrum can be seen. The human senses, however, do not respond to nuclear radiations except at very high intensities (or dose rates), when itching and tingling of the skin are experienced. Special instrumental methods, based on the interaction of these radiations with matter, have therefore been developed for the detection and measurement of various nuclear radiations.

8.16 When gamma rays pass through any material, either solid, liquid, or gas, they interact with the atoms in a number of different ways. From the viewpoint of gamma-ray dose measurement, two ultimate consequences of these interactions are important. One result is that from many atoms an electron is expelled. Since the electron carries a negative electrical charge, the residual part of the atom is positively charged, i. e., it is a positive ion. This process is referred to as "ionization," and the separated electrons and positive ions are called "ion pairs."

8.17 The second consequence of gamma ray interaction occurs readily in certain solids and liquids, as well as in gases. Instead of the electron being removed completely from the atom, as is the case in ionization, it acquires an additional amount of energy. As a result, the atom is converted into a high energy (or excited) electronic state. This phenomenon is called "excitation."

8.18 Both ionization and excitation have been used for the detection or the measurement of gamma rays, as well as of other nuclear radiations. Normally a gas will not conduct electricity to any appreciable extent, but as a result of the formation of ion pairs, by the passage of nuclear radiations, the gas becomes a reasonably good conductor. Several types of instruments, e. g., the Geiger counter and the pocket chamber (or dosimeter), for the measurement of gamma (and other) radiations, are based on the formation of electrically charged ion pairs in a gas and its consequent ability to conduct electricity.

8.19 The operation of scintillation counters, on the other hand, depends upon excitation. When an atom or molecule becomes excited, it will generally give off the excess (or excitation) energy within about one millionth of a second. Certain materials, usually in the solid or liquid state, are able to lose their electronic excitation energy in the form of visible flashes of light or scintillations. These scintillations can be counted by means of a photomultiplier tube and associated electronic devices.

8.20 In addition to the direct effects of ionization and excitation, as just described, there are some indirect consequences, notably chemical changes. One example is the blackening or fogging of photographic film which appears after it is developed. Film badges, for the measurement of nuclear radiations, generally contain two or three pieces of film, similar to those used by dentists for taking X-rays. They are wrapped in paper (or other thin material) which is opaque to light but is readily penetrated by gamma rays. The films are developed and the degree of fogging observed is a measure of the gamma ray exposure. In addition, self-indicating chemical dosimeters are in an advanced state of development. With these devices the nuclear radiation exposure can be determined directly by observation of the color changes accompanying certain chemical reactions induced by radiation.

## RADIATION UNITS: THE ROENTGEN

8.21 In order to express the exposure to gamma radiation at any particular point, it is necessary to have a suitable unit of measurement. The unit which is used in this connection is called the "roentgen." Its merit lies in the fact that the magnitude of the exposure dose in roentgens can be related to the expected biological effect (or injury) resulting from radiation.

8.22 It is generally believed that the harmful consequences of nuclear radiations to the living organism are largely due to the chemical decomposition of the molecules present in animal (or vegetable) cells. Fundamentally, it is the ionization (and excitation) caused by nuclear radiations that is responsible for this chemical action. The amount of ionization or number of ion pairs produced by the radiation would thus appear to provide a basis for its measurement. Although the actual definition is somewhat more involved, the roentgen is the quantity of gamma radiations (or X-rays) which will form $1.61 \times 10^{12}$ ion pairs when absorbed in 1 gram of air. The absorption of 1 roentgen results in the release of about 87 ergs of energy per gram of air.

8.23 Radiation measuring instruments do not record the number of roentgens directly. However, by suitable design, the quantities observed, e. g., electrical pulses, scintillations, or fogging of a photographic film, can be made to provide a practical measurement of the exposure in roentgens. The various radiation measuring devices are thus calibrated with a standard gamma-ray source. For this purpose, a known quantity of radioactive cobalt or radium is generally used. The gamma-radiation exposure in roentgens at a specified distance in air from such a source is known from measurements with special laboratory instruments which are not suitable for general field application.

8.24 Two types of measurements, both of which have important uses, are made by radiation instruments. Some record the total radiation dose (or amount) in roentgens received during an exposure period. Others indicate the dose rate, expressed in roentgens per hour or, for smaller dose rates, in milliroentgens per hour, where a milliroentgen is a one-thousandth part of a roentgen. The total dose is equal to the properly averaged dose rate multiplied by the exposure time.

8.25 Although some special instruments will record both the total radiation dose and the dose rate, most radiation measuring devices are designed to indicate one or the other. As far as the initial nuclear radiation is concerned, it is the total dose that is the important quantity, but in connection with the delayed radiation, to be considered in Chapter IX, both the dose rate and the total dose are significant.

8.26 The biological effects of various gamma-radiation doses will be considered more fully in Chapter XI. However, in order to provide some indication of the significance of the numbers given below, it may be stated that a single exposure dose of less than 25 roentgens will produce no detectable clinical effects. Larger doses have increasingly more serious consequences and an exposure of 450 roentgens over the whole body is expected, within a period of a month or so, to prove fatal to about 50 percent of the exposed individuals. A whole-body exposure of 700 or more roentgens would probably be fatal in nearly all cases.

8.27 Attention should be called to the stipulation of whole-body exposure made in the preceding paragraph. In this respect, nuclear radiations and thermal radiations have something in common. A third-degree burn on a limited region might not be very serious, but a second-degree burn over a large part of the body might prove fatal. Similarly, a dose of a thousand or more roentgens of nuclear radiations on a small area would cause local damage, but would probably have little over-all consequences. If the whole or most of the body were exposed to the same number of roentgens, death would undoubtedly result.

### The Rad and the Rem

8.28 The roentgen, as a unit of radiation dosage, is defined with respect to gamma (or X) rays, and applies, strictly, only to these

radiations. Further, it is, in any event, a measure of the strength of the radiation field at a given location, rather than of the radiation absorbed by an individual at that location. The radiation dose in roentgens is thus referred to as an "exposure dose." In order to distinguish this from the "absorbed dose" another unit is required. One such unit is the "rep," the name being composed of the three initial letters of the expression "roentgen equivalent physical."

8.29 It was indicated in § 8.22 that a gamma-ray (exposure) dose of 1 roentgen is equivalent to the absorption of approximately 87 ergs of energy per gram of air. On this basis, a rep was originally defined as the dose of *any* nuclear radiation (gamma rays, beta particles, neutrons, etc.) that results in the absorption of this amount of energy, i. e., 87 ergs, per gram of animal tissue. However, it was found that exposure to a dose of 1 roentgen of gamma radiation was accompanied by the absorption of more like 97 ergs in a gram of soft tissue. The rep has therefore been used to denote a dose of 97 ergs of any nuclear radiation absorbed per gram of tissue.

8.30 The foregoing definition of the rep, based on the roentgen, is somewhat unsatisfactory because the number of ergs is determined, ultimately, by the value of the energy required to produce an ion pair in air. This quantity is not known with certainty, and as new experimental data have become available, the number of ergs in the definition of the rep has been changed. In order to avoid this difficulty, a new unit of radiation absorption, called the "rad," has been introduced which does not suffer from such a drawback. The rad is defined as the absorbed dose of any nuclear radiation which is accompanied by the liberation of 100 ergs of energy per gram of absorbing material. For soft tissue, the difference between the rep and the rad is insignificant, and numerical values of absorbed dose formerly expressed in reps are essentially unchanged when converted to rads.

8.31 Although all ionizing radiations are capable of producing similar biological effects, the absorbed dose, measured in rads, which will produce a certain effect may vary appreciably from one type of radiation to another. The difference in behavior, in this connection, is expressed by means of a quantity called the "relative biological effectiveness" (or RBE) of the particular nuclear radiation. The RBE of a given radiation is defined as the ratio of the absorbed dose in rads of gamma radiation (of a specified energy) to that of rads of the given radiation having the same biological effect.

8.32 The value of the RBE for a particular type of nuclear radiation depends upon several factors, such as the energy of the radiation, the kind and degree of the biological damage, and the nature of the organism or tissue under consideration. As far as weapons are concerned, the important criteria are disabling sickness and death, and the RBE's are estimated in terms of these consequences of the radiations from a nuclear explosion.

8.33 With the concept of the RBE in mind, it is now useful to introduce another unit, known as the "rem," an abbreviation of "roentgen equivalent mammal (or man)." The rad is a convenient unit for expressing energy absorption, but it does not take into account the biological effect of the particular nuclear radiation absorbed. The rem, however, which is defined by

$$\text{Dose in rems} = \text{RBE} \times \text{Dose in rads},$$

provides an indication of the extent of biological injury (of a given type) that would result from the absorption of nuclear radiation. Thus, the rem is a unit of biological dose, whereas the rad is a unit of absorbed dose and the roentgen one of exposure dose. According to the definition in § 8.31, the RBE for gamma rays is approximately unity, although it varies somewhat with the energy of the radiation. Hence, for gamma radiation, the biological dose in rems is numerically equal to the absorbed dose in rads, and in view of the similarity between the rad and the rep for soft tissue, it is also roughly equal to the exposure dose in roentgens. This equality does not necessarily apply, of course, to other nuclear radiations.

## GAMMA-RAY DOSE-DISTANCE RELATIONSHIP

8.34 As is to be expected, the gamma-ray exposure dose at a particular location, resulting from a nuclear explosion, is less the farther that location is from the point of burst. The relationship of the radiation dose to the distance is dependent upon two factors, analogous to those which apply to thermal radiation. There is, first, the general decrease, due to the spread of the radiation over larger and larger areas as it travels away from the bomb. This makes the dose received inversely proportional to the square of the distance from the explosion. In addition, there is an attenuation factor to allow for the decrease in intensity due to absorption and scattering of gamma rays by the intervening atmosphere.

8.35 The gamma radiation exposure doses at known distances from air bursts of different energy yields have been measured at a number of nuclear test explosions. The results obtained have been found to be consistent. The data may be summarized in the form of two graphs: the first (Fig. 8.35a) shows the dependence of the initial gamma-ray

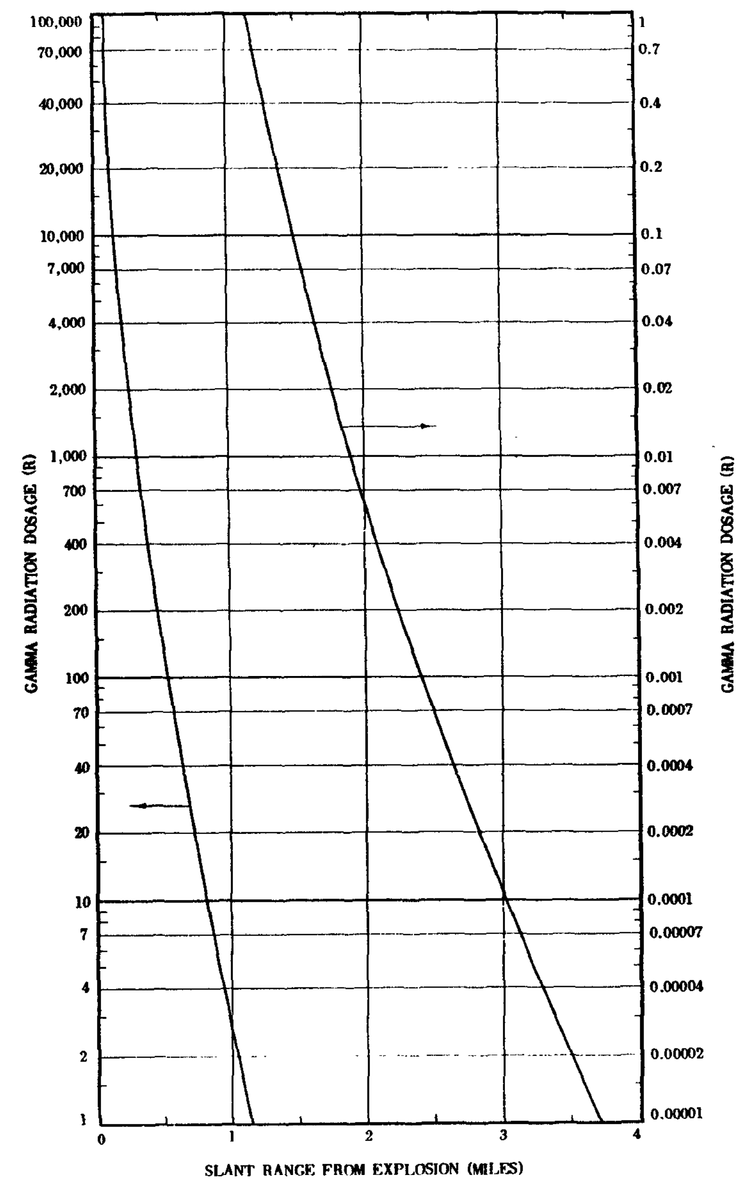

Figure 8.35a. Initial gamma radiation dosage for a 1-kiloton air burst.

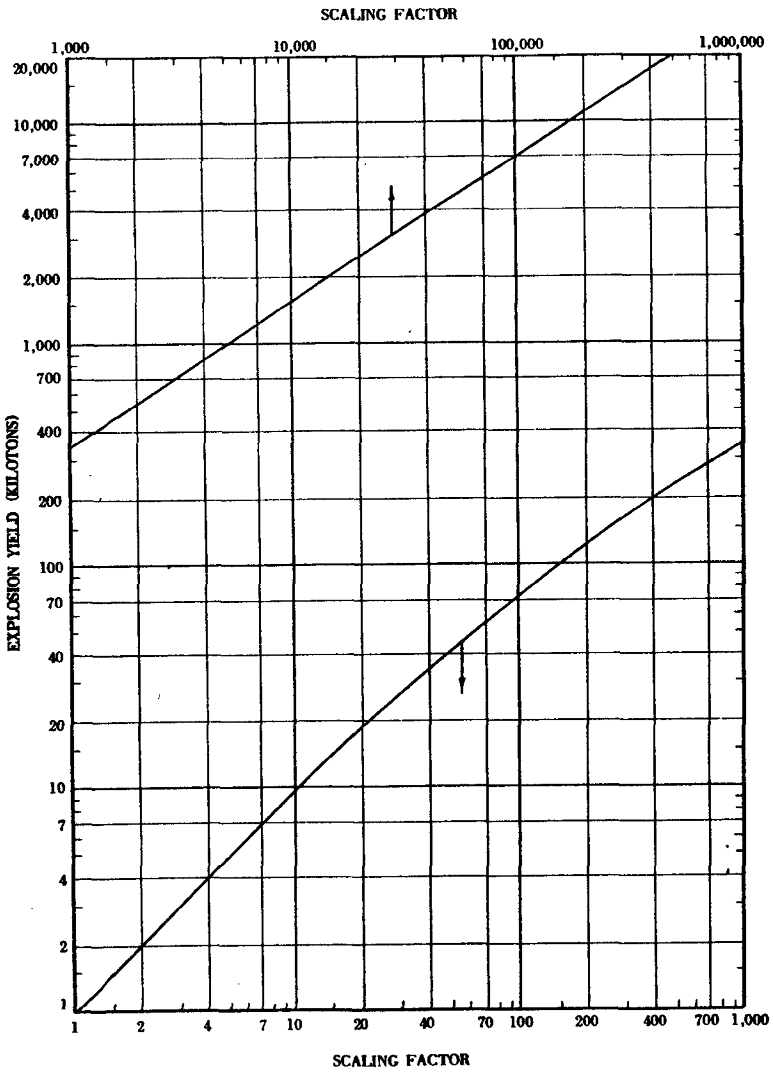

Figure 8.35b. Scaling factor for initial gamma radiation dosage.

dose on the distance (or slant range) from a 1-kiloton explosion; the second (Fig. 8.35b) gives the scaling factor to be used to determine the dose at the same slant distance from an explosion of any specific energy yield up to 20 megatons.

8.36 The method of using the curves in Figs. 8.35a and 8.35b may be illustrated by determining from them the initial gamma-radiation dose received at a distance of 1 mile from a 100-kiloton air burst. From Fig. 8.35a, the exposure dose at this distance from a 1-kiloton air burst is 2.5 roentgens. The scaling factor for 100 kilotons is found from Fig. 8.35b to be 150. Hence, the gamma ray dose in the case specified is 2.5 × 150=375 roentgens.

8.37 The values in Fig. 8.35a are somewhat dependent upon the density of the air between the center of the explosion and the point on the ground at which the radiation is received. This is so because the air absorbs some of the gamma radiation in the course of its transmission, the dense air near the earth's surface absorbing more than the less dense air at higher altitudes. The results in the figure are based upon the normal density of air at sea level.

8.38 It will be noted from Fig. 8.35b that, in the higher energy range, the scaling factor increases more rapidly than does the energy of the explosion. For example, for a 100 kiloton explosion the scaling factor is 150, and for a 1,000 kiloton (1 megaton) yield it is a little more than 5,000. The reason for this increase is the sustained low air density, following the passage of the positive phase of the blast wave (§ 3.5), especially for explosions of high energy yield. As a result, there is less attentuation of the (delayed) gamma rays from the fission products. For explosions of lower energy, e. g., about 100 kilotons or less, both the fission product radiation and the high-energy gamma rays emitted in the radiative capture of neutrons by nitrogen in the air contribute to the increase in the scaling factor.

8.39 The gamma ray doses to be expected from explosions of various energies can be expressed in another form, as in Fig. 8.39. The slant ranges, i. e., the distances from the point of the explosion, at which certain specified doses of initial gamma radiation would be received, from air bursts in the energy range from 1 kiloton to 20 megatons, can be read off directly. For intermediate doses, the corresponding slant distances can be estimated by interpolation.

8.40 The foregoing results have applied, in particular, to an air burst. For a surface burst there is some reduction in the exposure dose at a certain distance because of absorption by the dust and debris raised by the explosion. However, the decrease is not very large and, as a result, the distance from the point of burst (or slant range) at which a specified dose, e. g., 300 roentgens, is received is not greatly affected. In view of the uncertainties associated with a surface burst, it is probably best to assume that Figs. 8.35a, 8.35b, and 8.39 apply to this type of explosion as well as to an air burst.

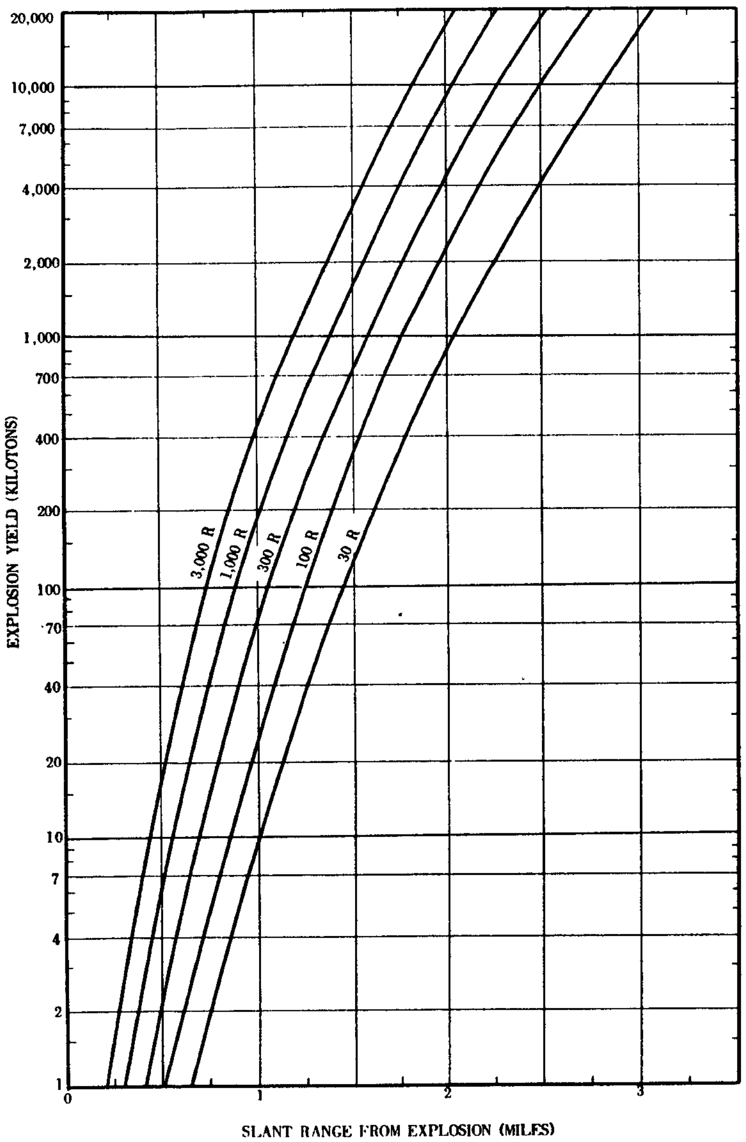

Figure 8.39. Ranges for specified initial gamma radiation dosages.

## SHIELDING AGAINST GAMMA RAYS

8.41 Gamma rays are absorbed (or attenuated) to some extent in the course of their passage through any material. As a rough rule, it may be said that the decrease in the radiation intensity is dependent upon the mass of material that intervenes between the source of the rays and the point of observation. This means that it would require a greater thickness of a substance of low density, e. g., water, than one of high density, e. g., iron, to attenuate the radiations by a specified amount. Strictly speaking, it is not possible to absorb gamma rays completely. Nevertheless, if a sufficient thickness of matter is interposed between the radiation source, such as an exploding nuclear bomb, and an individual, the exposure dose can be reduced to negligible proportions.

8.42 The effectiveness of a given material in decreasing the radiation intensity can be conveniently represented by a quantity called the "half-value layer thickness." This is the thickness of the particular material which absorbs half the gamma radiation falling upon it. Thus, if a person were in a position where the exposure dose is 400 roentgens, e. g., of initial gamma radiations, with no shielding, the introduction of a half-value layer of any material would decrease the dose to (approximately) 200 roentgens. The addition of another half-value layer would again halve the dose, i. e., to (approximately) 100 roentgens. Each succeeding half-value layer thickness decreases the radiation dose by half, as shown in Fig. 8.42. One half-value layer decreases the radiation dose to half of its original value; two half-value layers reduce it to one-quarter; three half-value layers to one-eighth; four half-value layers to one-sixteenth, and so on.[1]

8.43 Strictly speaking, the half-value thickness concept should be applied only to monoenergetic gamma radiation, i. e., radiation having a single energy, in a narrow beam or when the shielding (or absorbing) material is relatively thin. Actually, none of these conditions will apply in shielding against gamma rays from a nuclear explosion. The gamma radiation energies cover a wide range, the rays are spread out over a large area, and thick shields are necessary in regions of interest. Nevertheless, approximate (adjusted) half-value layer thicknesses, such as those quoted below, can serve a useful practical purpose in providing a rough indication of the degree of attenuation

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[1] The same general rule can be applied to any specified fraction, e. g., a one-tenth value layer which would reduce the radiation by a factor of 10; then two one-tenth value layers would reduce it by a factor of $10^2$, i. e., a 100; three one-tenth value layers by a factor of $10^3$, i. e., 1000, etc.

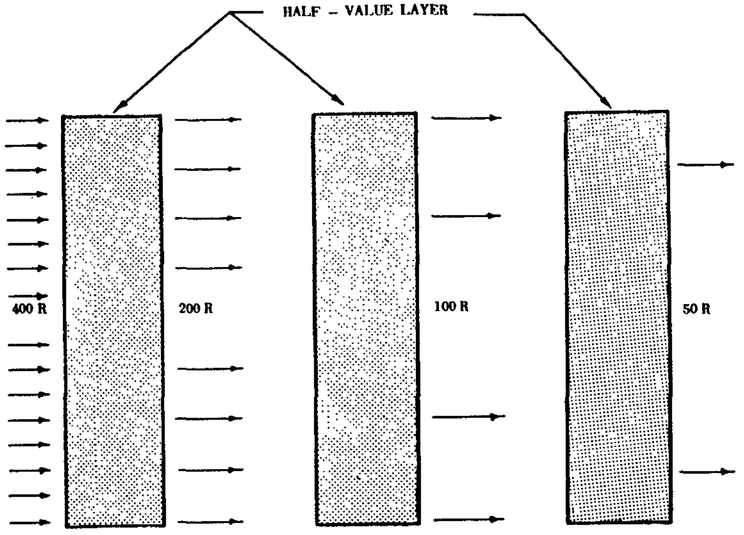


Figure 8.42. Representation of the half-value layer thickness.

of the initial gamma radiation that can be achieved by means of a given amount of shielding.

8.44 The chief materials likely to be available for shielding against the initial nuclear radiation from a nuclear explosion are steel, concrete, earth, and wood. The approximate half-value layer thicknesses of these substances for the gamma-radiation component are given in Table 8.44. The value for water is included since it may be of interest in connection with an air burst over water. The data in the table are applicable, with fair accuracy, to thick shields and to the energy that is most significant in the initial nuclear radiations.

8.45 It is apparent from Table 8.44 that steel of 1½ inches thickness is equivalent to 6 inches of concrete, to 7½ inches of earth, or to 23 inches of wood (Fig. 8.45). Consequently, a certain thickness of steel would provide more effective shielding than the same thickness of concrete, and this would be more effective than earth or wood. In general, as stated in § 8.41, the more dense the material, the smaller the thickness required to decrease the gamma radiation to a certain fraction of its original intensity. As indicated by the results in the last column of Table 8.44, the product of the density and the half-value thickness is roughly the same for the five materials. Consequently, if the half-value thickness of a substance is not known, but the density is, a fair estimate can be made by assuming that the product of the half-value layer in inches and the density in pounds per cubic foot is about 800.

Table 8.44

APPROXIMATE HALF-VALUE LAYER THICKNESSES OF MATERIALS FOR INITIAL GAMMA RADIATION

| Material | Density (lb/cu ft) | Half-value thickness (inches) | Product |
|---|---|---|---|
| Steel | 490 | 1.5 | 735 |
| Concrete | 144 | 6.0 | 864 |
| Earth | 100 | 7.5 | 750 |
| Water | 62.4 | 13 | 811 |
| Wood | 34 | 23 | 782 |

8.46 The attenuation factor of a given shield, that is, the ratio of the dose falling upon the shield to that which would be received behind the shield, can be readily calculated from the number of half-value thicknesses, together with the data in Table 8.44. For example, a 30-inch thick shield of earth will contain 30/7½=4.0 half-value

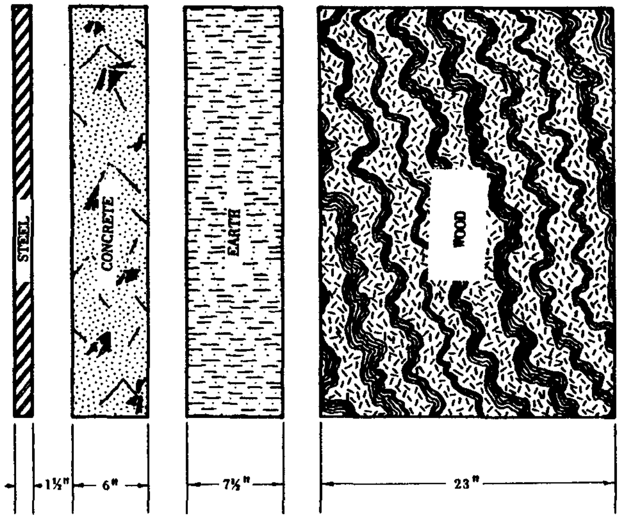


Figure 8.45 Comparison of the half-value layer thicknesses.

thicknesses. The attenuation factor is then $(2)^4$, i. e., 16, so that the gamma radiation dose will be decreased to roughly 1/16th of that which would have been received without the shield. Thus, in the case considered in § 8.36 the radiation dose would be decreased to 375/16, i. e., 23.4 roentgens.

8.47 The calculations may be simplified by the use of Fig. 8.47, in which the attenuation factors are plotted for various thicknesses of iron, concrete, earth, and wood. Suppose that, at a certain location, the gamma ray exposure dose without shielding, i. e., as given by Figs. 8.35a and b, would be 500 roentgens. What thickness of concrete would be needed to reduce the dose to 10 roentgens? The required attenuation factor is 500/10=50, and from Fig. 8.47, it is seen that this would be obtained with 29 inches of concrete.

8.48 In a vacuum, gamma rays travel in straight lines with the speed of light. However, in its passage through the atmosphere, gamma radiation, like thermal radiation, is scattered, particularly by the oxygen and nitrogen in the air. As a result, gamma rays will reach a particular target on the ground from all directions. Most of the dose received will come from the direction of the explosion but a considerable amount of scattered radiation will arrive from other directions. This fact has an important bearing on the problem of shielding from nuclear radiations.

8.49 A person taking shelter behind a single wall, an embankment, or a hill, will be (partially) shielded from the direct gamma rays, but will still be exposed to the scattered radiation, as shown by the broken lines in Fig. 8.49a. Adequate protection from gamma rays can be secured only if the shelter is one that surrounds the individual, so that he is shielded from all directions (Fig. 8.49b). In this case, both direct and scattered radiations can be attenuated. However, since the intensity of the scattered radiation is less than that of the incident radiation, the shielding in directions other than that of the (expected) detonation need not be so great in order to achieve the same degree of protection.

## Rate of Delivery of Initial Gamma Rays

8.50 Radiation dose calculations based on Fig. 8.35a involve the assumption that the exposure lasts for the whole minute which was somewhat arbitrarily set as the period in which the initial nuclear radiation is emitted. It is important to know, however, something about the rate at which the radiation is delivered from the exploding bomb. If this information is available, it is possible to obtain some

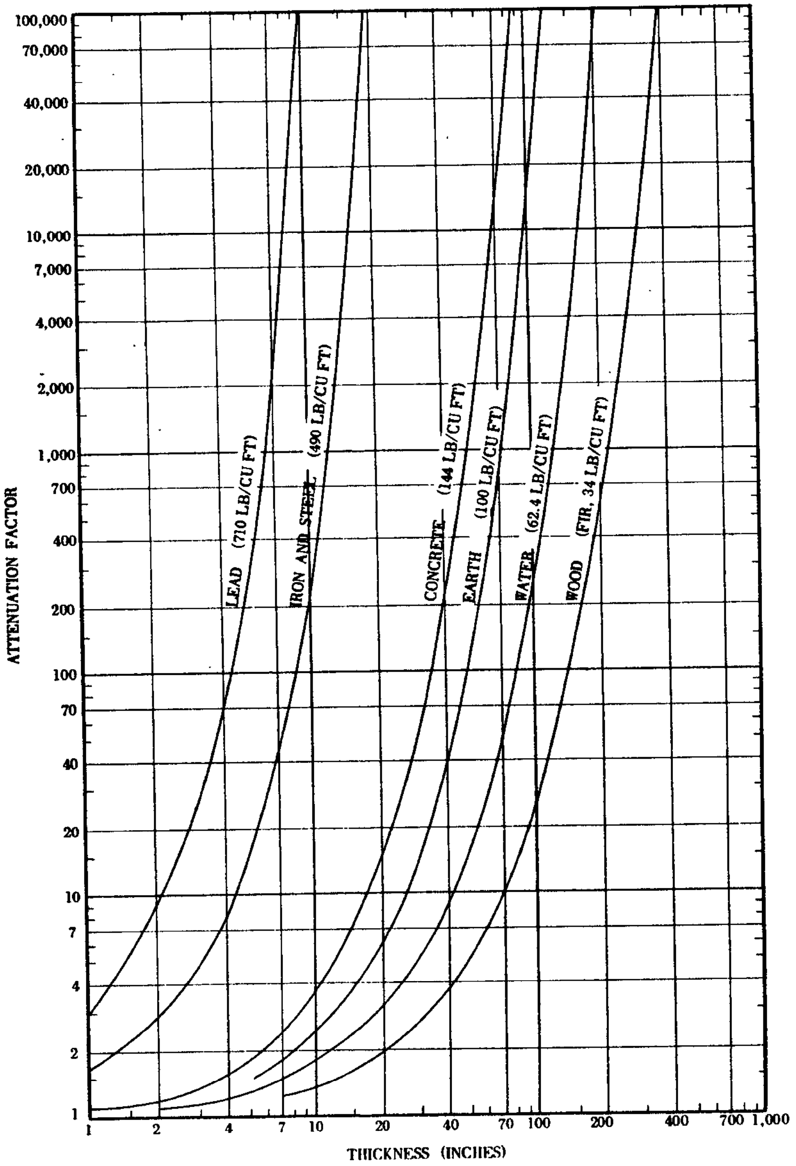
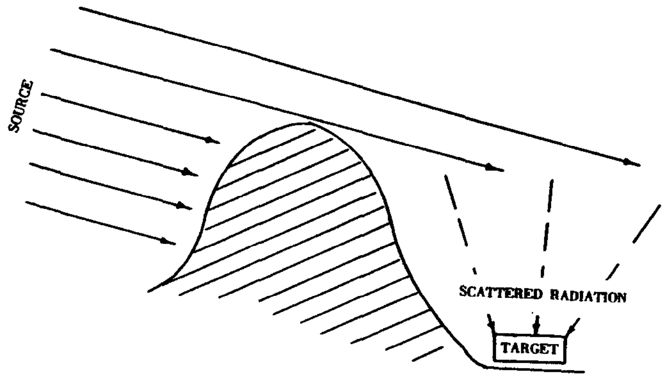
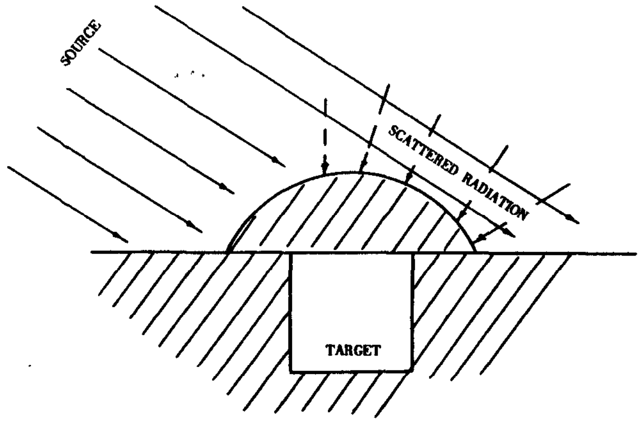


Figure 8.47. Attenuation of initial gamma radiation.

idea of the dose that would be received if part of the radiation could be avoided, e. g., by taking shelter within a second or two of observing the luminous flash of the explosion.



a



b

Figure 8.49a. Target exposed to scattered gamma radiation.
Figure 8.49b. Target shielded from scattered gamma radiation.

8.51 The rate of delivery of the initial gamma rays actually depends upon a number of circumstances, the most significant of which are the energy yield of the explosion and the distance from the point of burst. The percentage of the total dose received up to various times for two different cases are shown in Fig. 8.51. One curve represents the rate of delivery at a distance of ½ mile from a 20-kiloton air burst and the other at 1½ miles from a 5-megaton explosion. It is seen that in the former case about 65 percent and in the latter case about 4 percent of the total initial gamma radiation dose is received during the first second after the detonation.

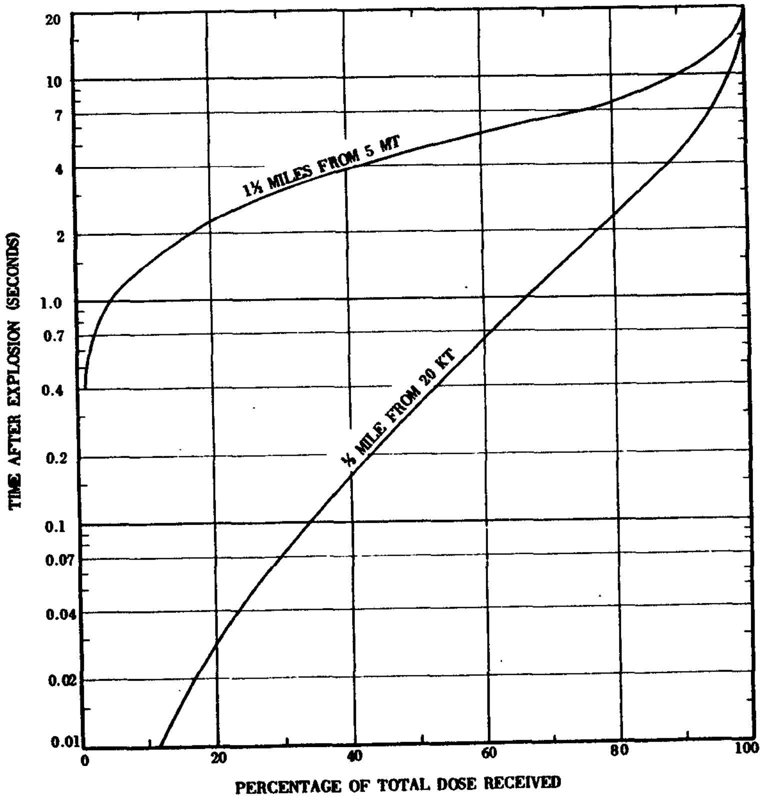


Figure 8.51. Percentage of total dosage of initial gamma radiation received at various times after explosion.

8.52 It would appear, therefore, that if some shelter could be obtained, e. g., by falling prone, as recommended in § 7.54, preferably behind a substantial object, within a second of seeing the bomb flash, in certain circumstances it might make the difference between life and death. The curves in Fig. 8.51 show that for a bomb of high energy the gamma radiation may be emitted more slowly, especially in the early stages immediately following the explosion, than for one of lower energy. Avoidance of part of the initial gamma ray dose would appear to be more practicable for explosions of higher energy yields.

## NEUTRONS

### SOURCES OF NEUTRONS

8.53 Although neutrons are nuclear particles of appreciable mass, whereas gamma rays are electromagnetic waves, analogous to X-rays, their harmful effects on the body are similar in character. Like gamma rays, only very large doses of neutrons may possibly be detected by the human senses. Neutrons can penetrate a considerable distance through the air and constitute a hazard that is greater than might be expected from the small fraction (about 0.025 percent) of the explosion energy which they carry.

8.54 Essentially all the neutrons accompanying a nuclear explosion are released either in the fission or fusion process (§§ 1.33, 1.57). All of the neutrons from the latter source and over 99 percent of the fission neutrons are produced almost immediately, probably within less than a millionth of a second of the initiation of the explosion. These are referred to as the "prompt" neutrons.

8.55 In addition, somewhat less than 1 percent of the fission neutrons, called the "delayed" neutrons, are emitted subsequently. Since the majority of these delayed neutrons are emitted within the first minute, however, they constitute part of the initial nuclear radiation. Some neutrons are also produced by the action of the gamma rays of high energy on the nuclear bomb materials. But these make a very minor contribution and so can be ignored.

8.56 Although the prompt fission neutrons are all actually released within less than a millionth of a second of the explosion, as noted above, they are somewhat delayed in escaping from the environment of the exploding bomb. This delay arises from the numerous scattering collisions suffered by the neutrons with the nuclei present in the bomb residues. As a result, the neutrons traverse a complex zigzag path before they finally emerge. They have fairly high speeds, but the actual (average) distance the neutrons travel is relatively large, and so some time elapses before they reach the outside of the ball of fire. However, the delay in the escape of the prompt neutrons is no more than about a one-hundredth part of a second.

8.57 It is true that neutrons travel with speeds less than that of light. Nevertheless, at such distances from the explosion that they represent a hazard, nearly all of the neutrons are received within a second of the explosion. The evasive action described in § 8.52 thus has little effect on the neutron dose received.

### DISTRIBUTION OF NEUTRON ENERGIES

8.58 The neutrons produced in the fission process have a range of energies, but they are virtually all in the region of high energy. Such high-energy neutrons are called "fast neutrons," their energy being kinetic in nature. In the course of the scattering collisions between the fast neutrons and atomic nuclei, there is an exchange of kinetic energy between the neutrons and nuclei. The net result is that the neutrons lose some of their energy and are, consequently, slowed down. The neutrons leaving the exploding bomb thus have speeds (or energies) covering a wide range, from fast, through intermediate, to slow. The neutrons of slowest speed are often called "thermal neutrons" because they are in thermal (or temperature) equilibrium with their surroundings.

8.59 After the neutrons leave the environment of the bomb, they undergo more scattering collisions with the nuclei of nitrogen, oxygen, and other elements present in the atmosphere. These collisions are less frequent than in the bomb, because of the lower pressure and smaller concentration of nuclei in the air. Nevertheless, the results of the collisions are important. In the first place, the fractional decrease in neutron energy per collision is, on the average, greatest for light nuclei. The nuclei of oxygen and nitrogen are relatively light, so that the neutrons are appreciably slowed down as a result of scattering collisions in the air.

8.60 Further, in some collisions, particularly with nitrogen nuclei, the neutrons can be captured, as described in § 8.9, so that they are completely removed. The probability of capture is greatest with the slow neutrons. Consequently, in their passage through the air, from the bomb to a location on the ground, for example, there are many interactions involving the neutrons. There is a tendency for the fast (high energy) neutrons to lose some of their energy and to be slowed down. At the same time, the slower neutrons have a greater chance of being captured and eliminated, as such, from the nuclear radiation, although the capture usually leads to the emission of gamma rays.

8.61 It is important in connection with the measurement of nuclear bomb neutrons and the study of their biological effects to know something of the manner in which the distribution of neutron energies (or the "neutron spectrum") varies with distance from the explosion. From a series of measurements made at the nuclear test explosions in Nevada in 1955, it seems that, at least for the devices tested, the energy spectrum remains the same for a given device over the range of distances which are of biological interest. This condition is referred to as an "equilibrium spectrum."

8.62 The probable explanation of this important result is that, due to a combination of circumstances, the loss of the slower neutrons by capture, e. g., by nitrogen nuclei, is just compensated by the slowing down of fast neutrons. The total number of neutrons received per unit area at a given location is less the farther that point is from the explosion, because, in addition to being spread over a large area (§ 8.34), some of the faster neutrons are slowed down and the slower ones are removed by capture. But the proportion (or fraction) of neutrons in any particular energy range appears to be essentially the same at all distances of interest.

### MEASUREMENT OF NEUTRONS

8.63 Neutrons, being electrically neutral particles, do not produce ionization or excitation directly in their passage through matter. They can, however, cause ionization to occur indirectly as a result of their interaction with certain light nuclei. When a fast neutron collides with the nucleus of a hydrogen atom, for example, the neutron may transfer a large part of its energy to that nucleus. As a result, the hydrogen nucleus is freed from its associated electron and moves off as a high-energy proton (§ 8.16). Such a proton is capable of producing a considerable number of ion pairs in its passage through a gas. Thus, the interaction of a fast neutron with hydrogen (or with any substance containing hydrogen) can cause ionization to occur indirectly. By a similar mechanism, indirect ionization, although to a smaller extent, results from collisions of fast neutrons with other light nuclei, e. g., carbon, oxygen, and nitrogen.[2]

8.64 Neutrons in the slow and moderate speed ranges can produce ionization indirectly in other ways. When such neutrons are captured by the lighter isotope of boron (boron-10), two electrically charged particles—a helium nucleus (alpha particle) and a lithium nucleus—of high energy are formed. Both of these particles can produce ion pairs. Indirect ionization by neutrons can also result from fission of plutonium or uranium isotopes. The fission fragments are electrically charged particles (nuclei) of high energy which leave considerable ionization in their paths.

8.65 All of the foregoing indirect ionization processes can be used to detect and measure neutron intensities. The instruments employed for the purpose, such as boron counters and fission chambers, are somewhat similar, in general principle, to the Geiger counters commonly used for gamma radiations. "Tissue equivalent" chambers have been developed in which the ionization produced indirectly by neutrons is related to the energy which would be taken up from these neutrons by animal tissue.

8.66 In addition to the methods described above, "foil activation" methods have been extensively applied to the detection and measurement of neutrons in various velocity ranges. Certain elements are converted into radioactive isotopes as a result of the capture of neutrons (§ 8.8). The amount of induced radioactivity, as determined from the ionization produced by the emitted beta particles or gamma rays, is the basis of the "activation" procedures. The detector is generally used in the form of a thin sheet (or foil), so that its effect on the neutron field is not significant.

8.67 The "fission foil" method, as its name implies, makes use of fission reactions. A thin layer of a fissionable material, such as an isotope of uranium or plutonium, is exposed to neutrons. The fission products formed are highly radioactive, emitting beta particles and gamma rays. By measuring the radioactivity produced in this manner, the amount of fission and, hence, the neutron flux can be determined.

8.68 The neutron dose in rads, absorbed at a particular location, can be determined by applying certain calculations to the measurements of foil activation. Instruments based on ionization measurements are usually calibrated by means of foil activation data, and so they can also be used to indicate the dose in rads of neutrons of specific energies (or energy ranges). It is seen, therefore, that methods are available for determining neutron absorption doses in rads.

8.69 To determine the biological dose in rems, if the absorbed dose in rads has been measured, the RBE for neutrons must be known. The value of this quantity for neutrons associated with a nuclear explosion has long been in doubt. Observations made on mice suggest that the RBE of bomb neutrons, at distances where casualties due to neutron absorption may be expected, is about 1.7. Some confirmation of the applicability of a similar value to man has been obtained from an analysis of the data on radiation injury and death collected after the nuclear explosions in Japan.[3]

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[2] The ionization resulting from the interaction of fast neutrons with hydrogen and nitrogen in tissue is the main cause of biological injury by neutrons.

[3] The figure of 1.7 for the RBE of bomb neutrons may perhaps be too high, but it is probably the best value to use at the present time. The RBE values of 10 for fast neutrons and 3 to 4 for slow (thermal) neutrons are to be found in the literature, but they apply, in particular, to (non-vision disturbing) cataract formation.

### NEUTRON DOSE-DISTANCE RELATIONSHIP

8.70 Whereas the magnitude of the initial gamma-radiation dose from a nuclear explosion can be expressed in a simple manner that is consistent with the observations made at a number of tests (§ 8.35), such is not the case for the neutron dose. This seems to vary quite markedly with changes in the characteristics of the nuclear device. The bomb materials, for example, have a considerable influence on the extent of neutron capture and, consequently, on the number and energy distribution of the fission neutrons that succeed in escaping into the air. Further, as stated in § 1.15, the thermonuclear reaction between deuterium and tritium is accompanied by the liberation of neutrons of high energy. Hence, it is to be expected that, for an explosion in which part of the energy yield arises from thermonuclear (fusion) processes, there will be a larger proportion of high-energy (fast) neutrons than from a purely fission system.

8.71 It is obvious, therefore, that both the number of neutrons per kiloton of energy and their energy spectrum may vary from one weapon to another. Hence, a single curve for neutron dose versus distance, such as was given for the initial gamma-radiation dose (Fig. 8.35a), from which the results for a weapon of any specified yield can be estimated, must represent a compromise. It is with this limitation in mind that the neutron dose curve in Fig. 8.71, for a 1-kiloton air burst, is presented. The dose is given in rems so that it is a measure of the biological effectiveness. In order to determine the dose received at a specified distance from an explosion of energy *W* kilotons, the value for that distance as obtained from Fig. 8.71 is multiplied by *W*. This scaling procedure is by no means exact, but it is probably adequate. As with other types of radiation, the dose becomes less at greater distances from the explosion center, partly because the neutrons are spread over a larger area (inverse square law), and partly because of absorption and scattering.

8.72 The data in Fig. 8.71 may be represented in an alternative manner, as in Fig. 8.72. This shows the distances from the explosion center (or slant ranges) at which various neutron (biological) doses would be received from air bursts with energies in the range of 1 kiloton to 20 megatons. Using either Fig. 8.71 and the simple proportional scaling law or Fig. 8.72, with interpolation between the curves, it is found that at 1 mile from the explosion center the neutron dose received from a 100-kiloton air burst would be about 200 rems.

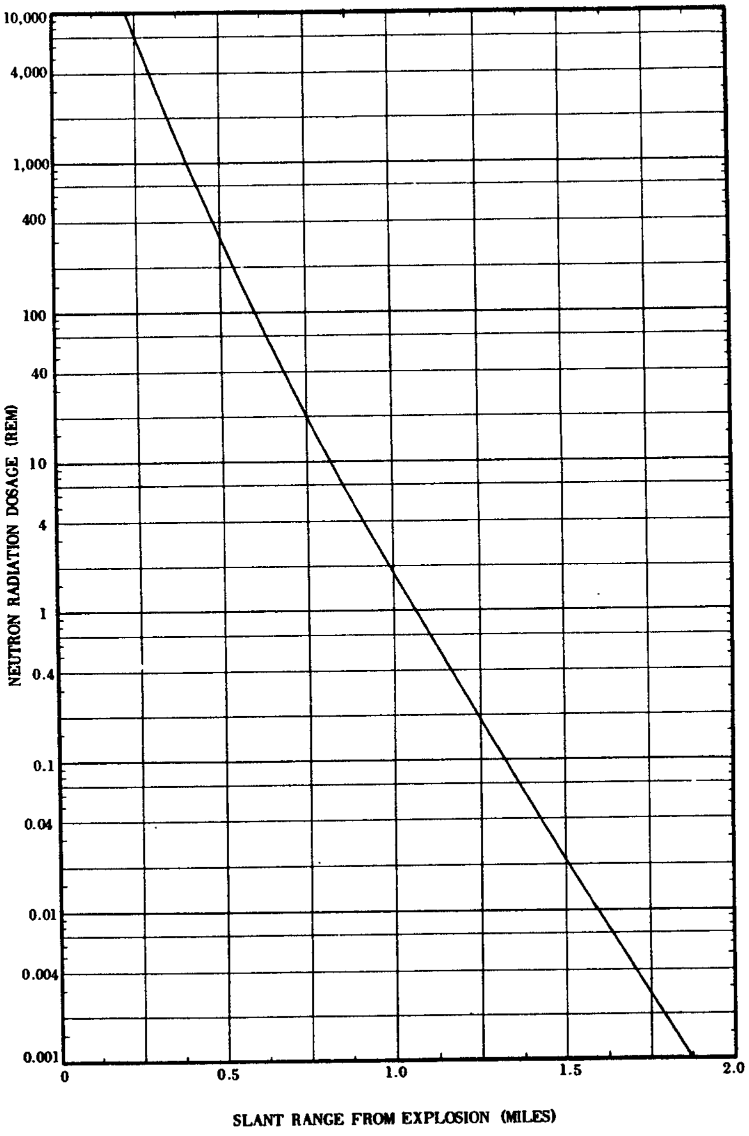

Figure 8.71. Neutron biological dosage for a 1-kiloton air burst.

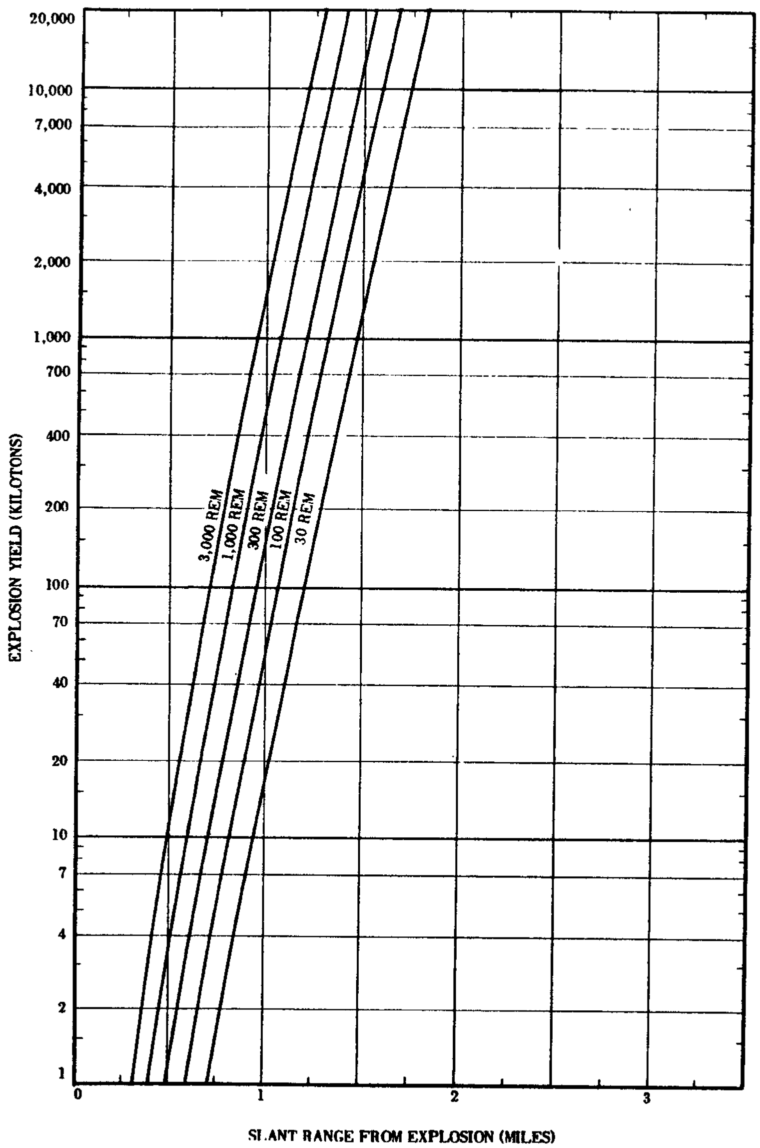

Figure 8.72. Ranges for specified neutron biological dosages.

## SHIELDING AGAINST NEUTRONS

8.73 Neutron shielding is a different, and more difficult, problem than shielding against gamma rays. As far as the latter are concerned, it is merely a matter of interposing a sufficient mass of material between the source of gamma radiations and the recipient. Heavy metals, such as iron and lead, are good gamma ray shields because of their high density. Such elements alone, however, are not quite as satisfactory for neutron shielding. An iron shield will attenuate bomb neutrons to some extent, but it is less effective than one of the type described below.

8.74 The attenuation of neutrons from a nuclear explosion involves several different phenomena. First, the very fast neutrons must be slowed down into the moderately fast range; this requires a suitable (inelastic) scattering material, such as one containing barium or iron. Then, the moderately fast neutrons have to be decelerated into the slow range by means of an element of low atomic weight. Water is very satisfactory in this respect, since its two constituent elements, i. e., hydrogen and oxygen, both have low atomic weights. The slow (thermal) neutrons must then be absorbed. This is not a difficult matter, since the hydrogen in water will serve the purpose. Unfortunately, however, most neutron capture reactions are accompanied by the emission of gamma rays (§ 8.8). Consequently, sufficient gamma-attenuating material must be included to minimize the escape of the capture gamma rays from the shield.

8.75 In general, concrete or damp earth would represent a fair compromise for neutron, as well as for gamma-ray, shielding. Although these materials do not normally contain elements of high atomic weight, they do have a fairly large proportion of hydrogen to slow down and capture neutrons, as well as calcium, silicon, and oxygen to absorb the gamma radiations. A thickness of 10 inches of concrete, for example, will decrease the neutron dose by a factor of about 10, and 20 inches by a factor of roughly 100. The initial gamma radiation would be decreased to a somewhat lesser extent, but, in sufficient thickness, concrete could be used to provide shielding against both neutrons and gamma rays from a nuclear explosion. Damp earth may be expected to act in a similar manner.

