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The Effects of

NUCLEAR WEAPONS

Revised Edition
Reprinted February 1964

LOS ALAMOS NATIONAL LABORATORY
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The Effects of
Nuclear Weapons

LOS ALAMOS NATL. LAB. LIBS
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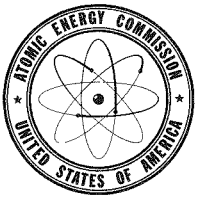
Fireball of the world's first thermonuclear explosion, Eniwetok Proving Grounds, November 1, 1952 (local time)

The Effects of

Nuclear Weapons



SAMUEL GLASSTONE
Editor

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Foreword

This book is a revision of "The Effects of Nuclear Weapons" which was issued in 1957. It was prepared by the Defense Atomic Support Agency of the Department of Defense in coordination with other cognizant governmental agencies and was published by the U.S. Atomic Energy Commission. Although the complex nature of nuclear weapons effects does not always allow exact evaluation, the conclusions reached herein represent the combined judgment of a number of the most competent scientists working on the problem.

There is a need for widespread public understanding of the best information available on the effects of nuclear weapons. The purpose of this book is to present as accurately as possible, within the limits of national security, a comprehensive summary of this information.

Robert S. McNamara

Secretary of Defense

Glenn T. Seaborg

Chairman
Atomic Energy Commission

Preface

When "The Effects of Atomic Weapons" was published in 1950, the explosive energies of the atomic bombs known at that time were equivalent to some thousands of tons (i.e., kilotons) 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 20 kilotons of TNT. With the development of thermonuclear (hydrogen) weapons, having explosive energies in the range of millions of tons (i.e., megatons) of TNT, it became necessary to provide an entirely new presentation, "The Effects of Nuclear Weapons." The first edition of this work, issued in 1957, gave the best information then available concerning the effects on man and materials of nuclear weapons with explosive energy yields up to the equivalent of 20 megatons of TNT. After the cessation of U.S. nuclear tests at the end of October 1958, it was decided to prepare a revision of "The Effects of Nuclear Weapons" incorporating new information which had become available. Although the testing of nuclear weapons has since been resumed, the time is nevertheless opportune for the publication of this revised edition.

It is known that weapons having an explosive energy release of more than 20 megatons TNT equivalent can be produced. However, the limit of 20 megatons has been retained in the present volume, as in the original version. The expected effects of explosions of higher energy yield can be estimated by means of scaling laws. What are believed to be the most reliable scaling laws are given in the text, and with their aid it is possible to calculate, within the limitations mentioned below, the effects to be expected from a nuclear explosion of any prescribed TNT equivalent.

Extensive changes, both in information and presentation, have been made in this revision. The material on the protection against nuclear explosions has been rewritten from a new standpoint so as to bring out the principles involved. In this connection, quantitative data on weapons effects are given in simple tabular form suitable for ready reference. A new chapter has been included on the effects of nuclear explosions on radio communications and radar, and appendices dealing with nuclear weapons safety and methods for detecting distant nuclear explosions have been added. A list, with dates, times, and other unclassified information, of announced weapons tests, made by all countries is also provided.

Although every effort has been made to include the best possible information in this book, it should be kept in mind that, where numerical values are given, inevitable uncertainties are involved. For example, there are inherent difficulties in making exact measurements of weapons effects. The results are often dependent upon circumstances which are difficult, and sometimes impossible, to control even

in tests, and would certainly be unpredictable in the event of an attack. Furthermore, two weapons of different design may have the same explosive energy yield yet differ markedly in their actual effects. Where such possibilities exist, the text calls attention to the limitations of the data presented and of the appropriate scaling laws.

The phenomena of air blast, ground and water shock, thermal (heat) radiation, and nuclear radiations associated with nuclear explosions are very complex. The descriptions of these phenomena and their related effects are thus somewhat technical in nature. However, this book has been organized in such a manner as to serve the widest possible range of readers. With this end in view, most of the chapters are presented in two parts. The first consists of a general treatment of a particular topic in a less technical manner, whereas the second discusses some of the more technical aspects. The material is so arranged that the reader will experience no loss of continuity by the omission of any or all of the more highly technical sections. It is hoped that this format, which was also used in the previous edition, will permit the general reader to obtain a good understanding of each subject without the necessity for coping with the technical aspects with which he may not be concerned. On the other hand, the technical material is available for the use of specialists, such as architects, engineers, medical practitioners, and others, who may have need of such information in their work connected with defense planning.