8.76 An increase in the absorption of the nuclear radiations can be achieved by using a modified ("heavy") concrete made by adding a considerable proportion of an iron (oxide) ore, e. g., limonite, to the mix and incorporating small pieces of iron, such as steel punchings. The presence of a heavy element improves both the neutron and gamma ray shielding properties of a given thickness (or volume) of the material. Attenuation of the neutron dose by a factor of 10 requires about 7 inches of this heavy concrete.

8.77 The presence of boron or a boron compound in neutron shields has certain advantages. The lighter (boron-10) isotope of the element captures slow neutrons very readily (§ 8.64), the process being accompanied by the emission of gamma rays of moderate energy (0.48 Mev) that are not difficult to attenuate. Thus, the mineral colemanite, which contains a large proportion of boron, can be incorporated into concrete in order to improve its ability to absorb neutrons.

8.78 It was pointed out in § 8.49 that, because of the scattering suffered by gamma rays, an adequate shield must provide protection from all directions. Somewhat the same situation applies to neutrons. As seen earlier, neutrons undergo extensive scattering in the air, so that, by the time they reach the ground, even at a moderate distance from the explosion, their directions of motion are almost randomly distributed. At considerable ranges, however, many of the scattered neutrons have relatively low energies and do not make a large contribution to the total biological dose. Partial protection from injury by neutrons may then be obtained by means of an object or structure that provides shielding only from the direction of the explosion, although better protection, as in the case of gamma rays, would be given by a shelter which shielded in all directions.

## INITIAL GAMMA RAYS AND NEUTRONS

### Comparison of Doses

8.79 In the preceding sections of this chapter, the gamma rays and neutrons constituting the initial nuclear radiation from a nuclear explosion have been described separately. It is of interest to compare the dosages received from these two types of radiation and to consider their combined effect, since they both cause similar injury to human beings. Although the nuclear radiation doses are not strictly proportional to the energy yield of the explosion, the general conclusions are not basically affected if such proportionality is assumed.

8.80 In Fig. 8.80, the curves from Figs. 8.35a and 8.71 for the gamma-ray and neutron doses, respectively, from a 1-kiloton air burst, are superimposed for purposes of comparison. There is also included a curve giving the total biological dose in rems at various distances

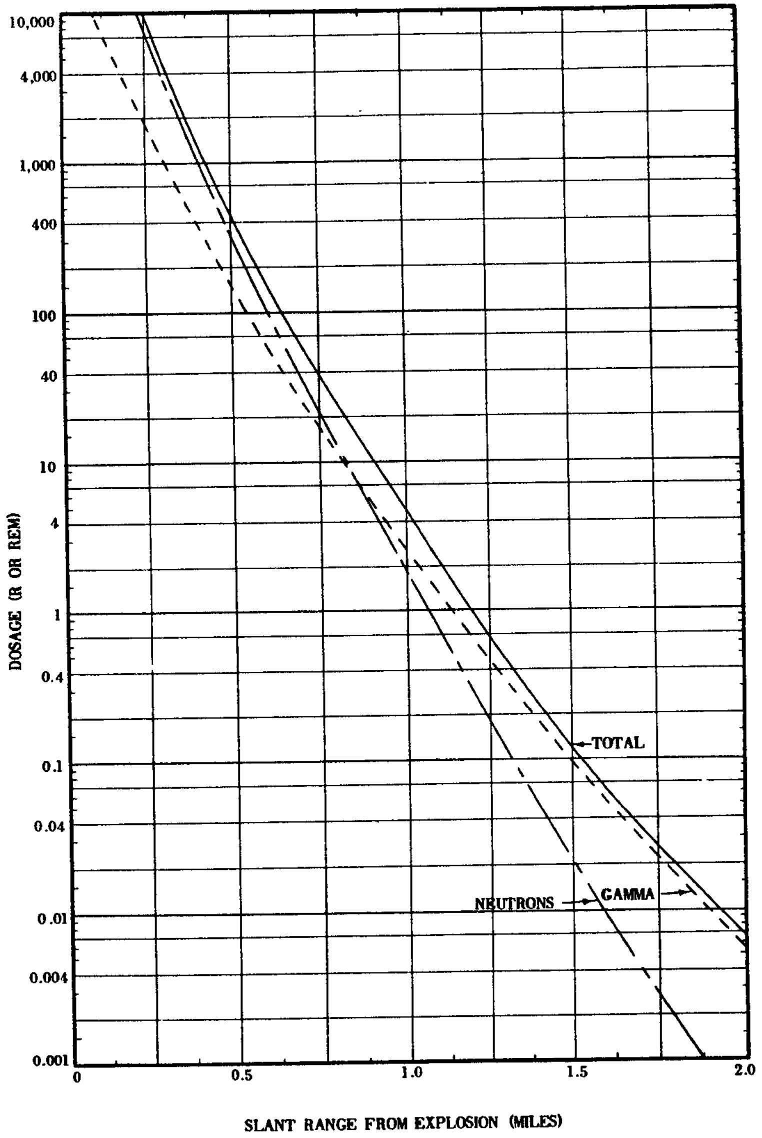

Figure 8.80. Comparison of neutron and initial gamma radiation dosages for a 1-kiloton air burst.

from the 1-kiloton explosion. An examination of the gamma-ray and neutron dose curves shows that near the explosion center the neutron dose is the greater of the two. However, with increasing distance, the neutron dose falls off more rapidly than does that of gamma radiation, so that beyond a certain point the gamma rays predominate. Ultimately, the neutrons become insignificant in comparison with the gamma radiations.

### Dependence Upon Energy Yield

8.81 Another interesting point, related to that just considered, can be brought out by means of Fig. 8.81. Assuming total initial nuclear radiation (biological) doses of 600 and 200 rems, respectively, the curves show the proportions contributed by gamma rays and by neutrons for a range of explosion energy yields. The particular values of the total dose were selected because they are in the region where effective protection by the use of a shield of reasonable thickness, e. g., 3 feet of earth, is feasible. It is seen from Fig. 8.81 that, in these particular circumstances, the neutron contribution to the total radiation dose is significant only for weapons of low energy yield. For explosions of moderate and high energy yields, the gamma rays become relatively more important.

8.82 It should be emphasized that the foregoing conclusions apply to the specified total radiation doses. The slant distances from the explosion at which these doses would be received can be obtained by interpolation from the curves in Fig. 8.82 which indicates the relation between total initial nuclear radiation dose, yield, and distance. For higher doses, i. e., at shorter respective distances from ground zero, neutrons make an increasingly greater contribution. The character of the initial nuclear radiation at a given location will thus be determined by the energy yield of the postulated explosion and by the total dose received. For high doses or low energy yields, neutrons make a relatively larger contribution than do gamma rays; for moderate doses or high energy yields, the reverse will be true.

## TECHNICAL ASPECTS OF NUCLEAR RADIATION TRANSMISSION AND ABSORPTION[4]

### Interaction of Gamma Rays with Matter

8.83 There are three important types of interaction of gamma rays with matter, as a result of which they are scattered and absorbed. The first of these is called the "Compton effect." In this interaction, the gamma ray photon collides with one of the atomic electrons, and as a result some of the energy of the photon is transferred to the electron. The photon, with its energy decreased, then usually moves off in a direction at an angle to its original direction of motion. That is to say, the gamma ray suffers scattering and loss of energy as a result of the Compton interaction with matter.

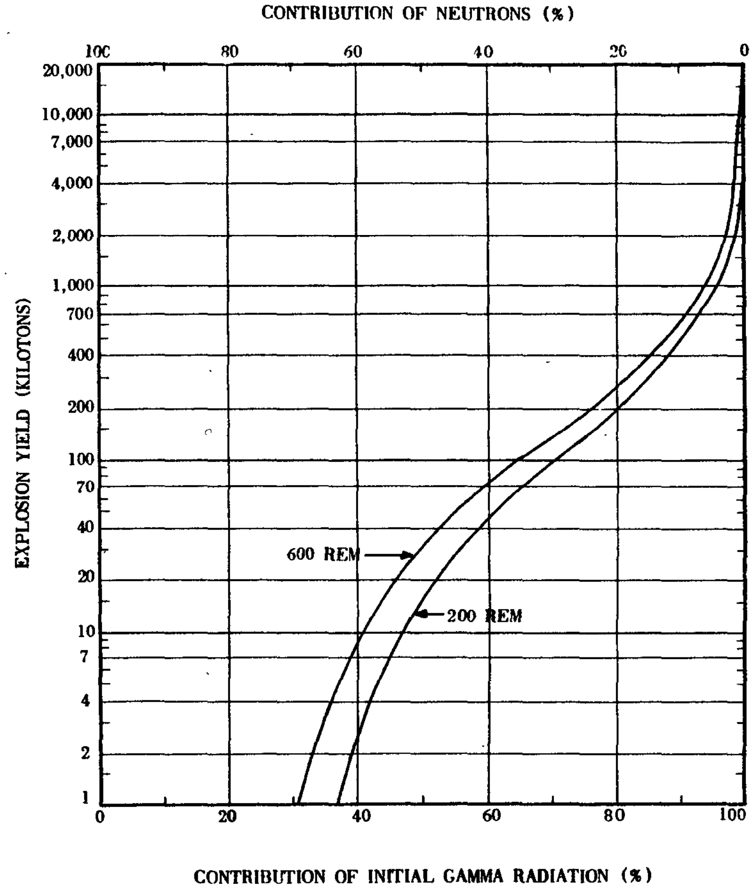

**Figure 8.81.** Relative contribution of neutron and initial gamma radiation to total biological dose.

8.84 The total extent of Compton scattering per atom of the material with which the radiation interacts is proportional to the

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[4] The remaining sections of this chapter may be omitted without loss of continuity.

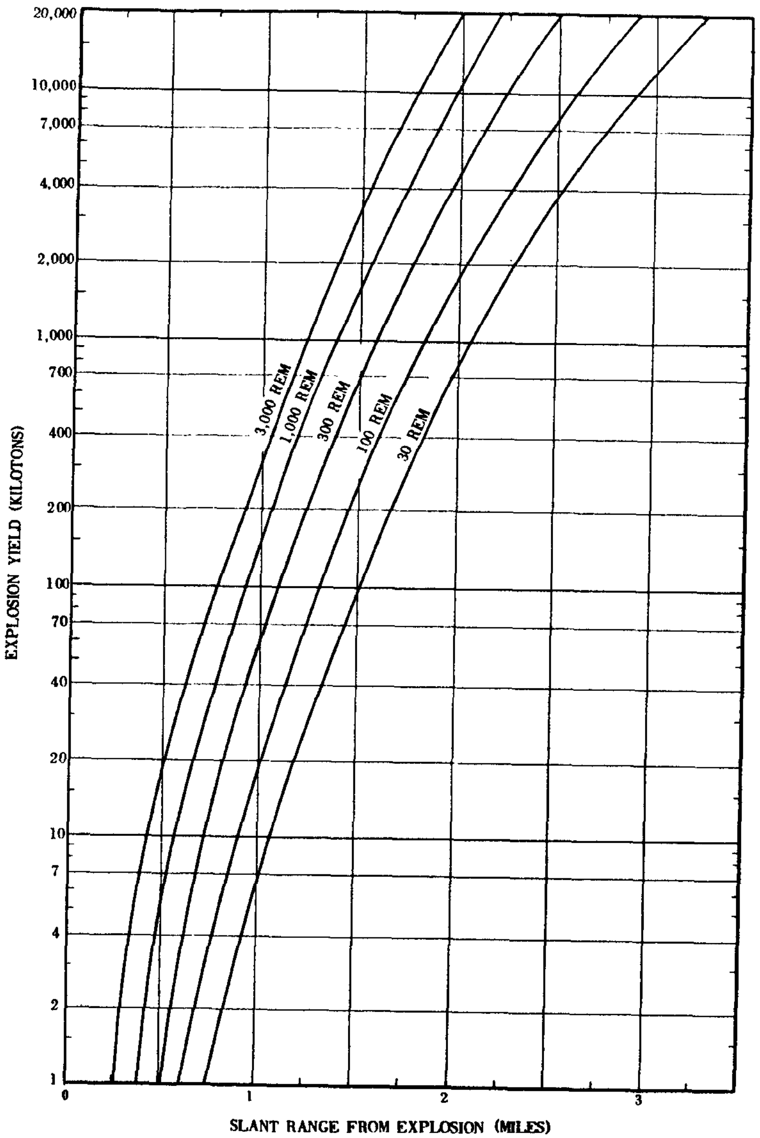

**Figure 8.82.** Ranges for specified total initial radiation dosages (neutron plus initial gamma radiation).

number of electrons in the atom, i. e., to the atomic number (§ 1.8). It is, consequently, greater per atom for an element of high atomic number than for one of low atomic number. The Compton scattering decreases rapidly with increasing energy of the gamma radiation for all materials, irrespective of their atomic weight.

8.85 The second type of interaction of gamma rays and matter is by the "photoelectric effect." A photon, with energy somewhat greater than the binding energy of an electron in an atom, transfers all its energy to the electron which is consequently ejected from the atom. Since the photon involved in the photoelectric effect loses all of its energy, it ceases to exist. In this respect, it differs from the Compton effect, in which the photon still remains after the interaction, although with decreased energy. The magnitude of the photoelectric effect per atom, like that of the Compton effect, increases with the atomic number of the material through which the gamma rays pass, and decreases very rapidly with increasing energy of the photon.

8.86 Gamma radiation can interact with matter in a third manner, namely, that of "pair production." When a gamma-ray photon with energy in excess of 1.02 Mev passes near the nucleus of an atom, the photon may be converted into matter with the formation of a pair of particles, namely, a positive and a negative electron. As in the case of the photoelectric effect, pair production results in the disappearance of the gamma ray photon concerned. However, the positive electron soon interacts with a negative electron with the formation of two photons of lesser energy than the original one. The occurrence of pair production per atom, as with the other interactions, increases with the atomic number of the material, but it also increases with the energy of the photon in excess of 1.02 Mev.

8.87 In reviewing the three types of interaction described above, it is seen that, in all cases, the magnitude per atom increases with increasing atomic number (or atomic weight) of the material through which the gamma rays pass. Each effect, too, is accompanied by either the complete removal of photons or a decrease in their energy. The net result is some attenuation of the gamma-ray intensity or dose rate. Since there is an approximate parallelism between atomic weight and density, the number of atoms per unit volume does not vary greatly from one substance to another. Hence, a given volume (or thickness) of a material containing elements of high atomic weight ("heavy elements") will be more effective as a gamma ray shield than the same volume (or thickness) of one consisting only of elements of low atomic weight ("light elements"). An illustration of this difference in behavior will be given below.

8.88 Another important point is that the probabilities of the Compton and photoelectric effects (per atom) both decrease with increasing energy of the gamma-ray photon. However, pair production, which starts at 1.02 Mev, increases with the energy beyond this value. Combination of the various attenuating effects, two of which decrease whereas one increases with increasing photon energy, means that, at some energy in excess of 1.02 Mev, the absorption of gamma radiation by a particular material should be a minimum. That such minima do exist will be seen shortly.

## GAMMA-RAY ABSORPTION COEFFICIENTS

8.89 If a narrow (or collimated) beam of gamma rays of a specific energy, having an intensity of $I_0$,[5] falls upon a thickness $x$ of a given material, the intensity, $I$, of the rays which emerge can be represented by the equation

$$I=I_0e^{-\mu x}, \tag{8.89.1}$$

where $\mu$ is called the "linear absorption coefficient." The distance $x$ is usually expressed in centimeters, so that the corresponding units for $\mu$ are reciprocal centimeters ($\text{cm}^{-1}$). The value of $\mu$, for any material and for gamma rays of a specific energy, is proportional to the sum of the Compton, photoelectric, and pair production effects. It can be seen from equation (8.89.1) that, for a given thickness $x$ of material, the intensity or dose, $I$, of the emerging gamma rays will be less the larger the value of $\mu$. In other words, the linear absorption coefficient is a measure of the shielding ability of a definite thickness, e. g., 1 cm, 1 foot, or other thickness, of any material.

8.90 The value of $\mu$, under any given conditions, can be obtained with the aid of equation (8.89.1) by determining the gamma-ray intensity (or dose) before ($I_0$) and after ($I$) passage through a known thickness, $x$, of material. Some of the data obtained in this manner, for gamma rays with energies ranging from 0.5 Mev to 10 Mev, are recorded in Table 8.90. The values given for concrete apply to the common form having a density of 2.3 grams per cubic centimeter (144 pounds per cubic foot). For special heavy concretes, containing iron, iron oxide, or barytes, the coefficients are increased roughly in proportion to the density.

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[5] The radiation intensity is defined as the rate at which the energy (from monoenergetic radiation) flows past unit area at a given location. It is essentially proportional to the exposure dose rate. However, an expression of the form of equation (8.89.1) may be used to determine the attenuation of the total (accumulated) dose received at a given location, due either to a shield or to intervening air.

TABLE 8.90

LINEAR ABSORPTION COEFFICIENTS FOR GAMMA RAYS

| Gamma ray energy (Mev) | Linear absorption coefficient ($\mu$) in $\text{cm}^{-1}$ | | | | |
|---|---|---|---|---|---|
| | Air | Water | Concrete | Iron | Lead |
| 0.5 | $1.11\times10^{-4}$ | 0.097 | 0.22 | 0.66 | 1.7 |
| 1.0 | $0.81\times10^{-4}$ | 0.071 | 0.15 | 0.47 | 0.80 |
| 2.0 | $0.57\times10^{-4}$ | 0.049 | 0.11 | 0.33 | 0.52 |
| 3.0 | $0.46\times10^{-4}$ | 0.040 | 0.088 | 0.28 | 0.47 |
| 4.0 | $0.41\times10^{-4}$ | 0.034 | 0.078 | 0.26 | 0.47 |
| 5.0 | $0.35\times10^{-4}$ | 0.030 | 0.071 | 0.25 | 0.50 |
| 10 | $0.26\times10^{-4}$ | 0.022 | 0.060 | 0.23 | 0.61 |

8.91 By suitable measurements and theoretical calculations, it is possible to determine the separate contributions of the Compton effect ($\mu_c$), of the photoelectric effect ($\mu_{pe}$), and of pair production ($\mu_{pp}$) to the total linear absorption coefficient. The results for lead, a typical heavy element (high atomic weight) with a large absorption coefficient, are given in Fig. 8.91a and those for air, a mixture of light elements (low atomic weight) with a small absorption coefficient, in Fig. 8.91b. It is seen that, at low gamma ray energies, the linear absorption coefficient decreases in each case with increasing energy. This is obviously due to the Compton and photoelectric effects, as stated above. At energies in excess of 1.02 Mev, pair production begins to make an increasingly significant contribution. Therefore, at sufficiently high energies the absorption coefficient begins to increase after passing through a minimum. This is apparent in Fig. 8.91a, as well as in the last column of Table 8.90, for lead. For elements of lower atomic weight, the increase does not set in until very high gamma-ray energies are attained, e. g., about 17 Mev for concrete and 50 Mev for water.

8.92 The fact that the absorption coefficient decreases as the gamma-ray energy increases, and may pass through a minimum, has an important bearing on the problem of shielding. For example, a shield intended to attenuate gamma rays of 1 Mev energy will be much less effective for radiations of 10 Mev energy because of the lower value of the absorption coefficient, irrespective of the material of which the shield is composed. The initial gamma rays from a nuclear explosion cover a wide range of energies, up to 10 Mev or more. But, for the purpose of making approximate shielding esti-

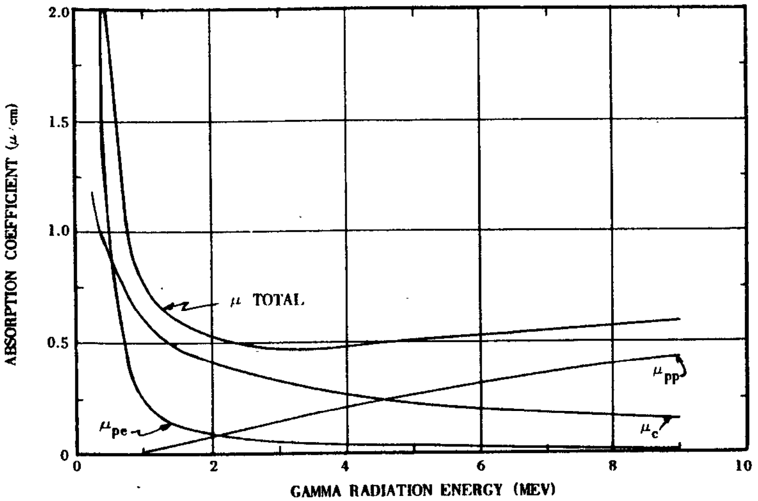

Figure 8.91a. Absorption coefficient of lead for gamma radiations.

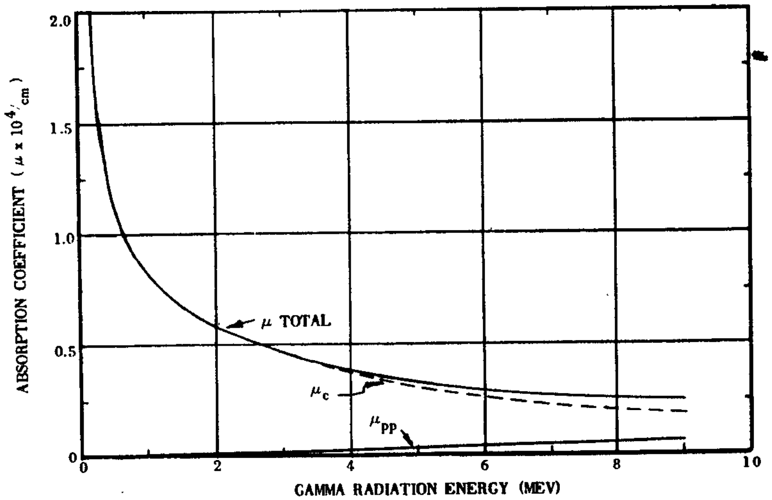

Figure 8.91b. Absorption coefficient of air for gamma radiations.

mates, an empirical (or effective) value of 4.5 Mev appears to give satisfactory results. (This figure does not apply to the residual nuclear radiation, as will be seen in Chapter IX.)

8.93 An examination of Table 8.90 shows that, for any particular energy value, the linear absorption coefficients increase from left to right, that is, with increasing density of the material. Thus, a given thickness of a dense substance will attenuate the gamma radiation more than the same thickness of a less dense material. This is in agreement with the statement in § 8.41, that a small thickness of a substance of high density will make as effective a gamma ray shield as a greater thickness of one of lower density.

### MASS ABSORPTION COEFFICIENT

8.94 As a very rough approximation, it has been found that the linear absorption coefficient for gamma rays of a particular energy is proportional to the density of the absorbing (shield) material. That is to say, the linear absorption coefficient divided by the density, giving what is called the "mass absorption coefficient," is approximately the same for all substances for a specified gamma-ray energy. This is especially true for elements of low and medium atomic weight, up to that of iron (about 56), where the Compton effect makes the major contribution to the absorption coefficient for energies up to a few million electron volts (Fig. 8.91b). For the initial gamma rays, the effective mass absorption coefficient has a value close to 0.021 for water, concrete, earth, and iron, the densities being expressed in grams per cubic centimeter.[6]

8.95 If the symbol $\rho$ is used for the density of the shield material, then equation (8.89.1) can be rewritten in the form

$$I_0/I = e^{\mu x} = e^{(\mu/\rho)(\rho x)}, \qquad (8.95.1)$$

where $I_0/I$ is the attenuation factor (as defined in § 8.46) of the shield of thickness $x$ cm, and $\mu/\rho$ is, by definition, the mass absorption coefficient. Taking $\mu/\rho$ to be 0.021 for initial gamma rays, it follows, from equation (8.95.1), that

$$\text{Attenuation factor} = e^{0.021\rho x},$$

so that the attenuation factor of a thickness $x$ centimeters of any material of known density, provided it consists of elements of low or moderate atomic weight, can be calculated to a good approximation.

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[6] In taking the effective mass absorption coefficient as 0.021, an attempt is made to allow for the conditions applying to thick shields or broad radiation beams (see § 8.99, *et seq.*).

### HALF- AND TENTH-VALUE LAYERS

8.96 A half-value layer, as defined in § 8.42, is the thickness of any material which will attenuate a specified (monoenergetic) gamma radiation by a factor of two. Thus, setting $I/I_0$ in equation (8.89.1) equal to ½, it follows that

$$e^{-\mu x_{\frac{1}{2}}} = \tfrac{1}{2}, \qquad (8.96.1)$$

where $x_{\frac{1}{2}}$ is the half-value layer thickness in centimeters. From equation (8.96.1), it is readily shown that

$$x_{\frac{1}{2}} = \frac{0.693}{\mu}. \qquad (8.96.2)$$

The half-value thickness is consequently inversely proportional to the linear absorption coefficient of the given material for the specified gamma rays. It is seen to be independent of the radiation intensity (or dose).

8.97 If the mass absorption coefficient, $\mu/\rho$, may be taken to be constant, i. e., 0.021 for gamma rays in the initial nuclear radiation, then it is found from equation (8.96.2) that

$$x_{\frac{1}{2}} = \frac{0.693}{0.021} = \frac{33}{\rho}\ \text{cm},$$

where $x_{\frac{1}{2}}$ is in centimeters and the density, $\rho$, is expressed in grams per cubic centimeter. For ordinary concrete, for example, the density is 2.3 grams per cubic centimeter, so that $x_{\frac{1}{2}}$ is about 14 cm or approximately 6 inches, as given in Table 8.44.

8.98 For a tenth-layer value, $I/I_0$ is 0.1; the thickness, $x_{0.1}$ is thus obtained from equation (8.89.1) as

$$x_{0.1} = \frac{2.30}{\mu}\ \text{cm},$$

and for initial gamma rays from a nuclear explosion, a good approximation is

$$x_{0.1} = \frac{110}{\rho}\ \text{cm}.$$

For concrete, the tenth-value thickness is thus about 48 cm or 19 inches.

### THICK SHIELDS: BUILD-UP FACTOR

8.99 Equation (8.89.1) is strictly applicable only to cases in which the photons scattered in Compton interactions may be regarded as essentially removed from the gamma ray beam. This situation holds reasonably well for narrow beams or for shields of moderate thickness, but it fails for broad beams or thick shields. In the latter circumstances, the photon may be scattered several times before emerging from the shield. For broad radiation beams and thick shields, such as are of interest in shielding from nuclear explosions, the value of $I$, the intensity (or dose) of the emerging radiation, is larger than that given by equation (8.89.1). Allowance for the multiple scattering of the radiation is made by including a "build-up factor," represented by $B(x)$, the value of which depends upon the thickness of the shield; thus, equation (8.89.1) is now written as

$$I = I_0 B(x) e^{-\mu x}.$$

8.100 The magnitude of the build-up factor has been calculated for a number of elements from theoretical considerations of the scattering of photons by electrons. The build-up factors for monoenergetic gamma rays having energies of 4 Mev and 1 Mev, respectively, are given in Figs. 8.100a and b as a function of the atomic number of the absorbing material, for shields of various thicknesses expressed in terms of $\mu x$, i. e., in terms of the number of relaxation lengths (see § 8.104). The build-up factors in Fig. 8.100a can be applied to the absorption of the initial gamma radiation, to a good approximation, and those in Fig. 8.100b can be used for shielding calculations involving the residual nuclear radiation (see Chapter IX).

8.101 It will be apparent from the foregoing discussion that the concept of half-value (and tenth-value) layers will apply only to monoenergetic radiations and thin shields, for which the build-up factor is unity. However, by taking the mass absorption coefficient for the initial gamma radiation to be 0.021, as given in § 8.94, an approximate (empirical) allowance or adjustment has been made both for the polyenergetic nature of the gamma radiations from a nuclear explosion and the build-up factors due to multiple scattering of the photons. Consequently, the expressions given in § 8.96 and § 8.98, for $x_{\frac{1}{2}}$ and $x_{0.1}$, hold reasonably well for the attenuation of the initial gamma radiations by thick shields. It may be noted, too, that the attenuation factors in Fig. 8.47 also include allowances for multiple scattering in thick shields.

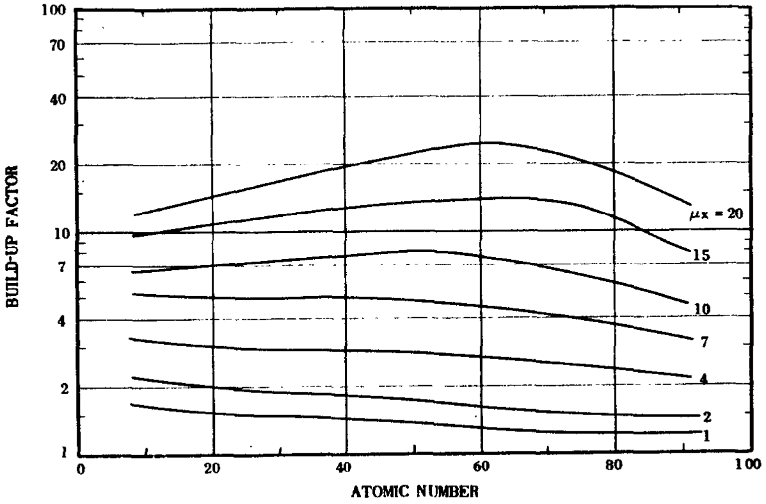

Figure 8.100a. Build-up factor as a function of atomic number for gamma rays in initial nuclear radiation (4.0 Mev).

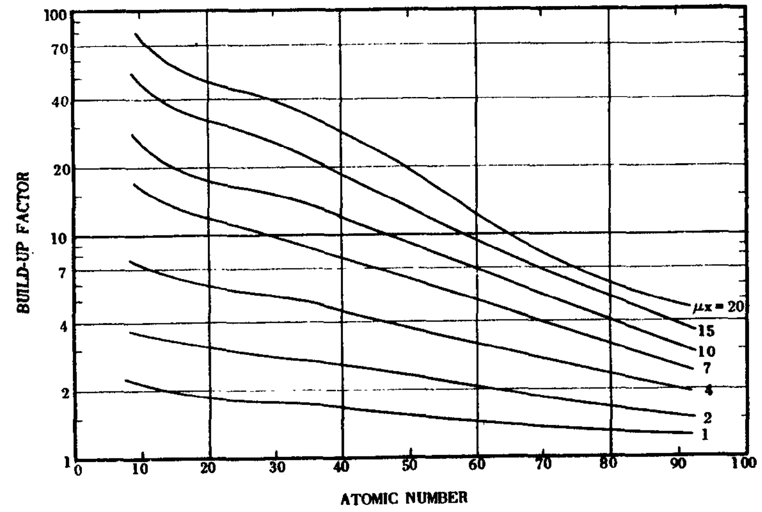

Figure 8.100b. Build-up factor as a function of atomic number for gamma rays in residual nuclear radiation (1.0 Mev).

### TRANSMISSION OF GAMMA RAYS FROM SOURCE

8.102 In the foregoing treatment, no account has been taken of the source of the gamma rays, e. g., a nuclear explosion, or of its distance away. All that has been considered is the relationship between the intensity of the radiation incident upon a thickness of material, which acts as a shield by attenuating the radiation, and the intensity (or dose) emerging from the shield. The connection between the incident dose, which is related to $I_0$, and the properties of the source, i. e., the nuclear explosion, require two factors to be taken into account. These are, first, the inverse square law for the decrease of dose with increasing distance, due to spread of the radiation over a larger area; and, second, the attenuation due to scattering and absorption in the atmosphere. The latter aspect of the problem, however, is not essentially different from that considered above in connection with shielding.

8.103 Because the distances of interest are large in comparison, the exploding bomb may be treated as a point source, emitting a total $R_\gamma$ of initial gamma radiation, expressed in appropriate units. Hence, at a distance, $D$, from the explosion, there will be received $R_\gamma/4\pi D^2$ per unit area, apart from losses due to attenuation by means of intervening air. Allowance for this should be made by means of equation (8.99.1), since for the distances of interest the build-up factor is appreciably greater than unity. However, it is simpler to use equation (8.89.1) and to adjust the absorption coefficient to fit the results. It follows, therefore, that $I_0$, expressed as a radiation dose, can be represented (approximately) by

$$I_0=\frac{R_\gamma}{4\pi D^2}e^{-\mu D}, \tag{8.103.1}$$

where $\mu$ does not apply to any particular energy but is rather an empirical mean value for the range of photon energies present in the initial nuclear radiation.

8.104 For various reasons, it is convenient to replace $\mu$ by $1/\lambda$, where $\lambda$ is called the "relaxation length" of the radiation. It is, for practical purposes, the thickness of material, e. g., air, required to attenuate the radiation by a factor of $e$, the base of natural logarithms. Thus, equation (8.103.1) is generally written as

$$I_0=\frac{R_\gamma}{4\pi D^2}e^{-D/\lambda}, \tag{8.104.1}$$

where $I_0$ is the gamma radiation dose received at a distance $D$ from the explosion without shielding. It is, in fact, the values of $I_0$, expressed in roentgens, for various distances from a 1-kiloton explosion, that are plotted in Fig. 8.35a.

8.105 By rearranging equation (8.104.1), so that the left side becomes $I_0D^2$, and taking logarithms, it is found that

$$\log I_0D^2 = \text{Constant } -0.4343\frac{D}{\lambda}.$$

This means that if $I_0D^2$ is plotted on a logarithmic scale against $D$ on a linear scale, the result should be a straight line. From the slope of this line, which is equal to $=0.4343/\lambda$, the relaxation length of the gamma rays can be calculated. An example of such a plot, based on the data in Fig. 8.35a for an explosion of 1-kiloton yield, is shown in Fig. 8.105. The value of $\lambda$ is found to be 338 yards, and from the intercept $R_\gamma/4\pi$ is $1.4\times10^9$ roentgens-yards². The expression, of the form of equation (8.104.1), representing the variation of the dose in roentgens (or rems) with distance, $D$, in yards, then becomes

$$I_0 = \frac{1.4\times10^9}{D^2}e^{-D/338}\text{ [illegible]ntgens/kiloton,}$$

that is, for a 1-kiloton explosion.

8.106 If the total initial gamma radiation is proportional to the energy yield of the explosion and the relaxation length of the photons in air is assumed to be constant, the dose received from a $W$-kiloton burst would be obtained upon multiplying the above expression by $W$. However, because of the sustained decrease in air pressure during the transmission of the delayed contribution of the initial gamma rays, and for other reasons, as mentioned in § 8.38, the value of $\lambda$, for yields higher than about 20 kilotons, is actually greater than 338 yards and varies with the energy yield. Instead of adjusting this, however, it is simpler to use a scaling factor, $W'$, obtained from Fig. 8.35b, in place of $W$, the actual energy yield. The general equation for the dose of initial gamma radiation at a distance $D$ yards from an explosion of $W$ kilotons is then

$$I_0 = \frac{1.4\times10^9W'}{D^2}e^{-D/338}\text{ roentgens.}$$

### The Neutron Energy Spectrum

8.107 The energies of the neutrons received at some distance from a nuclear explosion cover a very wide range, from several millions

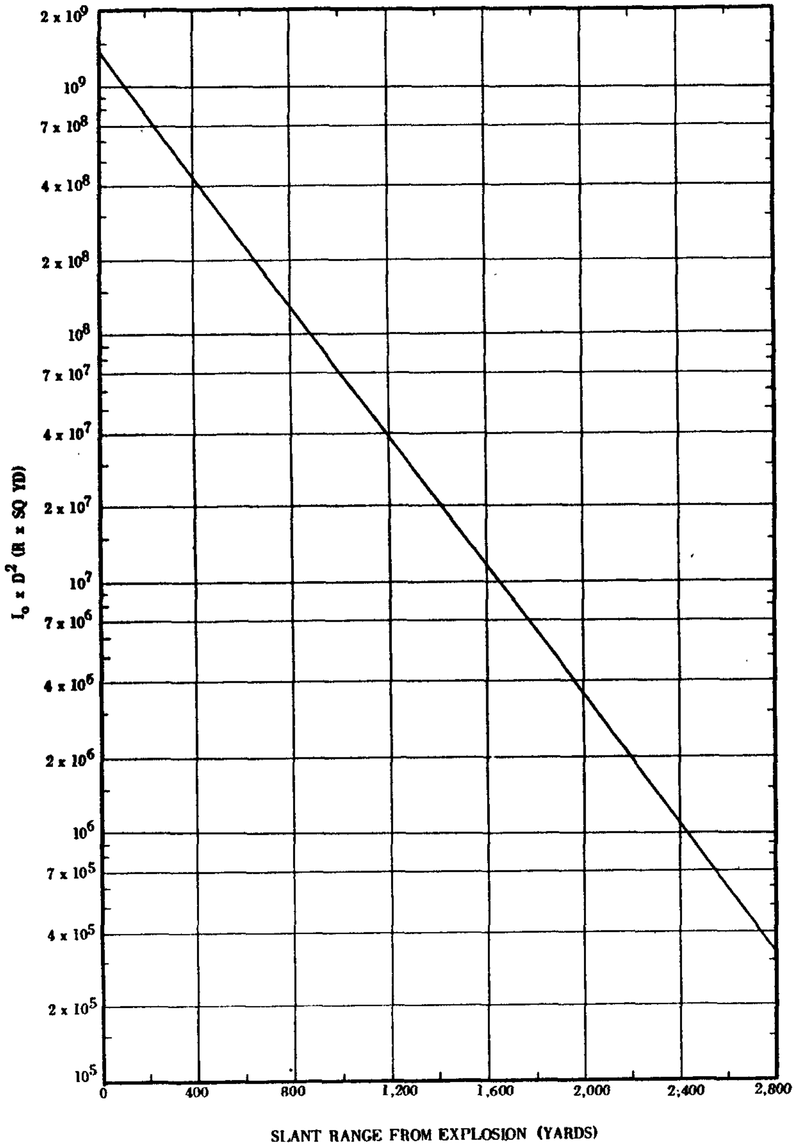

**Figure 8.105.** Initial gamma radiation dose times distance squared versus distance for a 1-kiloton explosion.

down to a fraction of an electron volt. The determination of the complete energy spectrum, either by calculation, which could be done in principle, or by experiment, is virtually impossible. Recourse must, therefore, be had to measurements of the neutron intensities within a few specified ranges, from the results of which a general idea of the spectrum can be obtained.

8.108 Measurements of this kind are made by the use of "threshold" detectors of the activated foil or fission foil type (§§ 8.66, 8.67). For example, the element sulfur acquires induced radioactivity as the result of the capture of neutrons having energies greater than 2.5 Mev but not if the neutrons have lower energies. Hence, the extent of activation of a sulfur foil is a measure of the intensity of neutrons with energies in excess of 2.5 Mev. Similarly, the appreciable fission of uranium-238 requires neutrons having an energy of 1.5 Mev or more, so that from the fission product activity there can be determined the intensity of neutrons having energies above 1.5 Mev. The difference between the two results obtained as just described gives the neutron intensity in the energy range from 1.5 to 2.5 Mev. Other foil materials, which are used in the same manner, are neptunium-237, fission threshold 0.7 Mev; plutonium-239 (shielded with boron), fission threshold 100 ev; and gold, which is activated by slow neutrons.

8.109 The results of a series of measurements, made at various distances from a nuclear test explosion, are shown in Fig. 8.109, in which $ND^2$ on a logarithmic (vertical) scale, is plotted against $D$ on a linear (horizontal) scale. In this case, $N$ represents the number of neutrons per square centimeter which produce fission or activation of foils of the indicated materials at a distance $D$ from the explosion. Since the actual values of $ND^2$ are not necessary for the present purpose, relative values are given in the figure.

8.110 It will be observed from Fig. 8.109 that, as is to be expected, the various lines slope downward to the right, indicating a steady decrease in the intensities of the neutrons at all energies with increasing distance from the explosion. However, the really significant fact is that the lines are all parallel. Hence, although the total number of neutrons received per square centimeter decreases with increasing distance, the proportions in the various energy ranges remain essentially the same throughout. In other words, over a considerable range of distances there is an equilibrium spectrum in which the energy distribution of the neutrons in the initial nuclear radiation is independent of distance from the explosion.

8.111 One consequence of this conclusion is that, if the results are of general applicability, it should be possible, to treat the neutrons

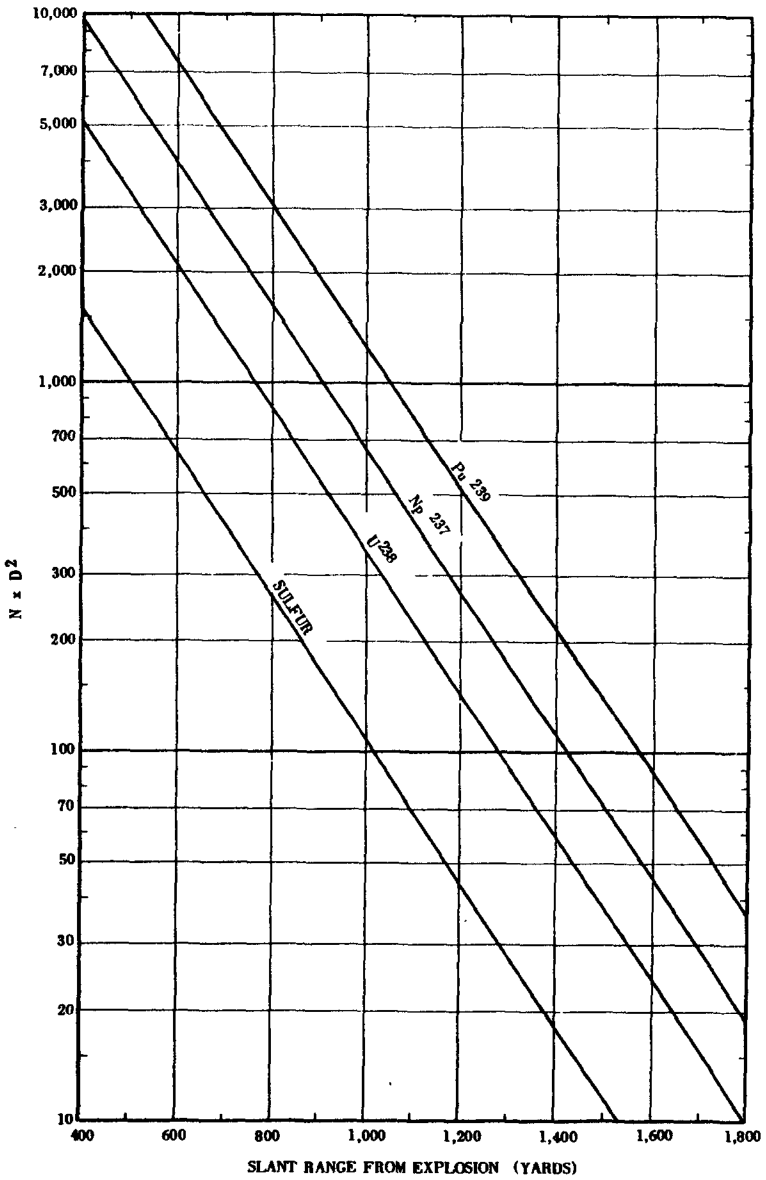

Figure 8.109. Typical threshold detector results for fast neutrons in air.

as a single group, with a definite energy distribution beyond a certain distance. Thus, assuming an equilibrium spectrum, one foil measurement would be sufficient to indicate the total neutron dose at any given location. Further, the analytical expression of the variation of neutron dose with distance would be simplified.

8.112 In relation to the neutron energy spectrum, the slow neutrons, with energies less than about 1 ev, contribute no more than 2 percent of the total neutron dose received at distances of biological interest. In the majority of significant situations it appears, therefore, that the thermal neutrons can be neglected as a nuclear radiation hazard. About 75 percent of the dose is received from fast neutrons, with energies above 0.75 Mev.[7]

### TRANSMISSION OF NEUTRONS FROM SOURCE

8.113 The transmission of neutrons through the air from the exploding bomb, treated as a point source, to a location an appreciable distance away, can be represented in a manner quite similar to that described earlier for gamma rays. If $N_0$ represents the total neutron dose received at a distance $D$ from the point of burst, then, by analogy with equation (8.104.1),

$$N_0 = \frac{R_n}{4\pi D^2} e^{-D/\lambda_n}, \tag{8.113.1}$$

where $R_n$ is a neutron dose related to the explosion yield and $\lambda_n$ is here the relaxation length for neutrons in air. Since the bomb neutron spectrum is essentially independent of distance, $\lambda_n$ has a single value which is a weighted mean for all energies. It is equivalent to the distance traveled by the radiation in air for a decrease by a factor of $e$ in the total effective neutron dose.

8.114 Upon rearranging equation (8.113.1) and taking logarithms, as in § 8.105, the result is

$$\log N_0 D^2 = \text{Constant} - 0.4343 \frac{D}{\lambda_n},$$

so that a semilogarithmic plot of $N_0 D^2$ versus $D$ should be a straight line. The data in Fig. 8.71, which gives $N_0$ in rems as a function of $D$ in yards for a 1-kiloton explosion, have been used to obtain Fig.

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[7] Most of the neutrons produced in fission have energies of from 1 to 3 Mev before being slowed down. *Neutrons produced by the fusion reaction between deuterium and tritium have 14-Mev energy.*

8.114. From the slope of the straight line, $\lambda_n$ is calculated as 242 yards, and from the intercept the value of $R_n/4\pi$ for the 1-kiloton explosion is found to be $8.4 \times 10^9$ rems-yards$^2$. Consequently, assuming that the neutron dose is directly proportional to the energy yield of the explosion, although this is not a good approximation (see § 8.71), it follows that

$$N_0 = \frac{8.4 \times 10^9 W}{D^2} e^{-D/242} \text{ rems},$$

where $W$ kilotons is the explosion yield; the distance from the explosion, $D$, in this expression is in yards.

8.115 Since the relaxation length for the initial gamma radiation is 338 yards, whereas that for the neutrons is 242 yards, it is evident that bomb neutrons travel, on the average, a shorter distance through the air than do the initial gamma rays before they are attenuated by the same factor. This is the physical basis of the fact, discussed in § 8.80, that the neutron dose decreases more rapidly than the gamma-ray dose with increasing distance from the explosion.

### NEUTRON SHIELDING

8.116 The attenuation of a narrow beam of neutrons by a shield can be represented by an equation similar to that used for gamma rays, namely,

$$N = N_0 e^{-\Sigma x},$$

where $N_0$ is the dose that would be received without the shield, and $N$ is the dose penetrating the shield of thickness $x$ centimeters. The symbol $\Sigma$ stands for the macroscopic cross section, which is equivalent to the linear absorption coefficient of gamma rays. Actually, there is a specific value of $\Sigma$ for every neutron energy and for each type of reaction the neutron can undergo. However, for shielding calculations, an empirical $\Sigma$, based on actual measurements, is used. It is a complex average for all the possible neutron interactions over the range of energies involved. Some rough values of $\Sigma$ for fast neutrons are contained in Table 8.116; these include an allowance for broad neutron beams and thick shields.

TABLE 8.116

EMPIRICAL MACROSCOPIC CROSS SECTIONS FOR ATTENUATION OF FAST NEUTRONS

| *Material* | $\Sigma$ (cm$^{-1}$) |
|---|---|
| Water | 0.1 |
| Concrete | 0.09 |
| Iron concrete | 0.16 |

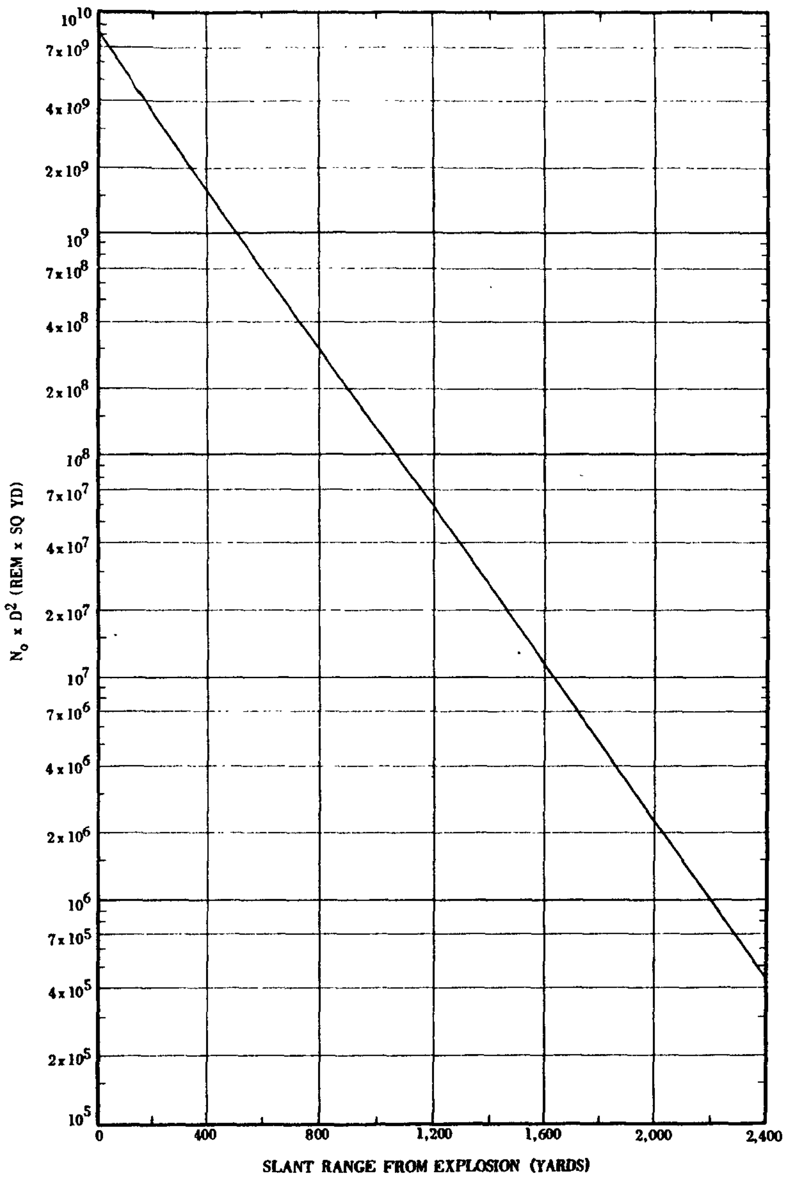

**Figure 8.114.** Relative neutron dose times distance squared versus distance for a 1-kiloton explosion.

8.117 A relatively large macroscopic cross section means that a smaller thickness of the material will be as effective as a greater thickness of a substance with a smaller cross section. Thus, concrete containing iron is more effective than ordinary concrete (§ 8.76). However, there is no simple correlation between attenuation of neutrons and the density of the material, as is the case, to a good approximation, with gamma rays. It should be emphasized, in conclusion, that, as explained in § 8.74, an adequate neutron shield must do more than attenuate fast neutrons. It must be able to capture the slowed down neutrons and to absorb any gamma radiation accompanying the capture process.

## *CHAPTER IX*

# RESIDUAL NUCLEAR RADIATION AND FALLOUT

## SOURCES OF RESIDUAL RADIATION

### INTRODUCTION

9.1 The residual nuclear radiation is defined, for reasons given earlier, as that emitted after 1 minute from the instant of a nuclear explosion. This radiation arises mainly from the bomb residues, that is, from the fission products and, to a lesser extent, from the uranium and plutonium which have escaped fission. In addition, the residues will usually contain some radioactive isotopes formed as a result of neutron capture by the bomb materials (§ 8.8). Another source of residual nuclear radiation is the activity induced by neutrons captured in various elements present in the earth, in the sea, or in substances which may be in the explosion environment. It may be mentioned, in passing, that radioactivity induced by the gamma rays from a nuclear explosion is either insignificant or completely absent.

9.2 In the case of an air burst, particularly when the ball of fire is well above the earth's surface, a fairly sharp distinction can be made between the initial nuclear radiation, considered in the preceding chapter, and the residual radiation. The reason is that, by the end of a minute, essentially all of the bomb residues, in the form of very small particles, will have risen to such a height that the nuclear radiations no longer reach the ground in significant amounts. Subsequently, the fine particles are widely dispersed in the atmosphere and descend to earth very slowly.

9.3 With surface and, especially, subsurface explosions, the demarcation between initial and residual nuclear radiations is not as definite. Some of the radiations from the bomb residues will be within range of the earth's surface at all times, so that the initial and residual categories merge continuously into one another. For very deep underground and underwater bursts the initial gamma rays and neutrons produced in the fission process may be ignored. Essentially the only nuclear radiation of importance is that arising from the bomb residues. It can, consequently, be treated as consisting exclusively of the residual radiation. In a surface burst, however, both initial and residual nuclear radiations must be taken into consideration.

### FISSION PRODUCTS

9.4 As stated in Chapter I, the fission products constitute a very complex mixture of some 200 different forms (isotopes) of 35 elements. Most of these isotopes are radioactive, decaying by the emission of beta particles, frequently accompanied by gamma radiation. About 1¾ ounces (0.11 pound) of fission products are formed for each kiloton (or 110 pounds per megaton) of fission energy yield. The total radioactivity of the fission products initially is extremely large, but it falls off at a fairly rapid rate as the result of decay (§ 1.23).

9.5 At 1 minute after a nuclear explosion, when the residual nuclear radiation has been postulated as beginning, the radioactivity from the 1¾ ounces of fission products, from a 1-kiloton explosion, is comparable with that of a hundred thousand tons of radium. It is seen, therefore, that for explosions in the megaton energy range the amount of radioactivity produced is enormous. Even though there is a decrease from the 1-minute value by a factor of over 6,000 by the end of a day, the radiation intensity will still be large.

9.6 It has been calculated that if the products from an explosion with a fission yield of 1 megaton could be spread uniformly over an area of 10,000 square miles, the radiation intensity after 24 hours would be 2.7 roentgens per hour at a level of 3 feet above the ground. In actual practice, a uniform distribution would be improbable, since a larger proportion of the fission products would be deposited near ground zero than at farther distances. Hence, the radiation intensity will greatly exceed the average at points near to the explosion center, whereas at much greater distances it will be less.

9.7 Some indication of the rate at which the fisssion product radioactivity decreases with time may be obtained from the following approximate rule: for every seven-fold increase in time after the explosion, the activity decreases by a factor of ten. For example, if the radiation intensity at 1 hour after the explosion is taken as a reference point, then at 7 hours after the explosion the intensity will have decreased to one-tenth; at 7×7=49 hours (or roughly 2 days) it will be one-hundredth; and at 7×7×7=343 hours (or roughly 2 weeks) the activity will be one-thousandth of that at 1 hour after the burst. Another aspect of the rule is that at the end of 1 week (7 days), the radiation will be one-tenth of the value after 1 day. This rule is roughly applicable for about 200 days, after which time the radiation intensity decreases at a more rapid rate.

9.8 Information concerning the decrease of activity of the fission products can be obtained from Fig. 9.8, in which the ratio of the approximate exposure dose rate (in r/hr, i. e., in roentgens per hour) at any time after the explosion to the dose rate at 1 hour is plotted against the time. It will be noted that the dose rate at 1 hour after the burst is used here as a reference value. This is done purely for the purpose of simplifying the calculation and representation of the results. At great distances from explosions of high energy yield the fission products may not arrive until several hours have elapsed. Nevertheless, the hypothetical (reference) dose rate at 1 hour after the explosion is still used in making calculations. It is, in principle, the dose rate referred back to what it would have been at 1 hour after the explosion, if the fallout had been complete at that time.

9.9 Suppose, for example, that at a given location, the fallout commences at 5 hours after the explosion, and that at 15 hours, when the fallout has ceased to descend, the observed dose rate is 3.9 roentgens per hour. From the curve in Fig. 9.8 (or the results in Table 9.11), it is readily found that the hypothetical (reference) dose rate at 1 hour after the explosion is 100 roentgens per hour. By means of this reference value and the decay curve in Fig. 9.8, it is possible to determine the actual dose rate at the place under consideration at any time after fallout is complete. Thus, if the value is required at 24 hours after the explosion, Fig. 9.8 is entered at the point representing 24 hours on the horizontal axis. Moving upward vertically until the plotted line is reached, it is seen that the required dose rate is 0.02 times the 1-hour reference value, i. e., $0.02 \times 100 = 2$ roentgens per hour.

9.10 If the dose rate at any time is known, by actual measurement, that at any other time can be estimated. All that is necessary is to compare the ratios (to the 1-hour reference value) for the two given times as obtained from Fig. 9.8. For example, suppose the dose rate at 3 hours after the explosion is found to be 50 roentgens per hour; what would be the value at 18 hours? The respective ratios, as given by the line in Fig. 9.8, are 0.27 and 0.031, with respect to the 1-hour reference dose rate. Hence, the dose rate at 18 hours after the explosion is $50 \times 0.031/0.27 = 5.7$ roentgens per hour.

9.11 The results in Fig. 9.8 may be represented in an alternative form, as in Table 9.11, that is more convenient, although somewhat less complete. The 1-hour reference dose rate is taken as 1,000, in any

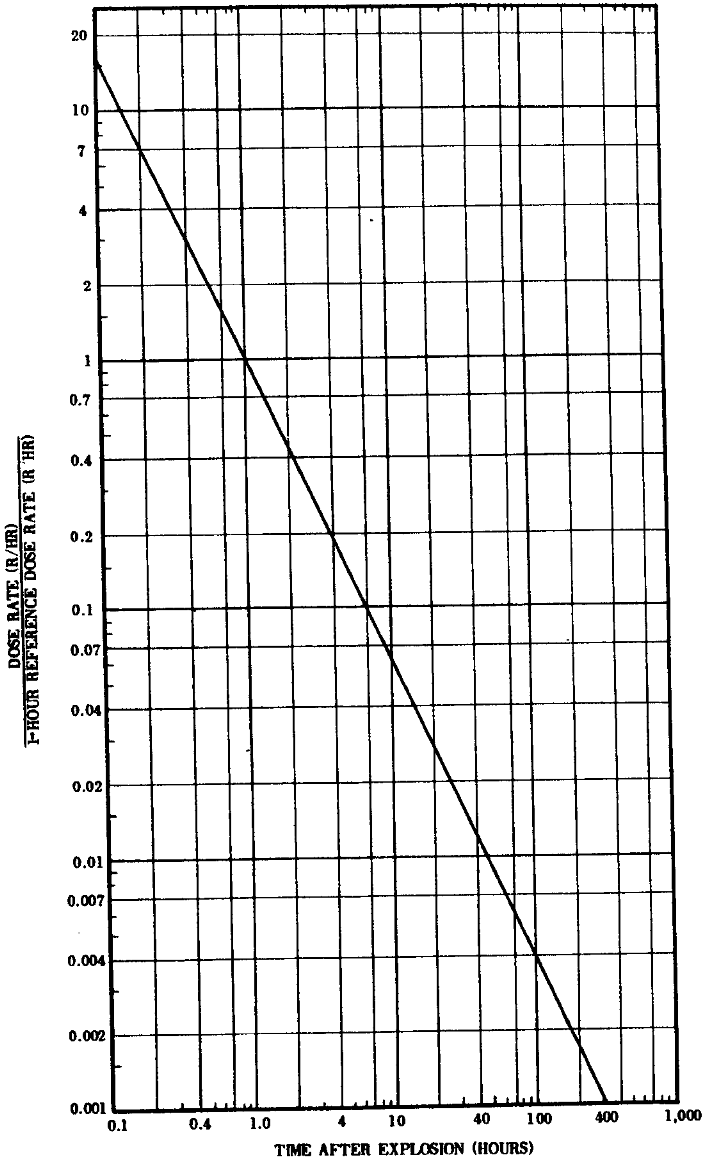

Figure 9.8. Decrease of dose rate from fission products with time.

desired units. The dose rates at a number of subsequent times, in the same units, are given in the table. If the actual dose rate at 1 hour (or any other time) after the explosion is known, the value at any specified time, up to 1,000 hours, can be obtained by simple proportion.[1]

### TABLE 9.11

### RELATIVE DOSE RATES AT VARIOUS TIMES AFTER A NUCLEAR EXPLOSION

| Time (hours) | Relative dose rate | Time (hours) | Relative dose rate |
|---|---|---|---|
| 1 | 1, 000 | 30 | 17 |
| 1½ | 610 | 40 | 12 |
| 2 | 440 | 60 | 7. 3 |
| 3 | 270 | 100 | 4. 0 |
| 5 | 150 | 200 | 1. 7 |
| 7 | 97 | 400 | 0. 75 |
| 10 | 63 | 600 | 0. 46 |
| 15 | 39 | 800 | 0. 33 |
| 20 | 27 | 1, 000 | 0. 25 |

9.12 It should be noted that Fig. 9.8 and Table 9.11 are used for calculations of dose *rates*. In order to determine the actual or total radiation dose received it is necessary to multiply the average dose rate by the exposure time (§ 8.24). However, since the dose rate is steadily decreasing during the exposure, appropriate allowance must be made. This is best achieved by the mathematical process of integration, using a simple formula which represents the change in the dose rate with time (§ 9.112). The results of the calculations are expressed by the curve in Fig. 9.12. It gives the total dose received from fission products, between 1 minute and any other specified time after the explosion, in terms of the 1-hour reference dose rate.

9.13 To illustrate the application of Fig. 9.12, suppose that an individual becomes exposed to a certain quantity of fission products 2 hours after a nuclear explosion and the dose rate, measured at that time, is found to be 1.5 roentgens per hour. What will be the total dose received during the subsequent 12 hours, i. e., by 14 hours after

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[1] Several simple devices, similar to a slide rule, are available for making rapid calculations of fallout decay dose rates and related matters.

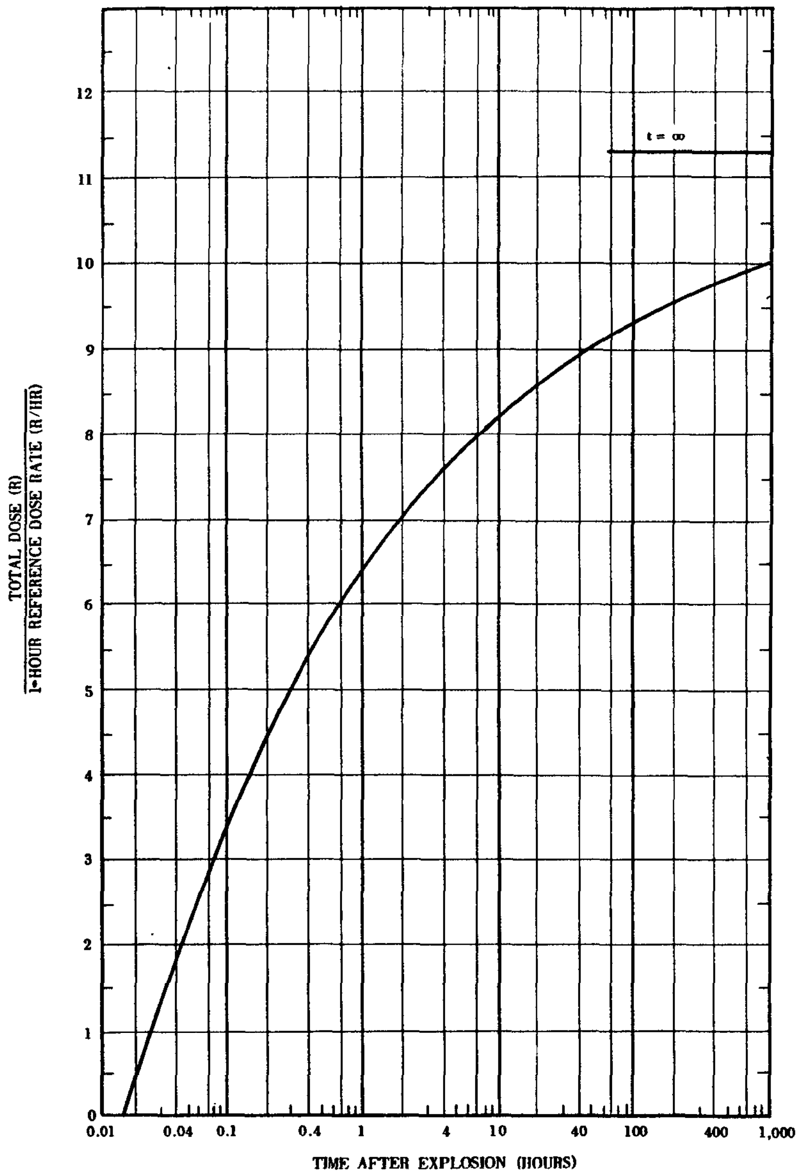

Figure 9.12. Accumulated total dose of residual radiation from fission products from 1 minute after the explosion.

the explosion? The first step is to determine the (hypothetical) 1-hour reference dose rate. From Fig. 9.8 it is seen that

$$\frac{\text{Dose rate at 2 hours after explosion}}{\text{1-hour reference dose rate}}=0.43$$

and, since the dose rate at 2 hours is known to be 1.5 roentgens per hour, the reference value at 1 hour is 1.5/0.43=3.5 roentgens per hour. Next, from Fig. 9.12, it is found that for 2 hours and 14 hours, respectively, after the explosion,

$$\frac{\text{Total dose at 2 hours after explosion}}{\text{1-hour reference dose rate}}=7.0$$

and

$$\frac{\text{Total dose at 14 hours after explosion}}{\text{1-hour reference dose rate}}=8.4.$$

Hence, by subtraction

$$\frac{\text{Dose received between 2 and 14 hours after explosion}}{\text{1-hour reference dose rate}}=1.4.$$

The reference dose rate at 1 hour is 3.5 roentgens per hour, and so the total dose received in the 12 hours, between 2 and 14 hours after the explosion, is $3.5\times1.4=4.9$ roentgens.

9.14 The percentage of the "infinity (residual radiation) dose" that would be received from a given quantity of fission products, up to various times after a nuclear explosion, is given in Table 9.14. The infinity dose is essentially that which would be received as a result of continued exposure to a certain quantity of fission products for many years. These data can be used to determine the proportion of the infinity dose received during any specified period following the complete deposition of the fission products from a nuclear explosion.

9.15 For example, if an individual is exposed to a certain amount of fission products, e. g., from fallout, during the interval from 2 hours to 14 hours after the explosion, the percentage of the infinity dose received may be obtained by subtracting the respective values in Table 9.14, i. e., 74 (for 14 hours) minus 62 (for 2 hours), giving 12 percent of the infinity dose. The actual value of the infinity dose computed from 1 minute after detonation, is 11.3 times the 1-hour reference dose rate (in roentgens per hour), as shown in Fig. 9.12. Hence, if this reference dose rate is known (or can be evaluated), the dose received during any period of time can be calculated from Table 9.14, instead of using Fig. 9.12.

9.16 With the aid of Figs. 9.8 and 9.12 (or the equivalent Tables 9.11 and 9.14) many different types of calculations relating to radiation dose rates and total doses received from fission products can be made. The procedures can be simplified, however, by means of special charts based on these figures, as will be shown later (Figs. 12.107 and 12.108).

TABLE 9.14

PERCENTAGES OF INFINITY RESIDUAL RADIATION DOSE RECEIVED UP TO VARIOUS TIMES AFTER EXPLOSION

| Time (hours) | Percent of infinity dose | Time (hours) | Percent of infinity dose |
|---|---|---|---|
| 1 | 56 | 48 | 80 |
| 2 | 62 | 72 | 81 |
| 4 | 67 | 100 | 82 |
| 6 | 69 | 200 | 85 |
| 12 | 73 | 500 | 87 |
| 24 | 77 | 1,000 | 89 |
| 36 | 79 | 2,000 | 90 |

9.17 It is essential to understand that the tables and figures given above, and the calculations of radiation dose rates and doses in which they are used, are based on the assumption that an individual is exposed to a certain quantity of fission products and remains exposed continuously (without protection) to this same quantity for a period of time. In an actual fallout situation, however, these conditions would probably not exist. For one thing, any shelter which attenuates the radiation will reduce the exposure dose rate (and dose) as given by the calculations. Further, the action of wind and weather will generally tend to disperse the fallout particles. As a result, there may be a decrease in the quantity of fission products at a given location, thus decreasing the radiation dose rate (and dose).

### NEUTRON-INDUCED ACTIVITY

9.18 The neutrons liberated in the fission process, but which are not involved in the propagation of the fission chain, are ultimately captured by the bomb materials through which they must pass before they can escape, by nitrogen (especially) and oxygen in the atmosphere, and by various elements present in the earth's surface. As a result of capturing neutrons many substances become radioactive. They, consequently, emit beta particles, frequently accompanied by gamma radiation, over an extended period of time following the explosion. Such neutron-induced activity, therefore, is part of the residual nuclear radiation.

9.19 The activity induced in the bomb materials is highly variable, since it is greatly dependent upon the design or structural characteristics of the weapon. Any radioactive isotopes produced by neutron capture in the bomb residues will remain associated with the fission products. Although they will have some effect on the over-all observed rate of decay, so that the radiation dose rates and doses will not be in agreement with Figs. 9.8 and 9.12, the deviations from the basic fission decay curve are not likely to be significant, except possibly soon after an explosion.

9.20 When neutrons are captured by oxygen and nitrogen nuclei present in the atmosphere, the resulting activity is of little or no significance, as far as the residual radiation is concerned. Oxygen, for example, interacts to a slight extent with fast neutrons, but the product, an isotope of nitrogen, has a half life of only 7 seconds. It will thus undergo almost complete decay within a minute or two. The radioactive product of neutron capture by nitrogen is carbon-14; this emits beta particles of relatively low energy but no gamma rays. Nuclear explosions cannot add appreciably to the fairly large amount of this isotope already present in nature, and so the radiations from carbon-14 are a negligible hazard.

9.21 An important contribution to the residual nuclear radiation can arise from the activity induced by neutron capture in certain elements in the soil. The one which probably deserves most attention is sodium. Although this is present only to a small extent in average soils, the amount of radioactive sodium-24 formed by neutron capture can be quite appreciable. This isotope has a half life of 14.8 hours and emits both beta particles, and, more important, gamma rays of relatively high energy.[2]

9.22 Another source of induced activity is manganese which, being an element that is essential for plant growth, is found in most soils, even though in small proportions. As a result of neutron capture, the radioisotope manganese-56, with a half life of 2.6 hours, is formed. It gives off several gamma rays of high energy, in addition to beta particles, upon decay. Because its half life is less than that of sodium-24, the manganese-56 loses its activity more rapidly. But, within the first few hours after an explosion, the manganese may constitute a serious hazard, greater than that of sodium.

9.23 A major constituent of soil is silicon, and neutron capture leads to the formation of radioactive silicon-31. This isotope, with a half life of 2.6 hours, gives off beta particles, but gamma rays are emitted in not more than about 0.07 percent of the disintegrations. It will be seen later that only in certain circumstances do beta particles themselves constitute a serious radiation hazard. Aluminum, another common constituent of soil, can form the radioisotope aluminum-28, with a half life of only 2.3 minutes. Although isotopes such as this, with short half lives, contribute greatly to the high initial activity, very little remains within an hour after the nuclear explosion.

9.24 When neutrons are captured by the hydrogen nuclei in water, the product is the nonradioactive (stable) isotope, deuterium, so that there is no resulting activity. As seen above, the activity induced in oxygen can be ignored because of the very short half life of the product. However, substances dissolved in the water, especially the salt (sodium chloride) in sea water, can be sources of considerable induced activity. The sodium produces sodium-24, as already mentioned, and the chlorine yields chlorine-38 which emits both beta particles and high-energy gamma rays. However, the half life of chlorine-38 is only 37 minutes, so that within 4 to 5 hours its activity will have decayed to about 1 percent of its initial value.

9.25 Apart from the interaction of neutrons with elements present in soil and water, the neutrons from a nuclear explosion may be captured by other nuclei, such as those contained in structural and other materials. Among the metals, the chief sources of induced radioactivity are probably zinc, copper, and manganese, the latter being a constituent of many steels, and, to a lesser extent, iron. Wood and clothing are unlikely to develop appreciable activity as a result of neutron capture, but glass could become radioactive because of the large proportions of sodium and silicon. Foodstuffs can acquire induced activity, mainly as a result of neutron capture by sodium. However, at such distances from a nuclear explosion and under such conditions that this activity would be significant, the food would probably not be fit for consumption for other reasons, e. g., blast and fire damage. Some elements, e. g., boron, absorb neutrons without becoming radioactive, and their presence will tend to decrease the induced activity.

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[2] *In each act of decay of sodium-24, there are produced two gamma ray photons, with energies of 1.4 and 2.8 Mev, respectively. The mean energy per photon from fission products is 0.7 Mev, although gamma rays of higher energy are emitted in the early stages.*

### URANIUM AND PLUTONIUM

9.26 The uranium and plutonium which may have escaped fission in the nuclear bomb represent a further possible source of residual nuclear radiation. The fissionable isotopes of these elements emit alpha particles and also some gamma rays of low energy. However, because of their very long half-lives, the activity is very small compared with that of the fission products.

9.27 It will be seen below (§ 9.30) that the alpha particles from uranium and plutonium, or from radioactive sources in general, are completely absorbed in an inch or two of air. This, together with the fact that the particles cannot penetrate ordinary clothing, indicates that uranium and plutonium deposited on the earth do not represent a serious external hazard. Even if they actually come in contact with the body, the alpha particles emitted are unable to penetrate the unbroken skin.

9.28 Although there is negligible danger from uranium and plutonium outside the body, the situation might be different if either of these elements entered the body through the lungs, the digestive system, or breaks in the skin. Plutonium, for example, tends to concentrate in bone, where the prolonged action of the alpha particles may cause serious harm.

9.29 At one time it was suggested that the explosion of a sufficiently large number of plutonium bombs might result in such an extensive distribution of the lethal material as to represent a world-wide hazard. Calculations have shown that it would require the very large amount of over a million pounds of plutonium to produce this situation. It is now realized that the fission products—the radioisotope strontium-90 in particular—are a more serious hazard than plutonium is likely to be. Further, any steps taken to minimize the danger from fission products, which are incidentally much easier to detect, will automatically take care of the plutonium. Some reference to the behavior of this element in the body will be made in Chapter XI.

## ATTENUATION OF RESIDUAL NUCLEAR RADIATION

### ALPHA AND BETA PARTICLES

9.30 In their passage through matter, alpha particles produce considerable direct ionization and thereby rapidly lose their energy. After traveling a certain distance, called the "range," an alpha particle ceases to exist as such.[3] The range of an alpha particle depends upon its initial energy, but even those from plutonium, which have a fairly high energy, have an average range of just over 1½ inches in air. In more dense media, such as water or body tissue, the range is even less, being about a one-thousandth part of the range in air. Consequently, alpha particles from radioactive sources are unable to penetrate even the outer layer of the skin (epidermis). It is seen, therefore, that as far as alpha particles arising from sources outside the body are concerned, attenuation is no problem.

9.31 Beta particles, like alpha particles, are able to cause direct ionization in their passage through matter. But the beta particles dissipate their energy less rapidly and so have a greater range in air and in other materials. Many of the beta particles emitted by the fission products traverse a total distance of 10 feet (or more) in the air before they are absorbed. However, because the particles are continually deflected by electrons and nuclei of the medium, they follow a tortuous path, and so their effective (or net) range is somewhat less.

9.32 The range of a beta particle is shorter in more dense media, and the average net distance a particle of given energy can travel in water, wood, or body tissue is roughly one-thousandth of that in air. Persons in the interior of a house would thus be protected from beta radiation arising from fission products on the outside. It appears that even moderate clothing provides substantial attenuation of beta radiation, the exact amount varying, for example, with the weight and number of layers.

### GAMMA RADIATION

9.33 The residual gamma radiations present a different situation. These gamma rays, like those which form part of the initial nuclear radiation, can penetrate considerable distances through air and into the body. If injury is to be minimized, definite action of some kind must be taken to attenuate the gamma rays from external sources. Incidentally, any method used to decrease the gamma radiation will also result in a much greater attenuation of both alpha and beta particles.

9.34 The absorption of the residual gamma radiation from fission products and from radioisotopes produced by neutron capture, e. g., in sodium and manganese, is based upon exactly the same principles as were described in Chapter VIII in connection with the initial

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[3] An alpha particle is identical with a nucleus of the element helium (§ 1.51). When it has lost most of its (kinetic) energy, it captures two electrons and becomes a harmless (neutral) helium atom.

gamma radiation. Except for the earliest stages of decay, however, the gamma rays from fission products have much less energy, on the average, than do those emitted in the first minute after a nuclear explosion.[4] This means that the residual gamma rays are more easily attenuated; that is to say, compared with the initial gamma radiation, a smaller thickness of a given material will produce the same degree of attenuation.

9.35 Bearing in mind the limitations stated in § 8.43, the approximate half-value thicknesses of some common materials for the gamma radiations from fission products are given in Table 9.35. Upon comparing these thicknesses with those in Table 8.44 for the initial gamma radiation, it is seen that the residual radiation is more easily attenuated. The order of effectiveness of different materials is, however, the same in both cases, since it is largely (although not entirely) determined by the density. The figures in the last column of Table 9.35 show that the product of the half-value thickness and the density of the material is roughly the same in all the cases mentioned (§ 8.45).

TABLE 9.35

APPROXIMATE HALF-VALUE LAYER THICKNESSES OF MATERIALS FOR GAMMA RAYS FROM FISSION PRODUCTS

| Material | Density (lb/cu ft) | Half-value thickness (inches) | Product |
|---|---|---|---|
| Steel | 490 | 0. 7 | 343 |
| Concrete | 144 | 2. 2 | 317 |
| Earth | 100 | 3. 3 | 330 |
| Water | 62. 4 | 4. 8 | 300 |
| Wood | 34 | 8. 8 | 300 |

9.36 The attenuation factors, as defined in § 8.46, for steel, concrete, soil, and wood, for a range of thicknesses of these materials, are represented graphically in Fig. 9.36, which is analogous to Fig. 8.47 for the initial gamma radiation. It is seen that attenuation of the residual radiation by a factor of 50 requires 15 inches of concrete. This is compared with 29 inches needed to produce the same degree of attenuation of the initial gamma radiation, as given in § 8.47.

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[4] The average energy of the gamma rays from fission products, except during the early stages of decay, is about 0.7 Mev per photon. This may be compared with an effective value of roughly 4.5 Mev for the initial gamma radiations (§ 8.92).

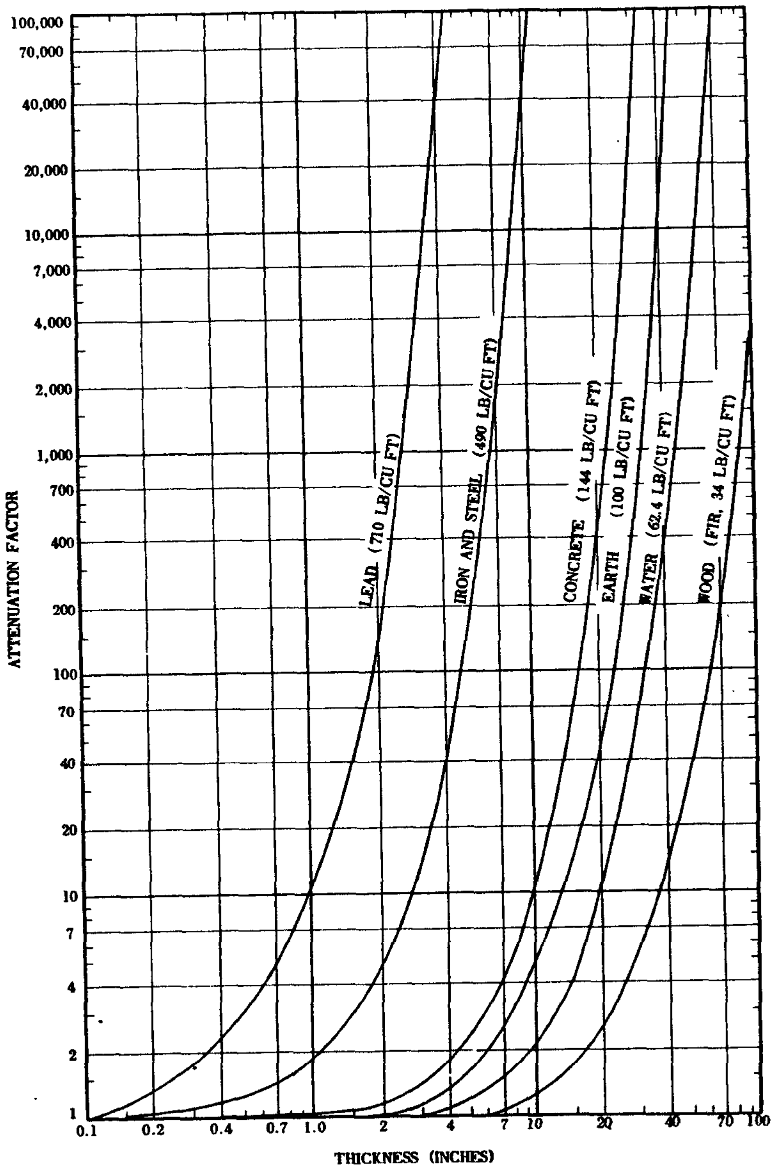

Figure 9.36. Attenuation of fission product radiation.

9.37 From the practical standpoint, it is of interest to record the attenuation factors that might be expected inside various structures. Two factors are responsible for this attenuation. First, there is the effect of distance, because the source of the radiation will be mostly outside, e. g., on the roof or in the street; and second, there is partial absorption of the radiation by the roof and walls. The approximate values given in Table 9.37 have been estimated partly from calculations and partly on the basis of field measurements. It will be noted that in the basement of a frame house the residual gamma radiation is reduced to about one-tenth of its value outside the house. A 3-foot layer of earth attenuates the radiations to one-thousandth (or less) of the intensity it would otherwise have at the same location.

TABLE 9.37

ESTIMATED ATTENUATION FACTORS IN STRUCTURES FOR RESIDUAL GAMMA RADIATION

| Type of Structure | Approximate attenuation factor |
|---|---|
| Frame house: | |
| First floor | 2 |
| Basement | 10 |
| Multistory, reinforced concrete: | |
| Lower floors (away from windows) | 10 |
| Basement (surrounded by earth) | *1, 000 |
| Shelter below grade: | |
| 3 feet of earth | *1, 000 |

*Or more.

# ASPECTS OF RADIATION EXPOSURE

## ACUTE AND CHRONIC EXPOSURE

9.38 In considering the injurious effects on the body of gamma radiations from external sources, it is necessary to distinguish between an "acute" (or "one-shot") exposure and a "chronic" exposure. In an acute exposure the whole radiation dose is received in a relatively short interval of time. This is the case, for example, in connection with the initial nuclear radiation considered in the preceding chapter. It is not possible to define an acute dose precisely, but it may be somewhat arbitrarily taken to be a dose received during a 24-hour period. The delayed radiations from the fission products persist over a longer period of time, however, and the exposure may then be of the chronic type.

9.39 The importance of making a distinction between acute and chronic exposures lies in the fact that, if the dose rate is not too large, the body can achieve partial recovery from some of the consequences of nuclear radiations while still exposed. Thus, apart from certain effects mentioned below, a greater total gamma-radiation dose would be required to produce a certain degree of injury if the dose were spread over a period of several days than if the same dose were received within a minute or so.

9.40 It was stated in § 8.26 that an acute gamma-radiation exposure dose of 450 roentgens, over the whole body, would be expected to prove fatal to about 50 percent of the individuals so exposed. If the same number of roentgens were received over a period of a few weeks, the probability of death would be less. Because of the many factors involved, it is not possible to state, at the present time, the exact degree of recovery that might be expected during the course of chronic radiation exposure. From some effects, e. g., genetic changes, there is apparently no recovery (see § 11.124), but, as far as the more obvious injuries are concerned, all that can be said definitely is that a given radiation dose spread over a period of time, e. g., two weeks or more, is less harmful than an acute dose of the same number of roentgens (or rems) received in 24 hours.

## NATURAL BACKGROUND RADIATION

9.41 In connection with the matter of chronic radiation doses, it may be noted that human life has become adapted to a certain amount of radiation, received continuously over a long period of time. This statement is based on the fact that all living creatures are always exposed to radiations from various natural sources, both inside and outside the body. The chief internal source is the radioisotope potassium-40, which is a normal constituent of the element potassium as it exists in nature. Carbon-14 in the body is also radioactive, but it is only a minor source of internal radiation. There is also some potassium-40, as well as radioactive uranium, thorium, and radium, in varying amounts, present in soil and rocks. Finally, an important source of nuclear radiation in nature is the so-called "cosmic rays," originating in outer space. The radiation dose received from those rays increases with altitude; at 15,000 feet, it is more than five times as large as at sea level.

9.42 An estimate of the total radiation dose, due to purely natural sources, received per annum by human beings, over the whole body, is given in Table 9.42. It is assumed that the underlying rock is granite, and data are given for sea level and an elevation of 5,000 feet. In some locations the background radiation dose from soil and rocks is less than from granite, but it appears that, in most parts of the United States, the natural radiation exposure dose is about 0.14 to 0.16 roentgen per year.

TABLE 9.42

ESTIMATED DOSE PER ANNUM FROM NATURAL BACKGROUND RADIATION

| Radiation source | Roentgens per year | |
|---|---|---|
| | Sea level | 5,000 feet altitude |
| Potassium in body | 0. 020 | 0. 020 |
| Thorium, uranium, and radium in granite | 0. 055 | 0. 055 |
| Potassium in granite | 0. 035 | 0. 035 |
| Cosmic rays | 0. 035 | 0. 050 |
| Total | 0. 145 | 0. 16 |

9.43 It follows, therefore, that during the average lifetime every human being receives a total of 10 to 12 roentgens of nuclear radiation over the whole body from natural sources. In addition, there may be localized exposures associated with dental and chest X-rays, and similar treatments, and even from the luminous dials of wrist watches and instruments. The exposure to radiation from natural sources has undoubtedly continued during the whole period of man's existence.

## MAXIMUM PERMISSIBLE RADIATION EXPOSURE

9.44 It is evident that human beings have been (and are being) continually exposed to nuclear radiations, from sources both inside and outside the body. As a result, a steady (or equilibrium) biological state has been attained. This fact suggests that, apart from genetic effects, there is a certain chronic radiation dose over which the body has partial power of recovery. As to what this chronic dose is, there is no definite knowledge. In any event, it probably varies from one individual to another.

9.45 In spite of the uncertainty concerning what might be called the "permissible" dose, some general conclusions have been reached on the basis of information obtained from radiologists and X-ray technicians, from observations on biological damage caused by radium, and from animal experiments. These conclusions may be revised from time to time as further data on the effects of various nuclear radiations on living organisms become available.

9.46 With the development of peaceful, as well as military, applications of nuclear energy, many people are now exposed to additional amounts of nuclear radiations during working hours, over and above that of the background. In order to safeguard the health of occupationally exposed adults, a "maximum permissible exposure" of 0.3 roentgen per week has been established in the United States. It is considered at present, therefore, that such persons, occupied in atomic industries, may be exposed to 0.3 roentgen per week, i. e., 15 roentgens per year, of nuclear radiation over the whole body for a period of many years without undue risk.[5]

9.47 The purpose of the foregoing discussion is to point out that exposure to nuclear radiation is by no means a new experience for the human race. Further, it appears to be established that the body has the power of partial recovery from certain effects due to moderate chronic doses of radiation. The maximum permissible chronic dose recommended for workers in nuclear energy projects is felt to include a factor of safety. There is evidence, in fact, of individuals who have received much larger doses of nuclear radiation, and have no discernible evidence of permanent damage. Nevertheless, it must not be forgotten that exposure to sufficiently large doses of radiation, either chronic or acute, can cause serious injury and even death (see Chapter XI).

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[5] Recommendations of the National Committee on Radiation Protection and Measurement appearing in a paper on "Maximum Permissible Radiation Exposures to Man" *Radiology*, 68, 260 (1957) state that "The maximum permissible accumulated dose, in rems, at any age, is equal to 5 times the number of years beyond age 18, provided no annual increment exceed 15 rems", and that "The maximum permissible dose to the gonads for the population of the United States as a whole from all sources of radiation, including medical and other man-made sources, and background, shall not exceed 14 million rems per million of population over the period from conception up to age 30, and one-third that amount in each decade thereafter."

## RADIOACTIVE CONTAMINATION IN NUCLEAR EXPLOSIONS

### CONTAMINATION IN AN AIR BURST

9.48 There are two main ways in which the earth's surface can become contaminated with radioactive material as a result of a nuclear explosion. One is by the induced activity following the capture of neutrons by various elements present in the soil (or sea), and the other is by the fallout, that is, by the subsidence of radioactive particles from the column and cloud formed in the explosion (§ 2.21). Both the relative and actual importance of these two sources of contamination depend very greatly upon the location of the point of burst with regard to the surface of the earth, and also upon the energy yield of the explosion. Other factors which may affect the contamination are the nature of the terrain and meteorological conditions.

9.49 In an air burst the radioactive bomb residues, consisting largely of the fission products, condense into very small solid particles. In this finely divided state a portion of the radioactive particles enter the stratosphere and will remain suspended for many years, even circling the earth several times, before descending to the surface. During this period they undergo decay and loss of activity. Hence, when the particles do reach the earth's surface, they will be widely dispersed and their radioactivity will be very greatly reduced. In fact the external radiation produced by the fallout from a weapon with a fission yield in the megaton range would be extremely small in comparison with the natural background radiation (see, however, Chapter X).

9.50 Under certain meteorological conditions, e. g., abnormal winds or a rainfall situation, there might be appreciable fallout, probably of a localized character. For example, in a moist atmosphere the fine particles of bomb residue could attach themselves to water droplets which might subsequently fall as radioactive rain. Such was apparently the case in the moderately low air burst over Bikini Lagoon (Test ABLE) in 1946, as stated in § 2.98. The extent of the activity was, however, small, since most of the fission products were probably above the rain clouds at the time.

9.51 A special case of interest is that of a warm front rainfall situation, such as frequently occurs in temperate latitudes. The rain-bearing clouds may have a thickness of 20,000 feet and can extend over many hundreds of square miles. The rain is usually gentle, but continues to fall steadily for some time. If the situation existed at the time of the explosion, the radioactive particles formed in the air burst might ascend into the rain-bearing clouds. In a short time, the atomic cloud, if it did not rise above the rain-bearing cloud, would become so mixed with the latter as to become an integral part of the rain-producing system. The radioactive material might then be expected to deposit with the rain over a large area, in a surface pattern dependent upon the winds at the cloud level.

9.52 An air burst of a small yield weapon would not be accompanied by serious local fallout except possibly in unusual circumstances, as is borne out by the fact that there were no casualties in the nuclear bombings of Japan that could be attributed to residual radiation. At Nagasaki, about 0.02 percent of the fission products was deposited on the surface within a radius of 2,000 feet (0.4 mile) of ground zero. However, at no time did this represent a significant radiation hazard. Observations made at tests indicate that the local fallout from air bursts is also small for large yield weapons.

9.53 An important source of contamination due to residual nuclear radiation from an air burst can be the activity induced by neutrons captured by elements, notably sodium and manganese, on the earth's surface (§ 9.21, *et seq.*) The amount of the contamination, which will be appreciable only in a limited area about ground zero, will depend upon the height of burst, the energy yield, and the time elapsed since the explosion. At Hiroshima and Nagasaki, for example, the induced radioactivity on the surface was believed to be negligible. In the ABLE test at Bikini, however, where the height of burst was less than in the Japanese explosions, an appreciable amount of radioactive sodium-24 was formed in the water. The gamma rays from this isotope gave a dose rate of about 1 roentgen per hour just above the surface of the lagoon at 2 hours after the burst.

9.54 A low air burst of a nuclear weapon of high energy could result in extensive contamination due to induced activity in the vicinity of ground zero. In this region, destruction by blast and fire, except for strong underground structures, would be virtually complete.

### CONTAMINATION IN A SURFACE BURST

9.55 In an air burst, the neutron-induced activity may be significant, but the local fallout, soon after the explosion, will generally be unimportant. The fission products will, however, contribute to the activity of the gradual fallout extending over large areas. With a surface (or subsurface) burst, on the other hand, the local fallout will assume major significance. Although there will undoubtedly be a considerable amount of induced radioactivity near ground zero, the activity of the fission product fallout will be so much greater in a surface burst that the induced activity can be neglected in comparison.

Consequently, the subsequent discussion of the residual radiation following a surface burst will deal mainly with the (local) fallout of fission products.

9.56 The fraction of the total radioactivity of the bomb residues that appears in the fallout depends upon the extent to which the ball of fire touches the surface. Thus, the proportion of the available activity increases as the height of burst decreases and more of the fireball comes into contact with the earth. In the case of a contact burst, i. e., one in which the bomb is actually on the surface when it explodes, some 50 percent of the total residual radioactivity will be deposited on the ground within a few hundred miles of the explosion. The remainder of the activity will stay suspended for a long time and will eventually reach the earth many hundreds or thousands of miles away, as in the case of an air burst (§ 9.49).

9.57 In a surface burst, large amounts of earth, dust, and debris are taken up into the fireball in its early stages. Here they are fused or are vaporized and become intimately mixed with the fission products and other bomb residues, as described in § 2.21. As a result, there is formed upon cooling a tremendous number of small particles contaminated to some distance below their surfaces with radioactive matter. In addition, there are considerable quantities of pieces and particles, covering a range of sizes from large lumps to fine dust, to the surfaces of which fission products are more or less firmly attached.

9.58 The larger (heavier) pieces, which will include a great deal of contaminated material scoured and thrown out of the crater (§ 5.4), will not be carrried up into the mushroom cloud, but will descend from the column. Provided the wind is not excessive, this large particulate material, as it falls, will form a roughly circular pattern around ground zero. Actually, the center of this circular pattern, called the "ground zero circle," will usually be displaced somewhat from ground zero by the wind.

9.59 Most of the contaminated material referred to above, forming the ground zero circle, descends within a short time, not more than an hour or so. The smaller particles present in the atomic column are, however, carried upward to a height of several miles (§ 2.16) and may spread out some distance in the mushroom cloud before they begin to descend. The time taken to reach the earth and the horizontal distance traveled will depend upon the height reached before they begin to fall, the size of the particles, and upon the wind pattern in the upper atmosphere. The smallest (and lightest) particles, like those formed in an air burst, will enter the stratosphere and remain suspended for long periods and may travel many thousands of miles before descending (§ 9.49). Most of the larger particulate matter, however, will probably reach the earth as local fallout within a few hundred miles from ground zero.

9.60 As a general rule, it is to be expected that, except for the very smallest particles which descend over a wide area, the fallout of particles of moderate and small size will form, in the course of time, a kind of elongated (or cigar-shaped) pattern of contamination. The shape and dimensions will be determined by the wind velocities and directions at all altitudes between the ground and the atomic cloud. For simplicity of representation, the actual complex wind pattern may be replaced by an approximately equivalent "effective wind." The direction and velocity of this wind are intended to represent weighted averages over the whole wind system to which the particles of the fallout are subjected as they descend to earth as local fallout from the atomic cloud (see § 9.140).

9.61 In Fig. 9.61 an attempt is made to generalize the pattern of contamination due to the residual nuclear radioactivity from a nuclear explosion near the earth's surface. The figure shows the ground zero (GZ) circle, corresponding to a particular dose rate (or total dose) of nuclear radiation at a specified time. Its center is somewhat displaced from actual ground zero by the wind in the vicinity of the explosion. The direction of this wind is assumed to be the same as that of the effective wind for the fallout, but this will not necessarily always be the case. The complete ground zero contamination pattern will consist of a series of circles, each representing a dose-rate (or dose) contour, for a specified dose-rate (or dose) of residual radiation.

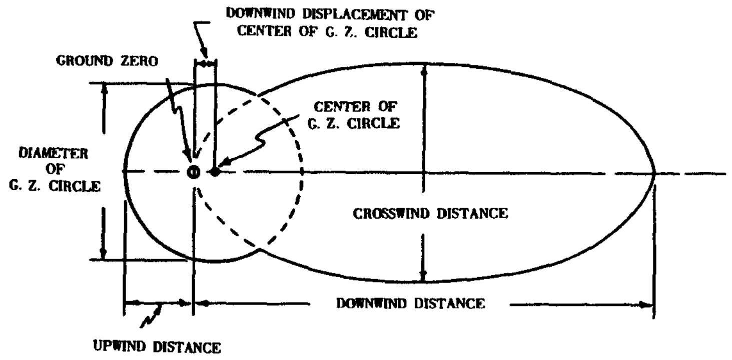

Figure 9.61. Generalized fallout pattern.

9.62 The ellipse, with its long axis in the direction of the effective wind, is a simplified dose-rate (or dose) contour for the fallout. Here again, the complete fallout contamination pattern can be represented by a series of such ellipses. At a particular time after the explosion, the dose rate (or dose) is apt to be less, the greater the distance from ground zero, because the amount of fallout per unit area is also likely to be less. In some cases (see Fig. 9.63b) the contours represent the total dose received from fallout up to a certain time. An additional factor then contributes to the decrease with increasing distance from the explosion. The later times of arrival of the fallout at these greater distances mean that the fission products have decayed to some extent while the particles were still suspended in the air. At the time the fallout reaches the ground, the activity of a certain mass at a considerable distance from the point of detonation will thus be less than that of an equal mass which has descended closer to ground zero.

9.63 Some indication of the manner in which the fallout pattern develops over a large area during a period of several hours following a nuclear surface burst of high yield may be illustrated by the diagrams in Figs. 9.63a and b. The effective wind velocity was taken as 15 miles per hour. Fig. 9.63a shows a number of contours for certain (arbitrary) round-number values of the dose rate, as would actually be observed on the ground, at 1, 6, and 18 hours, respectively, after the explosion. A series of total (or accumulated) dose contours for the same times are given in Fig. 9.63b. It will be understood, of course, that the various dose rates and doses change gradually from one contour line to the next. Similarly, the last contour line shown does not represent the limit of the contamination, since the dose rate (and dose) will fall off steadily over a greater distance.

9.64 Consider, first, a location 32 miles downwind from ground zero. At 1 hour after the detonation, the observed dose rate is seen to be about 30 roentgens per hour; at 6 hours the dose rate, which lies between the contours for 1,000 and 300 roentgens per hour, has increased to about 800 roentgens per hour; but at 18 hours it is down to roughly 200 roentgens per hour. The increase in dose rate from 1 to 6 hours means that at the specified location the fallout was not complete at 1 hour after the detonation. The decrease from 6 to 18 hours is then due to the natural decay of the fission products. Turning to Fig. 9.63b, it is seen that the total radiation dose received at the given location by 1 hour after the explosion is quite small, because the fallout has only just started to arrive. By 6 hours, the total dose has reached over 3,000 roentgens (probably around 4,000) and

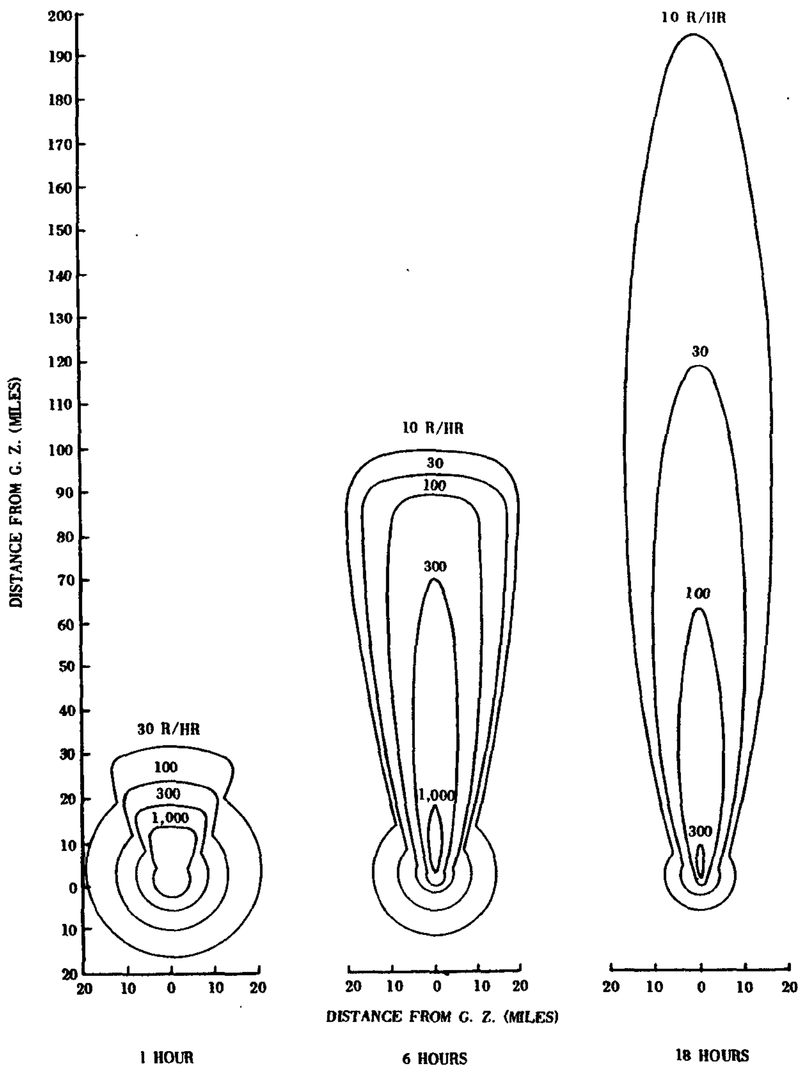

Figure 9.63a. Dose rate contours from fallout at 1, 6, and 18 hours after a surface burst with fission yield in the megaton range (15 mph effective wind).

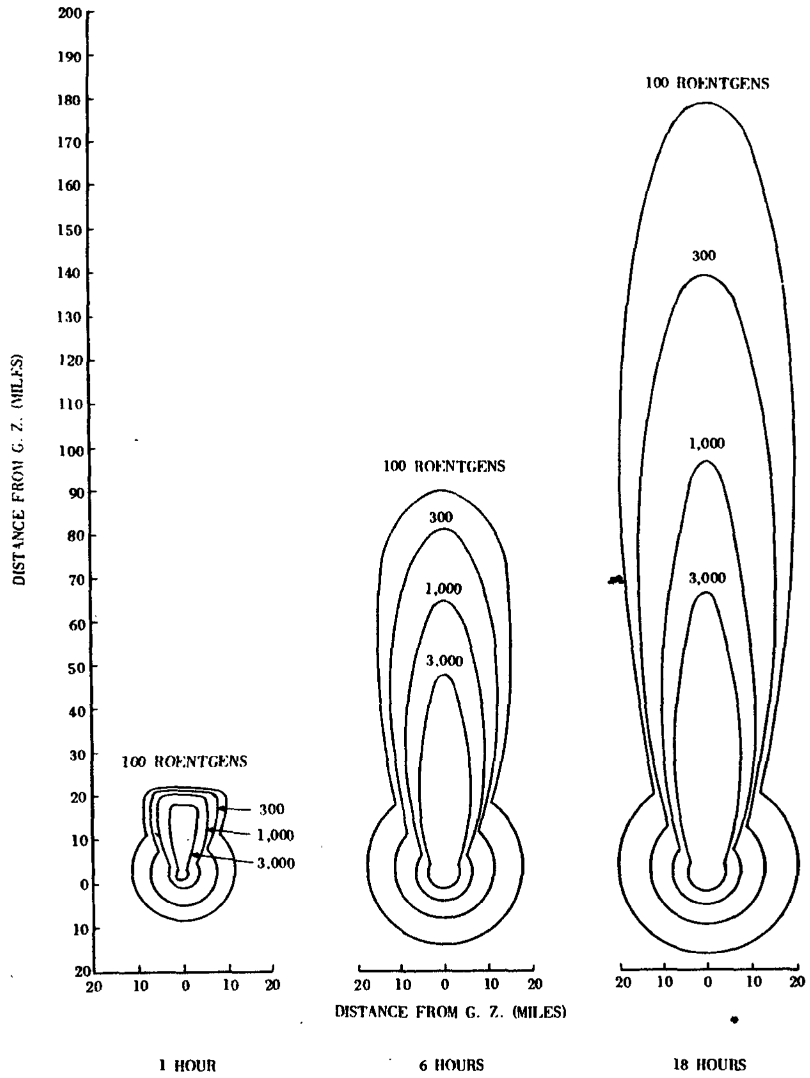

**Figure 9.63b.** Total (accumulated) dose contours from fallout at 1, 6, and 18 hours after a surface burst with fission yield in the megaton range (15 mph effective wind).

by 18 hours a total dose of some 5,000 roentgens will have been accumulated. Subsequently, the total dose will continue to increase, toward the infinity value, but at a slower rate (§ 9.14).

9.65 Next, consider a point 100 miles downwind from ground zero. At 1 hour after the explosion the dose rate, as indicated in Fig. 9.63a, is very small, probably zero, since the fallout will not have reached the specified location. At 6 hours, the dose rate is 10 roentgens per hour and at 18 hours about 50 roentgens per hour. The fallout commences at somewhat less than 6 hours after the detonation and it is essentially complete at 18 hours, although this cannot be determined directly from the contours given. The total accumulated dose, from Fig. 9.63b, is seen to be zero at 1 hour after the explosion, about 30 roentgens at 6 hours, and nearly 1,000 roentgens at 18 hours. The total (infinity) dose will not be as great as at locations closer to ground zero because the quantity of fission products reaching the ground decreases at increasing distances from the explosion.

9.66 In general, therefore, at any given location, at a distance from a surface burst, some time will elapse until the fallout arrives. This time will depend on the distance from ground zero, the time taken for the particles to descend to earth, and the effective wind velocity. When the fallout first arrives, the exposure dose rate is small, but it increases steadily as more and more fallout descends. In a few hours the fallout will be essentially (although not absolutely) complete, and then the radioactive decay of the fission products will be accompanied by a steady decrease in the dose rate. Until the fallout commences, the total dose will, of course, be zero, but after its arrival the total (accumulated) radiation dose will increase continuously, at first rapidly and then somewhat more slowly, over a long period of time, extending for many months and even years (see Table 9.90).

## LOW YIELD EXPLOSIONS

9.67 The basic fallout phenomena associated with a surface burst of low fission yield are essentially the same as those for a high fission yield. Such differences as may exist are ones of degree rather than of kind. The proportionately larger quantity of fission products resulting from a high-energy fission explosion will mean that a larger area will be contaminated to a serious extent than would be the case if the fission yield were low. However, in order to provide a more complete representation of the fallout pattern for a range of fission energies, the results will be given here for a surface burst in the kiloton range and in a later section for one in the megaton range.

9.68 In the program of nuclear test explosions in Nevada, the contamination in the vicinity of the burst has been given detailed study. The majority of these tests produced contamination patterns of the general form shown in Fig. 9.61. Hence, idealized contours of the same type are useful to indicate average, representative values for planning purposes. The contour dimensions for various 1-hour (reference) dose rates from the fallout from a 20-kiloton surface explosion, assuming a 15-mile per hour effective wind, are recorded in Table 9.68. These reference values were calculated from the dose-rate measurements made after fallout was complete, as indicated in § 9.9.

TABLE 9.68

APPROXIMATE RESIDUAL RADIATION 1-HOUR (REFERENCE) DOSE-RATE CONTOURS ON GROUND FOR 20-KILOTON SURFACE BURST

| Dose rate (r/hr) | Radius of GZ circle (miles) | Displacement of center of GZ circle (miles) | Downwind distance (miles) | Crosswind distance (miles) |
|---|---|---|---|---|
| 3,000 | 0.10 | 0.08 | 1.0 | 0.3 |
| 1,000 | 0.22 | 0.14 | 2.3 | 0.7 |
| 300 | 0.41 | 0.22 | 5.3 | 1.2 |
| 100 | 0.66 | 0.28 | 11.5 | 1.8 |
| 30 | 0.95 | 0.36 | 22 | 2.8 |
| 10 | 1.4 | 0.42 | 50 | 5.1 |

9.69 It is apparent that the dose rate close to ground zero, especially in the crater region, is very high, so that the area would be uninhabitable because of the radiation hazard. However, this area would be uninhabitable, in any event, because of the complete destruction due to blast and shock, and cratering of the ground.

9.70 In addition to the contamination in the vicinity of ground zero, which is equivalent to the ground zero circle representation in Fig. 9.61, regions of somewhat higher radioactivity than the surroundings, called "hot spots," have been detected on the surface several miles from the explosion center, both at Alamogordo and at the Nevada Test Site. This fallout of fission products is probably due to a special combination of meteorological, atmospheric, and ground conditions leading to increased deposition in a particular region.

## HIGH FISSION-YIELD EXPLOSIONS

9.71 The contour dimensions for a number of hypothetical (reference) 1-hour dose rates, relating to a 1-megaton fission yield surface burst, are given in Table 9.71, based on an effective wind velocity of 15 miles per hour. The data are obtained, as before, by using the fission product decay curve (Fig. 9.8), or an equivalent mathematical expression, to determine what the dose rate would have been at 1 hour after the explosion, if the fallout at each location had been complete at that time. The upwind extent of any particular dose rate contour given in the table is obtained by subtracting the ground zero (GZ) circle displacement from the ground zero circle radius. For example, the 10 roentgens per hour reference contour extends 11.0 − 1.65 = 9.35 miles upwind.

TABLE 9.71

APPROXIMATE RESIDUAL RADIATION 1-HOUR (REFERENCE) DOSE-RATE CONTOURS ON GROUND FOR 1-MEGATON SURFACE BURST

| Dose rate (r/hr) | Radius of GZ circle (miles) | Displacement of center of GZ circle (miles) | Downwind distance (miles) | Crosswind distance (miles) |
|---|---|---|---|---|
| 3,000 | 0.43 | 0.60 | 22 | 3.1 |
| 1,000 | 1.4 | 0.80 | 40 | 6.8 |
| 300 | 2.8 | 1.02 | 70 | 11.8 |
| 100 | 4.7 | 1.24 | 114 | 16.7 |
| 30 | 7.5 | 1.46 | 183 | 22.8 |
| 10 | 11.0 | 1.65 | 317 | 34.1 |

9.72 A more complete (idealized) representation of the contour pattern of the 1-hour (reference) dose rates, for the conditions stated above, is given in Fig. 9.72. Because of the lack of symmetry in the terrain and the effects of winds, the elliptical fallout contours for the residual radiation will not look exactly like those in Fig. 9.72. However, for representation purposes the contours are idealized in accordance with the form shown in Fig. 9.61.