Many organizations and individuals assisted in one way or another in the production of this revision of "The Effects of Nuclear Weapons," and their cooperation is acknowledged with gratitude. In particular, sincere thanks are due to Colonel T. A. Irving and Lieutenant J. L. Wray, Defense Atomic Support Agency, Headquarters; to Captain R. K. Parsons, Defense Atomic Support Agency, Field Command; and to R. L. Corsbie and L. J. Deal, U.S. Atomic Energy Commission, Division of Biology and Medicine, for their help in solving the numerous administrative, technical, and other problems which arose during the preparation of this book.

Advantage has been taken of this new printing to make some changes and additions, as well as to correct a few typographical errors. New laboratory measurements on the ignition of various fabrics and household materials (Tables 7.40 and 7.66) indicated that the fire hazard from thermal radiation was significantly less than implied in the first (April 1962) printing. It was felt, therefore, that the corrections in Chapter VII should be made at the earliest opportunity. Other changes of a minor nature have been introduced in this chapter to clarify certain aspects of the development and spread of fires. In addition, the compilation of Announced Nuclear Detonations in Appendix B has been extended through 1963.

Los Alamos, N. Mex. SAMUEL GLASSTONE
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CHAPTER I

GENERAL PRINCIPLES OF NUCLEAR EXPLOSIONS

CHARACTERISTICS OF NUCLEAR EXPLOSIONS

Introduction

1.01 An explosion, in general, results from the very rapid release of a large amount of energy within a limited space. This is true for a conventional "high explosive," such as TNT, as well as for a nuclear (or atomic) explosion,[1] although the energy is produced in quite different ways (§ 1.10). The sudden liberation of energy causes a considerable increase of temperature and pressure, so that all the materials present are converted into hot, compressed gases. Since these gases are at very high temperatures and pressures, they expand rapidly and thus initiate a pressure wave, called a "shock wave," in the surrounding medium—air, water, or earth. The characteristic of a shock wave is that there is a sudden increase of pressure at the front, with a gradual decrease behind it, as shown in Fig. 1.01. A shock wave in air is generally referred to as a "blast wave" because it resembles and is accompanied by a very strong wind. In water or in the ground, however, the term "shock" is used, because the effect is like that of a sudden impact.

1.02 Nuclear weapons are similar to those of more conventional types in so far as their destructive action is due mainly to blast or shock. On the other hand, there are several basic differences between nuclear and high-explosive weapons. In the first place, nuclear explosions can be many thousands (or millions) of times more powerful than the largest conventional detonations. Second, 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." It is capable of causing skin burns and of starting fires at considerable

[1] The terms "nuclear" and "atomic" may be used interchangeably as far as such weapons and explosions are concerned, but "nuclear" is preferred for the reason given in § 1.10.

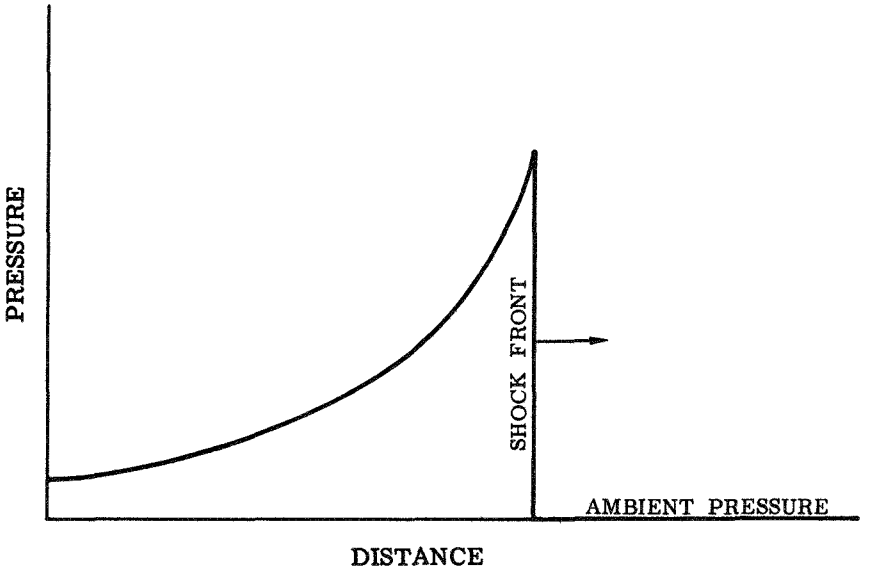

Figure 1.01. Variation of pressure (in excess of ambient) with distance in a shock wave.