9.73 It is of the utmost importance that the significance of the contours in Fig. 9.72 should not be misunderstood. The fact that the 1-hour (reference) dose rates extend to great distances from ground zero must not be taken to imply that such dose rates exist at 1 hour

(Text continued on page 420)

The figure shows the contours for various values of the 1-hour reference dose rate for the surface detonation of a weapon with a fission energy yield of 1 MT. The effective wind velocity is 15 miles per hour.

*Scaling.* For fission yields other than 1 MT, use may be made of the following approximate scaling law:

$$R=R_0\times W^{1/3} \text{ at } d=d_0\times W^{1/3},$$

where,

$R_0$ is the 1-hour (reference) dose rate for 1 MT at a distance $d_0$, and

$R$ is the 1-hour (reference) dose rate for $W$ MT at a distance $d$.

*Example*

*Given:* A weapon of 10 MT fission yield is exploded at the surface.

*Find:* The value of the dose rate from fallout at a location 215 miles downwind from ground zero at the time of arrival of the fallout at that point, assuming an effective wind of 15 miles per hour.

*Solution:* Since $W$ is 10, the value of $W^{1/3}$ is $10^{1/3}=2.15$. The distance $d$ is 215 miles, so that $d_0=d/W^{1/3}=215/2.15=100$ miles. From Fig. 9.72, it is seen that for a 1 MT surface burst, the value of $R_0$ at a distance of 100 miles downwind from ground zero, is roughly 150 roentgens per hour. Hence the 1-hour reference dose rate at 215 miles downwind from the 10 MT explosion is given by

$$150\times2.15=322 \text{ roentgens per hour.}$$

The time of arrival of the fallout at this point is approximately $215/15=14.3$ hours after the burst. From Fig. 9.8, the decay factor for 14.3 hours is 0.04. The required dose rate at a point 215 miles downwind from ground zero of a 10 MT surface burst at the time of arrival of the fallout is therefore

$$0.04\times322=12.9 \text{ roentgens per hour.} \quad \textit{Answer}$$

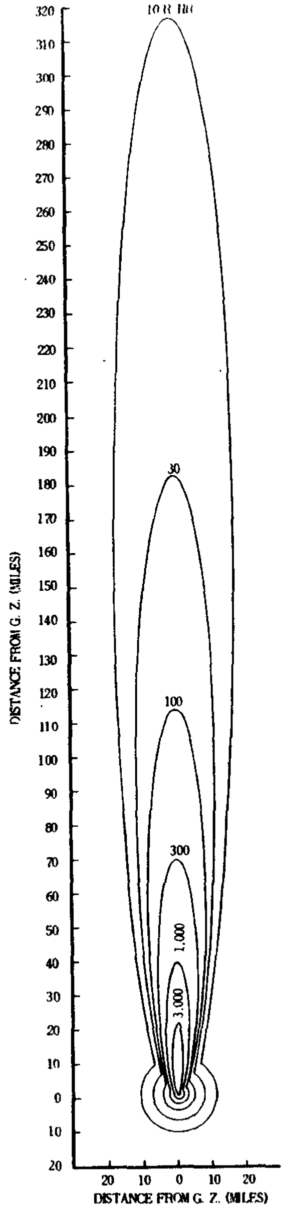

**Figure 9.72.** Idealized 1-hour reference dose rate contours for fallout after a 1-megaton surface burst (15 mph effective wind).

(Text continued from page 417)

after the explosion. In actual fact, of course, very little of the area shown will have received any fallout at this time. In most regions, as explained in § 9.64, *et seq.*, several hours will elapse before the fallout arrives. The hypothetical 1-hour (reference) dose rate is, nevertheless, very useful for calculations, as shown in the example facing Fig. 9.72.

### SCALING

9.74 The residual radiation contours near ground zero for a surface explosion of any specified energy yield can be derived from Tables 9.68 and 9.71 or Fig. 9.72 by the use of approximate scaling laws. For simplicity, it will be assumed that the effective wind is the same in all instances. If the 1-hour (reference) dose rate is $R$ roentgens per hour at a distance $d$ from ground zero for a surface explosion of $W$ megatons fission yield, then according to the approximate scaling law,

$$R=R_0\times W^{1/3} \text{ at a distance } d=d_0\times W^{1/3},$$

where $R_0$ is the 1-hour (reference) dose rate at a distance $d_0$ from ground zero in a surface explosion of 1 megaton fission yield. Instead of $d$ (and $d_0$) representing a distance from ground zero, the same scaling rule will apply to any of the contour dimensions, e. g., radius and displacement of ground zero circles, and downwind and crosswind distances.

9.75 In other words, the contours for a fission yield of $W$ megatons can be obtained by multiplying the data in Table 9.71, including distances and dose rates, by the factor $W^{1/3}$. This simple cube root scaling law has been found to give reasonably good results for fission energy yields between about 0.1 megaton (100 kilotons) and 10 megatons. For yields less than 100 kilotons it may be preferable to scale in a similar manner from data given in Table 9.68 for a 20-kiloton surface burst. In this case, the contours for a fission yield of $W$ kilotons can be obtained by multiplying the data in Table 9.68, including the dose rates, by the factor $(W/20)^{1/3}$. In general, if the atomic cloud does not reach the tropopause or is not significantly flattened by it, scaling should be done from the 20-kiloton surface burst data in Table 9.68; however, if the cloud does reach the tropopause, scaling from the 1-megaton values in Table 9.71 (or Fig. 9.72) will give better results.

9.76 The scaling procedures described above will apply (approximately) provided the effective wind velocity is always 15 miles per hour. If the actual effective wind velocity is different from this value, an approximate correction can be made in the following manner, especially at fairly great distances from ground zero. Suppose that with the 15-mile per hour effective wind, the contour for a certain reference dose rate extends 120 miles downwind. Then, for an effective wind of 20 miles per hour, the corresponding distance for the same value of the reference dose rate will be roughly $(20/15)\times 120=160$ miles.

9.77 The results described above (§ 9.71, *et seq.*) are based on the supposition that the fission yield and the total energy yield are equal, such as would be the case if all the energy of the explosion were derived from fission. In some high-yield weapons, however, part of the energy is produced by thermonuclear (fusion) reactions which do not contribute to the radioactivity of the fallout (§§ 1.13, 1.53). Allowance for this fact can be made in the following manner. Suppose the *total* energy yield of the explosion is $W$ megatons, and let $f$ represent the fraction of this energy due to fission. The calculations are first made, as described in the preceding paragraphs, for a *fission* yield of $W$ megatons; the reference dose rate, for any specified distance, is then multiplied by $f$ to give the required reference dose rate at that distance.

### FACTORS INFLUENCING FALLOUT CONTOUR PATTERN

9.78 The contamination contour pattern near ground zero can be predicted with moderate reliability, but it is almost impossible to forecast an accurate pattern of the fallout of the small radioactive particles present in the atomic cloud. In addition to such obvious variables as the fission energy yield and the height of burst, the meteorological conditions and the complex wind pattern at altitudes from perhaps 80,000 or 100,000 feet down to ground level will have important effects. It will be shown later (§ 9.133) that it is possible to estimate, to some extent, the influence of the wind on the general direction in which the fallout will travel, and the contours in Fig. 9.72 include an idealized estimate of this influence. However, there is always a possibility of a sudden and unexpected change in the prevailing winds at higher altitudes, such as have occurred occasionally in nuclear weapons tests.

9.79 One factor about which there is considerable uncertainty, but which plays an important part in the distribution of fallout contamination, is the size of the particles in the atomic cloud. Many of the particles are a few thousandths part of an inch (or less) in diameter and these may take a day or more to fall to earth. During this time they will have traveled some hundreds of miles from the point of burst. The radioactive fallout can thus produce serious contamination of the ground at such distances from the nuclear explosion that all other effects—blast, shock, thermal radiation, and initial nuclear radiation—are undetectable.

9.80 It is true that the longer the cloud particles remain suspended in the air, the less will be their activity when they reach the ground. But the total quantity of contaminated material produced by the surface burst of a high-fission-yield (megaton range) weapon is so large, that the activity may still be great even after it has decreased due to the lapse of time. It is for this reason, as well as because of the vast areas affected, that the residual nuclear (fallout) radiation from such an explosion must now be regarded as one of the major effects of nuclear weapons.

9.81 If other conditions, such as fission yield, height of burst, and wind pattern, were the same, an atomic cloud consisting mainly of fairly large particles would lead to a relatively small area of high contamination. On the other hand, if most of the particles are very small, the contaminated area would be much greater, although the radiation intensities, especially farther from ground zero, would not be so large. They might, nevertheless, be large enough to represent a hazard.

9.82 It is evident, therefore, that the fallout contour pattern will be greatly dependent upon the size distribution of the particles in the atomic cloud. And this, in turn, will depend, in a manner that is not yet understood, on the nature of the terrain. There is little doubt that a surface burst in a city will result in a particle size distribution, and consequently a fallout, quite different from that which would follow an exactly equivalent explosion in the open country. In any case, the nature of the underlying ground, both in a city and in the country, would probably influence the particle size characteristics of the atomic cloud.

9.83 Ideally, the fallout contours will be elliptical (or cigar-shaped), as shown in Fig. 9.72, extending downwind from the point of burst, with the long axis in the direction of the average wind. If there is a change in the wind pattern as the particles travel away from ground zero, the contours may be bent to the shape of a banana or like that of a boomerang. However, even in the ideal case of elliptical contours, the dose rates at various distances will depend upon the effects of all the factors mentioned above and may vary according to the existing conditions.

9.84 It was mentioned earlier (§ 9.70) that a combination of circumstances, e. g., atmospheric conditions and terrain, can often lead to somewhat higher deposition of fallout at certain localities (hot spots). Thus, the radiation intensity within a region of heavy fallout may be expected to vary from point to point, so that the contours in Fig. 9.72, which imply a steady decrease in the dose rate as the distance from the explosion center becomes greater, are idealized. They represent a general average behavior from which variations may occur due to such factors as air currents, rain, snow, and other meteorological conditions. By dispersing the fallout, strong winds near the surface would decrease the amount of contamination in certain areas, but the effect might well be to transfer the radioactive particles to a previously uncontaminated (or slightly contaminated) region. The possible effect of a rainfall situation in the case of an air burst was discussed in § 9.50. Somewhat similar circumstances could affect the distribution of the contamination after a surface burst.

9.85 Another aspect of fallout which is not shown in Fig. 9.72 is the harmful action of beta-particle emitters in contact with the skin. The doses to which the contours refer are essentially due to gamma radiation from the fission products and other bomb residues. If the fallout dust is allowed to remain on the skin for any appreciable time, the beta particles can cause serious burns, in addition to the other consequences of radiation exposure (see Chapter XI).

## CONTAMINATION FROM THE HIGH-YIELD EXPLOSION OF MARCH 1, 1954

9.86 The foregoing remarks may be supplemented by a description of the observations on the fallout contamination of the Marshall Islands made in connection with the high-yield test explosion at Bikini Atoll on March 1, 1954.[6] The device was detonated on a coral island and the resulting fallout, consisting of radioactive particles ranging from about one-thousandth to one-fiftieth of an inch in diameter, seriously contaminated an elongated, cigar-shaped area extending approximately 220 (statute) miles downwind and varying in width up to 40 miles. In addition, there was a severely contaminated region upwind extending some 20 miles from the point of detonation. A total area of over 7,000 square miles was contaminated to such an extent that survival might have depended upon evacuation of the area or taking protective measures.

9.87 From radiation dose measurements made at a number of stations, and from calculations based on known physical data and previous experience, reasonably good estimates could be made of several fallout contours. These are shown in somewhat idealized

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[6] "The Effects of High-Yield Nuclear Explosions." A report by the U. S. Atomic Energy Commission, Government Printing Office, February, 1955.

form in Fig. 9.87, for the total gamma radiation exposure (or accumulated dose) in roentgens that would be received in a period of 36 hours following the explosion. It should be noted that the doses, to which the contours in Fig. 9.87 refer, are values calculated from instrument records. They represent the maximum possible exposure and would be received only by those individuals who remained in the open, with no protection against the radiation, for the whole time. Any kind of shelter, e. g., within a building, or evacuation of the area would have reduced the dose received. On the other hand, persons remaining in the area for a longer period than 36 hours after the explosion would have received larger doses of the residual radiation.

9.88 A radiation dose of 700 roentgens spread over a period of 36 hours would probably prove fatal in nearly all cases. It would appear, therefore, that following the test explosion of March 1, 1954, there was sufficient radioactivity from the fallout in a downwind belt about 140 miles long and up to 20 miles wide to have seriously threatened the lives of nearly all persons who remained in the area for at least 36 hours following the detonation without taking protective measures of any kind. At distances of 220 miles or more downwind, the number of deaths due to radiation would have been negligible, although there would probably have been many cases of sickness resulting in temporary incapacity.

9.89 The period of 36 hours after the explosion, for which Fig. 9.87 gives the accumulated radiation exposures, was chosen somewhat arbitrarily as a time when essentially all the fallout remaining in the general vicinity will have descended to earth. It should be understood, however, as has been frequently stated earlier in this chapter, that the radiations from fission products will continue to be emitted for a long time, although at a steadily decreasing rate. The persistence of the external gamma radiation may be illustrated in connection with the March 1, 1954, test by considering the situation at two different locations in Rongelap Atoll in the Marshall Islands. Fallout began about 4 to 6 hours after the explosion and continued for several hours.

9.90 The northwestern tip of the atoll, 100 miles from the point of detonation, received 2,300 roentgens during the first 36 hours after the fallout started. This was the heaviest fallout recorded at the same distance from the explosion. About 25 miles south, and 115 miles from ground zero, the indicated dose over the same period was only 150 roentgens. The inhabitants of Rongelap Atoll were in this area, and were exposed to radiation dosages up to 175 roentgens before they were evacuated some 44 hours after the fallout began (see § 11.47). The

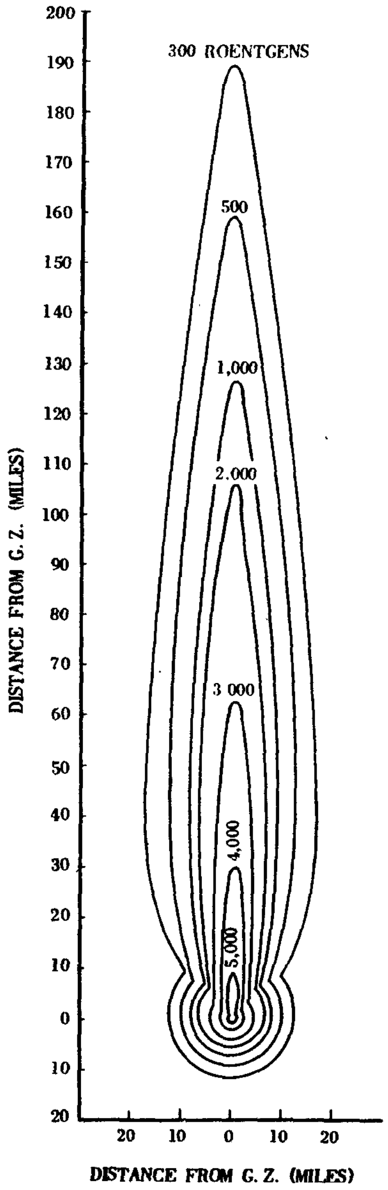

**Figure 9.87. Idealized total (accumulated) dose contours from fallout in first 36 hours after the high yield explosion at Bikini Atoll on March 1, 1954.**

maximum theoretical exposures in these two areas of the atoll for various time intervals after the explosion, calculated according to the generally accepted decay rule (§§ 9.7, 9.112), are recorded in Table 9.90.

TABLE 9.90

CALCULATED RADIATION DOSES AT TWO LOCATIONS IN RONGELAP ATOLL FROM FALLOUT FOLLOWING THE MARCH 1, 1954 TEST AT BIKINI

| Exposure period after the explosion | Accumulated dose in this period (roentgens) | |
|---|---|---|
| | Inhabited location | Uninhabited location |
| First 36 hours | 140 | 2, 150 |
| 36 hours to 1 week | 101 | 1, 310 |
| 1 week to 1 month | 73 | 950 |
| 1 month to 1 year | 83 | 1, 080 |
| Total to 1 year | 397 | 5, 490 |
| 1 year to infinity | About 129 | About 1,680 |

9.91 It must be emphasized that the calculated values given in Table 9.90 represent the maximum doses at the given locations, since they are based on the assumption that exposed persons remain out-of-doors for 24 hours each day and that no measures are taken to remove radioactive contamination (see § 12.81, *et seq.*). Further, no allowance is made for weathering, i. e., washing of fallout particles into the soil by rainfall, or the possible dispersal of the particles by winds. For example, the dose rates measured on parts of the Marshall Islands on the 25th day following the explosion were found to be about 40 percent less than the computed values. Rains were known to have occurred, after the second week, and these were probably responsible for the major decrease in the contamination.

9.92 In concluding the present discussion of fallout contamination, it may be noted that the 36-hour dose contours shown in Fig. 9.87, representing the fallout pattern in the vicinity of Bikini Atoll after the high-yield explosion of March 1, 1954, as well as the 1-hour (reference) dose-rate contours in Fig. 9.72, can be regarded as more or less typical, so that they may be used for planning purposes. Nevertheless, it should be realized that they cannot be taken as an absolute guide. The particular situation which developed in the Marshall Islands was the result of a combination of circumstances involving the energy yield of the explosion, the height of burst, the nature of the surface below the point of burst, the wind system over a large area and to a great height, and other meteorological conditions. A change in any one of these factors could have affected considerably the details of the fallout pattern.

9.93 In other words, it should be understood that the fallout situation described above is one that *can* happen, but is not necessarily one that *will* happen, following the surface burst of a high-fission-yield weapon. The general direction in which the fallout will move can be estimated fairly well if the wind pattern is known. However, the fission yield of the explosion or the height of burst, in the event of a nuclear attack, are unpredictable. Consequently, it is impossible to determine in advance how far the seriously contaminated area will extend, although the time at which the fallout will commence at any point could be calculated if the effective wind velocity and direction were known.

9.94 In spite of the uncertainties concerning the exact fallout pattern, there are highly important conclusions to be drawn from the results described above. One is that the residual nuclear radiation can, under some conditions, represent a serious hazard at great distances from a nuclear explosion, well beyond the range of blast, shock, thermal radiation, and the initial nuclear radiation. Another is that plans can be made to minimize the hazard, but such plans must be flexible, so that they can be adapted to the particular situation which develops after the attack.

## RADIOLOGICAL WARFARE

9.95 For some time, consideration has been given to the possibility of using radioactive material deliberately as an offensive weapon in what is called "radiological warfare." The basic idea is that radioactive contamination of areas, factories, or equipment would make their use either impossible or very hazardous without any accompanying material destruction. To be effective, a radiological warfare agent should emit gamma radiations and it should have a half life of a few weeks or months. Radioisotopes of long half life give off their radiations too slowly to be effective unless large quantities are used, and those of short half life decay too rapidly to provide an extended hazard.

9.96 Even if a radioisotope with suitable properties and which could be readily manufactured were selected as a radiological warfare agent, the problems of production, handling, and delivery of the weapon emitting intense gamma radiation would not be easily solved. In addition, stockpiling the radioactive material would present a difficulty. Other weapons can be prepared in advance, ready for an emergency. They can be kept for a long time without suffering deterioration. This is not true for radiological warfare agents, for natural decay would result in a continuous loss of active material. The production of a specific radioisotope is a slow process, at best, and so the continual and unavoidable loss would be a serious drawback.

9.97 The situation has undergone a change with the development of bombs having high fission energy yields. The explosion of such bombs at low altitudes can cause radioactive contamination over large areas that are beyond the range of physical damage. Consequently, they are, in effect, weapons of radiological warfare. Instead of preparing and stockpiling the contaminating agent in advance, with its attendant difficulties, the radioactive substances are produced by fission at the time of the explosion. Radiological warfare has thus become an automatic extension of the offensive use of nuclear weapons of high yield.

### CONTAMINATION OF AREAS

9.98 It was suggested in § 9.95 that radioactive contamination could deny the use of considerable areas for an appreciable period of time. There are two aspects of this situation which merit consideration. First, the direct effect of the radiation exposure on human beings who might have to live or work in a contaminated region, and second, the indirect effect due to the consumption of food grown (and animals raised) in such an area. The methods for calculating exposure doses from fission products, assuming no protection, have been given in this chapter (see also Figs. 12.107 and 12.108). The time that may be spent at a given location can thus be determined, provided some limit has been set concerning the total exposure dose. The value of such an emergency dose cannot be prescribed in advance, since it will depend entirely on the conditions existing in the particular circumstances.

9.99 In contaminated agricultural areas, the hazard to workers could be reduced by turning over the earth, so as to bury the fallout particles. But there still remains the matter of the absorption of fission products from the soil by plants and their ultimate entry into the human system in food. It is known that some elements are taken up more easily than others, but the actual behavior depends on the nature of the soil and other factors. This highly complex problem is being studied to determine the extent of the hazard which would result from the absorption of fission products by plants in various circumstances and how it might be minimized.

### CONTAMINATION IN SUBSURFACE BURSTS

9.100 The extent of the contamination due to residual nuclear radiation following a subsurface explosion will depend primarily on the depth of the burst. If the explosion occurs at a sufficient depth below the surface, essentially none of the bomb residues and neutron-induced radioactive materials will escape into the atmosphere. There will then be no appreciable fallout. On the other hand, if the burst is near the surface, so that the ball of fire actually breaks through, the consequences, as regards fallout, will not be very greatly different from those following a surface burst.

9.101 There will, in fact, be a gradual transition in behavior from a high air burst, at one extreme, where all the radioactive bomb residues are dissipated in the atmosphere, to a deep subsurface burst, at the other extreme, where the radioactive materials remain below the surface. In neither case will there be any significant local fallout. Between these two extremes are surface bursts or low air bursts which will be accompanied by extensive contamination due to fallout. These merge into shallow subsurface bursts, for which the behavior is similar. With increasing depth of explosion, more of the radioactive bomb residues remain in the vicinity of the burst point, i. e., in and around the crater, and proportionately less goes into the upper atmosphere to descend at a distance as fallout.

9.102 Since a shallow burst, in which the fireball emerges from the ground, is essentially similar to a low surface burst, in which a large part of the fireball touches the earth, this type of nuclear explosion need not be discussed further. The case of interest, however, is that of a subsurface burst at such a depth that the ball of fire does not emerge, yet a considerable amount of dirt (or water) is thrown up as a column into the air (§ 2.67).

9.103 It may be noted that some contribution to the residual nuclear radiations following a subsurface detonation is made by the radioisotopes, e. g., sodium-24 (§ 9.21), formed by neutron capture. However, as with a surface burst, this is so small in comparison with the radiations from the fission products that it may be ignored.

9.104 In the case of an underground explosion at a moderate depth there will be considerable crater formation. Much of the radioactive material will remain in the crater area, partly because it does not escape and partly because the larger pieces of contaminated rock, soil, and debris thrown up into the air will descend in the vicinity of the explosion. The finer particles produced directly or in the form of a base surge (§ 2.71) will remain suspended in the air and will descend as a fallout at some distance from ground zero.

9.105 The fallout contour pattern will be dependent upon the fission energy yield, the depth of burst, the nature of the soil, and also upon wind and weather conditions. Other circumstances being more or less equal, the contamination in the crater area following a subsurface burst will be about the same as for a surface explosion of equal fission yield. However, the total contaminated area will be greater for the (shallow) subsurface burst because a larger amount of fission products is present in the fallout.

9.106 The fallout following a shallow underwater burst, of the type used in the Bikini BAKER test in July 1946 (§ 2.49), will be very much like that of an underground explosion, as just described. In this particular test, the cloud did not ascend as high as in an air burst of the same energy yield. As a result, the fallout, which was in effect a radioactive rain, commenced to descend very soon after the explosion. In fact, the first fallout (or rain-out) reached the surface of the lagoon within about a minute of the detonation. A large proportion of the fission product (and other) activity was thus precipitated in a short time within a radius of a few thousand yards of the approximately 20-kiloton burst.

9.107 In the Bikini BAKER test the base surge, consisting of a contaminated cloud or mist of small water droplets, formed 10 to 12 seconds after the explosion and moved rapidly outward (§ 2.57). This undoubtedly contributed to the radioactivity deposited on the ships in the lagoon, but the base surge is now thought to be less significant as a source of contamination than the water (rain-out) which descended from the cloud system.

9.108 An important difference between an underwater burst and one occurring under the ground, is that the radioactivity remaining in the water is gradually dispersed, whereas that in ground is not. As a result of diffusion of the various bomb residues, mixing with large volumes of water outside the contaminated area, and natural decay, the radiation intensity of the water in which a nuclear explosion has occurred will decrease fairly rapidly. Some indication of the rate of decrease and of the spread of the active material is provided by the data in Table 9.108, obtained after the Bikini BAKER test. Thus, within 2 or 3 days the radioactivity had spread over an area of about 50 square miles, but the maximum radiation dose rate was then so low that the area could be traversed without danger.

TABLE 9.108

DIMENSIONS AND DOSE RATE OF CONTAMINATED WATER AFTER THE 20-KILOTON UNDERWATER EXPLOSION AT BIKINI

| Time after explosion (hours) | Contaminated area (square miles) | Mean diameter (miles) | Maximum dose rate (roentgens per hour) |
|---|---|---|---|
| 4 | 16.6 | 4.6 | 3.1 |
| 38 | 18.4 | 4.8 | 0.42 |
| 62 | 48.6 | 7.9 | 0.21 |
| 86 | 61.8 | 8.9 | 0.042 |
| 100 | 70.6 | 9.5 | 0.025 |
| 130 | 107 | 11.7 | 0.008 |
| 200 | 160 | 14.3 | 0.0004 |

9.109 In addition to the factors mentioned above, the settling of fission products to the bottom of the lagoon contributed to the decrease in activity after the BAKER test. From an examination of bottom material made a few days after the explosion, it appeared that a considerable proportion of the bomb residues must have been removed from the water in this manner. The results indicated that the major deposition had taken place within a week of the underwater explosion, and that the area covered was then about 60 square miles. Although the total amount of radioactivity on the bottom of the lagoon was very high, it was so widely distributed that it did not represent a hazard to marine life. Observations made several months later indicated that there was little or no tendency for the contaminated material to spread. But this may be attributed, in part at least, to the landlocked nature of Bikini Lagoon.

## TECHNICAL ASPECTS OF RESIDUAL NUCLEAR RADIATION[7]

### DECAY OF FISSION PRODUCTS

9.110 The mixture of radioisotopes constituting the fission products is so complex that a mathematical representation of the rate of

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[7] The remaining sections of this chapter may be omitted without loss of continuity.

decay in terms of the individual half lives is impractical. However, it has been found experimentally that for the period from several minutes to 2 or 3 years after detonation the *over-all* rate of radioactive disintegration (or rate of emission of radiations) by the fission products can be represented, to a fair degree of accuracy, by the relatively simple expression

$$\text{Rate of disintegration}=A_1t^{-1.2}, \qquad (9.110.1)$$

where $t$ is the time after formation of the fission products, i. e., the time after the explosion, and $A_1$ is a constant factor, defined as the rate of disintegration at unit time, that is dependent upon the quantity of fission products. This equation can also be used, with appropriate values for $A_1$, to give the rate of emission either of gamma rays or of beta particles. A beta particle is liberated in each act of disintegration, but gamma ray photons are produced in about one-half only of the fission product disintegrations, the fraction varying with the time after the explosion.

9.111 In considering the radiation dose (or dose rate) due to fission products, e. g., in fallout, the gamma rays, because of their long range and penetrating power, are of greater significance than the beta particles, provided the radioactive material is not actually on the skin or within the body. Consequently, the beta radiation can be neglected in estimating the variation with time of the dose rate from the residual nuclear radiation. If the fraction of fission product disintegrations accompanied by gamma ray emission and the energy of the gamma ray photons remained essentially constant with time, the dose rate, e. g., in roentgens per hour, would be directly related to the rate of emission of gamma rays. As mentioned in § 9.34, this is not the case. The gamma rays in the early stages of fission product decay have, on the average, higher energies than in the later stages. However, for the periods of practical interest, commencing a few hours after the explosion, the mean energy of the gamma ray photons may be taken as essentially constant, at about 0.7 Mev.

9.112 Although the fraction of gamma emitters varies with time, a fair approximation based on equation (9.110.1) is that, at any time $t$ after the explosion,

$$\text{Gamma radiation dose rate}=R_1t^{-1.2}, \qquad (9.112.1)$$

where $R_1$ is a constant. Physically, $R_1$ is equivalent to the (reference) dose rate at unit time. As a general rule, the time $t$ is expressed in hours, and then $R_1$ is the reference dose rate at 1 hour after the explosion. If $R_t$ represents the dose rate from a certain quantity of fission products at $t$ hours after the explosion, then, from equation (9.112.1),

$$\frac{R_t}{R_1}=t^{-1.2}, \qquad (9.112.2)$$

or, upon taking logarithims,

$$\log\frac{R_t}{R_1}=-1.2\log t. \qquad (9.112.3)$$

9.113 It follows from equation (9.112.3) that a log-log plot of $R_t/R_1$ against $t$ should give a straight line with a slope of $-1.2$. When $t=1$, i. e., at 1 hour after the explosion, $R_t=R_1$, so that $R_t/R_1=1$; this is the basic reference point through which the line of slope $-1.2$ is drawn in Fig. 9.8.

9.114 If the time, $t$, is in hours, the radiation exposure dose rates $R_t$ and $R_1$ are expressed in roentgens per hour. Then, the total dose in roentgens received from a given quantity of fission products during any specified period after the explosion can be readily obtained by direct integration of equation (9.112.2). For example, for the interval from $t_a$ to $t_b$ hours after the detonation,

$$\text{Total dose}=R_1\int_{t_a}^{t_b}t^{-1.2}dt$$

$$=\frac{R_1}{0.2}\left[\frac{1}{t_a^{0.2}}-\frac{1}{t_b^{0.2}}\right] \qquad (9.114.1)$$

Hence, if the reference dose rate, $R_1$ roentgens per hour, at 1 hour after the explosion, is known the total dose (in roentgens) for any required period can be calculated.

9.115 The curve in Fig. 9.12 is derived from equation (9.114.1) with $t_a$ being taken as 0.0167 hour, i. e., 1 minute, which is the time when the residual nuclear radiation is postulated as beginning. Hence, Fig. 9.12 gives the total radiation dose received up to any specified time after the detonation, assuming exposure during the whole period.

9.116 Another application of equation (9.114.1) is to determine the time which an individual can stay in a location contaminated by fission products without receiving more than a specified dose of radiation. In this case, the total dose is specified; $t_a$ is the known time of entry into the contaminated area and $t_b$ is the required time at (or before) which the exposed individual must leave. In order to solve this problem with the aid of equation (9.114.1), it is necessary to know the reference dose rate, $R_1$. This can be obtained from equation (9.112.2) if the dose rate, $R_t$, is measured at any time, $t$, after the explosion, e. g., at the time of entry. The results can be expressed graphically as in Figs. 12.107 and 12.108.

9.117 In principle, equation (9.114.1) could be used to estimate the total dose received from fallout in a contaminated area, provided the whole of the fallout arrives in a very short time. Actually, the contaminated particles may descend for several hours, and without knowing the rate at which the fission products reach the ground, it is not possible to make a useful calculation. When the fallout has ceased, however, equations (9.112.2) and (9.114.1) may be employed to make various estimates of radiation doses, provided one measurement of the dose rate is available.

## Fission Product Activities in Curies

9.118 The rate at which a radioactive material disintegrates (or decays), and hence the rate at which it emits beta particles or gamma rays, is generally stated in terms of a unit called the "curie." It is defined as the quantity of radioactive material undergoing $3.7 \times 10^{10}$ disintegrations per second. This particular rate was chosen because it is (approximately) the rate of disintegration of 1 gram of radium. Since the activities of fission products from a nuclear explosion are very high, it is more convenient to use the "megacurie" unit. This is equal to 1 million curies and corresponds to disintegrations at a rate of $3.7 \times 10^{16}$ per second.

9.119 As stated above, the gamma rays are, in general, more significant biologically than the beta particles from fission products. Consequently, the fission product activity as expressed in (gamma) curies is a measure of the rate of emission of gamma ray photons, rather than of the rate of disintegration. Using equation (9.110.1) as the basis, the total gamma activities of all the fission products from a 1-megaton explosion have been calculated for various times after the detonation. The results are given in Table 9.119.

## Radiation Dose Rates Over Contaminated Surfaces

9.120 If an area is uniformly contaminated with any radioactive material of known activity (in curies), it is possible to calculate the gamma-radiation dose rate at various heights above the surface, provided the average energy of the gamma-ray photons is known. The results of such calculations, assuming a contamination density of 1 (gamma) megacurie per square mile, for gamma rays having energies of 0.7 Mev, 1.5 Mev, and 3.0 Mev, respectively, are represented in Fig. 9.120. The curve for 0.7 Mev is approximately applicable to a surface contaminated with fission products. If the actual contamination density differs from 1 megacurie per square mile, the ordinates in the figure would be multiplied in proportion.

Table 9.119

### TOTAL GAMMA RADIATION ACTIVITY OF FISSION PRODUCTS FROM A 1-MEGATON EXPLOSION

| *Time after explosion* | *Activity (megacuries)* |
|---|---|
| 1 hour | 300, 000 |
| 1 day | 6, 600 |
| 1 week | 640 |
| 1 month | 110 |
| 1 year | 5. 5 |

9.121 It may be noted that in the calculations upon which the curves in Fig. 9.120 are based, the scattering of gamma radiation back to the ground by interaction with the oxygen and nitrogen in the air was neglected. This would tend to make the observed dose rates larger than those given. On the other hand, it was assumed that the surface over which the contamination is distributed is perfectly flat. For moderately rough terrain, the dose rate at a specified height is less than for a flat surface. In practice the two deviations largely compensate one another, so that Fig. 9.120 gives a relatively good value for the dose rate in air above an uneven surface.

9.122 The dose rate at greater heights above the ground, such as might be observed in an aircraft, can be estimated with the aid of Fig. 9.122. The curve gives the attenuation factor for fission product radiation as a function of altitude. It applies in particular to a uniformly contaminated area that is large compared to the altitude of the aircraft. If the dose rate near the ground is known, then the value at any specified altitude can be obtained upon dividing by the attenuation factor for that altitude. On the other hand, if the dose rate is measured at a known altitude, multiplication by the attenuation factor gives the dose rate near the ground.

9.123 A possible use of the curve in Fig. 9.122 is to determine the dose rate and contamination density of the ground from data obtained by means of an aerial survey (see § 12.77). For example, suppose a radiation measuring instrument suspended from an aircraft at a

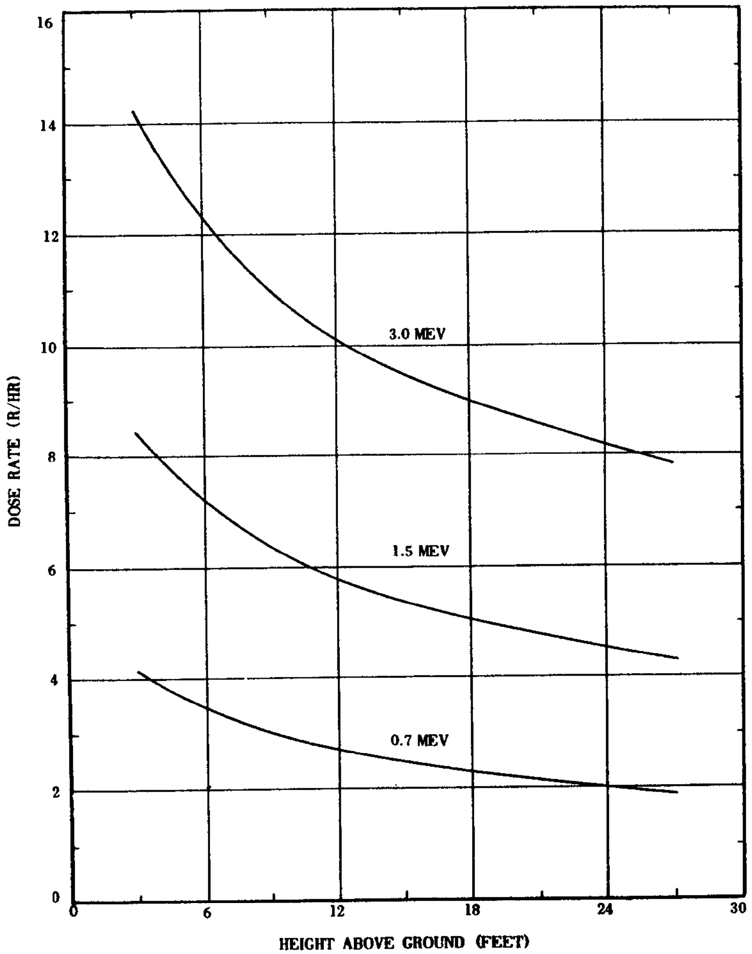

Figure 9.120. Dose rate of gamma radiation near ground with uniform contamination density of 1 megacurie per square mile.

height of 1,000 feet showed a radiation dose rate of 0.24 roentgen per hour. The attenuation factor for this altitude is 30 and so the dose rate on the ground is approximately 0.24×30=7.2 roentgens per hour. It is seen from Fig. 9.120 that for a contamination density of 1 megacurie per square mile the dose rate near the ground is about 4 roentgens per hour. Hence, in the present case, the contamination density is approximately 7.2/4=1.8 megacuries per square mile.

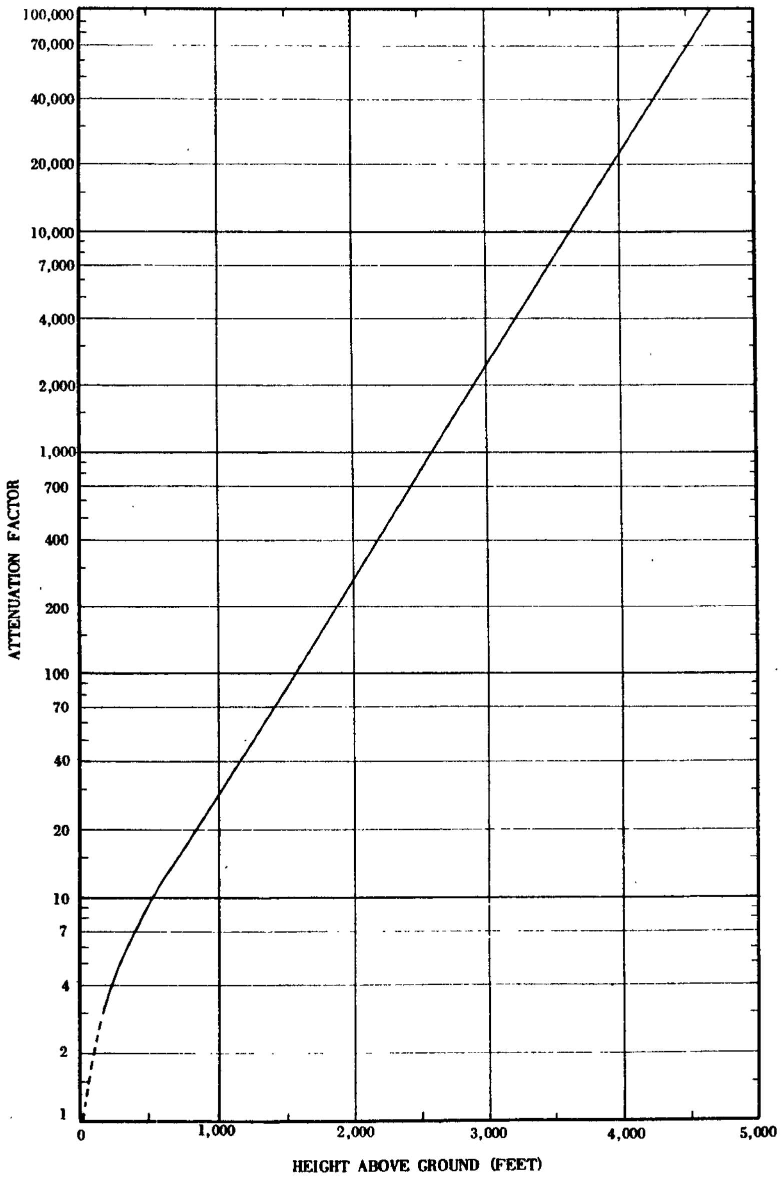

Figure 9.122. Altitude attenuation factor for fission product radiation from the ground.

9.124 The dose rates from gamma radiations of various energies above the surface of water uniformly contaminated with a density of 1 (gamma) curie per cubic yard (1 megacurie per million cubic yards) are shown in Fig. 9.124a. The curve for 0.7-Mev energy may be regarded as applicable to contamination by fission products. The dose rates at various altitudes can be estimated by the use of the attenuation factors in Fig. 9.122. Within the water itself, in which the contamination is assumed to be uniformly distributed, the dose rates are given by Fig. 9.124b, as a function of gamma-ray energy. From the measurement of dose rate made in an aircraft at a known altitude, it is possible to calculate the contamination density of the water, using Figs. 9.122 and 9.124a. Then, from Fig. 9.124b, the dose rate in the water can be evaluated.

## RATE OF FALL OF PARTICLES

9.125 An important aspect of the fallout problem is a theoretical study of the distribution of particle size as a function of distance from the region of the explosion. A simple treatment will be given here, which, although approximate, provides a picture that is believed to be qualitatively correct. For purposes of illustration, it will be supposed that a weapon of high-energy yield is exploded near the surface of the ground. Although the particles will descend from the atomic cloud at all heights between 60,000 and 100,000 feet, at least, it will be postulated, in order to simplify the calculations, that they all commence to fall when they reach the average height of 80,000 feet.

9.126 The rate of fall of small particles in air from great heights under the influence of gravity can be determined approximately by means of Stokes's law, in the form,

$$\text{Rate of fall} = 0.35 d^2 \rho \text{ feet per hour,} \qquad (9.126.1)$$

where $\rho$ is the density of the particle in grams per cubic centimeter and $d$ is its diameter in microns.[8] This expression applies moderately well for particles from 5 to 300 microns, i. e., $5 \times 10^{-4}$ to $3 \times 10^{-2}$ centimeters, in diameter. For larger particles, the rates of fall are actually slower than are given by the simple Stokes's law. Assuming that the fallout particles have the same density as sand, i. e., 2.6 grams per cubic centimeter, the approximate times required for particles of various diameters to descend to earth from a height of 80,000 feet, as calculated from equation (9.126.1), are given in Table 9.126. Particles

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[8] 1 micron is a one-millionth part ($10^{-6}$) of a meter or one ten-thousandth ($10^{-4}$) of a centimeter.

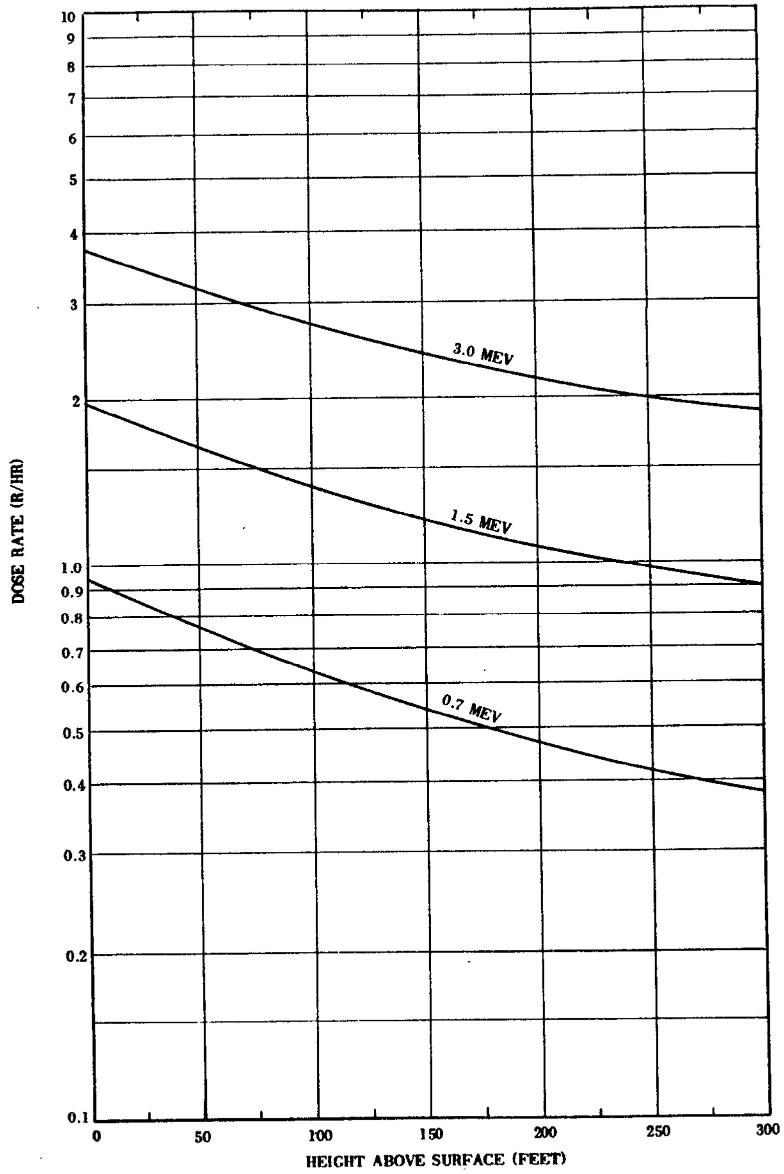

Figure 9.124a. Dose rate of gamma radiation near surface of water with uniform contamination density of 1 curie per cubic yard.

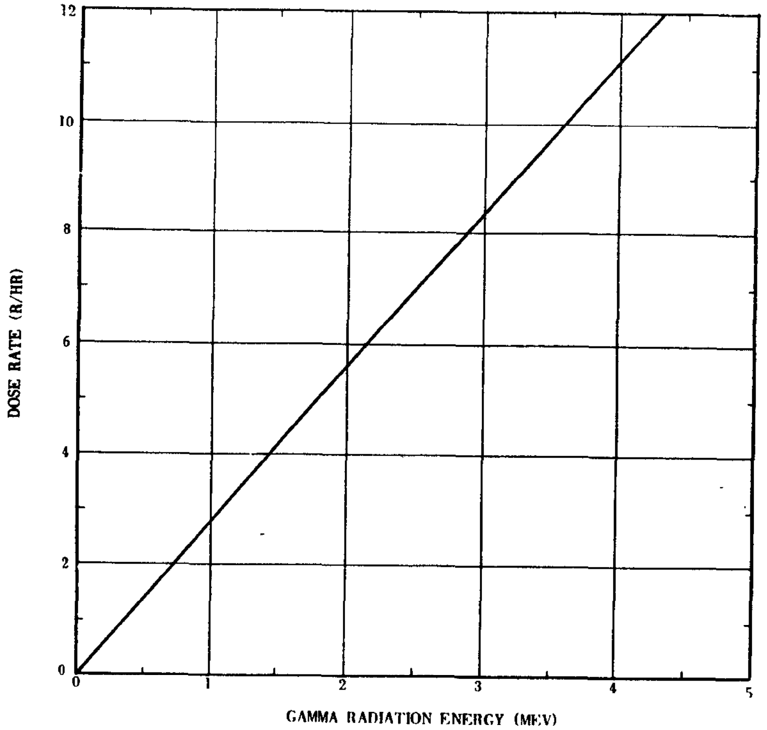

Figure 9.124b. Dose rate of gamma radiation within a large volume of water with uniform contamination density of 1 curie per cubic yard.

smaller than 5 microns in diameter are seriously affected by Brownian movement, resulting from collisions with air molecules, so that some of them, as seen earlier, remain suspended for very long periods. The rate of fall of even larger particles is affected by turbulence of the air.

TABLE 9.126

APPROXIMATE TIMES FOR PARTICLES TO FALL FROM 80,000 FEET

| *Particle diameter (microns)* | *Time of fall (hours)* |
|---|---|
| 340 | 0.75 |
| 250 | 1.4 |
| 150 | 3.9 |
| 75 | 16 |
| 33 | 80 |
| 16 | 340 |
| 8 | 1,400 |
| 5 | 3,400 |

9.127 If all the particles descended from the same level, the data in Table 9.126 (or calculated from equation (9.126.1)) could be used to estimate the variation of particle size in the fallout as a function of the distance from ground zero. The actual distance would depend upon the height of the cloud from which the particles fell, since this determines the time of fall, and upon the effective wind velocity. It is, nevertheless, possible to plot a generalized curve, such as that in Fig. 9.127; the distance from ground zero is equal to the time of fall from 80,000 feet multiplied by the average (effective) wind velocity, taken as 15 miles per hour. It is evident that particles having diameters in excess of about 250 microns (0.01 inch) or so, may be expected to fall within a relatively short distance of ground zero. Smaller particles, however, can travel much greater distances before descending to earth as fallout.

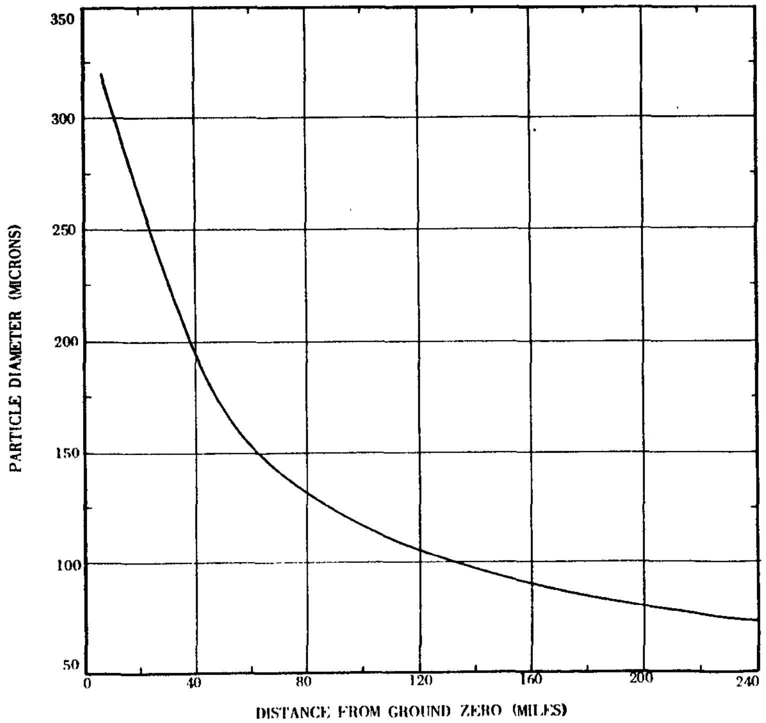

Figure 9.127. Distance traveled by particles of various sizes in fallout (fall from 80,000 feet with an assumed 15 mph effective wind).

9.128 In practice, the ideal conditions, upon which Fig. 9.127 is based, do not prevail. For example, Stokes's law is not obeyed, the particles do not all rise to the same height in the cloud before they begin to fall, and the wind velocity is variable. Further, irregularities in shape and the mutual adhesion of smaller particles, as well as turbulence of the air, will affect the rate of fall. Consequently, after a nuclear explosion the variation of particle size with distance is not as uniform as is implied by the foregoing discussion. It is probable, however, that the curve in Fig. 9.127 gives a good general idea of the distribution of particle size with distance from ground zero.

9.129 Disregarding the approximations made in deriving the curve in Fig. 9.127, the distances at which particles of various sizes are found depend on the postulated effective wind velocity (15 miles per hour) and the average height from which the particles are assumed to fall (80,000 feet). For an explosion of lower energy yield, the cloud will not rise so high and so particles of any given size will reach the earth sooner. The respective distances from ground zero will then be less than in Fig. 9.127, for the same wind velocity. On the other hand, a higher effective wind velocity will result in an increase in the distance traveled by particles of any specified size before reaching the ground.

9.130 From the standpoint of radioactive contamination, the surface area of the particles is of some significance, in addition to their rate of fall. Many fallout particles collected after test explosions have shown fairly uniform distribution of the radioactivity, but in others the activity has been found only near the surface (§ 2.21). However, with the object of simplifying the subsequent treatment, it will be assumed that the contamination is of the latter type and that the thickness of the radioactive layer is always the same. The total radioactivity carried by particles of a given size will then depend on the proportion of the total area associated with that size group. In order to make the calculations, it is necessary to know the size distribution among the fallout particles, i. e., the proportion in each size group. As a rough guide, in default of more definite information, the distribution is taken to be the same as in the soil over which the detonation occurs.

9.131 On the basis of the foregoing assumptions, the results in Table 9.131 have been obtained. The four particle size groups are based on the diameters in the first column of Table 9.126, and the fallout periods then correspond to the times of fall from a height of 80,000 feet, as given in the second column of this table. The data in Table 9.131 show that by the end of 16 hours after the explosion about 50 percent of the total fission product activity will have been deposited on the ground. During this time the particles will have traveled some 240 miles downwind, if the effective wind velocity is 15 miles per hour.

TABLE 9.131

PROPORTION OF ACTIVE MATERIAL DEPOSITED FROM ATOMIC CLOUD FROM 80,000 FEET ALTITUDE

| Diameter of particles (microns) | Period of arrival (hours) | Percentage of activity deposited |
|---|---|---|
| 340 | Up to 0.75 | 3.8 |
| 340-250 | 0.75 to 1.4 | 12.6 |
| 250-150 | 1.4 to 3.9 | 14.5 |
| 150-75 | 3.9 to 16 | 18.1 |

9.132 The results in the last column of Table 9.131 give the percentage of the *initial* fission product activity in the various particle size groups. In other words, no allowance is made for the natural radioactive decay during their ascent with the atomic cloud and their descent with the fallout. However, because of this decay, the material deposited on the ground at increasing times after the burst will be less and less active. Thus, Table 9.131 indicates that in the period from 3.9 hours to 16 hours after the explosion about 18 percent of the fission products will reach the earth's surface. But, if allowance is made for natural decay, it is probable that this would represent less than 0.1 percent of the original radioactivity of the atomic cloud.

## PREDICTION OF FALLOUT PATH

9.133 Several methods of various degrees of accuracy (and corresponding complexity) have been proposed for plotting the expected path of the fallout on the ground after a nuclear explosion. One of the simplest will be described below.[9] Although the results may *not* be as precise as could be obtained in other ways, the procedure has the great merit of rapidity and is capable of being carried out even under emergency conditions.[10] The basic information required is a knowl-

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[9] U. S. Department of Commerce, Weather Bureau Circular Letter 16-54.

[10] More refined fallout computations are made by hand and special purpose analog computers.

edge (or prognosis) of the mean wind direction and speed in a series of 5,000-foot thick layers of the atmosphere from the earth's surface to the top of the atomic cloud.

9.134 Starting at a point *O*, representing ground zero, in Fig. 9.134, a vector *OA* is drawn, indicating the direction and velocity (in miles per hour) of the wind in the first 5,000-foot level from the ground. This is followed by vectors *AB*, *BC*, . . ., *GH*, for successive levels up to the limit of observation, e. g., the top of the cloud, in this case, 8×5,000=40,000 feet. The line *OH* then represents the locus of particles which fall from a height of 40,000 feet at various times. The larger particles will be found close to ground zero, soon after the explosion, whereas the smaller particles fall at greater distances, at later times. The line *OG* is the locus of particles falling from a height of 35,000 feet, since these are not subjected to the wind represented by the vector *GH*. Similarly, *OF* is the locus for particles which begin to fall at 30,000 feet, and so on. The average wind for levels up to 40,000 feet is equal to the length of *OH* divided by the number of 5,000-foot levels, i. e., 8 in this case.

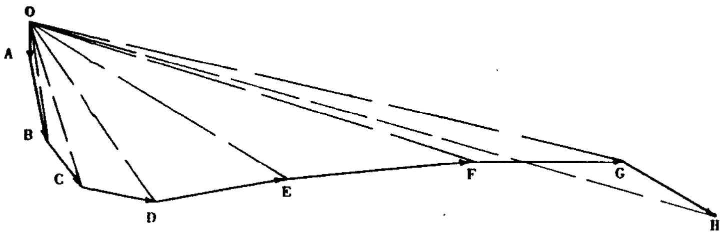

Figure 9.134. Prediction of approximate path of fallout based on wind pattern.

9.135 The region enclosed by the line *OH* and the various vectors may thus be regarded as providing a rough indication of the general direction of the fallout with respect to ground zero. There is, in addition to the effect of wind, some diffusion of the particles in the atmosphere, which will result in an extension in all directions about the idealized region derived from the wind vector.

9.136 Although Fig. 9.134 gives a general idea of the shape of the fallout area, it does not indicate its over-all extent. If, as is the case considered above, the wind vectors, expressed in miles per hour, are drawn at 5,000-foot levels, *OH* is the distance traveled by particles descending from the height of 40,000 feet in 8 hours. Similarly, *OG* is the distance traveled by particles descending from 35,000 feet in 7 hours. Thus, *OAB* . . . *HO* is dimensionally the approximate area in which particles having diameters of 75 microns (or more) will descend. Such particles fall at the rate of 5,000 feet per hour (or more). Smaller particles fall more slowly and will be found outside the area shown. The loci on the ground of particles descending from various heights will, however, have the same directions as before. Thus, particles with diameters less than 75 microns falling from 40,000 feet will appear along an extension of *OH*, those from 35,000 feet along an extension of *OG*. Hence the general shape of the fallout pattern is related to that in Fig. 9.134, although it covers a larger area.

9.137 It will be apparent that the procedure just described can provide only a rough guide concerning the probable fallout area. In actuality, the particle size distribution will not be known, and the height of the atomic cloud from which the particles descend will not be very certain. In addition, the wind directions and velocities may change with time, and the effect of sharp wind shears in thin layers has been neglected. Finally, there is the fundamental assumption that the wind pattern used in drawing Fig. 9.134 applies to the whole area of significant contamination which may extend as far as 200 miles from ground zero. Rain or snow falling at the time of (or soon after) the detonation will also change the fallout situation, since many radioactive particles will become attached to the drops and descend from various heights at rates which are characteristic of the rain or snow.

9.138 In the event that no upper wind information at (or near) the time of the explosion is available, use may be made of the general pattern to be expected in the given location at the particular time of year. This information, based on observations made at weather stations over long periods, may perhaps be supplemented by visual estimates of the direction of cloud movements at various heights. It is important to emphasize that fallout patterns based on surface winds alone may be completely misleading.

## *CHAPTER X*

# WORLD-WIDE FALLOUT AND LONG-TERM RESIDUAL RADIATION

## LOCAL AND WORLD-WIDE FALLOUT

### INTRODUCTION

10.1 The fallout of nuclear bomb debris considered in the preceding chapter may be described as being "local" in character. It consists chiefly of the larger particles which descend to earth, under the influence of gravity, in a matter of hours. The distances traveled are comparatively short and are not more than a few hundred miles from ground zero, in a downwind direction, even for the largest explosions. The early danger from the local fallout is due primarily to nuclear radiations from radioactive materials outside the body. During the first few days or weeks after the detonation, the radiation levels may be high enough to represent a danger to exposed persons. The radiation intensity decreases rapidly with time and, except for areas of very high initial contamination, it ceases to be a serious hazard within a few weeks. However, as seen earlier, the radioactivity diminishes more slowly as time passes, so that, even after several years, some will still persist.

10.2 There is another form of fallout that is much more widespread than the local type. It is that portion of the bomb residues which consists of very fine material that remains suspended in the air for times ranging from days to years. These fine particles can be carried over large areas by the wind and may, ultimately, be deposited in parts of the earth remote from the point of burst. The fallout of this fine debris is referred to as "world-wide fallout". It should not be inferred from this term, however, that none of the fine material is deposited in areas near the explosions, nor that such material is deposited uniformly over the earth. The nature of the distribution will be considered below; for the present, the main point is that the fallout under consideration is very much more widespread than the local type.

10.3 An overexposure to radiation from the local fallout could lead to harmful consequences that are experienced within a few days (or weeks) of the explosion; these are called "short-term" effects. In addition, there will be certain "long term" (or delayed) effects which may never become apparent or may become apparent years after the explosion. Nuclear radiation from early (or local) fallout as well as that received at much lower dose rates over succeeding months or years, from both local and world-wide fallout, could contribute to the probability of these delayed effects. Such radiation may originate in material both inside and outside the body.

10.4 One of the long-term effects may be that of genetic changes brought about by exposure to nuclear radiation of the cells which transmit inherited characteristics from one generation to the next. This aspect of the action of residual (and other) radiations will be examined in more detail in Chapter XI. The long term effects to be considered here are those which could result from exposure of body tissues to radiation from materials which may have accumulated within the body over long periods of time. It is in this connection that the world-wide fallout is of interest.

### TROPOSPHERIC FALLOUT

10.5 It has already been seen in earlier chapters of this book that local fallout is important only when the nuclear burst occurs at or near (above or below) the earth's surface, so that a large amount of debris is carried up into the atomic cloud. On the other hand, contributions to world-wide fallout can come from nuclear explosions of all types, except those so far beneath the surface that the ball of fire does not break through and there is no atomic cloud. However, with regard to the mechanism of the world-wide fallout, a distinction must be drawn between the behavior of explosions of low energy yield and those of high energy yield. It will be assumed that the burst occurs in the lower part of the troposphere. (The troposphere is that part of the atmosphere which extends to a height of some 30,000 to 50,000 feet, depending on the existing climatic conditions.) Then, from nuclear detonations in the kiloton range, the atomic cloud will not generally rise above the top of the troposphere (§§ 2.14, 2.15). Consequently, nearly all the fine particles present in the bomb debris from such explosions will remain in the troposphere until they are eventually deposited.

10.6 The mechanism of deposition of the fine fallout particles from the troposphere is complex, since various processes, in addition to simple gravitational settling, are involved. The most important of these processes appears to be the scavenging effect of rain or other form of moisture precipitation. The rate of removal of material from the troposphere at any time is apparently proportional to the amount present at that time. Hence, the time for one half of the material to be deposited, called the "residence half-time," is a characteristic quantity. For the tropospheric fallout this half-time is of the order of a few weeks, so that bomb debris does not remain for very long in the troposphere.

10.7 While the fine debris is suspended in the troposphere, the major part of the material is moved by the wind at high altitudes. In general, the wind pattern is such that the debris is carried rapidly in an easterly direction, making a complete circuit of the globe in some 4 to 7 weeks. Diffusion of the cloud to the north and south is relatively slow, with the result that most of the fine tropospheric fallout is deposited, in a short period of weeks, in a fairly narrow band encircling the world at the latitude of the nuclear detonation.

### STRATOSPHERIC FALLOUT

10.8 For explosions of high energy yield, in the megaton range, nearly all of the bomb debris will pass up through the troposphere and enter the stratosphere. The larger particles will be deposited locally for a surface or subsurface burst. The very fine particles, from bursts of all types, can then be assumed to remain in the stratospheric debris, which spreads worldwide. Due to their fineness, and the absence of clouds and rainfall at such high altitudes, the particles will settle earthward very slowly. Estimates based on the limited information at present available indicate that about 10 percent of the debris stored in the stratosphere descends to earth annually; the corresponding residence half-time is thus about 7 years. During its long residence in the stratosphere, the bomb residues diffuse slowly but widely, so that they can enter the troposphere above any point of the globe. Once in the troposphere, the fine material probably behaves like that which remained initially in that part of the atmosphere from a low energy explosion, and so is brought to earth fairly rapidly by rain or snow.

10.9 An important feature of this stratospheric world-wide fallout is the fact that the radioactive particles are, in effect, stored in the stratosphere, with a small fraction continuously dribbling down to the earth's surface. While in stratospheric storage, the debris does not represent a direct radioactive hazard. In fact, during this time most of the short-lived activity decays away, and some of the longer-lived activities are appreciably reduced. Thus, stratospheric worldwide fallout is a slow, continuous deposition of radioactive material over the entire surface of the earth, the rate of deposition depending on the total amount of bomb debris still present in the stratosphere.

## LONG-TERM RESIDUAL RADIATION HAZARD

### INTRODUCTION

10.10 Of the fission products which present a potential long-term hazard, from either the testing of nuclear weapons in peacetime or their use in warfare, the most important are probably the radioactive isotopes cesium-137 and strontium-90. Since both of these isotopes are fairly abundant among the fission products and have relatively long half-lives, they will constitute a large percentage of any worldwide fallout. Of course, the activity level due to these isotopes at late times in the local fallout pattern from a surface or subsurface burst will be considerably larger than in the world-wide fallout from a given nuclear burst.

### CESIUM-137

10.11 Cesium has a radioactive half-life of 30 years and is of particular interest in fallout that is more than a year old because it is the principal constituent whose radioactive decay is accompanied by the emission of gamma rays.[1] The chemical properties of cesium resemble those of potassium. The compounds of these elements are generally more soluble than the corresponding compounds of strontium and calcium (see § 10.17); and the details of the transfer of these two pairs of elements from the soil to the human body are quite different.

10.12 Cesium is a relatively rare element in nature and the body normally contains only small traces. Consequently, the biochemistry of cesium has not been studied as extensively as that of some of the more common elements. It has been determined, however, that cesium-137 distributes itself within living cells in the same way as potassium, so that it is found mostly in muscle. Based on one experiment with several human subjects, the current estimate of the time required for normal biological processes to reduce the amount of ce-

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[1] The gamma rays are actually emitted, within a very short time, by a high-energy state of the decay product, barium-137.

sium in the body by one-half, i. e., the biological half-life (see § 11.110), is 140 days. Because of the penetrating properties of the gamma rays from the decay of cesium-137, the radiation is distributed more or less uniformly to all parts of the body. Although the radioactive decay of cesium-137 is accompanied by gamma-ray emission, the relatively short time of stay, together with most of the cesium being in a less sensitive location in the body, indicates that, for the same amount of stratospheric fallout, the residual cesium-137 will be less of a general pathological hazard than the residual strontium-90.

### STRONTIUM-90

10.13 Attention will now be given to what is probably the more serious long-term hazard. Because of its relatively long radioactive half-life of 28 years and its appreciable yield in the fission process, strontium-90 accounts for a considerable fraction of the total activity of fission products which are several years old. Thus, even such material as has been stored in the stratosphere for several years will be found to contain a large percentage of this radioactive species.

10.14 Strontium is chemically similar to calcium, an element essential to both plant and animal life; a grown human being, for example, contains over 2 pounds of calcium, mainly in bone. As a consequence of the chemical similarity, strontium entering the body follows a path similar to calcium and therefore is found almost entirely in the skeleton, from which it is eliminated very slowly. Thus, the half-life of strontium in human bone is estimated to be about 10 years.

10.15 The probability of serious pathological change in the body of a particular individual, due to the effects of internal radioactive material, depends upon the intensity and energy of the radioactivity and upon the length of time the source remains in the body (see § 11.102, *et seq.*). Although strontium-90 emits only beta particles (no gamma rays), a sufficient amount of this isotope can produce damage because once it gets into the skeleton it will stay there for a long time. As a result of animal experimentation, it is believed that the pathological effects which may result from damaging quantities of strontium-90 are anemia, bone necrosis, cancer, and possibly leukemia. It is the combination of physical and chemical properties of strontium-90, namely, its long radioactive half-life and its similarity to calcium, with the nature of the pathological changes which can result from concentrations of radioactive material in the skeleton, that make strontium-90 the most important isotope, so far as is known, as a possible cause of harmful long-term effects of fallout.

10.16 Genetic effects due to strontium-90 are relatively insignificant. In the first place, owing to their very short range in the body, the beta particles from this isotope in the skeleton do not penetrate to the reproductive organs. Further, the intensity of the secondary radiation (bremsstrahlung) produced by the beta particles is low. Finally, the amount of strontium-90 in soft tissue, from which the beta particles might reach the reproductive organs, is small and may be neglected in this regard.

### TRANSFER OF STRONTIUM-90 FROM SOIL TO THE HUMAN BODY

10.17 Since most of the strontium-90 is ultimately brought to earth by rain or snow, it will make its way into the soil and eventually into the human body through plants. At first thought, it might appear that the ratio of strontium to calcium in man would become similar to that in the soil from which he obtains his food. Fortunately, however, several processes in the chain of biological transfer of these elements from soil to the human body operate collectively to decrease the quantity of strontium-90 that is stored in man. These transfer processes include the following stages: (1) soil to plant, (2) plant to animal, and (3) animal to man. A certain proportion of calcium (and strontium) is obtained directly from plants, e. g., fruits and vegetables, but this is not very large, as will be seen shortly. Experiments show that in each of the three stages mentioned there is a natural discrimination in favor of calcium and against strontium, so that the ratio of strontium-90 to calcium in the human body is less than that in the top few inches of the soil.

10.18 Several factors make it difficult to generalize concerning the ratio of strontium-90 to calcium in the plant compared to that in the soil in which it grows. First, plants obtain most of their minerals through their root systems, but such systems vary from plant to plant, some having deep roots and others shallow roots. Most of the strontium-90 in undisturbed soil has been found close to the surface, so that the uptake of this isotope may be expected to vary with the growth habit of the plant. Second, although strontium and calcium, because of their chemical similarity, may be thought of as competing for entry into the root system of plants, not all of the calcium in soil is always available for assimilation. There are natural calcium compounds in soil which are insoluble and are not available as plant food until they have been converted to other compounds by agencies such as humic acid. Most of the strontium-90 in the present world-wide fallout, however, is in a water-soluble form. Third, although plants can substitute strontium for calcium, to some extent, it is apparent that they prefer calcium. Fourth, in addition to the strontium-90 which plants obtain from the soil, growing plants will also gather a certain amount of strontium-90 from fallout deposited directly on the surface of the plant. The experimental data at present available, however, indicate that the strontium-90/calcium ratio in plants is generally somewhat less than in the soil from which they were grown.

10.19 As the next link in the chain, animals consume plants as food, thereby introducing strontium-90 into their bodies. Once again, the evidence indicates that natural discrimination factors result in a strontium-90/calcium ratio in the edible animal products that is less than in the animal's feed. Very little strontium is retained in the soft tissue, so that the amount of strontium-90 in the edible parts of the animal is negligible. It is of particular interest, too, that the strontium-90/calcium ratio in cow's milk is also much lower than that in the cow's feed, since this is an important barrier to the consumption of strontium-90 by man. This barrier does not operate, of course, when plant food is consumed directly by human beings. However, it appears that about three-fourths of the calcium, and hence a large fraction of the strontium-90, in the average diet in the United States is obtained from milk and milk products. The situation may be different in areas where a greater or lesser dependence is placed upon milk and milk products in the diet.

10.20 Not all of the strontium-90 that enters the body in food is deposited in the human skeleton. An appreciable fraction of the strontium-90 is eliminated, just as is most of the daily intake of calcium. However, there is always some fresh deposition of calcium taking place in the skeletal structure of healthy individuals, so that strontium-90 is incorporated at the same time. The rate of deposition of both calcium and strontium-90 is, of course, greater in growing children than in adults.

10.21 In addition to the fact that the human metabolism discriminates against strontium, it will be noted that, in each link in the food chain, the amount of strontium-90 retained is somewhat less than in the previous link. Thus, a series of safeguards reduce deposition of strontium in human bone. A comparison, made in 1955, of the strontium-90/calcium ratio in the bones of children compared with the ratio in the soil gave a discrimination factor of about one-twelfth, that is to say, the strontium-90/calcium ratio in children's bones was found to be one-twelfth of the ratio in soil. Later measurements indicate that the proportion of strontium-90 getting into the bones may be considerably smaller than this.

### STRONTIUM-90 ACTIVITY LEVELS

10.22 As there has been no experience with appreciable quantities of strontium-90 in the human body, the relationship between the probability of serious biological effect and the body burden of this isotope is not known with certainty, since it must be estimated indirectly. Such tentative estimates have been based on a comparison of the effects of strontium-90 with radium on experimental animals, and on the known effects of radium on human beings. From these comparisons it has been estimated that a body content of 10 microcuries (1 microcurie is a one-millionth part of a curie, as defined in § 9.118) of strontium-90 in a large proportion of the population would produce a noticeable increase in the occurrence of bone cancer. On this basis, the National Committee on Radiation Protection and the International Commission on Radiological Protection have suggested that, for individuals exposed to strontium-90 due to their occupation, the maximum permissible (or safe) amount of strontium-90 in the body should be 1 microcurie. Since the average amount of calcium in the skeleton of an adult human is about 1 kilogram, this corresponds to a concentration in the skeleton of 1 microcurie of strontium-90 per kilogram of calcium, i. e., one-tenth of the concentration which might be expected, on the average, to produce an observable effect above normal. For the population as a whole, the limit generally considered to be acceptable is 0.1 microcurie of strontium-90 per kilogram of calcium. This limit is in accord with the recommendations made in 1956 by the U. S. National Academy of Sciences.

10.23 As a result of nuclear test explosions in various countries during the past several years, there has been a small but steady gain in the strontium-90 content of the soil, plants, and the bones of animals. This increase is world-wide and is not restricted to areas in the vicinity of the test sites, although it is naturally somewhat higher in these regions because of the more localized fallout.[2] As the fine particles descend from the stratosphere, over a period of years, the gradual increase in the amount of strontium-90 may be expected to continue for some time, although there will be a certain amount of compensation due to natural decay.

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[2] As stated in § 10.10, in the case of a surface or near-surface burst, an appreciable proportion of the strontium-90 formed will be found in the local fallout. It is then to be expected that areas near the explosion will be more highly contaminated in this isotope than are more distant regions, to an extent dependent upon such factors as the height (or depth) of burst, the total and fission yields of the explosion, and the prevailing atmospheric conditions. There is evidence that in the local fallout the strontium-90 constitutes a smaller percentage of the total fission products than it does farther away. This may be accounted for by the fact that the strontium-90 is not a direct fission product and so it is not formed at the instant of the explosion. It is produced gradually over a period of some minutes, as a result of two stages of radioactive decay starting with the gas krypton-90 which is formed in the fission process (see § 11.121).

10.24 The quantities of strontium-90 that have accumulated so far in human beings are well below limits regarded as acceptable for the general population, and much less than those which might be expected to cause an observable increase in the frequency of bone tumors. Because the skeletons of very young children have developed under current fallout conditions, their content of strontium-90 provides the best indication of the maximum levels which might be expected to exist. As of January 1957, this was somewhat below one-thousandth (0.001) microcurie of strontium-90 per kilogram of calcium. Although there will be some increase toward a higher level, it is fairly certain, that if nuclear tests are carried out in the future at about the same rate as in the past, the long-term biological effects of strontium-90 will not be detectable. In the event that nuclear weapons with high fission yields were used extensively in warfare, calculations, based on somewhat uncertain premises, suggest that bomb debris from many thousands of megatons of fission would have to be added to the stratosphere before the worldwide fallout from these weapons would lead to a concentration of 1 microcurie of strontium-90 per kilogram of calcium in human beings.[8]

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[8] A very thorough and comprehensive investigation of the strontium-90 hazard and of methods for combating it is being sponsored by the U. S. Atomic Energy Commission (Project Sunshine); for summary reports and references, see W. F. Libby, *Science, 123,* 657 (1956); *Proceedings of the National Academy of Sciences, 42,* 365, 945, (1956); J. L. Kulp, W. R. Eckelmann, and A. R. Schulert, *Science, 125,* 219 (1957).

## *CHAPTER XI*

# EFFECTS ON PERSONNEL

## INTRODUCTION

### Casualties in Nuclear Explosions

11.1 A nuclear explosion is accompanied by damage and destruction of buildings, by blast and fire, over a considerable area. Consequently, a correspondingly large number of casualties among personnel is to be expected. The data in Table 11.1 are the best available estimates for the civilian casualties resulting from all effects of the air bursts, over Hiroshima and Nagasaki in Japan, of nuclear bombs having approximately 20 kilotons energy yield. The standardized casualty rates are values calculated on the basis of a population density of 1 per 1,000 square feet. For comparative purposes, the standardized casualty rate in a city for a 1-ton high-explosive (TNT) bomb is about 40.

Table 11.1

ESTIMATED CASUALTIES AT HIROSHIMA AND NAGASAKI FROM 20-KILOTON NUCLEAR EXPLOSIONS

| | *Hiroshima* | *Nagasaki* |
|---|---|---|
| Total population | 255,000 | 195,000 |
| Square miles destroyed | 4.7 | 1.8 |
| Killed and missing | 70,000 | 36,000 |
| Injured | 70,000 | 40,000 |
| Standardized casualty rate | 260,000 | 130,000 |

11.2 The injuries to personnel associated with a nuclear explosion fall into three main categories: blast injuries, burns, and nuclear radiation injuries. The effects of blast from a nuclear bomb are, on the whole, similar to those due to conventional bombs. However, an important difference is the much greater number and variety of injuries suffered in a short interval of time in the case of a nuclear explosion. Most of the burns following an air burst are flash burns, although individuals trapped by spreading fires may be subjected to flame burns. The latter circumstances are not unlike those experienced as the result of an extensive attack with incendiary bombs. Nuclear radiation injuries, of course, represent an entirely new source of casualties in warfare.

11.3 The only information concerning casualties to be expected from the use of nuclear weapons is that obtained in connection with the air bursts over Japan, and so these will be used largely as the basis for the subsequent discussion. However, it is probable that both the total number of casualties and the distribution of the various types of injuries will be greatly affected by circumstances, even for an explosion of the same energy yield. Some of the factors, apart from yield, which may be mentioned are the height and type of burst, the nature of the terrain, the structural characteristics of the buildings in a city, the disposition of the populace (use of shelters, evacuation, etc.), and the state of the weather.

11.4 As pointed out in § 7.69, the high incidence of flash burns in Japan was undoubtedly connected with the warm and clear summer weather prevailing at the time of the attacks. Had there been a low cloud cover or appreciable haze and had the weather been cold, so that fewer people were outdoors and more layers of clothing worn, the number of flash burns would have been much less. Further, the fairly high air burst meant that there were no casualties due to the residual nuclear radiation, although many resulted from the initial radiation. The data given below thus refer to the particular circumstances existing in Japan and would not necessarily be typical. In Japan, too, lack of facilities for dealing with a disaster of such magnitude as that following the nuclear attacks contributed to the number of fatal cases.

### CAUSES OF FATALITIES

11.5 There is no exact information available concerning the relative significance of blast, burn, and nuclear radiation injuries as a source of fatalities in the nuclear bombings of Japan. It has been stated that some 50 percent of the deaths were caused by burns of one kind or another, although this figure is only a rough estimate. It has also been reported that close to two-thirds of those who died at Hiroshima during the first day after the explosion were badly burned. In addition, there were more deaths from flash burns during the first week than from other injuries.

11.6 One of the difficulties in assessing the importance of injuries of various types lies in the fact that many people who were injured by blast were also burned, and this was undoubtedly also the fate of others who would have ultimately succumbed to the effects of nuclear radiation. Within about half a mile of ground zero in the Japanese explosions, it is probable that blast, burns, and radiation could separately have been lethal in numerous instances.

11.7 It should be pointed out, however, that, owing to various circumstances, not everyone within a radius of half a mile was killed. Among those who survived the immediate consequences of the explosions at Hiroshima and Nagasaki, a number died two or more weeks later with symptoms that were ascribed to nuclear radiation injuries (see § 11.43, *et seq.*). These were believed to represent from 5 to 15 percent of the total fatal casualties. A rough estimate indicates that about 30 percent of those who died at Hiroshima had received lethal doses of nuclear radiation, although this was not always the immediate cause of death.

### CAUSES OF INJURIES

11.8 From surveys made among a large number of Japanese, a fairly good idea has been obtained of the distribution of the three types of injuries among those who became casualties but nevertheless survived the nuclear attacks. The results are quoted in Table 11.8. It will be observed that the totals add up to more than 100 percent, so that many individuals suffered multiple injuries.

TABLE 11.8

DISTRIBUTION OF TYPES OF INJURY AMONG SURVIVORS

| *Injury* | *Percent of Survivors* |
|---|---|
| Mechanical | 70 |
| Burns | 65–85 |
| Nuclear Radiation | 30 |

11.9 The over-all mortality rate in Japan was greatest among those who were in the open at the time of the explosions. It was less for persons in residential (adobe and wood frame) structures and least for those who were in concrete buildings. However, among the survivors the proportion of mechanical injuries, e. g., due to flying missiles, was smallest in the open and largest in concrete structures.

As may be expected, the situation was reversed with regard to thermal and nuclear radiation effects, since buildings, especially those of heavy construction, provided some shielding.

### TYPE OF BURST

11.10 Although an air burst is the only type of nuclear explosion for which there is any information available concerning casualties, it is possible to make certain inferences with regard to other kinds of bursts. In a subsurface explosion the number of casualties caused by thermal radiation (flash burns) and by the initial nuclear radiation will be much less because only a small proportion of these radiations escape into the air. Injuries due to blast will probably be less than for an air burst of the same energy yield, because of the lower air pressures. However, in the region of the crater formed in a shallow underground burst, there will probably be few survivors, as a consequence of mechanical injuries. Surface and subsurface explosions will be accompanied by casualties of another kind, namely, those resulting from exposure to the residual nuclear radiation from the fallout. Deaths from this cause, however, may not occur for some days or even weeks after the explosion.

11.11 The casualties following the surface burst of a nuclear bomb will be due to mechanical injuries resulting from air blast and cratering of the ground, to flash burns, to the initial nuclear radiation, and also to the residual nuclear radiation. The flash burns and initial nuclear radiation injuries may be somewhat less than for an air burst of the same energy yield, but the residual nuclear radiation effects may be serious, due to the extensive fallout.

## TYPES OF INJURIES

### BLAST INJURIES: DIRECT

11.12 Two types of blast injuries, namely, direct and indirect, may be considered. Direct blast injuries result from the positive phase of the air shock wave (see § 3.5) acting on the body so as to cause damage to the lungs, stomach, intestines, and eardrums, and also internal hemorrhage. Such injuries have been reported after large-scale air attacks with conventional high-explosive bombs. In Japan, however, the direct blast effect was not a significant primary cause of fatalities, since those near enough to suffer serious injury due to this cause were burned or crushed to death. There were no cases of direct damage to internal organs by the blast among the survivors although there were some ruptured eardrums. The number was not large and was restricted almost entirely to persons who were within about 3,000 feet (0.6 mile) of ground zero.[1]

11.13 Many persons, who suffered no serious injury, reported temporary loss of consciousness. It was thought that this might be due to the direct action of blast, but it is possible that the effect resulted from violent displacement of the individuals by the air pressure wave.

11.14 From observations made with conventional high-explosive bombs, it appeared that peak overpressures of about 200 to 300 pounds per square inch would be necessary to cause death in human beings due to the direct effect of the blast and that perhaps 80 pounds per square inch would produce injury. However, these conclusions do not necessarily apply to the situation accompanying a nuclear explosion. In addition to the peak blast overpressure, the rate of rise of the pressure and the duration of the positive phase have an important influence.

11.15 When the pressure at the shock front increases rapidly or the positive phase lasts for an appreciable time (or both), serious blast injury (or death) can result at much lower peak pressures than would be the case for a slow rise or short duration of the overpressure. For example, tests indicate that a seven-fold increase in the duration of the blast wave results in a three-fold decrease in the overpressure associated with fatality in dogs. Since the duration of the positive phase of a nuclear blast wave is considerably longer than that for a conventional bomb explosion, it is to be expected that peak overpressures much less than 200 or 80 pounds per square inch will cause death or injury, respectively.

11.16 The general interaction of a human body with a blast wave is somewhat similar to that of a structure, as described in Chapter III. Because of the small size of the body, the diffraction process is quickly over and the body is rapidly engulfed and subjected to severe compression by the blast wave. This continues, with decreasing intensity, for the duration of the positive phase. At the same time the blast wind exerts a drag force of considerable magnitude.

11.17 Due to the compression and subsequent decompression, damage to the body occurs mainly at junctions between tissue and air-

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[1] The air blast overpressure required to cause rupture of eardrums appears to be highly dependent upon circumstances. Several observations indicate that the minimum overpressure is in the range from 10 to 15 pounds per square inch, but both lower and higher values have been reported.

containing organs, and at areas of union where bone and cartilaginous tissue join soft tissue. The chief consequences are as follows: damage to the central nervous system; heart failure due to direct disturbance of the heart; and suffocation caused by lung hemorrhage or liquid extrusion into the lung tissue. There may also be internal hemorrhage of the gastro-intestinal tract.

11.18 The drag (or wind) pressure can cause translational displacement of the body as a whole. The resulting injury (if any) will depend upon many circumstances; the most obvious of these are the speed at which the body moves, its acceleration and deceleration, the object it strikes, and the part of the body receiving the impact. The translational force, which determines the rate of movement, will be greatly influenced by the frontal surface of the body exposed to the blast wind. A person lying in a prone position, will, for example, be much less affected than one standing up.

## BLAST INJURIES: INDIRECT

11.19 More important than the primary blast injuries in the nuclear attacks on Japan were the indirect or secondary effects due to collapsing buildings and to the great quantity and variety of the debris flung about by the air blast. Although a few persons were hurt by being hurled forcibly against solid objects, very many more were injured by flying objects and crushed or buried under buildings. Glass fragments in particular and, to a lesser extent, wood splinters and pieces of metal, penetrated up to an inch beneath the skin, occasionally through several layers of clothing. When the fragments were small, clothing provided some protection.

11.20 During the course of the Nevada tests in 1955, studies were made of the missiles produced inside houses and in the open behind the houses described in Chapter IV. Some of the results obtained, with special reference to the maximum density and velocity of the missiles, are given in Table 11.20. A fairly sharp missile, e. g., glass, with a velocity in the ranges quoted, can penetrate the abdominal wall of experimental animals. Most of the missiles collected inside the houses consisted of pieces of glass, while those outside were glass, pieces of masonry, rocks and sticks of wood. In locations shielded by houses or large pieces of machinery, the number of missiles was greatly reduced.

TABLE 11.20

DENSITY AND VELOCITY OF MISSILES

| *Peak overpressure (pounds per square inch)* | *Maximum missile density (number per square foot)* | *Missile velocity (feet per second)* |
|---|---|---|
| 5 | 66–207 | 60–340 |
| 3.8 | 17–66 | 60–280 |
| 1.9 | 0. 1–4 | 50–160 |

11.21 The nature of the indirect blast (or mechanical) injuries among the Japanese ranged from complete crushing, severe fractures, and serious lacerations with hemorrhage, to minor scratches, bruises, and contusions. Patients were treated for lacerations received out to 10,500 feet (2 miles) from ground zero in Hiroshima, and out to 12,000 feet (2.2 miles) in Nagasaki. These distances correspond roughly to those for significant damage to windows.

11.22 An interesting observation made among the Japanese survivors was the relatively low incidence of serious mechanical injuries. For example, among 675 patients there were no cases of fractures of the skull or back and only one fractured femur, although many such injuries must have undoubtedly occured. This was attributed to the fact that persons who suffered severe concussion or fracture or were rendered helpless by leg injuries, as well as those who were pinned beneath the wreckage, were trapped by the flames. Such individuals, of course, did not survive.

11.23 The type and degree of mechanical injuries, as well as their distribution among the types mentioned earlier, was found to depend very much on whether the persons were in the open or in a building at the time of the explosion. In general, mechanical injuries were less severe and less frequent among survivors in the open, where many died from other causes, as seen above. In buildings, the mechanical injuries were more serious, the extent of the injuries being dependent on the construction of the building, and, in particular, on the amount of glass.

11.24 Some reliable information concerning different types of mechanical injuries has been obtained from the study of a group of survivors at a military hospital in Hiroshima; the results are summarized in Table 11.24. In these cases, as in others, the incidence of fractures is low. In general, they may have represented only about 5 percent of the indirect blast injuries among survivors.

TABLE 11.24

TYPES OF MECHANICAL INJURIES AT HIROSHIMA

| *Injury* | *Percentage* |
|---|---|
| Fracture | 11 |
| Laceration | 35 |
| Contusion | 54 |

11.25 The healing of wounds was often slow, and accompanied by infection. There were several reasons for this situation. One was that mechanical injury was frequently accompanied by radiation injury which increased the susceptibility of the body to infection (see § 11.67). Another reason was the lack of proper treatment facilities, due to the large number of casualties and general disorganization following the nuclear explosions.

## FLAME AND FLASH BURNS

11.26 As stated in Chapter VII, two general types of burns were experienced at Hiroshima and Nagasaki; these were (1) fire or flame burns, and (2) flash burns due to thermal radiation. The two types could usually be distinguished by the characteristic "profile" nature of flash burns, due to partial shielding, e. g., by clothing (§ 7.71). Flame burns, on the other hand, covered large parts of the body since the clothing usually caught fire. Where large parts of the body were exposed to thermal radiation, the flash burns were also of considerable area.

11.27 Among the survivors, the incidence of flame burns appeared to be very small. They constituted probably not more than 5 percent of the total burn injuries. This was the case because most of those who suffered flame burns did not survive, since they were caught in burning buildings and could not escape. The character of the flame burns after the nuclear bombings of Japan was similar to that of burns caused by other conflagrations, and so the subject need not be considered further here.

11.28 Flash burns, as indicated earlier, were very common at both Hiroshima and Nagasaki. In the former city, for example, some 40,000 fairly serious burn cases were reported. Apart from other injuries, the flash burns would have been fatal to nearly all persons in the open, without appreciable protection, at distances up to 6,000 feet (1.1 miles) or more from ground zero. Even as far out as 12,000 to 14,000 feet (2.2 to 2.6 miles), there were instances of thermal radiation burns which were bad enough to require treatment.

11.29 The frequency of flash burns was, of course, greatest among persons who were in the open. Nevertheless, there was a surprising number of such burns among individuals who were indoors. This was largely due to the fact that many windows, especially in commercial structures, were uncurtained or were wide open because of the summer weather. Hence, many persons inside buildings were directly exposed to thermal radiation. In addition to the protection afforded by clothing, particularly if light in color, as mentioned in Chapter VII (see Figs. 7.72 and 7.78), some shielding was provided by the natural promontories of the body, e. g., the nose, supraorbital (eye socket) ridges, and the chin.

11.30 In spite of the thousands of flash burns experienced after the nuclear attacks on Japan, only their general features were reported. However, this information has now been supplemented by observations made, especially on anesthetized pigs, both in the laboratory and at nuclear test explosions. The skin of white pigs has been found to respond to thermal radiation in a manner which is in many respects similar to, and can be correlated with, the response of human skin.

11.31 In addition to being chiefly restricted in area to exposed parts of the body, the majority of flash burns show a much smaller depth of penetration of the skin than do flame burns. This is to be expected if the thermal radiation effective in causing burns is emitted during a very short time. In the 20-kiloton explosions over Japan, for example, this was about 1 second. A very high temperature is thus produced near the surface of the skin in a small interval of time. As a result, some of the characteristics of flash burns, in addition to depth, differ from those of other, more familiar, burns. These differences may be less apparent if the thermal radiation is effective over a longer period of time, e. g., from an explosion of high energy yield.

11.32 The severity of the flash burns in Japan ranged from mild erythema (reddening) to charring of the outermost layers of the skin. Unlike low-temperature contact burns, there was no accompanying edema (accumulation of fluid) of the underlying tissue. Among those who were within about 6,000 feet (1.1 miles) from ground zero, the burn injuries were depigmented lesions (light in color), but at greater distances, from 6,000 to 12,000 feet (1.1 to 2.2 miles), the initial erythema was followed by the development of a walnut coloration of the skin, sometimes called the "mask of Hiroshima."

11.33 Burns of moderate second degree (and milder) usually healed within four weeks, but more severe burns frequently became infected so that the healing process was much more prolonged. Even under the best conditions, it is difficult to prevent burns from becoming infected, and after the nuclear bombings of Japan the situation was aggravated by inadequate care, poor sanitation, and general lack of proper facilities. Nuclear radiation injury may have been a contributory factor in some cases due to the decrease in resistance of the body to infection.

11.34 Experimental flash burns have been obtained both in the laboratory and in nuclear tests which were apparently quite similar to those reported from Hiroshima and Nagasaki. In the more severe cases there was a central charred region with a white outer ring surrounded by an area of erythema. A definite demarcation both in extent and depth of the burns was noted, so that they were unlike contact burns which are generally variable in depth. The surface of the flash burns became dry without much edema or weeping of serum.

11.35 Another phenomenon which appeared in Japan after the healing of some of the more severe burns, was the formation of keloids, that is, thick overgrowths of scar tissue. It was suggested, at one time, that this might have been due to nuclear radiation, but such a view is no longer accepted. The degree of keloid formation was undoubtedly influenced by infections, that complicated healing of the burns, and by malnutrition. A secondary factor is the known disposition for keloid formation to occur among the Japanese, as a racial characteristic. Many spectacular keloids, for example, were formed after the healing of burns produced in the incendiary bomb attacks on Tokyo. It is of interest to note that a tendency has been observed for the keloids to disappear gradually in the course of time.

### Effects of Thermal Radiation on the Eyes

11.36 The effects of thermal radiation on the eyes fall into two categories: these are (1) retinal burns, and (2) flash blindness. Retinal burns can result from the concentration of sufficient direct thermal energy on the retina of the eye. Because of the focusing action of the lens, enough energy can be collected to produce a burn on the retina at such a distance from the explosion that the thermal radiation intensity is too small to produce a skin burn. As a result of accidental exposures at nuclear tests, a few retinal burns have been experienced at a distance of 10 miles from an explosion of approximately 20 kilotons energy yield. It is believed that under suitable conditions, such burns might result even farther away.

11.37 Much of the thermal radiation responsible for flash burns arrives so soon after the explosion that reflex actions, such as blinking and contraction of the eye pupil, give only limited protection. At night, when the eye is dark-adapted and the pupil is large, retinal burns could occur at greater distances from the nuclear explosion than in daylight. In all instances, there will be temporary loss of visual acuity, at least, but the ultimate effect will depend upon the severity of the burn and, to a greater extent, upon its location. If the burn is mild, or on the periphery of the visual field, the acuity may hardly be effected, but in more serious cases there may be considerable loss of vision.

11.38 There is a possibility that small permanent blind spots may be produced on the retinas of persons who focus their eyes directly on the fireball, so that the image of the fireball is formed in the region of central vision. The chance that an individual will be looking directly at the ball of fire is small, particularly for low-yield nuclear weapons which have a short period in which the rate of thermal radiation emission is high. Temporary "flash blindness" or "dazzle," due to the flooding of the eye with the brilliant light scattered from the sky, ground, and other surroundings, is much more probable. This is a temporary embarrassment, however, and vision is usually regained within a short time.

11.39 It is an interesting fact that among the survivors in Hiroshima and Nagasaki, eye injuries directly attributable to thermal radiation appeared to be relatively unimportant. There were many cases of temporary blindness, occasionally lasting up to 2 or 3 hours, but more severe eye injuries were not common.

11.40 The eye injury known as keratitis (an inflammation of the cornea) occurred in some instances. The symptoms, including pain caused by light, foreign-body sensation, lachrymation, and redness, lasted for periods ranging from a few hours to several days. Among 1,000 cases, chosen at random, of individuals who were in the open, within some 6,600 feet (1.25 miles) of ground zero at the time of the explosions, only 42 gave a history of keratitis coming on within the first day. Delayed keratitis was reported in 14 additional cases, with symptoms appearing at various times up to a month or more after the explosion. It is possible that nuclear radiation injury, which is associated with delayed symptoms, as will be seen below, may have been a factor in these patients.

11.41 Investigators have reported that in no case, among the 1,000 examined, was the thermal radiation exposure of the eyes apparently sufficient to produce permanent opacity of the cornea. This observation is surprising in view of the severe burns of the face suffered by many of the patients. Thus, in approximately one-quarter of the cases studied there had been facial skin burns and often burning of the eyebrows and eyelashes. Nevertheless, some three years later the corneas were normal. No persons in the survey group developed permanent central scotomata (blind spots), although several stated that they were looking in the direction of the bomb at the time of the explosion.

11.42 Several reasons have been suggested for the scarcity of severe eye injuries in Japan. For example, it seems probable that the blink reflex was rapid enough to provide significant protection. Another possible explanation is that the recessed position of the eyes and, in particular, the overhanging upper lids served to decrease the direct exposure to thermal radiation. On the basis of probability, only a small proportion of individuals would actually be facing the explosion and owing to the bright sunlight the pupils of the eyes would be small, thus decreasing the exposed area.

### NUCLEAR RADIATION INJURY

11.43 The injurious effects of nuclear radiation from a nuclear bomb represent a phenomenon which is completely absent from conventional explosions. For this reason the subject of radiation injury (or sickness) will be described at some length here. It should be understood, however, that the extended discussion is not necessarily meant to imply that nuclear radiation would be the most important source of casualties in a nuclear explosion. This was certainly not the case in Japan, as indicated earlier, where the bombs were detonated at a height of approximately 1,850 feet above the ground. Such injuries as were caused by nuclear radiation were due to the initial radiation. The effect of the residual nuclear radiation, in the form of fallout, was negligible. However, as was seen in Chapter IX, the situation could be very different in the event of a surface burst of a fission weapon.

11.44 It has long been known that excessive exposure to nuclear (or similar) radiations, such as X-rays, alpha and beta particles, gamma rays, and neutrons, which are capable of producing ionization, either directly or indirectly (§ 8.22), can cause injury to living organisms. After the discovery of X-rays and radioactivity, toward the end of the nineteenth century, serious and sometimes fatal exposure to radiation was sustained by radiologists before the dangers were realized. In the course of time, however, recommendations for preventing overexposures were adopted and radiation injuries became less frequent. Nevertheless, occasional overexposures have occurred among personnel operating radiographic equipment, powerful X-ray machines in industrial laboratories, cyclotrons, and nuclear reactors, or working with radioactive or fissionable materials.

11.45 The harmful effects of radiation appear to be due to the ionization (and excitation) produced in the cells composing living tissue. As a result of ionization, some of the constituents, which are essential to their normal functioning, are damaged or destroyed. In addition, the products formed may act as cell poisons. Among the observed consequences of the action of nuclear (or ionizing) radiations on cells is breaking of the chromosomes, swelling of the nucleus and of the entire cell, destruction of cells, increase in viscosity of the cell fluid, and increased permeability of the cell membrane. In addition, the process of cell division (or "mitosis") is delayed by exposure to radiation. Frequently, the cells are unable to undergo mitosis, so that the normal cell replacement occurring in the living organism is inhibited.

11.46 Before the bombings of Hiroshima and Nagasaki, radiation injury was a rare occurrence and relatively little was known of the phenomena associated with radiation sickness. In Japan, however, a large number of individuals were exposed to doses of radiation ranging from insignificant quantities to amounts which proved fatal. The effects were often complicated by other injuries and shock, so that the symptoms of radiation sickness could not always be isolated. Further, the great number of patients and the lack of facilities after the explosions made it impossible to make detailed observations and keep accurate records. Nevertheless, certain important conclusions have been drawn from Japanese experience with regard to the effects of nuclear radiation on the human organism.

11.47 Since 1945, further information on this subject has been gathered from other sources. These include animal experiments and a few laboratory accidents, involving about a dozen or so human beings. The most detailed knowledge, however, was obtained from a careful study of over 250 persons in the Marshall Islands, who were accidentally exposed to nuclear radiation from fallout following the test explosion on March 1, 1954 (§ 9.86). The exposed individuals included both Marshallese and a small group of American servicemen. The whole-body radiation doses ranged from relatively small values (14 roentgens), which produced no symptoms, to amounts (175 roentgens) somewhat less than would be expected to result in fatality to a few percent of those exposed.

11.48 It has been established that all radiations capable of producing ionization (or excitation) directly, e. g., alpha and beta particles, or indirectly, e.g., X-rays, gamma rays, and neutrons, can cause radiation injury of the same general type. However, although the effects are qualitatively similar, the various radiations differ in the depth to which they penetrate the body and in the degree of injury corresponding to a specified amount of energy absorption. As stated in § 8.31, this difference is (partly) expressed by means of the relative biological effectiveness (or RBE).

11.49 For beta particles, the RBE is close to unity; this means that for the same amount of energy absorbed in living tissue, beta particles produce about the same extent of injury within the body as do X-rays or gamma rays.[2] The RBE for alpha particles from radioactive sources has been variously reported to be from 10 to 20, but this is believed to be too large in most cases of interest. For nuclear bomb neutrons, the RBE for acute radiation injury has been taken as 1.7 (§ 8.69), but it is appreciably larger where the formation of opacities of the lens of the eye (cataracts) are concerned. In other words, neutrons are much more effective than other nuclear radiations in causing cataracts.

## GENERAL RADIATION EFFECTS

11.50 The effects of nuclear radiations on living organisms depend not only on the total dose, that is, on the amount absorbed, but also on the rate of absorption, i. e., on whether it is acute or chronic, and on the region and extent of the body exposed (§ 9.38). A few radiation phenomena, such as genetic effects (see § 11.124, *et seq.*), apparently depend only upon the total dose received and are independent of the rate of delivery. In other words, the injury caused by radiation to the germ cells is cumulative. In the majority of instances, however, the biological effect of a given total dose of radiation decreases as the rate of exposure decreases. Thus, to cite an extreme case, 700 roentgens in a single dose would be fatal, if the whole body were exposed, but it would not cause death or have any noticeable external effects if supplied more or less evenly over a period of 30 years.

11.51 A skin exposure dose of 700 roentgens of X-rays will cause a certain degree of erythema (reddening) if administered locally to a small area over a period of 1 hour. However, to produce the same apparent effect with two shorter treatments separated by an interval of 24 hours, each dose must be about 535 roentgens, so that a total of 1,070 roentgens is required. If the exposure is spread over a period of 1 month, the total dose may approach 2,000 roentgens in order to cause the same degree of erythema. The explanation of these results is that in the skin new cells are continually being produced at a rapid rate in order to take care of normal wear and tear. Hence, the majority of cells damaged (or killed) by radiation are replaced by new cells and there is a certain amount of natural recovery between successive doses.

11.52 Although in most cases the rate of formation of new cells is not as great as it is in the skin, the ability to recover, to some extent, from the effects of radiation appears to be possessed by many body tissues. The rate of replacement of mature cells of blood-forming tissues and of the lining of the gastro-intestinal tract, as well as of sperm cells, is also very great.

11.53 It was seen in Chapter IX that the human body is able to withstand continual exposure to small doses of radiation from natural sources without any obviously harmful consequences. The probable reason, as implied above, is that most of the cells damaged by the radiation are replaced by new ones. But if the rate of delivery of the radiation is high or the total dose received in a relatively short time is large, recovery cannot keep pace with the damage, and injury results.

11.54 Whether the injury due to nuclear radiation is reparable or not, appears to depend to a large extent on the natural capability of the affected organ (or organ system) to repair itself as a result of damage of any kind. Thus, radiation injury to brain and kidney is largely irreparable, but damage to bone marrow, the gastro-intestinal tract, and skin, on the other hand, is to a great extent reparable.

11.55 It has already been indicated that the injury caused by a certain dose of radiation will depend upon the extent and part of the body that is exposed. For example, an acute exposure dose of 700 roentgens applied to a small region may result in considerable biological damage to the irradiated area, but the over-all health of the individual may be apparently unaffected. If the whole body receives the dose of 700 roentgens, however, death will probably result. One reason for this difference is that when the exposure is restricted, the unexposed regions can contribute to the recovery of the injured area. But if the whole body is exposed, many organs are affected and recovery is much more difficult.

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[2] Beta particles from sources on or near the body can also cause skin burns (see § 11.94).

11.56 Different portions of the body show different sensitivities to radiation, although there are undoubtedly variations of degree among individuals, as will be seen below. In general, the most radiosensitive parts include the lymphoid tissue, bone marrow, spleen, organs of reproduction, and gastro-intestinal tract. Of intermediate sensitivity are the skin, lungs, kidney, and liver, whereas muscle and full-grown bones are the least sensitive.

## EFFECTS OF ACUTE RADIATION DOSES

11.57 In the present section there will be described some of the more obvious effects of an acute dose of radiation received over the whole body. Such a situation could result from exposure of persons to the initial nuclear radiation from a nuclear explosion. The results given in Table 11.57, which apply to man, are based upon experiments with animals, as well as upon the conclusions drawn from observations made in Japan and of the individuals exposed on the Marshall Islands. The percentage of fatalities corresponding to any particular dose may be decreased to some extent by treatment without delay. The data in Table 11.57 are also plotted in Fig. 11.57; the two curves show the expected percentage incidence of radiation sickness and of subsequent deaths within 30 days (or so), respectively, for various acute radiation doses over the whole body.

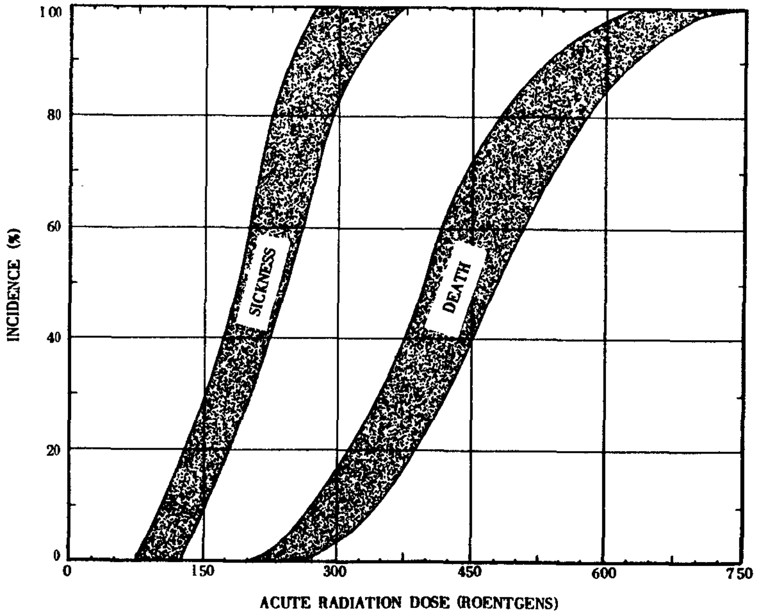

**Figure 11.57.** Incidence of sickness and death due to acute exposure to various doses of nuclear radiation.

TABLE 11.57

EXPECTED EFFECTS OF ACUTE WHOLE-BODY RADIATION DOSES

| *Acute dose (roentgens)* | *Probable effect* |
|---|---|
| 0 to 50 | No obvious effect, except possibly minor blood changes. |
| 80 to 120 | Vomiting and nausea for about 1 day in 5 to 10 percent of exposed personnel. Fatigue but no serious disability. |
| 130 to 170 | Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 25 percent of personnel. No deaths anticipated. |
| 180 to 220 | Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 50 percent of personnel. No deaths anticipated. |
| 270 to 330 | Vomiting and nausea in nearly all personnel on first day, followed by other symptoms of radiation sickness. About 20 percent deaths within 2 to 6 weeks after exposure; survivors convalescent for about 3 months. |
| 400 to 500 | Vomiting and nausea in all personnel on first day, followed by other symptoms of radiation sickness. About 50 percent deaths within 1 month; survivors convalescent for about 6 months. |
| 550 to 750 | Vomiting and nausea in all personnel within 4 hours from exposure, followed by other symptoms of radiation sickness. Up to 100 percent deaths; few survivors convalescent for about 6 months. |
| 1000 | Vomiting and nausea in all personnel within 1 to 2 hours. Probably no survivors from radiation sickness. |
| 5000 | Incapacitation almost immediately. All personnel will be fatalities within 1 week. |

11.58 It will be noted that, both in Table 11.57 and in Fig. 11.57, a particular effect (or incidence) is associated with a range of exposure doses in roentgens. The reason for this uncertainty is that there are many factors, some known and some unknown, which determine the effect on the body of a specified radiation exposure dose. In addition to biological variations among individuals, which will be referred to shortly, there are such considerations as the ages of the exposed persons and their state of health, depth of penetration into the body and the organs absorbing the radiation, and the orientation of the body with reference to the source of the radiation, leading to possible shielding of one part of the body by another. These and other factors will influence the consequence of exposure to a specified dose in roentgens.

11.59 The differences in response to radiation by individuals is brought out by the fact that not all members of a group of human beings, assumed to be irradiated with the same dose under the same conditions, react in the same manner. For example, only 20 percent of those exposed would be expected to succumb to an acute dose in the vicinity of 300 roentgens. The other 80 percent will suffer from radiation sickness but will probably recover. The difference in the effect of the radiation on different individuals is attributed to what is called "biological variability." It is not a unique characteristic of nuclear radiation effects, since it occurs when other physiological stimuli are involved. The existence of this natural variability factor thus makes it necessary to deal with the average behavior of a large number of persons. It is impossible to predict how a given individual will respond to a specified dose of radiation, although the expected average effect on a large group may be known, provided the conditions are precisely defined.

11.60 As a point of reference, in considering the biological effects of acute radiation doses over the whole body, a quantity called the "median lethal dose" is commonly used.[3] It is the whole-body dose which is expected to result in the death within about a month (or so) of 50 percent of exposed individuals among a large group. The other 50 percent will be sick but will probably recover within 6 months. Bearing in mind the uncertainties, referred to above, in stating a precise value, it is generally accepted at the present time that the median lethal dose is an exposure of 450 roentgens. This may, however, be subject to change as more information on the effects of acute radiation on man becomes available.

11.61 It appears from recent studies, both in the laboratory and in the field, that there is probably no single value for the median lethal dose that applies under all conditions. For example, it was concluded, from observations on the blood changes among the individuals accidentally exposed to fallout radiation on the Marshall Islands (see § 11.73), that the median lethal dose would have been somewhat less than 450 roentgens. On the other hand, an examination of the data obtained from Japan indicates a higher value for the median lethal dose for exposure to the initial nuclear radiation. Although both values are subject to considerable errors, it is possible that the difference arises from the fact that the fallout material was spread over a large area, so that the radiation reached the exposed individuals from many directions. With the initial radiation, however, the exposure was essentially from one direction only, so that some parts of the body were shielded by others. A given radiation exposure in roentgens would then cause more damage in the former case, leading to a lower value for the median lethal dose. For the present purpose, the value of 450 roentgens will be adopted as a reasonable average.