distances. Third, the nuclear explosion is accompanied by highly-penetrating and harmful 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. 1.02).

1.03 It is because of these fundamental differences between a nuclear and a conventional explosion, including 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 the various radiation phenomena associated with a nuclear explosion are of vital importance.

1.04 The purpose of this book is to describe the different forms in which the energy of a nuclear explosion are released, to explain how they are propagated, and to show how they may affect men and materials. Where numerical values are given for specific observed effects, it should be kept in mind that there are inevitable uncertainties associated with the data, for at least two reasons. In the first place, there are inherent difficulties in making exact measurements of weapons effects. The results are often dependent on circumstances which are difficult, if not impossible, to control, even in a test and

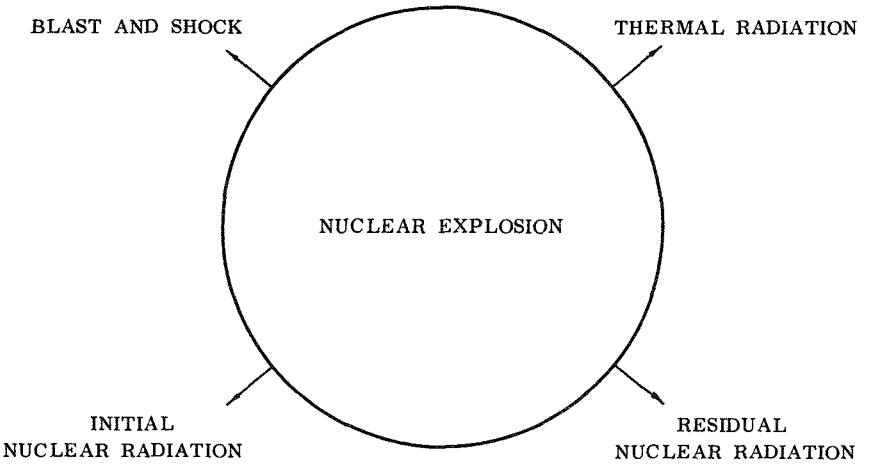

Figure 1.02. Effects of a nuclear explosion.

certainly cannot be predicted in the event of an attack. Furthermore, two weapons having the same yield of explosive energy may have different quantitative effects because of differences in composition and design.

1.05 It is hoped, nevertheless, that the information contained in this volume, which is the best available, may be of assistance to those responsible for defense planning and in making 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 which provide shielding against nuclear radiations.

Atomic Structure and Isotopes

1.06 All substances are made up from one or more of about 90 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.

1.07 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

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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.

1.08 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.

1.09 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: Fission and Fusion Reactions

1.10 As stated in § 1.01, an explosion is caused by the very rapid release of a large amount of energy. In the case of a conventional explosion, this energy arises from chemical reactions; these involve a rearrangement among the atoms, e.g., of hydrogen, carbon, oxygen, and nitrogen, present in the chemical high-explosive material. In a nuclear explosion, on the other hand, the energy is produced as a result of the formation of different atomic nuclei by the redistribution of the protons and neutrons within the interacting 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 weapons are preferably called "nuclear weapons." The forces between the protons and neutrons within atomic

nuclei are tremendously greater than those between the atoms; consequently, nuclear energy is of a much higher order of magnitude than conventional (or chemical) energy when equal masses are considered.

1.11 Many nuclear processes are known, but not all of these are accompanied by the release of energy. 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.

1.12 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.

1.13 The materials used to produce nuclear explosions by fission are certain isotopes of the elements uranium and plutonium. Uranium as found in nature consists of two isotopes, namely uranium-235 and uranium-238; the former, which is by far the less abundant, is the readily fissionable species used in nuclear weapons. The element plutonium does not occur naturally, and the fissionable isotope plutonium-239 is made artificially. 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 releases as much energy as the explosion of 8,000 tons of TNT.