## CHARACTERISTICS OF ACUTE RADIATION INJURY

### Large Dose (Over 700 Roentgens): Survival Improbable

11.62 Very large doses of whole-body radiation, e. g., 5,000 roentgens or more, result in very rapid injury to the central nervous system. The symptoms are hyperexcitability, ataxia (lack of muscular coordination), respiratory distress, and intermittent stupor. There is almost immediate incapacitation, and death is certain in a few hours to a week or so after the acute exposure. If the dose is in the range of about 700 to 1,000 roentgens, roughly, it is the gastro-intestinal system which exhibits the earliest severe clinical effects in the form of nausea and vomiting within the first 3 or 4 hours. The larger the dose the sooner are these symptoms experienced. They are then followed, in more or less rapid succession, by prostration, diarrhea, anorexia (lack of appetite and dislike for food), and fever. As observed after the nuclear attacks on Japan, the diarrhea was frequent and severe in character, being watery at first and tending to become bloody later.

11.63 The sooner the foregoing symptoms of radiation injury develop, the sooner is death likely to result. Although there is no pain during the first few days, patients experience feelings of discomfort or uneasiness (malaise), accompanied by marked depression and bodily fatigue. In some of the cases receiving a lower dose, the early stages of the severe radiation sickness are followed by a so-called "latent" period of 2 or 3 days (or more), during which the patient appears to be free from symptoms, although profound changes are taking place in the body, especially in the blood-forming tissues. This period, when it occurs, is followed by a recurrence of the early symptoms, often accompanied by delirium or coma, terminating in death usually within 2 weeks.

11.64 Other symptoms which have been observed are secondary infection and a tendency to spontaneous internal bleeding toward the end of the first week. At the same time, swelling and inflammation of the throat is not uncommon. Loss of hair (epilation), mainly from the head, will usually occur by the end of the second week. The de-

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[3] The median lethal dose is frequently abbreviated as MLD, LD/50, or $LD_{50}$.

velopment of severe radiation sickness among the Japanese was accompanied by an increase in the body temperature. Generally there was a step-like rise between the fifth and seventh days, sometimes as early as the third day, after exposure, usually continuing until the day of death. There were also striking changes in the blood of the patient, to which reference will be made shortly (§ 11.73). Examination after death revealed a decrease in size and degenerative changes in testes and ovaries. Ulceration of the tonsils and of the mucous membrane of the large intestine was also noted in some cases.

### DOSE OF 300 TO 500 ROENTGENS: SURVIVAL POSSIBLE

11.65 In the dose range from about 300 to 500 roentgens, from which survival is possible but by no means certain, the initial symptoms are similar to those following a somewhat larger dose, namely, nausea, vomiting, diarrhea, loss of appetite, and malaise. However, these symptoms will develop later, although generally during the day of the exposure, and be less severe. After the first day or two the symptoms disappear and there may be a latent period of several days up to two weeks during which the patient feels relatively well, although important changes are occurring in the blood. Subsequently, there is a return of the symptoms, including fever, diarrhea, and the step-like rise in temperature referred to above.

11.66 Commencing about 2 or 3 weeks after exposure, there is a marked tendency to bleed (hemorrhage) into various organs, and hemorrhages under the skin (petechiae) are observed. Particularly common are spontaneous bleeding in the mouth and from the lining of the intestinal tract. There may be blood in the urine from bleeding into the kidney or into the urinary tract leading from the kidney. The hemorrhagic tendency depends mainly upon depletion of certain components of the blood, resulting in defects in the complex blood-clotting mechanism (see § 11.79). Loss of hair, which is very characteristic of radiation exposure, also starts after about 2 weeks, that is, immediately following the latent period.

11.67 Susceptibility to infection of wounds, burns, and other lesions, is a serious complicating factor. This results to a large degree from the loss of white blood cells, and a marked depression in the body's normal immunological mechanism. For example, ulceration about the lips commences after the latent period and spreads from the mouth through the entire gastro-intestinal tract in the terminal stage of the sickness. The multiplication of bacteria, made possible by the decrease of the white cells of the blood, thus allows an overwhelming infection to develop.

11.68 In the more serious cases in Japan, who had received a fairly large dose of radiation, there was severe emaciation with fever and delirium, followed by death within 2 to 12 weeks after exposure. Those patients who survived for 3 to 4 months, and did not succumb to tuberculosis, lung diseases, or other complications, gradually recovered. There was no evidence of permanent loss of hair, and examination of 824 survivors some 3 to 4 years later showed that their blood composition was not significantly different from that of a control group in a city not subjected to nuclear attack. The incidence of long-term effects, such as cataracts and leukemia, will be considered below.

### DOSES OF 100 TO 250 ROENTGENS: SURVIVAL PROBABLE

11.69 Exposure of the whole body to a radiation dose in the range of approximately 100 to 250 roentgens will result in a certain amount of sickness, but it will probably not prove fatal. Doses of this magnitude were common in Hiroshima and Nagasaki, particularly among persons who were at some distance from the nuclear explosion. Of the 250 individuals accidentally exposed to fallout in the Marshall Islands following the test explosion of March 1, 1954, a group of 64 received radiation doses in this range. It should be pointed out that the exposure of the Marshallese was not strictly of the acute type, as arbitrarily defined in § 9.38, since it extended over a period of some 45 hours. More than half the dose, however, was received within 24 hours and the observed effects were undoubtedly similar to those to be expected from an acute exposure of the same amount.

11.70 The sickness resulting from radiation doses in the range from 100 to 250 roentgens presents much the same general picture as in the case of more severe exposure, except that the onset is less abrupt and the symptoms are less marked. There is usually some nausea, vomiting, and diarrhea on the first day or so following irradiation, but subsequently there is a latent period, up to 2 weeks or more, during which the patient has no disabling illness and can proceed with his regular occupation. The usual symptoms, such as loss of appetite, malaise, loss of hair, diarrhea, and tendency to bleed then appear, but they are not very severe (Fig. 11.70). The changes in the character of the blood, which accompany radiation injury, become significant during the latent period and persist for some time. If there are no complications, due to other injuries or to infections, there will be recovery in nearly all cases, with hair growth recommencing after about 2 months. In general, the more severe the early stages of the radiation sickness, the longer and more difficult will be the

Figure 11.70. Loss of hair in child exposed to approximately 175 roentgens of gamma radiation.

process of recovery. Adequate care and the use of antibiotics, as may be indicated clinically, can greatly expedite complete recovery of the more serious cases.

### Small Doses: Minor Injury

11.71 Single exposures of from 25 to 100 roentgens over the whole body may produce mild and somewhat indefinite symptoms, or there may be nothing other than the blood changes which have been observed, to a minor extent, following doses as small as 14 roentgens. Disabling sickness is not common, and exposed individuals should be able to proceed with their usual duties.

### Summary of Clinical Symptoms of Radiation Sickness

11.72 The most obvious and earliest symptoms of radiation sickness are nausea, vomiting, and diarrhea. The appearance, severity, and duration of these symptoms bear a direct relationship to the degree of exposure and an inverse relationship to the probability of recovery. The occurrence and length of the latent period which follows the initial symptoms, and the subsequent effects, are also related to these factors. A simplified summary of the clinical symptoms (or syndrome) of radiation sickness of three degrees of severity are given in Table 11.72. It should be understood that the time scale is approximate and that the order of appearance of the various symptoms after the latent period, as well as the symptoms themselves, may vary from one individual to another.

Table 11.72

SUMMARY OF CLINICAL SYMPTOMS OF RADIATION SICKNESS

| Time after exposure | Survival improbable (700 r or more) | Survival possible (550 r to 300 r) | Survival probable (250 r to 100 r) |
|---|---|---|---|
| | Nausea, vomiting, and diarrhea in first few hours. | Nausea, vomiting, and diarrhea in first few hours. | Possibly nausea, vomiting, and diarrhea on first day. |
| 1st week | No definite symptoms in some cases (latent period). | | |
| | Diarrhea<br>Hemorrhage<br>Purpura<br>Inflammation of mouth and throat.<br>Fever | No definite symptoms (latent period). | No definite symptoms (latent period). |
| 2nd week | Rapid emaciation<br>Death (Mortality probably 100 percent). | Epilation<br>Loss of appetite and general malaise.<br>Fever | |
| 3rd week | | Hemorrhage<br>Purpura<br>Petechiae<br>Nosebleeds<br>Pallor<br>Inflammation of mouth and throat.<br>Diarrhea<br>Emaciation | Epilation<br>Loss of appetite and malaise<br>Sore throat<br>Hemorrhage<br>Purpura<br>Petechiae<br>Pallor<br>Diarrhea<br>Moderate emaciation. |
| 4th week | | | |
| | | Death in most serious cases. (Mortality 50 percent for 450 roentgens.) | Recovery likely in about 3 months unless complicated by poor previous health or superimposed injuries or infections. |

### EFFECTS OF RADIATION ON BLOOD CONSTITUENTS

11.73 Among the biological consequences of exposure of the whole body to a single dose of nuclear radiation, perhaps the most striking and characteristic are the changes which take place in the blood. These changes have been observed, to a small extent, among a group of individuals with doses as low as 14 roentgens, but they become more marked with increasing dosage. Much information on the hematological response of human beings to nuclear radiation was obtained after the nuclear explosions in Japan and also from observations on victims of laboratory accidents. The situation which developed in the Marshall Islands in March 1954, however, provided the opportunity for a very thorough study of the effects of small and moderately large doses of radiation, up to 175 roentgens, on the blood of human beings. The descriptions given below, which are in general agreement with the results observed in Japan, are based largely on this study.

11.74 One of the most striking hematological (blood) changes associated with radiation injury is that in the leukocyte (white blood cell) content. The leukocytes are those cells concerned with resisting bacterial invasion of the body. Their numbers in the blood are observed to increase rapidly during the course of an infection, as they are required to combat the invading organisms. The loss of this ability to meet the bacterial invasion, whether due to radiation or any other injury, is a very grave matter, and bacteria which are normally held in check by the leukocytes can then multiply rapidly, causing serious consequences. There are several types of leukocytes with different specialized functions, but which have in common the general property of resisting infection or removing toxic products from the body, or both. Leukocytes are named according to their appearance, e. g., granulocytes, to their origin, e. g., lymphocytes, or to their acid-base affinities, e. g., acidophiles, neutrophiles, and basophiles.

11.75 After the body has been exposed to radiation in the sublethal range, i. e., about 250 roentgens or less, the total number of leukocytes increases sharply during the first two days or so, and then decreases below normal levels. The white blood cell count fluctuates over the next 5 or 6 weeks, with no definite minimum. In the course of this fluctuation the count may possibly rise above normal on occasions. During the seventh or eighth weeks the white count becomes stabilized at low levels, and a minimum probably occurs at about this time. An upward trend is observed in succeeding weeks, but complete recovery may require several months or more.

11.76 The neutrophiles, which defend the body against invading bacteria, are chiefly formed in the bone marrow. The neutrophile count parallels the total white blood cell count, so that the initial increase observed in the latter is apparently due to the increase in the mobilization of neutrophiles. Complete return of the number of neutrophiles to normal does not occur for several months.

11.77 In contrast to the behavior of the neutrophiles, the number of lymphocytes, produced in parts of the lymphatic tissues of the body, e. g., lymph nodes and spleen, shows a sharp drop soon after exposure to radiation. It continues to remain considerably below the normal value for several months and recovery may require many months or even years. However, to judge from the observations made in Japan, the lymphocyte count of exposed individuals 3 or 4 years after exposure was not significantly different from that of unexposed persons.

11.78 As seen above, the function of the white blood cells is to defend the body against infection and to remove toxic products. The failure of the bone marrow and of the lymphoid tissues to produce granulocytes and lymphocytes, respectively, as a result of the action of radiation, means that an important defense mechanism of the body is rendered largely inoperative. This accounts in part for the increased susceptibility to infection, mentioned earlier, which accompanies radiation sickness. Other contributory factors are deficiencies in the ability to produce antibodies and defective functioning of the remaining lymphocytes.

11.79 A further significant hematological effect is that in the platelets, a constituent of the blood which plays an important part in connection with blood clotting. Unlike the fluctuating total white count, the number of platelets falls steadily and, for a sublethal dose, reaches a minimum at the end of about a month. For higher radiation doses the platelet count falls off more rapidly and attains a lower minimum in a shorter time. The decrease in the number of platelets is followed by a partial recovery, but a normal count may not be attained for several months or even years after exposure. It is the decrease in the platelet content which partly explains the appearance of hemorrhage and purpura as a result of radiation injury.

11.80 The erythrocyte (red blood cell) count also undergoes a decrease as a result of radiation exposure, so that symptoms of anemia, e. g., pallor, become apparent. However, the change in the number of erythrocytes is much less striking than that in the white blood cells and platelets, especially for exposures in the range of 200 to 400 roentgens. Whereas the response in these cells is rapid, the red cell count shows little or no change for several days. Subsequently, there is a decrease which may continue for 2 or 3 weeks, but this is followed by a gradual increase in those who survive.

11.81 As an index of severity of radiation exposure, particularly in the sublethal range, the total white cell or neutrophile counts are of limited usefulness because of the wide fluctuations and also because several weeks may elapse before the maximum depression is observed. The lymphocyte count is of more value in this respect, particularly in the low dose range, since depression occurs within a few hours of exposure. However, a marked decrease in the number of lymphocytes occurs even with low doses and there is relatively little difference with larger doses. Consequently, the white cell count is not very useful as an index of exposure at the higher dose levels.

11.82 The platelet count, on the other hand, appears to exhibit a regular pattern, with the maximum depression being attained at approximately the same time for various exposures in the sublethal range. Further, in this range, the degree of depression from the normal value is roughly proportional to the estimated dose. It has been suggested, therefore, that the platelet count might serve as a convenient and relatively simple direct method for determining the severity of radiation injury in the sublethal range. The main disadvantage is that an appreciable decrease in the platelet count is not apparent until some time after the exposure.

## LATE EFFECTS OF NUCLEAR RADIATION

### Cataracts

11.83 There are a number of consequences of nuclear radiation which may not appear for some years after exposure. Among them, apart from genetic effects, are the formation of cataracts, leukemia, and retarded development of children *in utero* at the time of the exposure. Information concerning these late effects have been obtained from continued studies in Japan made chiefly under the direction of the Atomic Bomb Casualty Commission.[4]

11.84 An examination for the incidence of cataracts among the survivors of the bombings of Hiroshima and Nagasaki has revealed well over 100 cases of non-vision-disturbing lens opacities in persons who were within about 3,000 feet (0.6 mile) from ground zero at the times of the respective explosions. In a small proportion only of the patients was the opacity serious enough to require an operation. The cataracts are similar to those which have been previously associated with overexposure to X-rays or gamma rays, and so they are probably due to the initial nuclear radiation from the nuclear bombs. Because of the high biological effectiveness of fast neutrons for the formation of lens opacities (§ 11.49), it is probable that this radiation was largely responsible for the Japanese cases.

11.85 Most persons in the same zone, with respect to the center of the explosion, died either from thermal or mechanical injuries or from radiation sickness. Consequently, it is probable that all (or nearly all) the survivors who later developed cataracts must have received at least moderate doses of radiation. This view is supported by the fact that essentially all these individuals suffered complete (but transient) epilation and many exhibited other characteristic clinical symptoms of radiation sickness.

### Leukemia

11.86 A review of mortality rates has shown that, as a cause of death, leukemia, a disease associated with an overproduction of white blood cells, is much more common among radiologists than among other physicians. It has therefore been accepted that chronic exposure to moderate doses of nuclear radiation is conducive to leukemia. It now appears from a study of the survivors of the nuclear explosions over Japan, that the disease may result from a large single (acute) dose of radiation. The first definite evidence of an increase in the incidence of leukemia among the inhabitants of Hiroshima and Nagasaki was obtained in 1947. At least 2 years elapsed, therefore, between exposure and the development of the symptoms. The number of new cases reported has increased fairly regularly in succeeding years.

11.87 Essentially all of the cases of leukemia, which could be attributed to radiation because of other symptoms, e. g., epilation, occurred among individuals who were within about 4,600 feet (0.9 mile) of ground zero. In this region, the minimum radiation dose, probably received over an extensive part of the body, must have approached the median lethal value of 450 roentgens. A survey of a large number of these patients showed that the incidence of leukemia among the survivors was, on the average, about one in 500 compared with one in 50,000 among the general (unexposed) population of Japan.

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[4] The Atomic Bomb Casualty Commission of the U. S. National Research Council is sponsored by the Atomic Energy Commission. One of its purposes is to study the long-term effects of exposure to nuclear radiation.

### RETARDED DEVELOPMENT OF CHILDREN

11.88 Among the mothers who were pregnant at the times of the nuclear explosions in Japan, and who received sufficiently large doses to show the usual radiation symptoms, there was a marked increase over normal in the number of still-births and in the deaths of newly born and infant children. A study of the surviving children made 4 or 5 years later has shown a slightly increased frequency of mental retardation. However, nearly all the mothers of these children, then *in utero*, were so close to ground zero that they must have been exposed to at least 450 roentgens of nuclear radiation. Maldevelopment of the teeth, attributed to injury of the roots, was also noted in many of the children.

11.89 A comparison made about 1952 of exposed children, whose ages ranged from less than 1 to about 14 years at the time of the explosions, with unexposed children of the same age, showed that the former had somewhat lower average body weight and were less advanced in stature and sexual maturity. On the other hand, no significant differences were observed in various neuromuscular coordination and muscular tests.

11.90 In connection with the subject of the development of children, it should be mentioned that those who were conceived in Japan after the nuclear attacks, even by irradiated parents, appear to be quite normal. The fear expressed at one time that there would be a sharp increase in the frequency of abnormalities has not been substantiated (see, however, § 11.124).

### EFFECT OF RADIATION ON OTHER INJURIES

11.91 The superposition of radiation injury upon injuries from other causes may be expected to result in an increase in the number of cases of shock. For example, the combination of sublethal exposure and moderate thermal burns will produce earlier and more severe shock than would the comparable burns alone. The healing of wounds of all kinds will be retarded because of the susceptibility to secondary infection accompanying radiation injury and for other reasons. In fact, infections, which could normally be dealt with by the body, may prove fatal in such cases.

## RESIDUAL RADIATION HAZARDS

### GAMMA RADIATION

11.92 The biological effects of the residual nuclear radiation are, in general, similar to those of the initial radiation, but there are certain aspects, arising from the nature of the fission products and fallout, that require special consideration. The topics to be discussed here are (1) the residual gamma radiation, (2) beta-particle emitters, and (3) internal sources of radiation.

11.93 Although the gamma rays from fission products have a lower energy and are somewhat less penetrating than those present in the initial nuclear radiation, their biological effects are similar. However, as indicated in § 11.61, a certain number of roentgens of residual gamma radiation from fallout may produce greater biological injury than that number of roentgens of initial gamma radiation. In the latter case, when most of the radiation comes from one direction, namely, that of the exploding bomb, there may be partial shielding of one portion of the body by another. Radiation from fallout, on the other hand, can reach the body from many directions and there is very little self-shielding. The fact that the residual radiation is spread over a longer period than the initial radiation is not of great significance, because most of the dose from fallout will generally be received during the first day or two following the nuclear explosion. The normal recovery in this time is not large, so that the dose may be treated essentially as acute.

### BETA-PARTICLE EMITTERS

11.94 Injury to the body from external sources of beta particles can arise in two general ways. If the beta-particle emitters, e. g., fission products in the fallout, come into actual contact with the skin and remain for an appreciable time, a form of radiation damage, sometimes referred to as "beta burn," will result. In addition, in an area of extensive fallout, the whole surface of the body will be exposed to beta particles coming from many directions. It is true that clothing will attenuate this radiation to a considerable extent; nevertheless, the outer layers of the skin could receive a large dose of beta particles. In some circumstances this might cause serious burns.

11.95 Valuable information concerning the development and healing of beta burns has been obtained from observations of the Marshall Islanders who were exposed to fallout in March 1954. Within about

5 hours of the burst, radioactive material commenced to fall on some of the islands. Although the fallout was observed as a white powder, consisting largely of particles of lime (calcium oxide) resulting from the decomposition of coral (calcium carbonate) by heat, the island inhabitants did not realize its significance. Because the weather was hot and damp, the Marshallese remained outdoors; their bodies were moist and they wore relatively little clothing. As a result, appreciable amounts of fission products fell upon and remained in contact with the hair and skin for a considerable time. Further, since the islanders, as a rule, did not wear shoes, their bare feet were continually subjected to contamination from fission products on the ground.

11.96 During the first 24 to 48 hours, a number of individuals in the more highly contaminated groups experienced itching and a burning sensation of the skin. These symptoms were less marked among those who were less contaminated with fission products. Within a day or two all skin symptoms subsided and disappeared, but after the lapse of about 2 to 3 weeks, epilation and skin lesions were apparent on the areas of the body which had been contaminated by fallout particles. There was apparently no erythema, either in the early stages (primary) or later (secondary), as might have been expected, but this may have been obscured by the natural coloration of the skin.

11.97 The first evidence of skin damage was increased pigmentation, in the form of dark colored patches and raised areas (macules, papules, and raised plaques). These lesions developed on the exposed parts of the body not protected by clothing, and occurred usually in the following order: scalp (with epilation), neck, shoulders, depressions in the forearm, feet, limbs, and trunk. Epilation and lesions of the scalp, neck, and foot were most frequently observed (Figs. 11.97a and b).

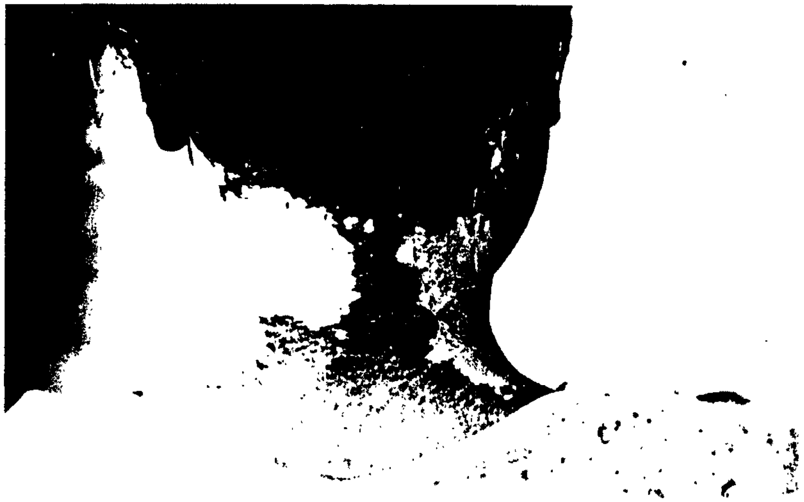

Figure 11.97a. Beta burn on neck 1 month after exposure.

Figure 11.97b. Beta burn on feet 1 month after exposure.

11.98 In addition, a bluish-brown pigmentation of the fingernails was very common among the Marshallese and also among American Negroes. The phenomenon appears to be a radiation response peculiar to the dark-skinned races, since it was not apparent in any of the white Americans who were exposed at the same time. The nail pigmentation occurred in a number of individuals who did not have skin lesions. It is probable that this was caused by gamma rays, rather than by beta particles, as the same effect has been observed in colored patients undergoing X-ray treatment in clinical practice.

11.99 Most of the lesions were superficial without blistering. Microscopic examination at 3 to 6 weeks showed that the damage was most marked in the outer layers of the skin (epidermis), whereas damage to the deeper tissue was much less severe. This is consistent with the short range of beta particles in animal tissue. After formation of dry scab, the lesions healed rapidly leaving a central depigmented area, surrounded by an irregular zone of increased pigmentation. Normal pigmentation gradually spread outward in the course of a few weeks.

Figure 11.100a. Beta burn on neck 1 year after exposure (see Fig. 11.97a).

Figure 11.100b. Beta burn on feet 6 months after exposure (see Fig. 11.97b).

11.100 Individuals who had been more highly contaminated developed deeper lesions, usually on the feet or neck, accompanied by mild burning, itching, and pain. These lesions were wet, weeping, and ulcerated, becoming covered by a hard, dry scab; however, the majority healed readily with the regular treatment generally employed for other skin lesions, not connected with radiation. Abnormal pigmentation effects persisted for some time, and in several cases about a year elapsed before the normal (darkish) skin coloration was restored (Figs. 11.100a and b).

11.101 Regrowth of hair, of the usual color (in contrast to the skin pigmentation) and texture, began about 9 weeks after exposure and was complete in 6 months. By the same time, nail discoloration had grown out in all but a few individuals.

## INTERNAL SOURCES OF RADIATION

11.102 Wherever fallout occurs there is a possibility that radioactive material will enter the body through the digestive tract (due to the consumption of food and water contaminated with fission products), through the lungs (by breathing air containing fallout particles), or through wounds or abrasions. The general biological effects of nuclear radiations from internally deposited sources are the same as those from external sources. However, it should be noted that even a very small quantity of radioactive material present in the body can produce considerable injury.

11.103 In the first place, radiation exposure of various organs and tissues from internal sources is continuous, subject only to depletion of the quantity of active material in the body as a result of physical (radioactive decay) and biological (elimination) processes. Further, the body tissues in which injury may occur are nearer the source of radiation and not shielded from it by intervening materials. This is of particular importance with alpha and beta particles which cannot reach sensitive regions, except the outer layers of the skin, if originating outside the body. But if the sources, e. g., plutonium (alpha-particle emitter) or fission products (beta-particle emitters) are internal, the particles can dissipate their entire energy within a small, possibly sensitive, volume of body tissue, thus causing considerable damage.

11.104 The situation just described is sometimes aggravated by the fact that certain chemical elements tend to concentrate in specific cells or tissues, some of which are highly sensitive to nuclear radiation. The fate of a given radioisotope which has entered the blood stream will depend upon its chemical nature. Radioisotopes of an element which is a normal constituent of the body will follow the same metabolic processes as the naturally occurring, inactive (stable) isotopes of the same element. This is the case, for example, with iodine which tends to concentrate in the thyroid gland.

11.105 An element not usually found in the body, except perhaps in minute traces, will behave like one with similar chemical properties that is normally present. Thus, among the fission products, strontium and barium, which are similar chemically to calcium, are largely deposited in the calcifying tissue of bone. The radioisotopes of the rare earth elements, e. g., cerium, which constitute a considerable proportion of the fission products, and plutonium, which may be present to some extent in the fallout, are also "bone-seekers." Since they are not chemical analogues of calcium, however, they are deposited to a lesser extent and in other parts of the bone than strontium and barium (Fig. 11.105). All bone-seekers, are, nevertheless, potentially very hazardous because they can injure the sensitive bone marrow where many blood cells are produced. The damage to the blood-forming tissue thus results in a reduction in the number of blood cells and so adversely affects the entire body.

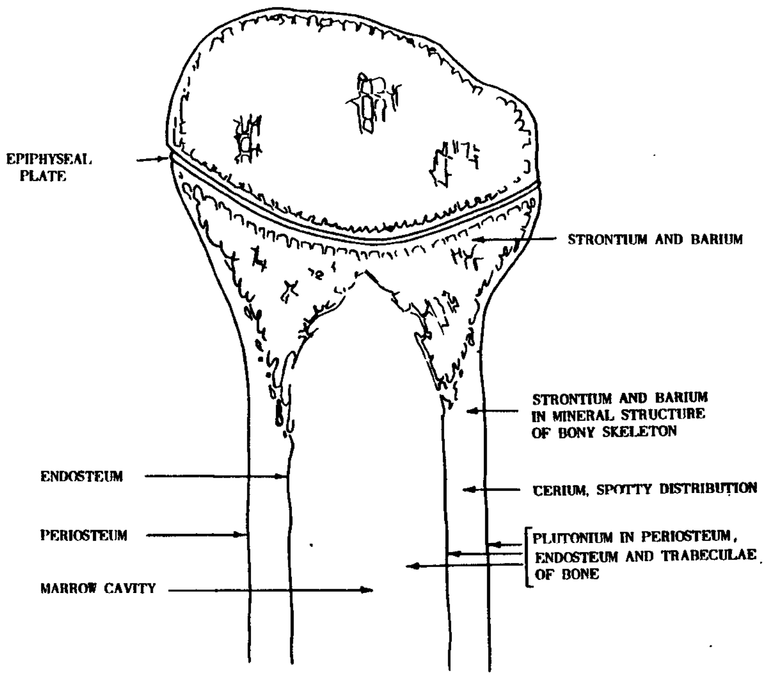

**Figure 11.105. Deposition of elements in growing bone of rodents.**

11.106 In order to constitute an internal radiation source, the active materials must gain access to the circulating blood, from which they can be deposited in the bones, liver, etc. While the radioactive substances are in the lungs, stomach, and intestines, they are, for all practical purposes, an external, rather than internal, source of radiation. The extent to which fallout contamination can get into the blood stream will depend upon two main factors: the size of the particles and their solubility in the body fluids. Whether the material is subsequently deposited in some particular tissue will be determined by the chemical properties of the elements present, as indicated above. Elements which do not tend to concentrate in a particular part of the body are eliminated fairly rapidly by natural processes.

11.107 If other things, e. g., particle size and solubility, are equal, a greater proportion of the material entering the body by breathing will find its way into the blood than of that entering through the digestive system. This may be accounted for by the different mechanisms whereby materials pass through the lungs and the intestinal tract. The amount of radioactive material absorbed from fallout by inhalation, however, appears to be relatively small.

11.108 The reason is that the nose can filter out almost all particles over 10 microns (0.001 centimeter) in diameter, and about 95 percent of those exceeding 5 microns (0.0005 centimeter). Most of the particles descending in the fallout during the critical period of highest activity, e. g., within 24 hours of the explosion, will be considerably more than 10 microns in diameter (§ 9.125, *et seq.*). Consequently, only a small proportion of the fallout particles present in the air will succeed in reaching the lungs. Further, the optimum size for passage from the alveolar (air) space of the lungs to the blood stream is less than 5 microns. The probability of entry into the circulating blood of fission products and other bomb residues present in the fallout, as a result of inhalation, is thus low.

11.109 The extent of absorption of fission products and other radioactive materials through the intestine is largely dependent upon the solubility of the particles. In the fallout, the fission products, as well as uranium and plutonium, are chiefly present as oxides, many of which do not dissolve to any great extent in body fluids. The oxides of strontium and barium, however, are soluble, so that these elements can readily enter the blood stream and find their way into bones. The element iodine is also chiefly present in a soluble form; it soon enters the blood and is concentrated in the thyroid gland.

11.110 In addition to the tendency of a particular element to be taken up by a radiosensitive organ, the main consideration in determining the hazard from a given radioactive isotope inside the body is the total biological dose delivered while it is in the body (or critical organ). The most important factors in determining this dose are the mass and half-life (§ 1.49) of the radioisotope, the nature and energy of the radiations emitted, and the length of time it stays in the body. This time is dependent upon two factors; one is the ordinary radioactive half-life and the other is called the "biological half-life." The latter is defined as the time taken for the amount of a particular element in the body to decrease to half of its initial value due to elimination by natural (biological) processes. Combination of the radioactive and biological half-lives gives rise to the "effective half-life," which is the time required for the amount of a specified radioactive isotope in the body to fall to half of its original value as a result of both radioactive decay and natural elimination. In most cases of interest, the effective half-life in the body as a whole is essentially the same as that in the principal tissue (or organ) in which the element tends to concentrate.

11.111 The isotopes representing the greatest potential internal hazard are those with short radioactive half-lives and comparatively long biological half-lives. A certain mass of an isotope of short radioactive half-life will emit particles at a greater rate than the same mass of another isotope, possibly of the same element, having a longer half-life. Further, the long biological half-life means that the active material will not be readily eliminated from the body by natural processes. For example, the element iodine has a biological half-life of about 180 days, because it is quickly taken up by the thyroid gland from which it is eliminated slowly. The radioisotope iodine-131, a fairly common fission product, has a radioactive half-life of only 8 days. Consequently, if a sufficient quantity of this isotope enters the blood stream it is capable of causing serious damage to the thyroid gland. It should be mentioned that, apart from immediate injury, any radioactive material that enters the body, even if it has a short effective half-life, may contribute to damage which does not become apparent for some time.

11.112 In addition to radioiodine, the most important potentially hazardous fission products, assuming sufficient amounts get into the body, fall into two groups. The first, and more significant, contains strontium-89, strontium-90, and barium-140, whereas the second consists of a group of rare earth and related elements, particularly cerium-144 and the chemically similar yttrium-91. As seen earlier, these elements are readily deposited and held in various parts of the bone where the emitted beta and gamma radiations can injure blood-forming tissues and may also cause tumor formation.

11.113 Another potentially hazardous element, which may be present to some extent in the fallout, is plutonium, in the form of the alpha-particle emitting isotope plutonium–239, that has escaped fission. Plutonium-239 has a long radioactive half-life (24,000 years) as well as a long biological half-life (over 100 years). Consequently, once it is deposited in the body, mainly on certain surfaces of the bone (Fig. 11.105), the amount of plutonium present, and its activity, decrease at a very slow rate. In spite of their short range in the body, the continued action of alpha particles over a period of years can cause significant injury. In sufficient amounts, radium, which is very similar to plutonium in these respects, is known to cause necrosis and tumors of the bone, and anemia resulting in death.

11.114 In addition to concentrating in skeletal tissue, strontium, barium, and plutonium are found to accumulate to some extent in both liver and spleen. The rare earths also deposit in the liver and to a lesser extent in the spleen. However, many radioisotopes are readily eliminated from the liver. It is of interest to note that despite the large amounts of radioactive material that may pass through the kidneys, in the process of elimination, these organs ordinarily are not greatly affected. By contrast, uranium causes damage to the kidneys, but as a chemical poison rather than because of its radioactivity.

## EXPERIENCE WITH FALLOUT AS AN INTERNAL HAZARD

11.115 The fallout accompanying the nuclear air bursts over Japan was so insignificant that no information was available concerning the potentialities of fission products and other bomb residues as internal sources of radiation. Following the incident in the Marshall Islands in March 1954, however, data of considerable interest were obtained. Because they were not aware of the significance of the fallout, many of the inhabitants ate contaminated food and drank contaminated water from open containers for periods up to 2 days or so.

11.116 Internal deposition of fission products resulted mainly from ingestion rather than inhalation for, in addition to the reasons given above, the radioactive particles in the air settled out fairly rapidly, but contaminated food, water, and utensils were used all the time. The belief that ingestion was the chief source of internal contamination was supported by the observations on chickens and pigs made soon after the explosion. The gastro-intestinal tract, its contents, and the liver were found to be more radioactive than lung tissue.

11.117 From radiochemical analysis of the urine of the Marshallese subjected to the fallout, it was possible to estimate the body burden, i. e., the amounts deposited in the tissues, of various isotopes. It was found that iodine–131 made the major contribution to the activity at the beginning, but it soon disappeared because of its relatively short radioactive half-life (8 days). Somewhat the same was true for barium–140 (12.8 days half-life), but the activity of the strontium isotopes was more persistent. Not only do they have longer radioactive half-lives, but the biological half-life of the element is also relatively long.

11.118 No elements other than iodine, strontium, barium, and the rare earth group were found to be retained in appreciable amounts in the body. Essentially all other fission product and bomb residue activity is rapidly eliminated, because of either the short effective half-lives of the radioisotopes, the sparing solubility of the oxides, or the relatively large size of the fallout particles.

11.119 The body burden of radioactive material among the more highly contaminated inhabitants of the Marshall Islands was never very large and it decreased fairly rapidly in the course of 2 or 3 months. The activity of the strontium isotopes fell off somewhat more slowly than that of the other radioisotopes, because of the longer radioactive (and biological) half-life and greater retention in the bone. Nevertheless, even strontium could not be regarded as a dangerous source of internal radiation in the cases studied. At 6 months after the explosion, the urine of most individuals contained only barely detectable quantities of radioactive material, indicating that the body burden was then extremely small.

11.120 In spite of the fact that the Marshallese people lived under conditions where maximum probability of contamination of food and water supplies existed, and that they took no steps to protect themselves in any way, the degree of internal hazard due to the fallout was small. There seems to be little doubt, therefore, that, at least as far as short term effects are concerned, the radiation injury by fallout due to internal sources is quite minor in comparison with that due to the external radiation. If reasonable precautions are taken, as will be described in Chapter XII, the short term, internal hazard can probably be greatly reduced.

## LONG-TERM INTERNAL HAZARD

11.121 Apart from the possible long-term effects of radioactive material that has been inhaled or ingested and subsequently eliminated, about which little is yet known, there has been some speculation concerning the relatively long lived strontium-90, to which reference was made in Chapter X. Perhaps because one of the predecessors of strontium-90, namely krypton-90, is a gas, the initial fission products, especially those deposited in the region of the more-or-less immediate fallout, are somewhat depleted in this isotope of strontium. In any event, to judge from the experience with the inhabitants of the Marshall Islands, the probability that strontium will be taken up and held firmly in the body as a result of inhalation or ingestion of local fallout particles is not great. The possibility that strontium-90 may be absorbed over the course of time in certain foods is, however, a different matter.

11.122 As discussed in Chapter X, the strontium-90 and other fission products that have entered the stratosphere as very small particles, will eventually settle to the ground. The strontium may then find its way, mainly through milk and milk products, into the human body. Because it is eliminated slowly by natural processes, the strontium-90, with a radioactive half-life of about 28 years, will accumulate in the skeletal structure of the body. If sufficient quantities are present, the long-term injuries may be similar to those caused by excessive amounts of radium and plutonium, described above (§ 11.113).

## GENETIC EFFECTS OF RADIATION

### Spontaneous and Induced Mutations

11.123 The genetic effects of radiation are effects of a long-term character which produce no visible injury in the exposed individual but may have notable consequences in future generations. These effects differ from most other changes produced by nuclear radiation in that they appear to be cumulative and, to a great extent, independent of the dose rate. In other words, the extent of the genetic effects depends upon the total radiation dose received and not on whether the exposure is of short duration or spread over many years. Thus, as far as genetic changes are concerned, it is largely immaterial whether the radiation dose is chronic or acute.

11.124 The mechanism of heredity, which is basically similar in all sexually reproducing plants and animals, including man, is somewhat as follows. The nuclei of all dividing cells contain a definite number of thread-like entities called "chromosomes" that are visible under the microscope. These chromosomes are believed to be differentiated along their length into thousands of distinctive units, referred to as "genes." The chromosomes (and genes) exist in every cell of the body, but from the point of view of genetics (or heredity), it is only those in the germ cells, which exist in the reproductive organs, that are important.

11.125 Human body cells normally contain 48 chromosomes, made up of two similar (but not identical) sets of 24 chromosomes each.[5] One of these sets was inherited from the mother, for the egg cell (produced in the ovaries) carries a set of 24 chromosomes, whereas the other set came from the father, for the sperm cell (produced in the testes) carries a set of 24 similar (but not identical) chromosomes. As the individual develops, following upon the fusion of the original egg and sperm cells, the chromosomes and genes are, in general, duplicated without change.

11.126 In rare instances, however, a deviation from normal behavior occurs and instead of a chromosome duplicating itself in every respect, there is a change in one or more of the genes. This change, called a "mutation," is essentially permanent, for the mutant gene is reproduced in its altered form. If this mutation occurs in a body cell, there may be some effect on the individual, but the change is not passed on. But if the mutation occurs in a germ cell of either parent, a new characteristic will appear in a later generation. The mutations which occur naturally, without any definitely assignable cause or human intervention, are called "spontaneous mutations."

11.127 The matter of immediate interest is that the frequency with which mutations occur can be increased in various ways, one being by exposure of the sex glands (or "gonads"), i. e., testes or ovaries, to radiation. This effect of radiation has been observed with various insects and mammals, and it undoubtedly occurs also in human beings. The gene mutations induced by radiation do not differ qualitatively from those occurring spontaneously. In practice, it is impossible to determine in any particular instance whether the change has occurred naturally or whether it was due to radiation. It is only the frequency with which the mutations occur that is increased by radiation.

11.128 All genes have the property of being either "dominant" or "recessive." If a gene is dominant, then the appropriate characteristic affected by that gene will appear in the offspring even if it is produced by the gonads of only one of the parents. On the other hand, a particular recessive gene must occur in the gonads of both parents if the characteristic is to be apparent in the next generation. A recessive gene may consequently be latent for a number of generations, until the occasion arises for the union of sperm and egg cells both of which contain this particular gene.

11.129 As a general rule, new mutations, whether spontaneous or induced by radiation, are recessive. Nevertheless, it appears that a mutant gene is seldom completely recessive, and some effect is ob-

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[5] Recent evidence indicates that these numbers may be 46 and 23, respectively.

servable in the next generation even if the particular gene is inherited from only one parent. Further, in the great majority of cases, mutations have deleterious effects of some kind. A very few of the changes accompanying mutations are undoubtedly beneficial, but their consequences become apparent only in the slow process of biological evolution.

11.130 The harmful effects of a deleterious mutation may be quite minor, such as increased susceptibility to disease or a decrease in life expectancy by a few months, or they may be more serious, such as death in the embryonic stage or the inability to produce children at all. Thus, individuals bearing harmful genes are handicapped relative to the rest of the population, particularly in the respects that they tend to have fewer children or to die earlier. It is apparent, therefore, that such genes will eventually be eliminated from the population. A gene that does great harm will be eliminated rapidly, since few (if any) individuals carrying such genes will survive to the age of reproduction. On the other hand, a slightly deleterious mutant gene may persist much longer, and thereby do harm, although of a less severe character, to a larger number of individuals.

### Mutations and Radiation Dose

11.131 Experiments with various types of animals have shown that the increased frequency of the occurrence of gene mutations, as a result of exposure to radiation, is approximately proportional to the total amount of radiation absorbed by the gonads of the parents from the beginning of their development to the time of conception of the progeny. There is apparently no amount of radiation, however small, that does not cause some increase in the normal mutation frequency. The dose rate of the radiation exposure or its duration have little influence; it is the total accumulated dose to the gonads that is the important quantity. It should be pointed out, however, that a large dose of radiation does not mean that the resulting mutations will be more harmful than for a smaller dose. With a large dose the mutations will be of the same general type as for a small dose, or as those which occur spontaneously, but there will be more of them in proportion to the dose.

11.132 In reviewing the possible genetic effects resulting from the use of nuclear weapons, there are two aspects to be considered. First, the consequences of exposure to the initial and residual radiations soon after the explosion, and second, the results of the slow accumulation of strontium-90 (and perhaps other fission products) in the body. Of these two, the former is undoubtedly more important. It has been estimated that the amount of radiation, in addition to that received from natural background sources (§ 9.41), required to double the rate at which spontaneous mutations are already occurring, is a dose to the gonads of probably between 30 and 80 roentgens, prior to conception, for each member of the population. A proportionately larger dose to a smaller fraction of the populace would have a somewhat similar effect on the frequency of mutations and their ultimate consequences.

11.133 The genetic effects of strontium-90, on the other hand, may be expected to be very small. This isotope tends to accumulate in the skeleton, and since it emits only beta particles, but no gamma rays, the radiation dose to the gonads from strontium-90 in bone will be of minor significance. The same would be generally true for other fission products that might be concentrated in the skeleton or other parts of the body.

## PATHOLOGY OF RADIATION INJURY[6]

### Cellular Sensitivity

11.134 The discussion presented above has been mostly concerned with over-all symptoms and effects of radiation injury; even the changes in the blood are, to a great extent, indirectly due to the action of nuclear radiation on the bone marrow and lymphatic tissue. It is of interest, therefore, to consider briefly the pathological changes produced by radiation in some individual organs and tissues.

11.135 The damage caused by radiation undoubtedly originates in the individual cells. As mentioned in § 11.45, a number of observable changes in the cells and their contents results from exposure to nuclear radiation. Different types of cells show remarkable variations in their response. In general, rapidly multiplying or actively reproducing cells are more radiosensitive than are those in a more quiescent state. One of the most striking effects of irradiation is the sharp decrease or even complete cessation of cell division (mitosis) in organs which are normally in a state of continuous regeneration.

11.136 Of the more common tissues, the radiosensitivity decreases in the following order: lymphoid tissue and bone marrow; epithelial tissue (tests and ovaries, salivary glands, skin, and mucuous mem-

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[6] The remaining sections of this chapter may be omitted without loss of continuity.

brane); endothelial cells of blood vessels and peritoneum; connective tissue cells; bone cells, muscle cells, and differentiated (or specialized) nerve cells. However, some brain and nerve cells, especially those of embryos, are fairly sensitive to radiation. The behavior of certain of these tissues under the influence of radiation is outlined below.

### LYMPHOID TISSUE

11.137 The lymphoid tissue is the tissue characteristic of lymph glands, tonsils, adenoids, spleen, and certain areas of the intestinal lining. The so-called lymph glands, found in various parts of the body, are a network of connective tissue in the meshes of which are the lymphoid cells. These cells, when mature, are carried off by the lymph fluid, flowing through the glands, and become the lymphocyte constituents of the white blood cells (§ 11.77). As indicated in the preceding paragraph, the lymphoid tissue is one of the most radiosensitive of all tissues.

11.138 Lymphoid cells are injured or killed when the tissue is exposed to radiation. Microscopic examination shows degenerative changes characteristic of cell death. The degeneration of the lymphoid tissue, including the formation of cells of abnormal types, was an outstanding phenomenon among the victims of the nuclear bombs in Japan. Damage to the lymphoid cells accounts for the decrease in the number of lymphocytes in the circulating blood; the radiation not only damages the lymphocyte-bearing tissue but it may also kill or injure the lymphocytes already in the blood. It appears that if there is no appreciable drop in the lymphocyte count within 72 hours of exposure to radiation, the dose has been too small to cause any significant sickness.

11.139 Lymphoid tissue injured by radiation tends to become edematous, that is, to swell due to the accumulation of serous fluid. Wasting of the lymph glands, as well as of the tonsils and lymphoid patches of the intestines, was common among the radiation casualties in Japan.

### BONE MARROW

11.140 Since most of the constituent cells of the blood, other than the lymphocytes, are produced in the bone marrow, the fact that this tissue is very radiosensitive is of great importance. Under normal circumstances, the mature blood cells leave the marrow and make their way into the blood stream. Here they remain for various periods before being destroyed by natural processes. In general, the shorter the life of a particular type of blood cell, the more quickly will it reveal evidence of radiation injury by a decrease in the number of such cells. The red blood cells, which have the longest lives, are the last to show a reduction in number after exposure to radiation (§ 11.80).

11.141 Bone marrow exhibits striking changes soon after irradiation. The tissue forming the blood cells ceases to function and in some severe cases in Japan it was observed that tissue which normally produces granulocytes was forming plasma-like cells. Extreme atrophy of the bone marrow was characteristic of many of those dying from radiation injury up to 3 or 4 months after exposure, although there was some evidence of attempts of the body at repair and regeneration. In some instances a gelatinous deposit had replaced the normal bone marrow.

### REPRODUCTIVE ORGANS

11.142 Almost every post mortem examination of males dying from radiation exposure revealed profound changes in the testes. Even as early as the fourteenth day after exposure, when gross changes were not apparent, microscopic observation showed alterations in the layers of epithelium from which the spermatozoa develop. Many of the cells were degenerated, and evidence of healthy cell division was lacking.

11.143 Although the ovaries were also highly radiosensitive, the obvious changes, as observed among females in Japan, appeared to be less striking than in the testes in males. Except for hemorrhages, as part of the general tendency to bleed, there were no especially significant changes of either a gross or a microscopic character. In many cases among survivors, the ova were not developing normally after exposure, and this induced alterations in the menstrual cycle. Cessation of menstruation occurred, but it was transient. There was an increased incidence of miscarriages and premature births, and a greater death rate among expectant mothers. In general, these manifestations varied in severity according to the proximity of the individual to the explosion center.

11.144 In connection with changes in the reproductive organs, it may be noted that the dose required to produce sterility in human beings is believed to be from 450 to 600 roentgens, which would be lethal in most cases if received over the whole body. Temporary sterility can occur with smaller doses, however, as happened among Japanese men and women. The great majority of these individuals have since returned to normal, although it cannot be stated with certainty that all have recovered, because many were undoubtedly sterile from other causes, such as disease and malnutrition. Many who were exposed to appreciable doses of radiation have since produced apparently normal children, as noted earlier.

### Loss of Hair

11.145 Epilation (loss of hair), mainly of the scalp, was common among those Japanese who survived for more than 2 weeks after the explosion. The time of onset of epilation reached a sharp peak, for both males and females, between the thirteenth and fourteenth days. The hair suddenly began to fall out in bunches upon combing or plucking, and much fell out spontaneously: this continued for 1 or 2 weeks and then ceased.

11.146 In most instances the distribution of epilation was that of ordinary baldness, involving first the front, and then the top and back of the head. The hair of the eyebrows and particularly the eyelashes and beard came out much less easily. In a small group of Japanese, which may or may not have been typical, 69 percent had lost hair from the scalp, 12 percent from the armpits, 10 percent from pubic areas, 6 percent from the eyebrows, and 3 percent from the beard. In severe cases, hair began to return within a few months and in no instance was the epilation permanent.

### Gastro-Intestinal Tract

11.147 The mucous linings of the gastro-intestinal tract were among the first tissues to show gross changes in the irradiated Japanese. Even before hemorrhage and associated phenomena were noticed, there was swelling, discoloration, and thickening of the mucous membranes of the caecum (blind gut) and large intestine. Patches of lymphoid tissue were especially involved. In many patients there was first swelling, then ulceration of the most superficial layers of the mucous membranes of the intestinal tract, proceeding to deeper ulceration, and a membrane-like covering of the ulcer, suggesting, but not entirely simulating, that seen in bacillary dysentery.

11.148 In the third and fourth weeks, inflammation of the intestines, and occasionally of the stomach, was a common post-mortem observation. In the early stages the small intestine was affected but later, among those who survived, the whole of the large intestine, from the lower end of the small intestine to the rectum, was involved. Thickening of the intestinal wall and a tendency to produce false membranes were common features, as in acute bacillary dysentery. The effects apparently depended upon the devitalization of tissues as a primary result of irradiation, lowered local resistance, and lowered efficiency of the defense mechanisms ordinarily supplied by the components of the circulating blood. Under the microscope, notable changes were the swelling of cells and the absence of infiltration of the white blood cells.

### Hemorrhage and Infection

11.149 Certain parts of the urinary tract, the muscles, and all the soft tissues of the body may show subsurface hemorrhage varying in size from a pin-point to several inches across. These changes are significant, for they present clinical evidence of the nature and severity of radiation injury. If the hemorrhages occur in important centers of the body, e. g., the heart, lungs, or brain, the consequences may be disastrous. The damage depends upon the location of the large hemorrhagic lesions in relation to the tissues of the particular vital organ involved. Some hemorrhages present external signs, or may be observed upon examination, such as those into the linings of the mouth, nose, and throat, behind the retina of the eye, or into the urinary tract. Large hemorrhagic lesions may occur in the drainage tracts of the kidney, in the small tubes leading from the kidney to the bladder, and in the urinary bladder.

11.150 Hemorrhages breaking through a surface layer of epithelium, laden with bacteria, may give rise to other effects. The tissues may become devitalized and so lacking in resistance to infection that they make an ideal place for the multiplication of bacteria that are either weakly invasive or rarely dangerous under ordinary circumstances. This bacterial invasion may lead to serious local tissue destruction and perhaps systemic infection. Normally harmless bacteria, generally found within the digestive tract and on the skin, may actually gain access to the blood stream and cause blood poisoning and fatal infection. Boils and abscesses may form in any part of the body through a similar cause, but they are characterized by being more localized.

11.151 When this form of tissue change occurs in the throat, the medical findings may resemble a condition found after certain chemical intoxications that injure the bone marrow and the reticulo-endothelial system. In other instances, they may be similar to that observed in some blood diseases associated with an absence of granulocytes in the circulating blood (agranulocytosis). In radiation sickness, ulcers may extend to the tongue, the gums, the inner lining of the mouth, the lips, and even the outer part of the skin of the face. These ulcerations may occur independently of any associated local hemorrhagic change. Similar effects have been observed throughout the entire gastro-intestinal tract. Within the lungs, a form of pneumonia may develop which differs from most pneumonias in the almost complete absence of infiltrating white blood cells.

## *CHAPTER XII*

# PROTECTIVE MEASURES

## INTRODUCTION

### TYPES OF PROTECTION

12.1 In the preceding chapters of this book the destructive effects of nuclear weapons have been described and discussed. These effects include damage to structures and injury to personnel caused by air blast, ground and water shock, thermal radiations, and initial and residual nuclear radiations. In the present chapter an attempt will be made to state some of the many considerations involved in planning countermeasures against these various effects. The problem of protection is a complex one, since it involves not only the effects themselves, but also economic, social, and psychological considerations, in addition to the methods and efficacy of the systems for providing warning of an impending attack.

12.2 The descriptions of various effects in this book have been given in terms that are reasonably exact. But in planning protection, so many uncertainties are encountered that precise analysis of a particular situation is impossible. Among the more obvious variables are the aiming point for a given target, yield of weapon, height and nature of burst, bombing errors, topography of the target, and weather conditions.

12.3 In general, there are two categories of protection against weapons effects; they may be summed up as "distance" and "shielding." In other words, it is necessary either to get beyond the reach of the effects, or to provide protection against them within their radii of damage. The first principle, that of distance, determines the Civil Defense concept of evacuation of populations from potential target areas.[1] In any discussion of evacuation, this book is of value only as an aid to determining what might constitute a safe distance for evac-

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[1] The evacuation problem is treated in the following publications of the Federal Civil Defense Administration: "Procedure for Evacuation Traffic Movement Studies," TM–27–1; "Evacuation of Civil Populations in Civil Defense Emergencies," TB–27–1; "Evacuation Check List," TB–27–2.

uees, bearing in mind that the effect of fallout enormously complicates the evacuation problem by producing a hazard far beyond the zone of direct damage. Consequently, this chapter will be devoted only to some of the considerations involved in the principle of shielding, which may also be defined as shelter or protective construction.

12.4 The problem of protection by the provision of suitable shielding is itself a very complex one. It is not quite as difficult, however, as the existence of so many factors, as mentioned in § 12.1, might imply. In many cases, proper precautions against blast, shock, and fire damage would also decrease the hazards to personnel from various radiations, both thermal and nuclear.

12.5 As far as burning caused by thermal radiation is concerned, the essential points are protection from direct exposure for human beings, and the avoidance of easily combustible trash and dark-colored materials, especially near windows. The only known defense against gamma rays and neutrons present in the nuclear radiations is the interposition of a sufficient mass of material between the individual and the nuclear bomb, including the rising ball of fire and the subsequent fallout, if any. The use of concrete as a construction material, which is desirable for reducing air-blast and ground-shock damage, will diminish to a great extent the nuclear radiation hazard. The addition of an earth cover will be helpful in this connection.

12.6 From the standpoint of physical damage, the problems of construction to resist the action of blast from nuclear weapons are somewhat different from those associated with bombs of the conventional type. A TNT bomb will generally blow a building into pieces, but a nuclear weapon causes failure by collapsing or pushing over the structure as a whole. The relatively long duration of the blast wave from the large energy release of a nuclear explosion, as compared with that from an ordinary explosion, results in a significant difference in the nature of the effects (see Chapter III).

12.7 Another important difference between the consequences of nuclear and conventional explosions is the great increase in the area damaged in the former case. Even bombs of 20-kiloton energy yield, such as were exploded over Japan, can cause devastation over an area of several square miles (Fig. 12.7). With weapons in the megaton range, the damaged region may cover a hundred or more square miles.

## General Consideration of Protective Measures

12.8 The most effective, but not necessarily most practical, method of minimizing the danger from nuclear weapons would be by dispersal

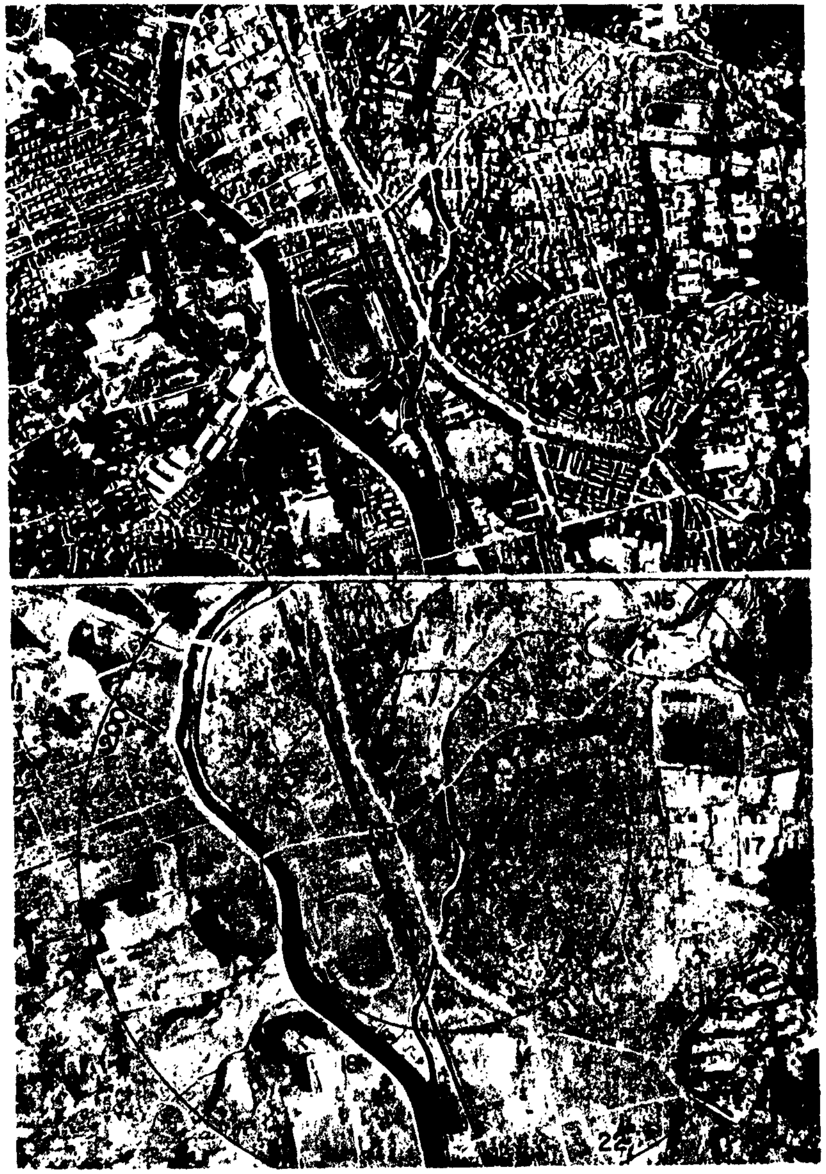

Figure 12.7. Area around ground zero at Nagasaki before and after the atomic explosion (1,000-foot radius circles are shown).

and underground construction. These measures are beyond the scope of the present discussion, but mention will be made of a number of other steps which can be taken to reduce both the personnel casualties and the physical damage caused by a nuclear explosion. The essential purpose of the treatment given here is to provide some of the basic information necessary for planning protective and control actions. The development of procedures and the dissemination of information regarding them is the function of the Federal Civil Defense Administration.

12.9 The design of new construction affords the best opportunity for the inclusion of protective measures at minimum cost. But existing structures can, in many cases, be modified so as to make them more resistant to blast, fire, and radiation, thus increasing the protection they would afford both to personnel and equipment. For example, blast damage can be reduced by increasing the strength of a structure, particularly against lateral forces. The fire hazard may be diminished by avoidance of exposed inflammable materials. Finally, some protection against gamma radiation and neutrons can be achieved by sufficient thickness of structural material.

12.10 In later sections of this chapter various suggestions will be made in connection with the design of new structures and the improvement of those already in existence. These apply in particular, however, to multistory buildings to be used for commercial, industrial, or administrative purposes. As far as ordinary dwellings are concerned, there is not a great deal that can be done, without unjustifiable increase in cost, to strengthen the superstructure against the effects of blast. Basement walls, structural supports for girders, and first-floor systems over the basement can be strengthened appreciably at reasonable cost, and shelters can be included in the basement area.

12.11 A blast wave having a peak overpressure of about 2 pounds per square inch will cause considerable damage to most dwellings, and it is doubtful whether it is practical to build a house, at a reasonable cost, which will survive more than 5 pounds per square inch peak overpressure. Structures of industrial and strategic value can be built to resist overpressures of 25 pounds per square inch or more when the extra cost is warranted.

12.12 Before proceeding with a discussion of the design of such structures, it is necessary to prescribe the conditions, e. g., blast overpressure and initial nuclear radiation intensity, against which the structure may be expected to offer protection. Of course, in making a choice, a definite risk must be accepted, since the conditions actually experienced in a nuclear attack may be more or less severe than those selected for design purposes, depending on the size of the weapon and the distance of the explosion from the structure. The alternative would seem to be to make the structure extremely strong, so that it could withstand high blast overpressures, possibly 100 pounds per square inch. Such an alternative imposes extreme requirements, such as underground construction. This would involve full dependence upon artificial lighting and air conditioning, and provision of an independent power supply and other disaster-proof facilities and services (see § 12.52).

12.13 In the great majority of structures, the design must represent a compromise between its ability to withstand various nuclear weapon effects, the strategic importance of the building, and the complexity and cost of construction. In making a decision concerning what may be called the practical design conditions, Fig. 12.13 may be consulted. This shows the limiting distances from ground zero, for air bursts of various energy yields, for the production of certain effects with respect to the initial nuclear radiation (gamma rays and neutrons), thermal radiation, and blast overpressure. It may be noted that only the strongest reinforced-concrete structures can resist overpressures of 24 pounds per square inch, and most homes will be destroyed or severely damaged at 5 pounds per square inch. (The dynamic pressures indicated on the curves in Fig. 12.13 are the values of the horizontal components for typical air bursts.) A dose of 700 rems of nuclear radiation may be expected to be fatal to nearly all exposed individuals.

## BLAST-RESISTANT STRUCTURES

### General Design Methods

12.14 The design of blast-resistant structures requires consideration of the effect of dynamic loading on the structure in question. As described in earlier chapters, the dynamic loading to be taken into account is applied suddenly and varies with time. The time variation is dependent upon the characteristics of the blast wave itself and the shape, dimensions, and strength of various parts of the structure. The determination of the response of a structure to a dynamic load involves a technique entirely different from that used in the conventional study of structural response to a static load (see Chapter VI).

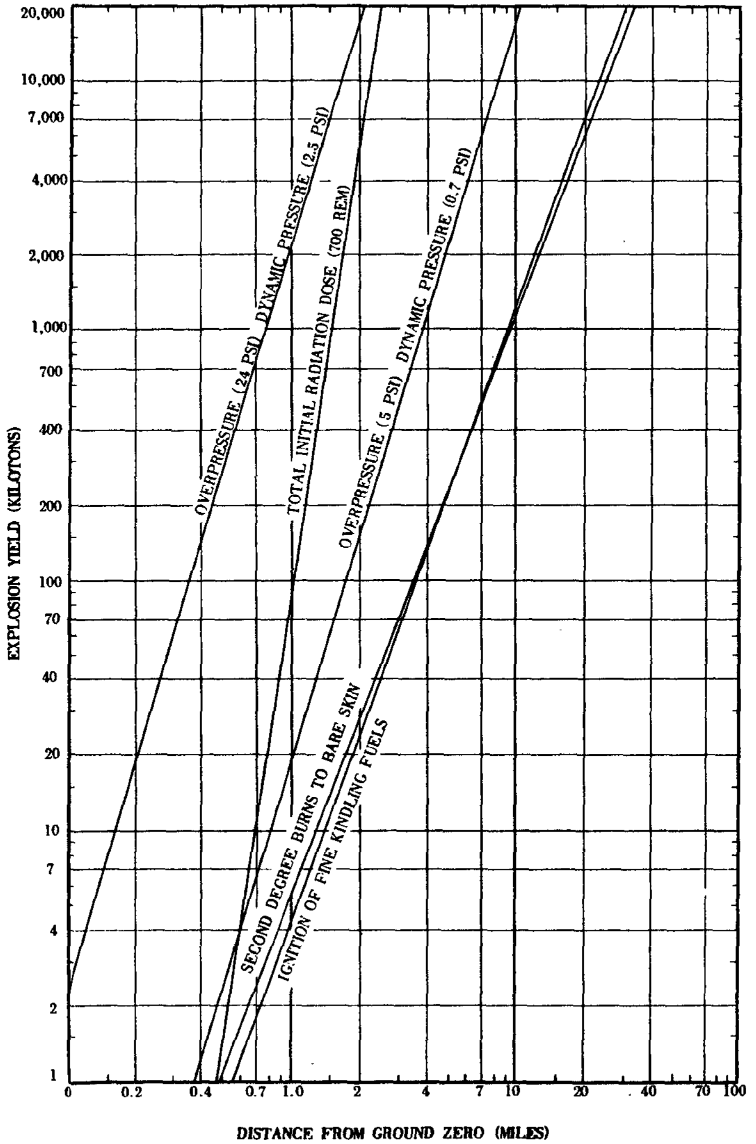

**Figure 12.13.** Limiting distances from ground zero at which various effects are produced, in an air burst.

12.15 In general, there are three main aspects in which blast-resistant design differs from the design procedures for static loads. First, mass is important, since, as structural displacement takes place, the various masses undergo large accelerations. Other things being equal, a heavy structure will usually withstand the action of blast better than one that is less massive. Second, many structural materials, including steel, concrete, and even wood, exhibit increased strength when subjected to rapid rates of strain, such as would occur when exposed to a blast wave. For high rates of loading the yield point may be increased 50 percent or more over the value at low rates of loading. Third, if ductile materials are used in blast-resistant design, it is possible and may be desirable for economic reasons to permit strains beyond the elastic limit.

12.16 Some degree of permanent deformation may be acceptable before a structure is rendered useless for its main purpose, and this can be taken into consideration in its design. The steel-mill type of building is a good example of a structure in which large permanent deformation may be accepted. On the other hand, office buildings, apartment houses, etc., containing elevator shafts, partitions, doors, windows and concealed utilities, may have their usefulness impaired by much smaller deformations.

12.17 In designing a particular type of structure to resist blast, it is necessary first to postulate the blast wave characteristics, i. e., the peak overpressure and dynamic pressure, and their variation with time. These factors depend upon the energy yield of the explosion, the expected distance of the structure from the point of burst, and the height of burst. Since none of these variables can possibly be known in advance, the postulates concerning the blast load which the structure is required to withstand inevitably involve considerable uncertainty. The choice of the blast load for design purposes must be based on a balance between the cost and the over-all importance of the particular structure.

12.18 After the loading has been prescribed, a dynamic analysis of the proposed structure must be undertaken to determine the stiffness and ultimate strength necessary to prevent collapse or to limit the plastic deformation to some specified amount. This limit will be determined by the functional requirements of the activities or operations for which the structure is to be used. The critical deformation may be restricted to that which will prevent the structure from collapsing, so that personnel can be protected and the contents of the building salvaged; or it may be required that the building shall still be capable of use for conventional loads after the blast. The next step in the design is then to prepare specifications of the structural members and connections to supply the required strength and stiffness.

12.19 The detailed methods and procedures of dynamic design are probably necessary in order to predict accurately the behavior of a structure exposed to loading from a blast wave. However, this requires familiarity with methods not customarily used in conventional engineering design.

### STRUCTURAL MATERIALS

12.20 In choosing structural materials it should be borne in mind that the energy absorbed by a structure undergoing plastic deformation can make an important contribution to resistance to dynamic loading. Brittle materials, e. g., glass, cast iron, and unreinforced masonry, cannot tolerate strains beyond the elastic limit without suffering failure by rupture. Upon failure, these materials can produce dangerous missiles and so should be avoided for this reason also (see § 12.35). On the other hand, ductile materials, e. g., structural steel, reinforced concrete, and reinforced masonry, can undergo considerable plastic deformation without collapse and, in many cases, without appreciable loss of strength.

12.21 Reinforced concrete offers many advantages as a structural material, since it has characteristics desirable in blast-resistant construction. The large mass and sluggish response of the relatively heavy members, and the continuity which is possible, contribute to the ability to withstand lateral forces. Concrete can be used for shear walls which provide resistance to motion and add little to the cost of the building.[2] The bulkiness of the members may be somewhat objectionable, although thick concrete walls can help in attenuating nuclear radiation.

### TYPES OF BLAST-RESISTANT MULTISTORY STRUCTURES

12.22 The type and arrangement of a structure designed to have appreciable resistance to blast will depend, to some extent, upon the intended use of the structure. In general, the ability to withstand the lateral forces due to blast will increase with the strength, rigidity, ductility, and mass of the members enclosing and supporting the structure. There are, however, certain structural forms which are inherently more suited to resist blast loading.

12.23 If the presence of solid or almost solid exterior walls and cross walls can be tolerated in the functional layout of the building, a satisfactory and economical design for a multistory structure appears to be a reinforced-concrete, shear-wall building. Shear-wall structures derive their principal strength from structural walls capable of resisting large lateral loads. Such walls are usually so stiff compared to beams and columns, which may be used in conjunction with shear walls, that essentially all the translational load is carried by these walls.

12.24 Where interior walls are required as fire barriers, stairwell enclosures, or partitions, these may be designed, with advantage, as shear walls. The same walls can then be used to carry vertical loads, thus replacing the framing ordinarily employed for this purpose. It is desirable, however, in the construction of bearing walls, supporting floor and roof systems, to avoid the use of unreinforced brick, stone, or block, since they are vulnerable to relatively low pressures acting transversely to the walls.

12.25 When the operations to be performed in the building are such as to rule out solid (or nearly solid) exterior walls, then partially solid shear walls at the ends of the building, in addition to fire walls and fixed partitions of shear-wall design, are desirable. This will permit the use of light columns designed to carry the vertical loads for the rest of the framing. Even if shear walls are limited to stairwells, elevator shafts, and to walls around the plumbing and duct passages, an important degree of blast resistance can be achieved at minimum cost.

12.26 The presence of window openings and light curtain walls may have some advantages. Windows and light partitions will fail rapidly, when exposed to blast, without offering substantial resistance. As a result there will be a decrease in the lateral impulsive load, due to the reduction in the effective resisting area, before appreciable deformation occurs. While these openings might be helpful in minimizing damage to the frame and decreasing the danger of overturning, they may be expected to increase both the hazard to personnel in the building and the destruction of its contents.

12.27 In the construction of a reinforced-concrete building it is essential that there should be good continuity at all joints subject to appreciable bending or shearing stresses in order to insure monolithic behavior. All intersecting walls and floors should be securely doweled together with reinforcement, and construction joints between previ-

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[2] Shear walls are walls (or partitions) designed for horizontal loads applied in the plane of the wall, as distinct from loads perpendicular to the wall. Shear walls may, of course, be designed to take such lateral loads as well.

ously poured and fresh concrete should be prepared to provide maximum bonding between the old and the new.

12.28 A reinforced-concrete structure, with shear walls and partitions having good continuity, will act as a single cell. The walls of the structure will then transmit floor and roof reactions to the foundations. Heavy beams or supporting columns can thus be eliminated and good resistance to blast forces retained.

12.29 For steel-frame structures with diagonal bracing there is a possibility of complete failure by local rupture of the bracing material. Sufficient load-carrying capacity must be provided in the bracing to prevent this from occurring. In order to insure full utilization of the members of the frame, the strength of the end connections of a diagonal brace should always be greater than that of the member itself.

12.30 In tier buildings with steel skeleton frames, the strength of the end connections should be sufficient to develop the ultimate strength of the members of the frame. If the floor slabs are keyed to the structural steel frame by means of bond or shear developers, so as to provide composite behavior, both the steel and the concrete contribute strength to the framework. Wall panels should be attached to the building frames in such a manner that the connections will withstand rebound loads as well as the positive and negative loads due to the blast wave.

### Reducing Blast Hazard in Existing Buildings

12.31 Aside from the question of the design of new construction considered above, there is the possibility of making changes in existing buildings so as to reduce the damage to their contents and injury to personnel resulting from blast action. This is a more difficult problem than that of incorporating appropriate measures in new design. The most serious danger to persons and equipment in a building is from total, or even partial, collapse. It is necessary, therefore, to analyze the structure in order to discover the weak points, and then to determine the best methods for strengthening them.

12.32 As a general rule, it will not be possible to strengthen the frame of a reinforced-concrete building, but increased resistance to collapse can be achieved by replacing interior walls, wherever possible, by shear walls. The addition of bracing can be effective in increasing the strength of a steel-frame building.

12.33 From an over-all point of view, an important consideration is the reduction in hazard to persons in a building strong enough not to collapse even though it might be damaged to some extent. Well-attached, reinforced-concrete or reinforced-masonry walls, on a frame of either structural steel or reinforced concrete, will provide a high degree of protection to persons inside the building. This type of construction will also contribute a minimum number of missiles. A poorly attached wall of unreinforced masonry, on the other hand, would provide almost no protection inside the building and would supply missiles both inside and outside.

12.34 Existing frames of steel or reinforced concrete may be strengthened by filling the areas between the columns and beams with shear walls. The effectiveness of such walls will depend upon their strength and also upon the strength of the connections between shear walls and floors, since in order for such walls to be effective they must carry the lateral forces to the foundation. Inclusion of shear walls of this type in a frame structure creates a new unit of greatly increased strength.

12.35 In all structures, no matter how blast resistant they may be, it is important to minimize the danger from flying glass, displaced equipment, falling fixtures, and false ceilings. The great hazard to personnel due to glass should be considered in design, and glass areas should be provided only to the extent essential for the use of the building.

12.36 Consideration should be given to the hazard in existing structures from fixtures and heavier ornamental plaster or other interior treatment that might be detached by the blast or by the wracking action of the building. The best procedures would be to remove any such hazardous items if possible. If this is not fully practicable, such partial safeguards should be provided as may appear feasible. Overhanging cornices and finials on the outside of a building will be a danger to persons in the vicinity, and their removal should be considered. Although the flying missile hazard is not peculiar to nuclear weapons, it is, nevertheless, one which is greatly magnified by the high pressures and long duration of the blast wave.

12.37 Blast walls of the type employed to localize destruction from ordinary high-explosive bombs will perhaps be helpful, to some extent, in reducing injuries from flying missiles and in protecting essential equipment (Figs. 12.37a and b). Particular care should be taken to make such walls resistant to overturning. Both reinforced-concrete walls and earth-filled wooden walls (Fig. 12.37c) were used in Japan for protection against blast. The former were more effective, but the latter, even though badly damaged by the nuclear bomb blast, did prevent serious harm to equipment.

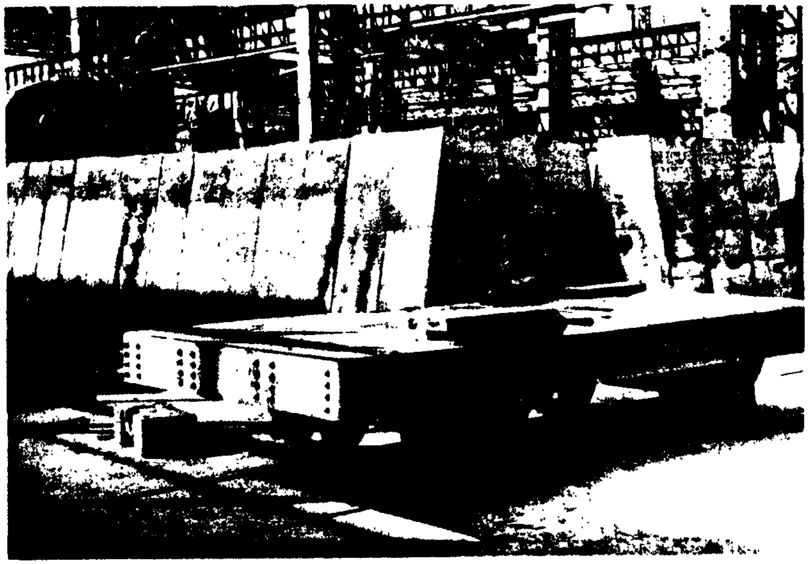

Figure 12.37a. Precast, reinforced-concrete blast walls (0.85 mile from ground zero at Nagasaki).

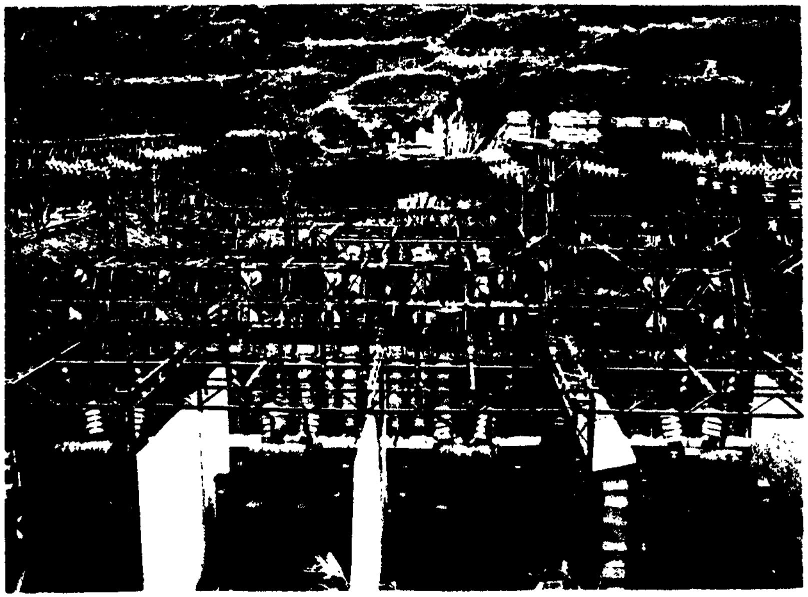

Figure 12.37b. Reinforced-concrete blast walls protecting transformers (1 mile from ground zero at Nagasaki).

Figure 12.37c. Earth-filled, wooden blast walls protecting machinery (0.85 mile from ground zero at Nagasaki).

## PROTECTION BY TRENCHES AND EARTH REVETMENTS

12.38 Although they are not strictly structures, in the sense used above, attention should be called to the significant protection that can be afforded by trenches and earth revetments, especially to drag-sensitive targets. A shallow pit provides little shielding, but pits or trenches that are deeper than the target have been found to be very effective in reducing the magnitude of the drag forces impinging on any part of the target. In these circumstances, the lateral loading is greatly reduced and the damage caused is restricted mainly to that due to the crushing action of the blast wave.

12.39 The only types of shielding against drag forces which have been found to be satisfactory so far are those provided by fairly extensive earth mounds (or revetments) and deep trenches, since these are themselves relatively invulnerable to blast. Such protective trenches are not recommended for use in cities, however, because of the damage that would result from debris falling into them. Although sandbag mounds have proved satisfactory for protection against conventional high explosives and projectiles, they are inadequate against nuclear blast because they may become damaging missiles.

Figure 12.40a. Earth-moving equipment subjected to nuclear blast in open terrain (30 psi overpressure).

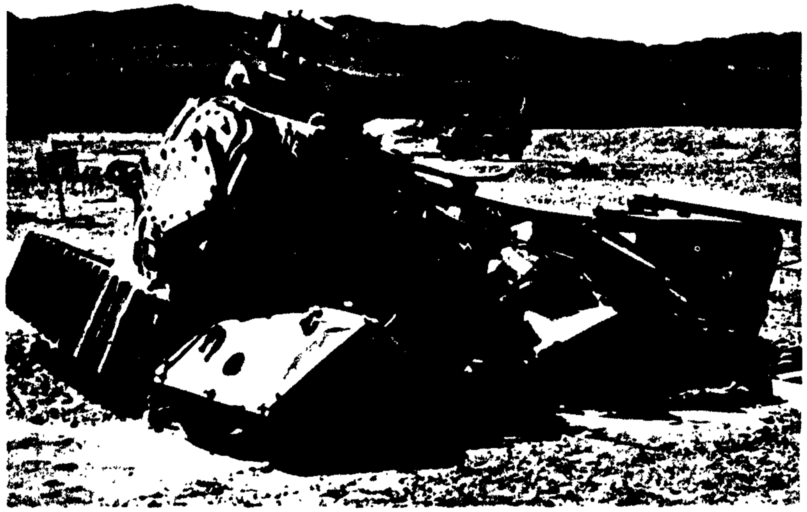

Figure 12.40b. Earth-moving equipment subjected to nuclear blast in open terrain (30 psi overpressure).

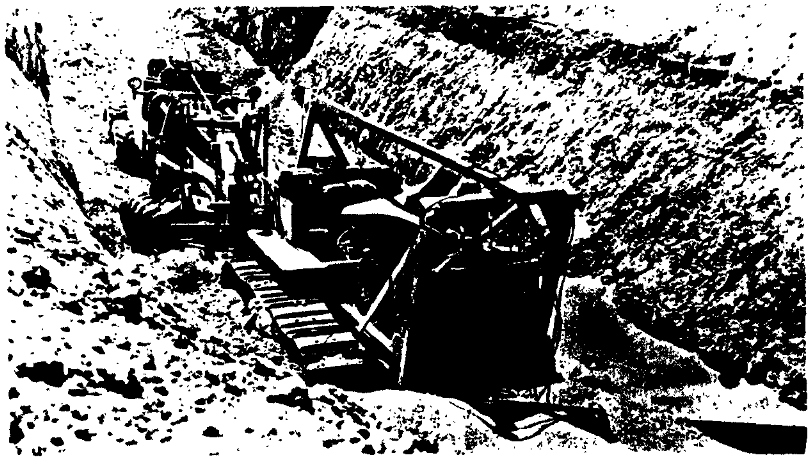

Figure 12.40c. Earth-moving equipment protected in deep trench at right angles to blast wave motion (30 psi overpressure).

12.40 The destruction caused by a nuclear explosion to two pieces of earth-moving equipment, which are largely drag-sensitive, is shown in Figs. 12.40a and b. Two similar pieces of equipment located in a deep trench, at the same distance from the explosion, are seen in Fig. 12.40c to have been essentially unharmed. It is important to mention that the main direction of the trench was at right angles to the motion of the blast wave. If the wave had been traveling in the same direction as the trench, the equipment would probably have been severely damaged. Consequently, in order to provide protection from drag forces, the orientation of the trench or earth revetment, with respect to the expected direction of the explosion, is of great importance.

## Fire Protection

12.41 It was noted in Chapter VII that fires following a nuclear explosion may be started by thermal radiation and by secondary effects, such as overturning stoves and furnaces, rupture of gas pipes, and electrical short circuits. Fire-resistive construction and avoidance of fabrics and other light materials of inflammable character are essential in reducing fire damage. As shown by the tests described in § 7.82, a well-maintained house, with a yard free from inflammable rubbish, was less easily ignited by thermal radiation than a house that has not had adequate care.

12.42 The methods of fire-resistive design and of city planning are well known and the subject need not be treated here. A special requirement is the reduction of the chances of ignition due to thermal radiation by the avoidance of trash piles and other finely divided fuel as well as combustible, especially dark colored, materials that might be exposed at windows or other openings. It has been recommended, in this connection, that all such openings be shielded against thermal radiation from all directions. The simple device of whitewashing windows will greatly reduce the transmission of thermal radiation and so decrease the probability of fires starting in the interior of the building. Other practical possibilities are the use of metal venetian blinds, reflective coatings on the window glass, and nonflammable interior pull curtains.

12.43 To judge from the experience in Japan, where the distortion by heat of exposed structural frames was considerable, it would appear desirable that steel columns and other steel members be protected from fire, especially where the contents of the building are flammable or where the building is located adjacent to flammable structures. Further, narrow firebreaks in Japan were found to be of little value. It is vital, therefore, that such firebreaks as may be provided in city planning or by demolition must be adequate for a major conflagration. A minimum width of 100 feet has been suggested.

12.44 One of the most important lessons learned from the nuclear bomb attacks on Japan is the necessity for the provision of an adequate water supply for the control of fires. In Nagasaki, the water pressure was 30 pounds per square inch at the time of the explosion, but chiefly because of numerous breaks in house service lines it soon dropped to 10 pounds per square inch. On the day following the explosion the water pressure was almost zero. This drop in the pressure contributed greatly to the extensive damage caused by fire. The experience in Hiroshima was quite similar.

## SHELTERS FOR PERSONNEL

### Introduction

12.45 Ideally, a shelter for personnel might be required to provide protection against air blast, ground shock, thermal radiation, initial nuclear radiation (neutrons and gamma rays), and residual nuclear radiation from fallout (external and internal sources). Such an ideal shelter is, however, virtually impossible to attain, in view of the uncertainties mentioned in § 12.2. Thus, shelter design, like that of other types of structures, must inevitably represent a compromise involving an element of risk. For example, structures of special design (see § 12.53), located underground, can withstand blast overpressures of 100 pounds per square inch or more and can greatly attenuate nuclear radiation. With suitable ventilation systems they can also protect against fallout, as well as against chemical and biological warfare agents. But even these shelters would probably be destroyed if they were fairly close to ground zero in the event of either a surface burst or a shallow underground burst.

12.46 A variety of personnel shelters have been designed and several types have been subjected to nuclear test explosions. These shelters range from minor modifications to existing homes, for use by a small family, to special blast-resistant construction, for buildings housing fairly large groups of individuals. For houses with basements, simple, inexpensive shelters can provide additional protection that could mean survival in a nuclear attack. If there is no basement, other worthwhile measures can be taken, although they would cost more.

12.47 In the design of special shelters for the protection of personnel, underground (or earth-covered) structures are preferred, since they reduce the hazards from thermal and nuclear radiations, as well as from air blast, at a moderate cost. In the design of such shelters there are three fundamental problems which must always be considered; these are (1) the structural (engineering) design; (2) proper ventilation of the occupied areas; and (3) the provision of adequately protected entranceways.

12.48 Past experience from nuclear tests has indicated that standard engineering practices are adequate for the design of underground shelters which will withstand air blast overpressures of 100 pounds per square inch. If the particular situation is such that a smaller design pressure would appear to be adequate then, as a general rule, it will be found more economical to use a shallow underground or earth-covered shelter of a simpler type. For example, the light earth-covered or buried structures referred to in Table 6.12, would not be seriously damaged by blast overpressures of 20 to 30 pounds per square inch. More vulnerable to air blast than the structures themselves are the ducts and ventilating equipment, which bring in the air supply, and the doors, door frames, and entranceways. These consequently require special consideration.

12.49 To insure an adequate supply of uncontaminated air during the critical period of occupancy of the shelter, the ventilating equipment and filters must remain in operating condition. This requires that intake and exhaust ducts be provided with some type of blast-arresting devices. Such devices should reduce the intensity of the blast force to the extent that the mechanical equipment and filters will not be harmed, and also that it will not be a hazard to persons in the shelter.

12.50 The entranceways to the shelter must be at least large enough to allow free access for personnel, and possibly to accommodate vehicular traffic. In addition, it is particularly important that the doors be designed to resist collapse, since the entrance of the blast wave through an opening, such as a doorway, might cause a sudden pressure rise inside the structure to a level that would be harmful to the occupants. It is always desirable that each doorway into the shelter be associated with an entranceway so placed that it will act as a blast-arresting device and also provide protection against flying missiles which might damage the door.

## FAMILY-TYPE (HOME) SHELTERS

12.51 It will be recalled from Chapter IV that, even when the houses exposed to the nuclear explosions were so severely damaged, by a blast overpressure of 5 pounds per square inch, as to be rendered useless, the basements suffered little damage. Since no appreciable amount of thermal radiation would penetrate and the depth of soil outside the house would result in a considerable attenuation of the nuclear radiation, it would appear that basements offer possibilities as home shelters. Several designs for basement shelters have been tested in Nevada.

12.52 In houses without basements or where the water table makes it difficult to construct a shelter below the ground, the bathroom may be designed so that it can serve as an indoor shelter. This can be achieved by making the walls and ceiling of reinforced concrete and strengthening the floor slab (see § 4.34). The window and door openings are protected by special blast doors. A shelter of this type will provide good protection against blast, up to 5 pounds per square inch overpressure, at least, and also against thermal radiation. The degree of protection against nuclear radiation depends primarily on the thickness of the concrete walls and ceiling; the greater the thickness, the better the protection.

## UNDERGROUND PERSONNEL SHELTER

12.53 Where essential industrial, civic, or military activities must be maintained before, during, and after a nuclear attack, it might be desirable to have a group shelter which could be occupied continuously, although not necessarily by the same individuals. A shelter of this kind would be of the closed type and would have to be provided with a suitable ventilating system. As a result of various tests, it has been found that in "open" shelters, i. e., in shelters which are open to the entry of the blast, the peak overpressure of the blast wave is not very different from that outside. Some reduction can be achieved by suitable design of the entrance and by the use of baffles, but the general impression is that, in strategic locations, where high overpressures may be expected, open group shelters would not be adequate.

12.54 The general features of a closed, underground personnel shelter, that can accommodate some 30 individuals at a time, but can be extended to hold more, are shown in Fig. 12.54. The design is based on experience gained at various nuclear tests in which shelters of this type have withstood peak overpressures of about 100 pounds per square inch. It was also found, as expected, to produce considerable attenuation of both gamma rays and neutrons.[3]

12.55 The main shelter chamber has reinforced-concrete walls 15 inches thick; the floor slab has a thickness of 18 inches and that of the roof is 21 inches. The chamber is covered with packed earth to a depth of at least 5 feet. The entrance is by concrete steps, in two sections at right angles. Instead of extending in the direction shown in the figure, the entranceway may be turned through 180°, so as to make the whole lay-out more compact. The stairway at the ground level is closed by means of an 8-inch thick horizontal door made of structural steel and reinforced concrete. The door has four wheels and is track mounted. It is so designed that as it rolls closed it seats itself on steel bed plates on each side of the stairwell, so that the blast load is removed from the wheels and axles. A heavy jack is mounted on the underside of the ceiling of the stairwell, so that the door can be forced open in case there is an accumulation of debris in the well behind the door.

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[3] The shelter described here was conceived and planned by the Federal Civil Defense Administration, with the assistance of the Army Ballistics Research Laboratory, the Army Chemical Center, and the Armed Forces Special Weapons Project. The structural design was by Ammann and Whitney, Consulting Engineers, under contract to the Federal Civil Defense Administration.

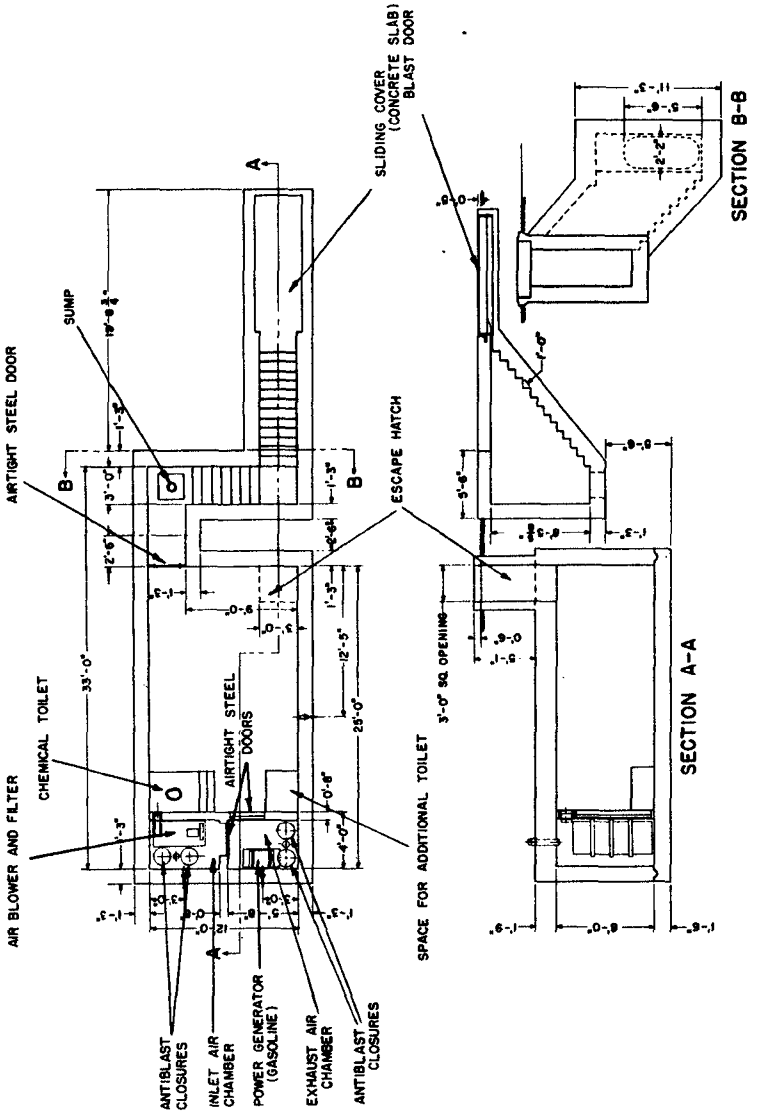

Figure 12.54. Sectional plan and section of underground personnel shelter.

12.56 Entrance to and exit from the shelter chamber is through a doorway fitted with a ½-inch steel, air tight (Navy bulkhead type) door. For emergency exit there is a 3 x 3-feet vertical escape hatch with a steel trap door. Normally the hatch is filled with washed and dried sand, but this can be run out and personnel can escape by climbing a vertical ladder in the wall.

12.57 The ventilation system for the shelter is contained in two compartments shown at the extreme left in Fig. 12.54. Air from outside enters the inlet chamber, passes through a filter, to remove particulate matter, e. g., fallout, as well as biological and chemical warfare agents, and is then blown into the shelter through ducts near the ceiling. The return air is expelled through the exhaust chamber. Both inlet and exhaust systems are fitted with special "antiblast closures." These are so constructed that a sudden increase in the exterior pressure, due to the passage of a blast wave, will cause them to close almost instantaneously. Relief of the pressure by the negative phase of the blast wave will then open them again. The closures have been found to operate satisfactorily at peak overpressures up to at least 100 pounds per square inch.

12.58 The exhaust chamber also contains a gasoline-driven, electric generator for emergency use in the event of failure of the main power supply. An underground tank holds enough fuel for 10 days. At the other end of the shelter is a buried water tank to provide water for drinking purposes.

## EMERGENCY SHELTERS

12.59 From experience gained in both nuclear and conventional explosions, there is little doubt that it is, as a general rule, more hazardous in the open than inside a structure. In an emergency, therefore, the best available shelter should be taken. Many subways would provide reasonably good emergency shelter, but they are to be found in a limited number of cities. As an alternative, that is more readily available, the basement of a building should be chosen. In this connection, a fire-resistive, reinforced-concrete or steel-frame structure is to be preferred, since there is less likelihood of a large debris load on the floor over the basement. Even basements of good buildings are not, however, an adequate substitute for a well-designed shelter, since the design live loads of floors over basements are usually small in comparison with the blast overpressure to which these floors may be subjected.

12.60 In the event of a surprise attack, when there is no opportunity to take shelter, immediate action could mean the difference between life and death. The first indication of an unexpected nuclear explosion would be a sudden increase of the general illumination. It would then be imperative to avoid the instinctive tendency to look at the source of light, but rather to do everything possible to cover all exposed parts of the body. A person inside a building should immediately fall prone and crawl behind or beneath a table or desk. This will provide a partial shield against splintered glass and other flying missiles. No attempt should be made to get up until the blast wave has passed, as indicated possibly by the breaking of glass, cracking of plaster, and other signs of destruction. The sound of the explosion also signifies the arrival of the blast wave.

12.61 A person caught in the open by the sudden brightness due to a nuclear explosion, should drop to the ground while curling up to shade the bare arms, hands, neck, and face with the clothed body. Although this action may have little effect against gamma rays and neutrons, it might possibly help in reducing flash burns due to thermal radiation. The degree of protection provided will vary with the energy yield of the explosion. As stated in § 7.53, it is only with high-yield weapons that evasive action against thermal radiation is likely to be feasible. Nevertheless, there is nothing to be lost, and perhaps much to be gained, by taking such action. The curled-up position should be held until the blast wave has passed.

12.62 If shelter of some kind, no matter how minor, e. g., in a doorway, behind a tree, or in a ditch, or trench can be reached within a second, it might be possible to avoid a significant part of the initial nuclear radiation, as well as the thermal radiation. But shielding from nuclear radiation requires a considerable thickness of material and this may not be available in the open. By dropping to the ground, some advantage may be secured from the shielding provided by the terrain and surrounding objects. However, since the nuclear radiation continues to reach the earth from the atomic cloud as it rises, the protection will be only partial. Further, as a result of scattering, the radiations will come from all directions.

## PROTECTION FROM FALLOUT

### Passive and Active Measures

12.63 Protection against the residual nuclear radiation from fallout presents a number of difficult and involved problems. This is so not only because the radiations are invisible, and require special instruments for their detection and measurement, but also because of the widespread and persistent character of the fallout. In the event of a surface burst of a high-yield nuclear weapon, for example, the area contaminated by the fallout could be expected to extend well beyond that in which casualties result from blast, thermal radiation, and the initial nuclear radiation. Further, whereas the other effects of a nuclear explosion are over in a few seconds, the residual radiation persists for a considerable time.

12.64 The protective measures which can be taken against sources of residual nuclear radiation fall into two main categories, namely, passive and active. Passive protection implies remaining in the contaminated area while taking all possible shelter from the gamma rays, in particular, emitted by the fission products in the fallout. As seen in Chapter IX, even the basement of a frame house can attenuate the radiation by a factor of about 10, and greater reduction is possible in a large building or in a shelter covered with several feet of earth.

12.65 There are two aspects of active protection which will be considered. One is evacuation, that is, removal of the population from a contaminated location to one that is either free from contamination or, at least, less contaminated. This action is by no means as simple as might at first appear, because it will generally involve passage, without protection, through contaminated areas. The resulting radiation exposure may thus be greater than if passive protective measures were taken without evacuation.

12.66 The other possible active procedure is decontamination after the fallout has settled. In most circumstances steps of one kind or another can be taken to decrease the amount of fallout in critical regions, e. g., roofs of houses and streets. Some of the more general methods of decontamination will be discussed later. It should be mentioned, however, that the procedures are inevitably hazardous, since they involve exposure of the operating personnel to fairly high levels of radiation.

12.67 The extent to which passive protection, evacuation, and decontamination should be practiced will depend upon the existing conditions and may vary widely from one case to another. It is impossible, therefore, to make any definite recommendations. The particular action taken must depend upon the judgment of responsible individuals, based on a knowledge of radiation intensities and various other factors, in addition to an appreciation of the characteristics of the residual nuclear radiation. A general guide to the possibilities may perhaps be provided by the discussion of a number of different circumstances in the following sections.

### PROTECTIVE ACTION

12.68 It was recognized at the beginning of this chapter (§ 12.3) that the concept of the evacuation of populations from potential target areas was greatly complicated by the possible effects of fallout. Some aspects of the situation which must be considered before the movement of large masses of individuals can be undertaken will be outlined here. First, there is always a possibility of a sudden change in the wind pattern, so that the evacuees might be moving unwittingly into the path of the fallout. A somewhat similar circumstance might develop as the result of further explosions, at other points, after evacuation had started. In any case, accurate prediction of the fallout pattern is very difficult and requires detailed and continuous knowledge of the wind pattern over a large area and to great heights. Once the order for evacuation has been given, it would be virtually impossible to rescind it or even to change the main direction of personnel movement.

12.69 It may be that the best initial step is to take passive protective measures by seeking shelter in relatively closed structures. The gamma radiations from sources external to the body will then be appreciably attenuated. In order to prevent contaminated material from entering the body, a ventilation system with filters for removing particulate matter may be a desirable feature. However, in most buildings, sufficient air leaks through cracks or penetrates through the walls to permit satisfactory breathing even with the doors and windows closed. It is true that some of the fallout may enter at the same time, but it is believed, on the basis of the experience of the inhabitants of the Marshall Islands in the 1954 nuclear tests (§ 11.115, *et seq.*), that inhalation of the contaminated particles will not be a serious hazard.

12.70 Since the shelters may have to be occupied continuously for a period of from 2 to 7 days (or more), depending upon the level of the contamination outside, supplies of food and water will be necessary. These should be kept covered to prevent access of fallout particles. If water is available the exposed food can be washed free of contamination before being eaten (see § 12.97).

12.71 At locations relatively near to ground zero, the fallout will arrive soon after the explosion and the radiation dose rate will initially be high. It may then be necessary to wait several days before it is possible to come out of the shelter without risking a radiation dose of sufficient magnitude to cause severe injury. Leaving the shelter to evacuate the area or to start preliminary decontamination operations, will represent a calculated risk, which should not be undertaken, except in dire emergency, without the advice of a monitor familiar with the radiation situation in the surrounding area.

12.72 The farther a point in the path of the fallout is from the explosion, in the same general direction, the lower will be the initial radiation level and the shorter will be the duration of the passive protection phase. However, in any area where the contamination is at all serious, it will probably be necessary to spend the first day or two after the explosion sheltered from the residual gamma radiation. During the early stages, the activity of the fission products in the fallout is very high, but by the end of 49 hours or roughly 2 days, it will have decreased to about 1 percent of the value at 1 hour after the explosion.

12.73 It is impossible to indicate in advance at what value of the external dose rate it may be permissible to leave the shelter. Much would depend upon the next stage, e. g., evacuation or decontamination (or both), and how long it will take, as well as upon the total dose already received during the passive protection phase. The graphs given at the end of this chapter should aid in the estimation of the approximate doses that might be received under a variety of conditions. Such information is necessary before a decision can be made in any given situation.

12.74 At the beginning of this discussion it was supposed that an appreciable time elapses between the explosion and the arrival of the fallout. If, for one reason or another, there is no prior warning, the steps to be taken are essentially similar to those described above. The first action should be to seek optimum shelter, providing the maximum attenuation of the gamma radiation originating from outside sources, as quickly as possible. Speed is essential, since the radiation intensity from the fallout is extremely high soon after the explosion, but drops fairly rapidly in the course of time. After a few days, the shelter may be evacuated by a route which will involve a minimum radiation exposure.

12.75 It is appropriate to emphasize here that the presence of dangerous fallout may not be visible to the eye, and its detection requires the use of suitable instruments sensitive to nuclear radiations. It is true that some (although not all) of the fallout in the Marshall Islands, after the test shot of March 1, 1954, could be seen as a white powder or dust. But this may have been due to the light color of the calcium oxide (or carbonate) of which the particles were mainly composed. Had the material been somewhat darker in color and the particles somewhat smaller in diameter, it is possible that the fallout would not have been seen. Continuous monitoring, with instruments, for radioactive contamination would thus appear to be essential in all areas in the vicinity of the burst.

### RADIOLOGICAL SURVEY

12.76 Soon after a nuclear explosion, general radiological surveys will have to be undertaken for a number of reasons. In the first place, it may be necessary for emergency crews to enter an area that is contaminated, and the level of the radiation intensity of the area must be known. The best, i. e., least contaminated, routes into and through the area should be determined. Further, persons sheltered within a contaminated region need radiological information from outside for the purpose of planning evacuation. In addition, highly contaminated areas must be located and marked to prevent accidental entry.

12.77. The most rapid method of estimating the extent of the radiation hazard in the early stages will probably be by means of an aerial survey. The great advantage of such a survey is that it can be carried out regardless of the debris, which would make roads impassable, or of the degree of contamination. Because of their long range in air, gamma rays from fission products on the earth's surface can be detected by sensitive instruments at a height of several thousand feet. Low-flying airplanes or helicopters carrying survey meters, which measure the gamma radiation dose rate, can fly over an affected area in accordance with a predetermined pattern. The initial flights might be at an altitude of 1,500 feet or so, where the radiation intensity is reduced by a factor of nearly 100 with respect to that on the surface (see Fig. 9.122). This could be followed by flights at lower levels, if necessary, for more exact identification of contaminated areas.

12.78 From the radiation intensities recorded by the survey instruments in the aircraft at a known altitude, it is possible to obtain a rough estimate of the dose rate, e.g., in roentgens per hour, which exists at the surface of the ground or water. The exact ratio between the reading in the air and the dose rate on the surface will depend on several factors, including the nature of the terrain and the time after the detonation at which the survey is made, because of the decrease in the energy of the gamma rays from fission products. If no more specific information is available, the data in Fig. 9.122 may be used to estimate the attenuation factor at a known altitude with reference to that on the ground.

12.79 The aerial survey is important because it can be made quickly and can provide valuable information which might be impossible to secure in any other way. Nevertheless, such a survey can serve only as a rough guide, and it must be supplemented by observations made on the ground. The information obtained from the measurements taken in the air will, however, help very greatly in planning the ground survey. In the first stages, the general extent of the contaminated area will be delineated, but later a more detailed investigation will be undertaken to determine the radiation levels at specific strategic points, to establish approximate dose-rate contours, and to locate "hot spots" of higher than average contamination.

12.80 It is important to remember that personnel performing monitoring operations will be continuously exposed to radiation, sometimes at high levels of intensity. As far as possible, they should be transported by vehicles which offer some degree of protection by attenuating the gamma radiation, e. g., by suitable shielding or distance. In order to avoid dangerous overexposure, the monitors must carry instruments which, at any time, indicate the total dose they have received. They will then know when they should return to headquarters, so that hitherto unexposed individuals may take their place and continue with the operation. If the results of a preliminary survey are available, some advance planning in this connection may be possible by using the graphs given at the end of this chapter.

### DECONTAMINATION PROCEDURES[4]

12.81 Since radioactive material cannot be destroyed, decontamination inevitably involves transfer of the source of the radiation, e. g., fallout, from a location where it is a hazard to one in which it can do little or no harm. All decontamination procedures thus have two basic aspects: first, the removal of the contaminant, and second, its disposal. Unless proper consideration is given to the latter aspect, the whole process may do little or no ultimate good. Covering the contamination without moving it, e. g., with a depth of soil, would be effectively combining both operations into one.

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[4] An extensive treatment of decontamination methods and equipment will be found in the manual (TM–11–6) entitled, "Radiological Decontamination in Civil Defense," prepared by the Federal Civil Defense Administration.

12.82 Decontamination may be either gross, i. e., rough, or detailed. Gross decontamination is the rapid, partial removal or covering of contamination on a large scale. Its purpose is to reduce the radiation dose rate as quickly as possible to a point where personnel can use a piece of equipment or remain within an area for a limited period of time, at least. Subsequently, detailed decontamination, which is a lengthy and thorough process, may be carried out. As a general rule, decontamination cannot (and need not) be complete. However, the procedure should be carried to the point where the situation no longer constitutes a significant hazard under the particular conditions of use or occupation.

12.83 The decision to undertake decontamination will depend upon the circumstances, and must involve a calculated risk. Since there is always a certain degree of danger to the operating personnel, the procedure should be deferred as long as is reasonably possible, so as to take advantage of natural radioactive decay. In some cases urgent action may be necessary, and decontamination may have to be started while the radiation level is still high. Such a situation might be met by replacement of the workers with fresh, previously unexposed, crews at short intervals.

12.84 There are a few useful general principles relating to contamination and decontamination which should be borne in mind. Because of its particulate nature, the fallout will obviously tend to collect on horizontal surfaces. Such surfaces will thus be more highly contaminated than vertical surfaces. Hence, in preliminary decontamination, at least, the latter can be ignored. Most of the fallout particles can be readily removed either by washing with a stream of water or by sweeping, preferably with a vacuum cleaner to avoid inhalation of dust.

12.85 Gross decontamination can generally be performed in one or other of these ways. For smooth, e. g., painted and metallic, surfaces, wet (washing) methods may be used, but for porous materials, e. g., fabrics, brick, concrete, and stone, dry methods are to be preferred. Broadly speaking, water washing can be employed outdoors and on the exterior of vehicles, whereas vacuum sweeping is more suitable for the interiors of buildings and vehicles. Experimental tests of decontamination procedures have shown that the major portions of contaminating material can be removed by these simple methods. Only a small part of the contamination is strongly held and requires more drastic treatment, e. g., with chemicals or abrasives.[5]

12.86 In a city, decontamination could be carried out by hosing the roofs of buildings and the streets with strong streams of water. The radioactive material would thus be transferred to the storm sewers, where it would represent only a minor hazard. As an alternative to hosing, the dose rate inside a building could also be reduced by covering the ground surrounding the building with uncontaminated earth or by removing the top layer of the ground to a distance with a bulldozer.

12.87 It is important to note, in connection with removal of contaminated earth, for the purpose just described or to provide a means of transit, that the gamma rays from fission products can travel considerable distances through air. For example, at 3 feet above the ground, roughly 50 percent of the dose rate received in the center of a large, flat, uniformly contaminated area comes from distances greater than 25 feet away, and about 25 percent from distances more than 50 feet away. Thus, complete removal of the contaminated surface from a circle 50 feet in radius would reduce the dose rate in the center to about one-fourth of its original value. However, if the contaminated earth were not completely removed, but just pushed to the outside of the circle, the dose rate would be considerably larger than one-fourth the initial value.

12.88 It is apparent, therefore, that if transit facilities are to be provided across open country which is contaminated over a large area, bulldozing the top few inches of contaminated soil to the sides will be satisfactory only if a wide strip is cleared. Thus, if the strip is 250 feet in width, the radiation dose rate in the middle will be reduced to one-tenth of the value before clearing. A similar result may be achieved by scraping off the top layer of soil and burying it under fresh soil. Something like a foot of earth would be required to decrease the dose rate by a factor of ten.

12.89 Badly contaminated clothing, as well as rugs, curtains, and upholstered furniture, would have to be discarded and buried or stored in an isolated location. When the radioactivity has decayed to a sufficient extent, or if the initial contamination is not too serious, laundering may be effective in reducing the activity of clothing and fabrics, to permit their recovery. Thorough vacuum cleaning of furniture might be adequate in some cases, but an instrument check would be necessary before further use.

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[5] Contamination due to neutron-induced activity is difficult to remove, but such contamination is of importance only near the explosion center (see § 9.18).

### PROTECTION OF OPERATING CREWS

12.90 All personnel entering a contaminated area, to perform survey monitoring, decontamination, or other emergency operations, should adapt their clothing to prevent the entry of dust. The main purpose of this precaution is to minimize the possibility of "beta burns" as a result of direct contact of the fallout with the skin (see § 11.94). It should be remembered, of course, that clothing offers virtually no protection against gamma radiation, and so this hazard will still exist to an undiminished extent.

12.91 For dry operations, heavy pants and shoes are recommended, as well as cotton or canvas work gloves and a tight-fitting cap. In dusty areas it is advisable that the bottoms of the pants and the ends of the sleeves (over the gloves) be tied to prevent the entry of contaminated material. A scarf around the neck would also help in this connection. After a nuclear attack, the dust may arise from rubble, disturbance of the ground, etc., and may not necessarily be radioactive. Precautions to reduce inhalation of the dust in large amounts would be desirable, in any event. Consequently, in operations in which considerable quantities of dust may be encountered, goggles and a filter mask are advisable.