1.14 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.

1.15 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.

1.16 In certain fusion processes, among nuclei of the hydrogen isotopes, neutrons of high energy are liberated (see § 1.68). These can cause fission in the most abundant isotope (uranium-238) in ordinary uranium as well as in uranium-235. Consequently, association of the appropriate fusion reactions with natural uranium can result in an extensive 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. On the average, in weapons of this type, roughly equal amounts of explosive energy result from fission and from fusion.

1.17 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

1.18 The power of a nuclear weapon is expressed in terms of the energy release (or yield) when it explodes compared with the energy liberated by the explosion of TNT. Thus, a 1-kiloton nuclear weapon is one which produces the same amount of energy in an explosion as does 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.

1.19 From the statement in § 1.13 that the fission of 1 pound of uranium or plutonium will release the same amount of energy as

8,000 tons of TNT, it is evident that in a 20-kiloton nuclear weapon 2.5 pounds of material undergo fission. However, the actual weight of uranium or plutonium in such a weapon 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.

Thermal Radiation

1.20 It has been mentioned that one important difference between nuclear and conventional (or chemical) explosions is the appearance of an appreciable proportion of the energy as thermal radiation in the former case. The basic reason for this difference is that, weight for weight, the energy produced in a nuclear explosion is millions of times as great as that in a chemical explosion. Consequently, the temperatures reached in the former case are much higher than in the latter, namely, tens of millions of degrees in a nuclear explosion compared with a few thousands in a conventional explosion. As a result of this great difference in temperature, the distribution of the explosion energy is quite different in the two cases.

1.21 Broadly speaking, the energy may be divided into three categories: kinetic (or external) energy, i.e., energy of motion of electrons, atoms, and molecules as a whole; internal energy of these particles; and thermal radiation energy. The proportion of thermal energy increases rapidly with increasing temperature. At the moderate temperatures attained in a chemical explosion, the amount of thermal radiation is comparatively small, and so essentially all the energy released at the time of the explosion appears as kinetic and internal energy. This is almost entirely converted into blast and shock, in the manner described in § 1.01. Because of the very much higher temperatures in a nuclear explosion, however, a considerable proportion of the energy released is present as thermal radiation which is ultimately emitted as intense heat and light rays. The manner in which this takes place is described later (§ 1.73 *et seq.*). Blast and shock are also produced as in a conventional explosion.

Distribution of Energy in Nuclear Explosions

1.22 The fraction of the explosion yield received as thermal energy at a distance from the burst point depends on the nature of the weapon and particularly on the environment of the explosion. For a detonation in the atmosphere below an altitude of about 100,000 feet, it ranges from about 30 to 40 percent. For purposes of

illustration it will be assumed here that 35 percent of the explosion energy is received as thermal energy. In this event, about 50 percent of the fission energy will be utilized in the production of blast and shock (Fig. 1.22). At higher altitudes, where there is less air with which the energy of the exploding weapon can interact, the proportion of the fission energy converted into blast is decreased, whereas the thermal radiation is increased. On the other hand, at the other extreme of a completely confined underground explosion of a nuclear weapon, little or no thermal radiation escapes.

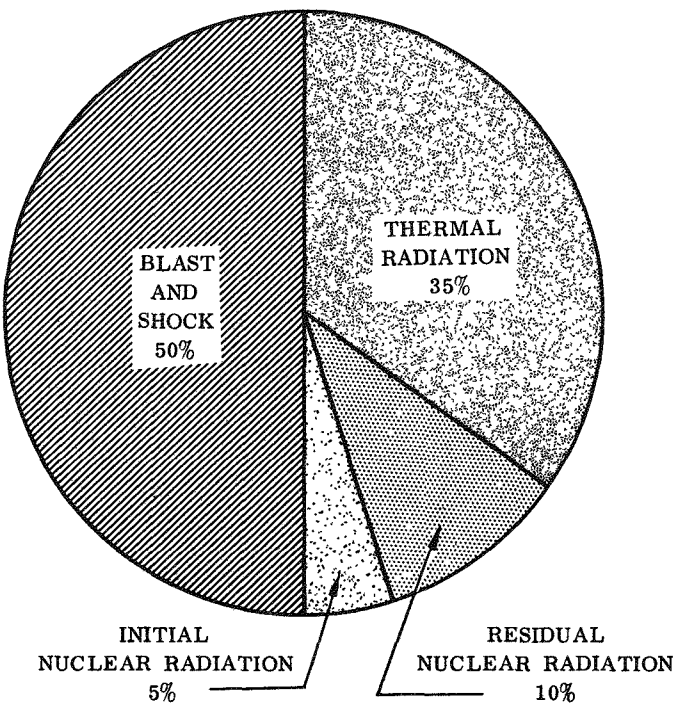

Figure 1.22. Distribution of energy in a typical air burst of a fission weapon in air at an altitude below 100,000 feet.

1.23 In addition to the 85 percent of the fission energy which is converted into blast, shock, and thermal radiation, the remaining 15 percent is released as various nuclear radiations. Of this, some 5 percent constitutes the initial nuclear radiations produced within a minute or so of the explosion. The final 10 percent of the total fission explosion energy represents that of the residual (or delayed)

nuclear radiation which is emitted over a period of time. This is due almost entirely to the radioactivity of the fission products present in the weapon residues (or debris) after the explosion. In a thermonuclear device, in which only about half of the total energy arises from fission (§ 1.16), the residual nuclear radiation carries only 5 percent of the energy released in the explosion. It should be noted that there are no nuclear radiations from a conventional explosion since the nuclei are unaffected in the chemical reactions which take place.

1.24 Since about 10 percent of the total fission energy is released in the form of residual nuclear radiation some time after the detonation, this is not included when the energy yield of a nuclear explosion is stated, e.g., in terms of the TNT equivalent as in § 1.18. Hence, in a pure fission weapon the explosion energy is about 90 percent of the total fission energy, and in a thermonuclear device it is, on the average, about 95 percent of the total energy of the fission and fusion reactions.

1.25 The initial nuclear radiations consist mainly of "gamma rays," which are electromagnetic radiations of high energy (see § 1.69) originating in atomic nuclei, and neutrons. These radiations, especially gamma rays, can travel great distances through air and can penetrate considerable thicknesses of material. Although they can neither be seen nor felt by human beings, except in very large doses which produce a tingling sensation, gamma rays and neutrons can produce harmful effects even at a distance from their source. Consequently, the initial nuclear radiations are an important aspect of nuclear explosions.

1.26 The delayed nuclear radiations, as mentioned earlier, arise from the fission products which, in the course of their radioactive decay, 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 (§ 1.08), moving with high speed. Beta particles, which are also invisible, are much less penetrating than gamma rays, but like the latter they represent a potential hazard.

1.27 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 decrease 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

1.28 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 five 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) high-altitude burst, (3) underwater burst, (4) underground burst, and (5) surface burst.

1.29 Almost immediately after a nuclear explosion, the weapon residues incorporate material from the surrounding medium and form an intensely hot and luminous mass, roughly spherical in shape, called the "fireball." An "air burst" is defined as one in which the weapon is exploded in the air at an altitude below 100,000 feet, but at such a height that the fireball (at roughly maximum brilliance in its later stages) does not touch the surface of the earth. For example, in the explosion of a 1-megaton weapon the fireball may grow until it is nearly 5,800 feet (1.1 mile) across at maximum brilliance. This means that, in this particular case, the explosion must occur at least 2,900 feet above the earth's surface if it is to be called an air burst.

1.30 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 some is generally also transmitted into the ground. 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 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.

1.31 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. 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 weapon, 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. However, at this distance the blast effect would be so great that only specially designed blast-resistant structures would survive.

1.32 In the event of a high or moderately high air burst, the fission products remaining after the nuclear explosion will be spread out over a large area. The residual nuclear radiations arising from these products will be of minor immediate 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, part of which will soon fall to the ground at points close to the explosion. This dirt and other debris will be contaminated with radioactive material and will, consequently, represent a possible danger to living organisms.