12.92 For wet decontamination operations, water-repellent clothing, rubber boots, and rubber gloves will be required (Fig. 12.92). They can be cleaned with a stream of water and used several times, provided there are no breaks or tears.

12.93 In addition to taking steps to prevent radioactive material from reaching the skin, workers will need protection from excessive exposure to radiation. For this purpose, each operator should carry a self-indicating meter, sometimes called an "organizational dosimeter," to record his total radiation exposure. Various types of dosimeters have been devised, and simple and reliable instruments, that can be produced cheaply and in large numbers, are available.[6]

12.94 Survey meters for the determination of radiation intensities (dose rates) will be required in order to detect regions of high activity and for estimating permissible times of stay in a contaminated area. As a general rule, instruments which measure the dose rate of gamma radiation will be satisfactory. In addition, special instruments sensitive to beta radiations are advantageous for such purposes as detecting beta-particle emitters on the body.

**Figure 12.92** Water-repellent clothing for use in wet decontamination operations.

12.95 In connection with this aspect of personnel protection, there arises the question of the amount of nuclear radiation exposure that is permissible for those taking part in emergency operations. It is difficult, if not impossible, to supply an exact answer, for a great deal will depend upon the circumstances and the risks that must inevitably be taken.

12.96 In those phases of emergencies in which immediate action is required, it would rarely be possible to predict in advance the radiation dose that might be received as a result of such action. The consequences to the exposed individuals, would, therefore, be equally unpredictable. However, where the hazard could be estimated from available dose rate data, it might be possible to establish an approxi-

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[6] For a description of dosimeters and other radiation instruments developed by the Federal Civil Defense Administration, see "Radiological Instruments for Civil Defense," TB-11-20.

mate guide concerning permissible radiation exposures under emergency conditions.[7]

### Food and Water

12.97 Foods that are properly covered or wrapped or are stored in closed containers should suffer little or no contamination. This will be true for canned and bottled foods as well as for any articles in impervious, dust-proof wrappings. If the contamination is only on the outside, all that would be necessary for recovery purposes would be the careful removal, e. g., by washing, of any fallout particles that might have settled on the exterior of the container.[8] Even vegetables could be satisfactorily decontaminated by washing. If this were followed by removal of the outer layers, by peeling, the food should be perfectly safe for human consumption. Unprotected food products of an absorbent variety that have become contaminated should be disposed of by burial.

12.98 As for food crops grown in contaminated soil, there is not yet sufficient information available. Some radioactive isotopes may be taken up by the plant, but their nature and quantity will vary from one species to another and also, probably, with the soil characteristics (§ 9.99). All that can be stated at the present time is that plants grown in contaminated soil should be regarded with suspicion until their safety can be confirmed by means of radiological instruments.

12.99 Most sources of public water supplies are located at a considerable distance from urban centers that might be targets of a nuclear attack. Nevertheless, appreciable contamination might result if the watershed were in the range of heavy fallout from a surface burst. Other possibilities are fallout particles dropping into a river or reservoir or the explosion of a nuclear bomb near a reservoir. In most cases it is to be expected that, as a result of the operation of several factors, e. g., dilution by flow, natural decay, and removal ("adsorption") by soil, the water will be fit for consumption, on an emergency basis, at least, except perhaps for a limited time immediately following the nuclear explosion. In any event, where the water from a reservoir is subjected to regular treatment, including coagulation, sedimentation, and filtration, it is probable that much of the radioactive material would be removed.

12.100 Because soil has the ability to take up and retain certain elements by the process of "adsorption," underground sources of water will generally be free from contamination. For the same reason, moderately deep wells, even under contaminated ground, can be used as safe sources of drinking water, provided, as is almost invariably the case, there is no direct drainage from the surface into the well.

12.101 In some cities, water is taken directly from a river and merely chlorinated before being supplied for domestic purposes. The water may be unfit for consumption for several days, but, as a result of dilution and natural decay, the degree of contamination will decrease with time. It would be necessary, in cases of this kind, to subject the water to examination for radioactivity and to withhold the supply until it is reasonably safe. Assuming the contamination is due to fission products, the acceptable total beta (or gamma) activities under emergency conditions, for 10 and 30 day periods, respectively, are given in Table 12.101. Thus, if it is anticipated that the water will have to be used regularly for a period of 30 days, the maximum permissible activity is $3\times10^{-2}$ microcuries per cubic centimeter (see § 9.125, *et seq.*). On the other hand, if it appears that the period will be shorter, water of proportionately higher activity may be consumed in an emergency.

Table 12.101

ACCEPTABLE EMERGENCY BETA (OR GAMMA) ACTIVITIES IN DRINKING WATER

| | *Activity* | |
|---|---|---|
| *Consumption period (days)* | *Microcuries per cubic centimeter* | *Disintegrations per second per cubic centimeter* |
| 10 | $9 \times 10^{-2}$ | $3 \times 10^{3}$ |
| 30 | $3 \times 10^{-2}$ | $1 \times 10^{3}$ |

12.102 The emergency limits for alpha particle emitters, such as uranium and plutonium, in water are appreciably less than those given in Table 12.101. However, it is expected that only in rare circumstances would these elements represent a contamination hazard in drinking water.

12.103 If the regular water supply is not usually subjected to any treatment other than chlorination, and an alternative source is not available, consideration should be given to the provision of ion-exchange columns (or beds) for emergency use in case of contamination.

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[7] See, for example, "Emergency Exposures to Nuclear Radiation," Federal Civil Defense Administration Technical Bulletin (TB–18–1).

[8] Food could become contaminated even inside containers due to neutron-induced activity, but this is not likely to be important in locations where the packaged foodstuffs have survived the nuclear explosion intact (§ 9.25).

Home water softeners might serve the same purpose on a small scale. Incidentally, the water contained in a domestic hot-water heater could serve as an emergency supply, provided it can be removed without admitting contaminated water.

12.104 In hospitals and on ships, sufficient water for emergency purposes could be obtained by distillation. It was found after the nuclear tests at Bikini in 1946, for example, that contaminated sea water when distilled was perfectly safe for drinking purposes; the radioactive material remained behind in the residual scale and brine. It should be emphasized, however, that mere boiling of water contaminated with fallout is of absolutely no value as regards removal of the radioactivity.

### RADIATION DOSES AND TIMES IN CONTAMINATED AREAS

12.105 For the planning of defensive action, either active or passive, or of survey operations in an area contaminated with fission products, it is necessary either to make some estimate of the permissible time of stay for a prescribed dose or to determine the dose that would be received in a certain time period. The basic equations and the related graphs (Figs. 9.8 and 9.12) were given in Chapter IX, but the same results may be expressed in an alternative form that is more convenient for many purposes.[9]

12.106 If the radiation dose rate from fission products is known at a certain time in a given location, Fig. 12.106 may be used to determine the dose rate at any other time at the same location, assuming there has been no change in the fallout other than natural radioactive decay. The same nomogram can be utilized, alternatively, to determine the time after the explosion at which the dose rate will have attained a specified value. If there has been any change in the situation, either by further contamination or by decontamination, in the period between the two times concerned, the results obtained from Fig. 12.106 will not be valid.

12.107 To determine the total radiation dose received during a specified time of stay in a contaminated area, if the dose rate in that area at any given time is known, use is made of Fig. 12.107, in conjunction with Fig. 12.106. The chart may also be employed to evaluate the time when a particular operation may be commenced in order not to exceed a certain total radiation dose.

12.198 Another type of calculation of radiation dose in a contaminated area is based on a knowledge of the dose rate at the time of entry into that area. The procedure described in the examples facing Fig. 12.107, which also require the use of Fig. 12.106, may then be applied to determine either the total dose received in a specified time of stay or the time required to accumulate a given dose of radiation. The calculation may, however, be simplified by means of Fig. 12.108, which avoids the necessity for evaluating the 1-hour reference dose rate, provided the dose rate at the time of entry into the contaminated area is known.

12.109 If the whole of the fallout reached a given area within a short time, Fig. 12.108 could be used to determine how the total radiation dose received by inhabitants of that area would increase with time, assuming no protection. For example, suppose the fallout arrived at 6 hours after the explosion and the dose rate at that time was $R$ roentgens per hour; the total dose received would be $8R$ roentgens in 1 day, $11R$ roentgens in 2 days, and $13R$ roentgens in 5 days.

12.110. It is evident that the first day or so after the explosion is the most hazardous as far as the exposure to residual nuclear radiation from fallout is concerned. Although the particular values given above apply to the case specified, i. e., complete fallout arrival 6 hours after the explosion, the general conclusions to be drawn are true in all cases. The radiation doses that would be received during the first day or two are considerably greater than on subsequent days. Consequently, it is in the early stages following the explosion that protection from fallout is most important.

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[9] Devices of the slide-rule type, referred to in the footnote to § 9.11, are very useful for making rapid calculations of the kind described here.

From the chart, the total radiation dose received from fission product fallout during any specified stay in a contaminated area can be determined if the dose rate at some definite time after the explosion is known. Alternatively, the time can be calculated for commencing an operation requiring a specified stay and a prescribed total radiation dose.

*Example*

*Given:* The dose rate at 4 hours after a nuclear explosion is 6 roentgens per hour.

*Find:* (*a*) The total dose received during a period of 2 hours commencing at 6 hours after the explosion.

(*b*) The time after the explosion when an operation requiring a stay of 5 hours can be started if the total dose is to be 4 roentgens.

*Solution:* The first step is to determine the 1-hour reference dose rate ($R_1$). From Fig. 12.106, a straight line connecting 6 roentgens per hour on the left scale with 4 hours on the right scale intersects the middle scale at 32 roentgens per hour; this is the value of $R_1$.

(*a*) Enter Fig. 12.107 at 6 hours after the explosion (vertical scale) and move across to the curve representing a time of stay of 2 hours. The corresponding reading on the horizontal scale, which gives the multiplying factor to convert $R_1$ to the required total dose, is seen to be 0.19. Hence, the total dose received is

$0.19 \times 32 = 6.1$ roentgens. *Answer*

(*b*) Since the total dose is given as 4 roentgens and $R_1$ is 32 roentgens per hour, the multiplying factor is $4/32 = 0.125$. Entering Fig. 12.107 at this point on the horizontal scale and moving upward until the (interpolated) curve for 5 hours stay is reached, the corresponding reading on the vertical scale, giving the time after the explosion, is seen to be 19 hours. *Answer*

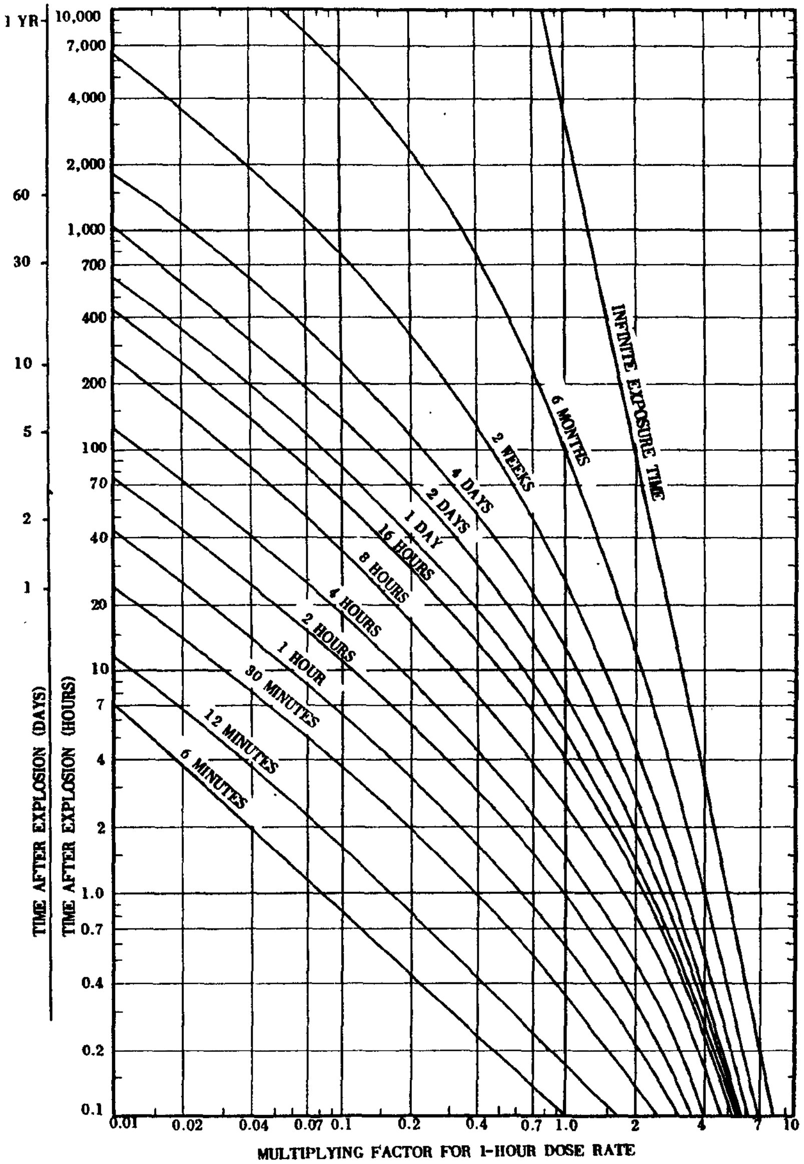

**Figure 12.107.** Total (accumulated) radiation dose due to fallout in a contaminated area based on 1-hour reference dose rate.

From the chart, the total radiation dose received from fission product fallout during any specified stay in a contaminated area can be determined if the dose rate at the time of entry into the area is known. Alternatively, the time of stay may be evaluated if the total dose is prescribed.

*Example*

*Given:* Upon entering a contaminated area at 12 hours after a nuclear explosion the dose rate is 5 roentgens per hour.

*Find:* (*a*) The total radiation dose received for a stay of 2 hours.
(*b*) The time of stay for a total dose of 10 roentgens.

*Solution:* (*a*) Start at the point on Fig. 12.108 representing 12 hours after the explosion on the vertical scale and move across to the curve representing a time of stay of 2 hours. The multiplying factor for the dose rate at the time of entry, as read from the horizontal scale, is seen to be 1.9. Hence, the total dose received is

$$1.9 \times 5 = 9.5 \text{ roentgens. } \textit{Answer}$$

(*b*) The total dose is 10 roentgens and the dose rate at the time of entry is 5 roentgens per hour; hence, the multiplying factor is $10/5 = 2.0$. Enter Fig. 12.108 at the point corresponding to 2.0 on the horizontal scale and move upward to meet a horizontal line which starts from the point representing 12 hours after the explosion on the vertical scale. The two lines are seen to intersect at a point indicating a time of stay of about 2⅓ hours. *Answer*

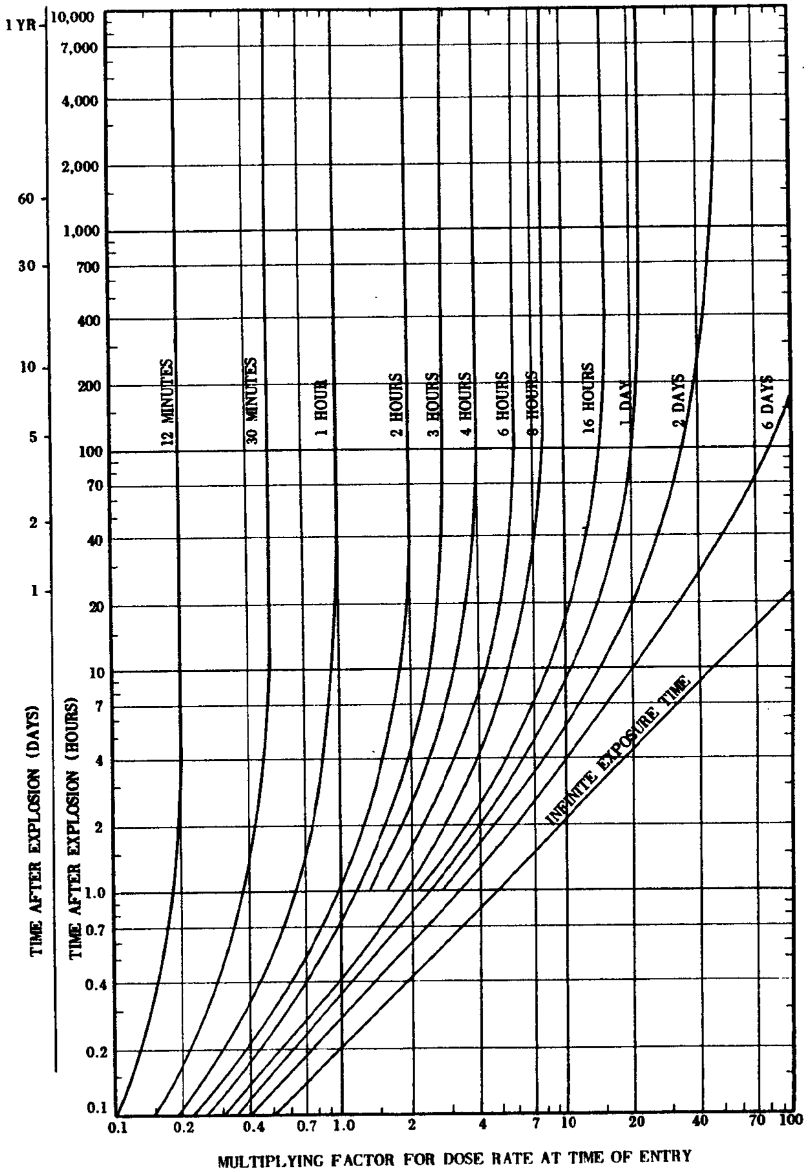

**Figure 12.108.** Total (accumulated) radiation dose due to fallout in a contaminated area based on dose rate at time of entry.

# GLOSSARY

A BOMB: An abbreviation for atomic bomb.

ABSORPTION COEFFICIENT: A number characterizing the ability of a given material to absorb radiations of a specified energy. The *linear absorption coefficient* expresses this ability per unit thickness and is stated in units of reciprocal length (or thickness). The *mass absorption coefficient* is equal to the linear absorption coefficient divided by the density of the absorbing material; it is a measure of the absorption ability per unit mass.

AFTERWINDS: Wind currents set up in the vicinity of a nuclear explosion directed toward the burst center, resulting from the updraft accompanying the rise of the fireball.

AIR BURST: The explosion of a nuclear weapon at such a height that the expanding ball of fire does not touch the earth's surface when the luminosity is a maximum (in the second pulse). A *typical air burst* is one for which the height of burst is such as may be expected to cause maximum blast destruction in an average city.

ALPHA PARTICLE: A particle emitted spontaneously from the nuclei of some radioactive elements. It is identical with a helium nucleus, having a mass of four units and an electric charge of two positive units. See *Radioactivity*.

ATOM: The smallest (or ultimate) particle of an element that still retains the characteristics of that element. Every atom consists of a positively charged central nucleus, which carries nearly all the mass of the atom, surrounded by a number of negatively charged electrons, so that the whole system is electrically neutral. See *Element, Electron, Nucleus.*

ATOMIC BOMB (OR WEAPON): A term sometimes applied to a nuclear weapon utilizing fission energy only. See *Fission, Nuclear Weapon.*

ATOMIC CLOUD: An all-inclusive term for the mixture of hot gases, smoke, dust, and other particulate matter from the bomb itself and from the environment, which is carried aloft in conjunction with the rising ball of fire produced by the detonation of a nuclear (or atomic) weapon.

ATOMIC NUMBER: See *Nucleus.*

ATOMIC WEIGHT: The relative weight of an atom of the given element. As a basis of reference, the atomic weight of oxygen is taken to be exactly 16; the atomic weight of hydrogen (the lightest element) is then 1.008. Hence, the atomic weight of any element is *approximately* the weight of an atom of that element relative to the weight of a hydrogen atom.

BACKGROUND RADIATION: Nuclear (or ionizing) radiations arising from within the body and from the surroundings to which individuals are always exposed. The main sources of the natural background radiation are potassium-40 in the body, potassium-40 and thorium, uranium, and their decay products (including radium) present in rocks, and cosmic rays.

BALL OF FIRE (OR FIREBALL): The luminous sphere of hot gases which forms a few millionths of a second after a nuclear (or atomic) explosion and immediately starts to expand and cool. The exterior of the ball of fire is initially sharply defined by the luminous shock front (in air) and later by the limits of the hot gases themselves. See *Breakaway.*

BASE SURGE: A cloud which rolls outward from the bottom of the column produced by a subsurface explosion. For underwater bursts the surge is, in effect, a cloud of liquid (water) droplets with the property of flowing almost as if it were a homogeneous fluid. For subsurface land bursts the surge is made up of small solid particles but it still behaves like a fluid. A soft earth medium favors base surge formation in an underground burst.

BEARING WALL: A wall which supports (or bears) part of the mass of a structure such as the floor and roof systems.

BETA PARTICLE: A charged particle of very small mass emitted spontaneously from the nuclei of certain radioactive elements. Most (if not all) of the fission fragments emit (negative) beta particles. Physically, the beta particle is identical with an electron moving at high velocity. See *Electron, Fission fragments, Radioactivity.*

BIOLOGICAL HALF-LIFE: See *Half-Life.*

BLAST LOADING: The loading (or force) on an object caused by the air blast from an explosion striking and flowing around the object. It is a combination of overpressure (or diffraction) and dynamic pressure (or drag) loading. See *Diffraction, Drag, Dynamic Pressure, Overpressure.*

BLAST SCALING LAWS: Formulas which permit the calculation of the properties, e. g., overpressure, dynamic pressure, time of arrival, duration, etc., of a blast wave at any distance from an explosion of specified energy from the known variation with distance of these properties for a reference explosion of known energy, e. g., of 1 kiloton. See *Cube root law.*

BLAST WAVE: A pressure pulse of air, accompanied by winds, propagated continuously from an explosion. See *Shock wave.*

BOMB DEBRIS: The residue of a nuclear (or atomic) bomb after it has exploded. It consists of the materials used for the casing and other components of the bomb, together with unexpended fissionable materials (isotopes of uranium and plutonium) and fission products.

BREAKAWAY: The onset of a condition in which the shock front (in the air) moves away from the exterior of the expanding ball of fire produced by the explosion of a nuclear (or atomic) weapon. See *Ball of fire, Shock front.*

BURST: Explosion or detonation. See *Air burst, Surface burst, Underground burst, Underwater burst.*

CHEMICAL DOSIMETER: A self-indicating device for determining total (or accumulated) radiation exposure dose based on color changes accompanying chemical reactions induced by the radiation.

CLOUD CHAMBER EFFECT: See *Condensation cloud.*

CLOUD COLUMN: The visible column of smoke extending upward from the point of burst of a nuclear (or atomic) weapon. The cloud column from an air burst may extend to the tropopause, i. e., the boundary between the troposphere and the stratosphere. See *Atomic cloud.*

CLOUD PHENOMENA: See *Atomic cloud, Ball of fire, Base surge, Cloud column, Fallout.*

COLUMN (OR PLUME): A hollow cylinder of water and spray thrown up from an underwater burst of a nuclear (or atomic) weapon, through which the hot, high-pressure gases formed in the explosion are vented to the atmosphere. A somewhat similar column of dirt is formed in an underground explosion.

**CONDENSATION CLOUD**: A mist or fog of minute water droplets which temporarily surrounds the ball of fire following a nuclear (or atomic) detonation in a comparatively humid atmosphere. The expansion of the air in the negative phase of the blast wave from the explosion results in a lowering of the temperature, so that condensation of water vapor present in the air occurs and a cloud forms. The cloud is soon dispelled when the pressure returns to normal and the air warms up again. The phenomenon is similar to that used by physicists in the Wilson cloud chamber and is sometimes called the cloud chamber effect.

**CONTACT SURFACE BURST**: See *Surface burst.*

**CONTAMINATION**: The deposit of radioactive material on the surfaces of structures, areas, objects, or personnel, following a nuclear (or atomic) explosion. This material generally consists of fallout in which fission products and other bomb debris have become incorporated with particles of dirt, etc. Contamination can also arise from the radioactivity induced in certain substances by the action of bomb neutrons. See *Bomb debris, Decontamination, Fallout, Induced radioactivity.*

**CRITICAL MASS**: The minimum mass of a fissionable material that will just maintain a fission chain reaction under precisely specified conditions, such as the nature of the material and its purity, the nature and thickness of the tamper (or neutron reflector), the density (or compression), and the physical shape (or geometry). For an explosion to occur, the system must be supercritical, i. e., the mass of material must exceed the critical mass under the existing conditions. See *Supercritical.*

**CUBE ROOT LAW**: A scaling law applicable to many blast phenomena. It relates the time and distance at which a given blast effect is observed to the cube root of the energy yield of the explosion.

**CURIE**: A unit of radioactivity; it is the quantity of any radioactive species in which $3.700 \times 10^{10}$ nuclear disintegrations occur per second. The *gamma curie* is sometimes defined correspondingly as the quantity of material in which this number of disintegrations per second are accompanied by the emission of gamma rays.

**DAMAGE CRITERIA**: Standards or measures used in estimating specific levels of damage.

**DECAY (OR RADIOACTIVE DECAY)**: The decrease in activity of any radioactive material with the passage of time, due to the spontaneous emission from the atomic nuclei of either alpha or beta particles, sometimes accompanied by gamma radiation. See *Half-life, Radioactivity.*

**DECAY CURVE**: The representation by means of a graph of the decrease of radioactivity with respect to time.

**DECONTAMINATION**: The reduction or removal of contaminating radioactive material from a structure, area, object, or person. Decontamination may be accomplished by (1) treating the surface so as to remove or decrease the contamination; (2) letting the material stand so that the radioactivity is decreased as a result of natural decay; and (3) covering the contamination so as to attenuate the radiation emitted. Radioactive material removed in process (1) must be disposed of by burial on land or at sea, or in other suitable way.

**DEUTERIUM**: An isotope of hydrogen of mass 2 units; it is sometimes referred to as heavy hydrogen. It can be used in thermonuclear fusion reactions for the release of energy. See *Fusion, Thermonuclear.*

**DIFFRACTION**: The bending of waves around the edges of objects. In connection with a blast wave impinging on a structure, diffraction refers to the passage around and envelopment of the structure by the blast wave. *Diffraction loading* is the force (or loading) on the structure during the envelopment process.

**DOME**: The mound of water spray thrown up into the air when the shock wave from an underwater detonation of a nuclear (or atomic) weapon reaches the surface.

**DOSAGE**: See *Dose.*

**DOSE**: A (total or accumulated) quantity of ionizing (or nuclear) radiation. The term dose is often used in the sense of the *exposure dose*, expressed in roentgens, which is a measure of the total amount of ionization that the quantity of radiation could produce in air. This should be distinguished from the *absorbed dose*, given in reps or rads, which represents the energy absorbed from the radiation per gram of specified body tissue. Further, the *biological dose*, in rems, is a measure of the biological effectiveness of the radiation exposure. See *Rad, RBE, Rem, Rep, Roentgen.*

**DOSE RATE**: As a general rule, the amount of ionizing (or nuclear) radiation to which an individual would be exposed per unit of time. It is usually expressed as roentgens per hour or in multiples or submultiples of these units, such as milliroentgens per hour. The dose rate is commonly used to indicate the level of radioactivity in a contaminated area.

**DOSIMETER**: An instrument for measuring and registering total accumulated exposure to ionizing radiations. See *Dosimetry.*

**DOSIMETRY**: The theory and application of the principles and techniques involved in the measurement and recording of radiation doses. Its practical aspect is concerned with the use of various types of radiation instruments with which measurements are made. See *Chemical dosimeter, Film badge, Survey meter.*

**DRAG LOADING**: The force on an object or structure due to the transient winds accompanying the passage of a blast wave. The *drag pressure* is the product of the dynamic pressure and a coefficient which is dependent upon the shape (or geometry) of the structure or object. See *Dynamic pressure.*

**DYNAMIC PRESSURE**: The air pressure which results from the mass air flow (or wind) behind the shock front of a blast wave. It is equal to the product of half the density of the air through which the blast wave passes and the square of the particle (or wind) velocity in the wave as it impinges on the object or structure.

**ELASTIC RANGE**: The stress range in which a material will recover its original form when the force (or loading) is removed. *Elastic deformation* refers to dimensional changes occurring within the elastic range. See *Plastic range.*

**ELECTRON**: A particle of very small mass, carrying a unit negative or positive charge. Negative electrons, surrounding the nucleus, are present in all atoms; their number is equal to the number of positive charges (or protons) in the particular nucleus. The term electron, where used alone, commonly refers to these negative electrons. A positive electron is usually called a positron, and a negative electron is sometimes called a negatron. See *Beta Particle.*

**ELEMENT:** One of the distinct, basic varieties of matter occurring in nature which, individually or in combination, compose substances of all kinds. Approximately ninety different elements are known to exist in nature and several others, including plutonium, have been obtained as a result of nuclear reactions with these elements.

**ENIWETOK PROVING GROUNDS:** An area in the Marshall Islands, including the Eniwetok and Bikini Atolls, used for nuclear (or atomic) tests. Formerly referred to as the Pacific Proving Grounds.

**FALLOUT:** The process or phenomenon of the fall back to the earth's surface of particles contaminated with radioactive material from the atomic cloud. The term is also applied in a collective sense to the contaminated particulate matter itself.

**FILM BADGE:** A small metal or plastic frame, in the form of a badge, worn by personnel, and containing X-ray (or similar photographic) film for estimating the total amount of ionizing (or nuclear) radiation to which an individual has been exposed.

**FIREBALL:** See *Ball of fire.*

**FIRE STORM:** Stationary mass fire, generally in built-up urban areas, generating strong, inrushing winds from all sides, which keep the fires from spreading while adding fresh oxygen to increase their intensity.

**FISSION:** The process whereby the nucleus of a particular heavy element splits into (generally) two nuclei of lighter elements, with the release of substantial amounts of energy. The most important *fissionable materials* are uranium-235 and plutonium-239.

**FISSION PRODUCTS:** A general term for the complex mixture of substances produced as a result of nuclear fission. A distinction should be made between these and the *direct fission products* or *fission fragments* which are formed by the actual splitting of the heavy-element nuclei. Something like 80 different fission fragments result from roughly 40 different modes of fission of a given nuclear species, e. g., uranium-235 or plutonium-239. The fission fragments, being radioactive, immediately begin to decay, forming additional (daughter) products, with the result that the complex mixture of fission products so formed contains about 200 different isotopes of over 30 elements.

**FLASH BURN:** A burn caused by excessive exposure (of bare skin) to thermal radiation. See *Thermal radiation.*

**FREE AIR OVERPRESSURE (OR FREE AIR PRESSURE):** The unreflected pressure, in excess of the ambient atmospheric pressure, created in the air by the blast wave from an explosion.

**FUSION:** The process whereby the nuclei of light elements, especially those of the isotopes of hydrogen, namely, deuterium and tritium, combine to form the nucleus of a heavier element with the release of substantial amounts of energy. See *Thermonuclear.*

**GAMMA RAYS (OR RADIATIONS):** Electromagnetic radiations of high energy originating in atomic nuclei and accompanying many nuclear reactions, e. g., fission, radioactivity, and neutron capture. Physically, gamma rays are identical with X-rays of high energy, the only essential difference being that the X-rays do not originate from atomic nuclei, but are produced in other ways, e. g., by slowing down (fast) electrons of high energy.

**GROUND ZERO:** The point on the surface of land or water vertically below or above the center of a burst of a nuclear (or atomic) weapon; frequently abbreviated to GZ. For a burst over or under water, the term *surface zero* should preferably be used.

**GUN-TYPE WEAPON:** A device in which two or more pieces of fissionable material, each less than a critical mass, are brought together very rapidly so as to form a supercritical mass which can explode as the result of a rapidly expanding fission chain.

**HALF-LIFE:** The time required for the activity of a given radioactive species to decrease to half of its initial value due to radioactive decay. The half-life is a characteristic property of each radioactive species and is independent of its amount or condition. The *biological half-life* is the time required for the amount of a specified element which has entered the body (or a particular organ) to be decreased to half of its initial value as a result of natural, biological elimination processes. The *effective half-life* of a given isotope is the time in which the quantity in the body will decrease to half as a result of both radioactive decay and biological elimination.

**HALF-VALUE LAYER THICKNESS:** The thickness of a given material which will absorb half the gamma radiation incident upon it. This thickness depends on the nature of the material—it is roughly inversely proportional to its density—and also on the energy of the gamma rays.

**H BOMB:** An abbreviation for hydrogen bomb. See *Hydrogen bomb.*

**HEIGHT OF BURST:** The height above the earth's surface at which a bomb is detonated in the air. The *optimum height of burst* for a particular target (or area) is that at which it is estimated a weapon of a specified energy yield will produce a certain desired effect over the maximum possible area.

**HOT SPOT:** Region in a contaminated area in which the level of radioactive contamination is somewhat greater than in neighboring regions in the area. See *Contamination.*

**HYDROGEN BOMB (OR WEAPON):** A term sometimes applied to nuclear weapons in which part of the explosive energy is obtained from nuclear fusion (or thermonuclear) reactions. See *Fusion, Nuclear weapon, Thermonuclear.*

**HYPOCENTER:** A term sometimes used for ground zero. See *Ground zero.*

**IMPLOSION WEAPON:** A device in which a quantity of fissionable material, less than a critical mass, has its volume suddenly decreased by compression, so that it becomes supercritical and an explosion can take place. The compression is achieved by means of a spherical arrangement of specially fabricated shapes of ordinary high explosive which produce an inwardly-directed implosion wave, the fissionable material being at the center of the sphere. See *Supercritical.*

**IMPULSE:** The product of the overpressure (or dynamic pressure) from the blast wave of an explosion and the time during which it acts at a given point. More specifically, it is the integral, with respect to time, of the overpressure (or dynamic pressure), the integration being between the time of arrival of the blast wave and that at which the overpressure (or dynamic pressure) returns to zero at the given point.

**INDUCED RADIOACTIVITY:** Radioactivity produced in certain materials as a result of nuclear reactions, particularly the capture of neutrons, which are accompanied by the formation of unstable (radioactive) nuclei. The activity induced by neutrons from a nuclear (or atomic) explosion in materials containing the elements sodium, manganese, silicon, or aluminum may be significant.

**INITIAL NUCLEAR RADIATION:** Nuclear radiation (essentially neutrons and gamma rays) emitted from the ball of fire and the cloud column during the first minute after a nuclear (or atomic) explosion. The time limit of one minute is set, somewhat arbitrarily, as that required for the source of the radiations (fission products in the atomic cloud) to attain such a height that only insignificant amounts reach the earth's surface. See *Residual nuclear radiation.*

**INTENSITY:** The energy (of any radiation) incident upon (or flowing through) unit area, perpendicular to the radiation beam, in unit time. The intensity of thermal radiation is generally expressed in calories per square centimeter per second falling on a given surface at any specified instant. As applied to nuclear radiation, the term intensity is sometimes used, rather loosely, to express the exposure dose rate at a given location, e. g., in roentgens (or milliroentgens) per hour.

**INTERNAL RADIATION:** Nuclear radiation (alpha and beta particles and gamma radiation) resulting from radioactive substances in the body. Important sources are iodine-131 in the thyroid gland, and strontium-90 and plutonium-239 in the bone.

**IONIZING RADIATION:** Electromagnetic radiation (gamma rays or X-rays) or particulate radiation (alpha particles, beta particles, neutrons, etc.) capable of producing ions, i. e., electrically charged particles, directly or indirectly in its passage through matter.

**ISOTOPES:** Forms of the same element having identical chemical properties but differing in their atomic masses (due to different numbers of neutrons in their respective nuclei) and in their nuclear properties, e. g., radioactivity, fission, etc. For example, hydrogen has three isotopes, with masses of 1 (hydrogen), 2 (deuterium), and 3 (tritium) units, respectively. The first two of these are stable (nonradioactive), but the third (tritium) is a radioactive isotope. Both of the common isotopes of uranium, with masses of 235 and 238 units, respectively, are radioactive, emitting alpha particles, but their half-lives are different. Further, uranium-235 is fissionable by neutrons of all energies, but uranium-238 will undergo fission only with neutrons of high energy.

**KILOTON ENERGY:** The energy of a nuclear (or atomic) explosion which is equivalent to that produced by the explosion of 1 kiloton (i. e., 1,000 tons) of TNT, i. e., $10^{12}$ calories or $4.2\times10^{19}$ ergs. See *Megaton energy, TNT equivalent.*

**LD-50, LD/50, or $LD_{50}$:** Abbreviations for median lethal dose. See *Median lethal dose.*

**LINEAR ABSORPTION COEFFICIENT:** See *Absorption coefficient.*

**LOADING:** The force on an object or structure or element of a structure. The loading due to blast is equal to the net pressure in excess of the ambient value multiplied by the area of the loaded object, etc.

**MACH FRONT:** See *Mach stem.*

**MACH REGION:** The region on the surface at which the Mach stem has formed as the result of a particular explosion in the air.

**MACH STEM:** The shock front formed by the fusion of the incident and reflected shock fronts from an explosion. The term is generally used with reference to a blast wave, propagated in the air, reflected at the surface of the earth. The Mach stem is nearly perpendicular to the reflecting surface and presents a slightly convex (forward) front. The Mach stem is also called the *Mach front.* See *Shock front, Shock wave.*

**MASS ABSORPTION COEFFICIENT:** See *Absorption coefficient.*

**MASS NUMBER:** See *Nucleus.*

**MAXIMUM PERMISSIBLE EXPOSURE (OR MPE):** The total amount of radiation exposure which it is believed a normal person may receive day-by-day without any harmful effects becoming evident during his lifetime.

**MEDIAN LETHAL DOSE:** The amount of ionizing (or nuclear) radiation exposure over the whole body which it is expected would be fatal to 50 percent of a large group of living creatures or organisms. It is commonly (although not universally) accepted, at the present time, that a dose of about 450 roentgens, received over the whole body in the course of a few hours or less, is the median lethal dose for human beings.

**MEGATON ENERGY:** The energy of a nuclear (or atomic) explosion which is equivalent to 1,000,000 tons (or 1,000 kilotons) of TNT, i. e., $10^{15}$ calories or $4.2\times10^{22}$ ergs. See *TNT equivalent.*

**MEV (OR MILLION ELECTRON VOLTS):** A unit of energy commonly used in nuclear physics. It is equivalent to $1.6\times10^{-6}$ erg. Approximately 200 Mev of energy are produced for every nucleus that undergoes fission.

**MILLIROENTGEN:** A one-thousandth part of a roentgen. See *Roentgen.*

**MONITORING:** The procedure or operation of locating (and measuring) radioactive contamination by means of survey instruments which can detect and measure (as dose rates) ionizing radiations. The individual performing the operation is called a *monitor.*

**NEGATIVE PHASE:** See *Shock wave.*

**NEUTRON:** A neutral particle, i. e., with no electrical charge, of approximately unit mass, present in all atomic nuclei, except those of ordinary (or light) hydrogen. Neutrons are required to initiate the fission process, and large numbers of neutrons are produced by both fission and fusion reactions in nuclear (or atomic) explosions.

**NEVADA TEST SITE:** An area within the continental United States used for nuclear (or atomic) tests. It is located northwest of Las Vegas, Nevada, within the boundaries of the Las Vegas Bombing and Gunnery Range.

**NOMINAL ATOMIC BOMB:** A term, now becoming obsolete, formerly used to describe an atomic weapon with an energy release equivalent to 20 kilotons (i. e., 20,000 tons) of TNT. This was approximately the energy yield of the bombs exploded over Japan and in the Bikini tests in 1946.

**NUCLEAR RADIATION:** Particulate and electromagnetic radiation emitted from atomic nuclei in various nuclear processes. The important nuclear radiations, from the weapons standpoint, are alpha and beta particles, gamma rays, and neutrons. All nuclear radiations are ionizing radiations, but the reverse is not true; X-rays, for example, are included among ionizing radiations, but they are not nuclear radiations since they do not originate from atomic nuclei. See *Ionizing radiation.*

**NUCLEAR (OR ATOMIC) TESTS:** Tests carried out either at the Nevada Test Site or at the Eniwetok Proving Grounds to supply information required for the design and improvement of nuclear (or atomic) weapons and to study the phenomena and effects associated with nuclear (or atomic) explosions. Many of the data presented in this book are based on measurements and observations made at such tests. The code names and some information concerning all the tests performed through 1956 by the U. S. Atomic Energy Commission are given in the appended table.

SUMMARY OF NUCLEAR TESTS

| Date | Code name | Location | Total No. | Air drops | Tower | Surface | Under-ground | Under-water |
|---|---|---|---|---|---|---|---|---|
| 1945 | TRINITY | New Mexico | 1 | | 1 | | | |
| 1946 | CROSSROADS | Pacific | 2 | 1 | | | | 1 |
| 1948 | SANDSTONE | Pacific | 3 | | 3 | | | |
| 1951 | RANGER | Nevada | 5 | 5 | | | | |
| 1951 | GREENHOUSE | Pacific | 4 | | 4 | | | |
| 1951 | BUSTER | Nevada | 5 | 4 | 1 | | | |
| 1951 | JANGLE | Nevada | 2 | | | 1 | 1 | |
| 1952 | TUMBLER | Nevada | 4 | 4 | | | | |
| 1952 | SNAPPER | Nevada | 4 | | 4 | | | |
| 1952 | IVY | Pacific | 2 | 1 | | 1 | | |
| 1953 | UPSHOT | Nevada | 9 | 2 | 7 | | | |
| 1953 | KNOTHOLE | Nevada | 2 | 2 | | | | |
| 1954 | CASTLE | Pacific | | | | | | |
| 1955 | TEAPOT | Nevada | 14 | 3 | 10 | | 1 | |
| 1955 | WIGWAM | At sea | 1 | | | | | 1 |
| 1956 | REDWING | Pacific | | | | | | |

NUCLEAR WEAPON (OR BOMB): A general name given to any weapon in which the explosion results from the energy released by reactions involving atomic nuclei, either fission or fusion or both. Thus, the A (or atomic) bomb and the H (or hydrogen) bomb are both nuclear weapons. It would be equally true to call them atomic weapons, since it is the energy of atomic nuclei that is involved in each case. However, it has become more-or-less customary, although it is not strictly accurate, to refer to weapons in which all the energy results from fission as A bombs or atomic bombs. In order to make a distinction, those weapons in which part, at least, of the energy results from thermonuclear (fusion) reactions among the isotopes of hydrogen have been called H bombs or hydrogen bombs.

NUCLEUS (OR ATOMIC NUCLEUS): The small, central, positively charged region of an atom which carries essentially all the mass. Except for the nucleus of ordinary (light) hydrogen, which is a single proton, all atomic nuclei contain both protons and neutrons. The number of protons determines the total positive charge, or *atomic number;* this is the same for all the atomic nuclei of a given chemical element. The total number of neutrons and protons, called the *mass number*, is closely related to the mass (or weight) of the atom. The nuclei of *isotopes* of a given element contain the same number of protons, but different numbers of neutrons. They thus have the same atomic number, and so are the same element, but they have different mass numbers (and masses). The nuclear properties, e. g., radioactivity, fission, neutron capture, etc., of an isotope of a given element are determined by both the number of neutrons and the number of protons. See *Atom, Element, Isotope, Neutron, Proton.*

OVERPRESSURE: The transient pressure, usually expressed in pounds per square inch, exceeding the ambient pressure, manifested in the shock (or blast) wave from an explosion. The variation of the overpressure with time depends on the energy yield of the explosion, the distance from the point of burst, and the medium in which the weapon is detonated. The *peak overpressure* is the maximum value of the overpressure at a given location and is generally experienced at the instant the shock (or blast) wave reaches that location. See *Shock wave.*

PACIFIC PROVING GROUNDS: See *Eniwetok Proving Grounds.*

PLASTIC RANGE: The stress range in which a material will not fail when subjected to the action of a force, but will not recover completely, so that a permanent deformation results, when the force is removed. *Plastic deformation* refers to dimensional changes occurring within the plastic range. See *Elastic range.*

PLUME: See *Column.*

POSITIVE PHASE: See *Shock wave.*

PROTON: A particle of mass (approximately) unity carrying a unit positive charge; it is identical physically with the nucleus of the ordinary (light) hydrogen atom. All atomic nuclei contain protons. See *Nucleus.*

RAD: A unit of absorbed dose of radiation; it represents the absorption of 100 ergs of nuclear (or ionizing) radiation per gram of the absorbing material or tissue.

RADIATION: See *Nuclear radiation, Thermal radiation.*

RADIATION SYNDROME: See *Syndrome.*

RADIOACTIVITY: The spontaneous emission of radiation, generally alpha or beta particles, often accompanied by gamma rays, from the nuclei of an (unstable) isotope. As a result of this emission the radioactive isotope is converted (or decays) into the isotope of a different element which may (or may not) also be radioactive. Ultimately, as a result of one or more stages of radioactive decay, a stable (nonradioactive) end product is formed.

RBE (OR RELATIVE BIOLOGICAL EFFECTIVENESS): The ratio of the number of rads of gamma (or X) radiation of a certain energy which will produce a specified biological effect to the number of rads of another radiation required to produce the same effect is the RBE of this latter radiation.

REFLECTED PRESSURE: The total pressure which results instantaneously at the surface when a shock (or blast) wave traveling in one medium strikes another medium, e. g., at the instant when the front of a blast wave in air strikes the surface of an object or structure.

REFLECTION FACTOR: The ratio of the total (reflected) pressure to the incident pressure when a shock (or blast) wave traveling in one medium strikes another.

REM: A unit of biological dose of radiation; the name is derived from the initial letters of the term "roentgen equivalent man (or mammal)." The number of rems of radiation is equal to the number of rads absorbed multiplied by the RBE of the given radiation (for a specified effect). See *Rad, RBE.*

REP: A unit of absorbed dose of radiation; the name is derived from the initial letters of the term "roentgen equivalent physical." Basically, the rep is intended to express the amount of energy absorbed per gram of soft tissue as a result of exposure to 1 roentgen of gamma (or X) radiation. This is estimated to be about 97 ergs, although the actual value depends on certain experimental data which are not precisely known. The rep is thus defined, in general, as the dose of any ionizing radiation which results in the absorption of 97 ergs of energy per gram of soft tissue. For soft tissue, the rep and the rad are essentially the same. See *Rad, Roentgen.*

RESIDUAL NUCLEAR RADIATION: Nuclear radiation, chiefly beta particles and gamma rays, which persists for some time following a nuclear (or atomic) explosion. The radiation is emitted mainly by the fission products and other bomb residues in the fallout, and to some extent by earth and water constituents, and other materials, in which radioactivity has been induced by the capture of neutrons. See *Fallout, Induced radioactivity, Initial nuclear radiation.*

ROENTGEN: A unit of exposure dose of gamma (or X) radiation. It is defined precisely as the quantity of gamma (or X) radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying one electrostatic unit quantity of electricity of either sign. From the accepted value for the energy lost by an electron in producing a positive-negative ion pair in air, it is estimated that 1 roentgen of gamma (or X) radiation, would result in the absorption of 87 ergs of energy per gram of air.

SCALING LAW: A mathematical relationship which permits the effects of a nuclear (or atomic) explosion of given energy yield to be determined as a function of distance from the explosion (or from ground zero), provided the corresponding effect is known as a function of distance for a reference explosion, e. g., of 1-kiloton energy yield. See *Blast scaling law, Cube root law.*

SCATTERING: The diversion of radiation, either thermal or nuclear, from its original path as a result of interactions (or collisions) with atoms, molecules, or larger particles in the atmosphere or other medium between the source of the radiations, e. g., a nuclear (or atomic) explosion, and a point at some distance away. As a result of scattering, radiations (especially gamma rays and neutrons) will be received at such a point from many directions instead of only from the direction of the source.

SHEAR WALL: A wall (or partition) designed to take a load in the direction of the plane of the wall, as distinct from lateral loads perpendicular to the wall. Shear walls may be designed to take lateral loads as well. See *Bearing wall.*

SHIELDING: Any material or obstruction which absorbs radiation and thus tends to protect personnel or materials from the effects of a nuclear (or atomic) explosion. A moderately thick layer of any opaque material will provide satisfactory shielding from thermal radiation, but a considerable thickness of material of high density may be needed for nuclear radiation shielding.

SHOCK FRONT (OR PRESSURE FRONT): The fairly sharp boundary between the pressure disturbance created by an explosion (in air, water, or earth) and the ambient atmosphere, water, or earth, respectively. It constitutes the front of the shock (or blast) wave.

SHOCK WAVE: A continuously propagated pressure pulse (or wave) in the surrounding medium which may be air, water, or earth, initiated by the expansion of the hot gases produced in an explosion. A shock wave in air is generally referred to as a blast wave, because it is similar to (and is accompanied by) strong, but transient, winds. The duration of a shock (or blast) wave is distinguished by two phases. First there is the *positive* (or *compression*) *phase* during which the pressure rises very sharply to a value that is higher than ambient and then decreases rapidly to the ambient pressure. The duration of the positive phase increases and the maximum (peak) pressure decreases with increasing distance from an explosion of given energy yield. In the second phase, the *negative* (or *suction*) *phase*, the pressure falls below ambient and then returns to the ambient value. The duration of the negative phase is approximately constant throughout the blast wave history and may be several times the duration of the positive phase. Deviations from the ambient pressure during the negative phase are never large and they decrease with increasing distance from the explosion. See *Overpressure.*

SLANT RANGE: The distance from a given location, usually on the earth's surface, to the point at which the explosion occurred.

SLICK: The trace of an advancing shock wave seen on the surface of reasonably calm water, as a circle of rapidly increasing size apparently whiter than the surrounding water. It is observed, in particular, following an underwater explosion.

SPRAY DOME: See *Dome.*

SUBSURFACE BURST: See *Underground burst, Underwater burst.*

SUPERCRITICAL: A term used to describe the state of a given fission system when the quantity of fissionable material is greater than the critical mass under the existing conditions. A highly supercritical system is essential for the production of energy at a very rapid rate so that an explosion may occur. See *Critical mass.*

SURFACE BURST: The explosion of a nuclear (or atomic) weapon at the surface of the land or water or at a height above the surface less than the radius of the fireball at maximum luminosity (in the second thermal pulse). An explosion in which the bomb is detonated actually on the surface is called a *contact surface burst* or a *true surface burst.* See *Air burst.*

SURFACE ZERO: See *Ground zero.*

SURGE (OR SURGE PHENOMENA): See *Base surge.*

SURVEY METER: A portable instrument, such as a Geiger counter or ionization chamber, used to detect nuclear radiation and to measure the dose rate. See *Monitoring.*

SYNDROME, RADIATION: The complex of symptoms characterizing the disease known as *radiation sickness*, resulting from excessive exposure of the whole (or a large part) of the body to ionizing radiation. The earliest of these symptoms are nausea, vomiting, and diarrhea, which may be followed by loss of hair (epilation), hemorrhage, inflammation of the mouth and throat, and general loss of energy. In severe cases, where the radiation exposure has been relatively large, death may occur within two to four weeks. Those who survive 6 weeks after the receipt of a single dose of radiation may generally be expected to recover.

TESTS: See *Nuclear tests.*

THERMAL ENERGY: The energy emitted from the ball of fire as thermal radiation. The total amount of thermal energy received per unit area at a specified distance from a nuclear (or atomic) explosion is generally expressed in terms of calories per square centimeter. See *Thermal radiation, Transmittance.*

THERMAL ENERGY YIELD (OR THERMAL YIELD): The part of the total energy yield of the nuclear (or atomic) explosion which is radiated as thermal energy. As a general rule, the thermal energy is one-third of the total energy of the explosion. It may be expressed in calories, ergs, or in terms of the TNT equivalent.

THERMAL RADIATION: Electromagnetic radiation emitted (in two pulses) from the ball of fire as a consequence of its very high temperature; it consists essentially of ultraviolet, visible, and infrared radiations. In the early stages (first pulse), when the temperature of the fireball is extremely high, the ultraviolet radiation predominates; in the second pulse, the temperatures are lower and most of the thermal radiation lies in the visible and infrared regions of the spectrum.

THERMONUCLEAR: An adjective referring to the process (or processes) in which very high temperatures are used to bring about the fusion of light nuclei, such as those of the hydrogen isotopes, deuterium and tritium, with the accompanying liberation of energy. A *thermonuclear bomb* is a weapon in which part of the explosion energy results from thermonuclear fusion reactions. The high temperatures required are obtained by means of a fission explosion. See *Fusion.*

THRESHOLD DETECTOR: An element (or isotope) in which radioactivity is induced only by the capture of neutrons having energies in excess of a certain threshold value characteristic of the element (or isotope). Threshold detectors are used to determine the neutron spectrum from a nuclear (or atomic) explosion, i. e., the numbers of neutrons in various energy ranges.

TNT EQUIVALENT: A measure of the energy released in the detonation of a nuclear (or atomic) weapon, or in the explosion of a given quantity of fissionable material, expressed in terms of the quantity of TNT which would release the same amount of energy when exploded. The TNT equivalent is usually stated in kilotons or megatons. The basis of the TNT equivalence is that the explosion of 1 ton of TNT releases $10^9$ calories of energy. See *Kiloton, Megaton, Yield.*

TRANSMITTANCE (ATMOSPHERIC): The fraction (or percentage) of the thermal energy received at a given location after passage through the atmosphere relative to that which would have been received at the same location if no atmosphere were present.

TRIPLE POINT: The intersection of the incident, reflected, and fused (or Mach) shock fronts accompanying an air burst. The height of the triple point above the surface, i. e., the height of the Mach stem, increases with increasing distance from a given explosion. See *Mach stem.*

TRITIUM: A radioactive isotope of hydrogen, having a mass of 3 units; it is produced in nuclear reactors by the action of neutrons on lithium nuclei.

TRUE SURFACE BURST: See *Surface burst.*

2*W* CONCEPT: The concept that the explosion of a weapon of energy yield *W* on the earth's surface produces blast phenomena identical to those produced by a weapon of twice the yield, i. e., 2*W*, burst in free air, i. e., away from any reflecting surface.

UNDERGROUND BURST: The explosion of a nuclear (or atomic) weapon with its center beneath the surface of the ground.

UNDERWATER BURST: The explosion of a nuclear (or atomic) weapon with its center beneath the surface of the water.

VISIBILITY RANGE (OR VISIBILITY): The horizontal distance (in miles) at which a large dark object can just be seen against the horizon sky in daylight. The visibility is related to the clarity of the atmosphere, ranging from more than 30 miles for an exceptionally clear atmosphere to less than a mile for dense haze or fog.

WEAPON, ATOMIC (OR NUCLEAR): See *Nuclear weapon.*

WILSON CLOUD CHAMBER: See *Condensation cloud.*

YIELD (OR ENERGY YIELD): The total effective energy released in a nuclear (or atomic) explosion. It is usually expressed in terms of the equivalent tonnage of TNT required to produce the same energy release in an explosion. The total energy yield is manifested as nuclear radiation, thermal radiation, and shock (and blast) energy, the actual distribution being dependent upon the medium in which the explosion occurs (primarily) and also upon the type of weapon and the time after detonation.

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# INDEX

## For definitions of various terms, *see* Glossary

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