1.33 A "high-altitude burst" is defined as one in which the explosion takes place at an altitude in excess of 100,000 feet. Above this level, the air density is so low that the interaction of the weapon energy with the surroundings is markedly different from that at lower altitudes and, moreover, varies with the altitude. The absence of relatively dense air causes the fireball characteristics in a high-altitude explosion to differ from those of an air burst. For example, the fraction of the energy of fission converted into blast and shock is less and decreases with increasing altitude. A larger proportion of the explosion energy is then in the form of thermal radiation. It has been estimated that at great heights, where the density of the air is extremely low, more than 50 percent of the fission energy might appear as thermal radiation at some distance from the exploding weapon.

1.34 In contrast to thermal radiation, the fraction of the explosion energy emitted as nuclear radiations is independent of the height of burst. However, the attenuation of the initial nuclear radiations with increasing distance from the explosion is determined by the total amount of air through which the radiation travels. This means that, for a given explosion energy yield, more initial nuclear radiation will be received at the same slant distance on the earth's surface from a high-altitude detonation than from a moderately high air burst. On the other hand, in a high-altitude nuclear explosion the fission products will be widely dispersed in the stratosphere, so that there is no immediate hazard on the surface from the residual nuclear radiations.

1.35 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. 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.

1.36 A "surface burst" is regarded as one which occurs either at or slightly above the actual surface of the land or water. Provided the distance above the surface is not great, the phenomena are essentially the same as for a burst occurring on the surface. As the height of burst increases up to a point where the fireball (at maximum brilliance in its later stages) no longer touches the land or water, there is a transition zone in which the behavior is intermediate between that of a true surface burst and of an air burst. In surface bursts, the air blast and ground (or water) shock are produced in varying proportions depending on the energy of the explosion and the height of burst.

1.37 Although the five 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, a high-altitude burst will become an air burst, and 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 fireball 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 five general types defined above.

SCIENTIFIC BASIS OF NUCLEAR EXPLOSIONS [2]

Fission Energy and the Chain Reaction

1.38 The significant point about the fission of a uranium (or plutonium) nucleus by means of a neutron, in addition to the release of a large quantity of energy, is that the process is accompanied by the instantaneous emission of two or more neutrons; thus,

$$\text{Neutron} + \begin{matrix}\text{uranium-235} \\ \text{(or plutonium-239)}\end{matrix} \rightarrow \begin{matrix}\text{fission fragments} + \\ \text{2 or 3 neutrons} + \text{energy.}\end{matrix}$$

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

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, as will be seen below.

1.39 There are many different ways in which the nuclei of a given fissionable species can split up into two fission fragments, but the total amount of energy liberated per fission does not vary greatly. A satisfactory average value of this energy is 200 million electron volts. The million electron volt (or 1 Mev) unit has been found convenient for expressing the energy released in nuclear reactions; it is equivalent to 1.6×10^{-6} erg or 1.6×10^{-13} joule. The manner in which this energy is distributed among the fission fragments and the various radiations associated with fission is shown in Table 1.39.

TABLE 1.39

DISTRIBUTION OF FISSION ENERGY

	Mev
Kinetic energy of fission fragments	165 ± 5
Instantaneous gamma-ray energy	7 ± 1
Kinetic energy of fission neutrons	5 ± 0.5
Beta particles from fission products	7 ± 1
Gamma rays from fission products	6 ± 1
Neutrinos from fission products	10
Total energy per fission	200 ± 6

1.40 The results in the table may be taken as being applicable to either uranium-233, uranium-235, or plutonium-239. These are the only three known substances, which are reasonably stable so that they can be stored without appreciable decay, that are capable of undergoing fission by neutrons of all energies. Hence, they are the only materials that can be used to sustain a fission chain. Uranium-238, the most abundant isotope (approximately 99.3 percent) in natural uranium, and thorium-232 will suffer fission by neutrons of high energy only, but not by those of lower energy. For this reason these substances cannot sustain a chain reaction. However, when fission does occur in these elements, the energy distribution is quite similar to that shown in the table.

1.41 Only part of the fission energy is immediately available in a nuclear explosion; this includes the kinetic energy of the fission fragments, most of the energy of the instantaneous gamma rays and neutrons, but only a small fraction of the decay energy of the fission

products. There is some compensation from energy released in reactions in which neutrons are captured by the weapon debris, and so it is usually accepted that about 180 Mev of energy are available per fission. There are 6.02×10^{23} nuclei in 235 grams of uranium-235 (or 239 grams of plutonium-239), and by making use of familiar conversion factors (cf. § 1.39) the results quoted in Table 1.41 may be obtained for the energy (and other) equivalents of 1 kiloton of TNT. The calculations are based on an accepted, although somewhat arbitrary, figure of 10^{12} calories as the energy released in the explosion of this amount of TNT.

TABLE 1.41

EQUIVALENTS OF 1 KILOTON OF TNT

Complete fission of 0.056 kg (56 grams) fissionable material
Fission of 1.45×10^{23} nuclei
10^{12} calories
4.2×10^{19} ergs
1.15×10^{6} kilowatt-hours
3.97×10^{9} British thermal units

1.42 An interesting insight into the rate at which the energy is released in a fission explosion can be obtained by treating the fission chain as a series of "generations." Suppose that a certain number of neutrons are present initially and that these are captured by fissionable nuclei; then, in the fission process other neutrons are released. These neutrons are, in turn, captured by fissionable nuclei and produce more neutrons, and so on. Each stage of the fission chain is regarded as a generation, and the "generation time" is the average time interval between successive generations. The time required for the actual fission of a nucleus is extremely short and most of the neutrons are emitted promptly. Consequently, the generation time is essentially equal to the average time elapsing between the release of a neutron and its subsequent 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, usually referred to as "fast neutrons," the generation time is about a one-hundred-millionth part of a second, i.e., one hundredth of a microsecond.[3]

1.43 Although from two to three neutrons are produced for each nucleus that undergoes fission, not all of them are available for causing more fissions; some of the neutrons escape altogether and others are

[3] A *microsecond* is a one-millionth part of a second, i.e., 10^{-6} second; a hundredth of a microsecond, i.e., 10^{-8} second, is often called a "shake." The generation time in fission by fast neutrons is thus roughly 1 shake.

removed in nonfission reactions. Suppose that when a nucleus captures a neutron and suffers fission f neutrons are released; let l be the average number of neutrons lost, in one way or another, for each fission. There will then be $f-l$ neutrons available to carry on the fission chain. If there are N neutrons present at any instant, then as a result of their capture by fissionable nuclei $N(f-l)$ neutrons will be produced at the end of one generation; hence, the increase in the number of neutrons per generation is $N(f-l)-N$ or $N(f-l-1)$. For convenience, the quantity $f-l-1$, representing the increase in neutrons per fission, will be represented by x. If g is the generation time, then the rate at which the number of neutrons increases is given by

$$\text{Rate of neutron increase } (dN/dt)=Nx/g.$$

The solution of this equation is

$$N=N_0e^{xt/g},$$

where N_0 is the number of neutrons present initially and N is the number at a time t later. The fraction t/g is the number of generations which have elapsed during the time t, and if this is represented by n, it follows that

$$N=N_0e^{xn}. \tag{1.43.1}$$

1.44 If the value of x is known, equation (1.43.1) can be used to calculate either the neutron population after any prescribed number of generations in the fission chain or, alternatively, the generations required to attain a particular number of neutrons. For uranium-235, f is about 2.5, l may be taken to be roughly 0.5, so that x, which is equal to $f-l-1$ is close to unity; hence, equation (1.43.1) may be written as

$$N\approx N_0e^n \text{ or } N\approx N_010^{n/2.3}. \tag{1.44.1}$$

1.45 According to the data in Table 1.41, it would need 1.45×10^{22} fissions, and hence the same number of neutrons, to produce 0.1 kiloton equivalent of energy. If the fission chain is initiated by one neutron, so that N_0 is 1, it follows from equation (1.44.1) that it would take approximately 51 generations to produce the required number of neutrons. Similarly, to release 100 kilotons of energy would require 1.45×10^{25} neutrons and this number would be attained in about 58 generations. It is seen, therefore, that 99.9 percent of the energy of a 100-kiloton fission explosion is released during the last 7 generations, that is, in a period of roughly 0.07 microsecond. The same result is obtained for any fission explosion energy.

1.46 The data given above show that in a little more than 50 generations, i.e., about half a microsecond, after the initiation of the fission

chain, so much energy will have been released that extremely high temperatures will be attained. Consequently, in spite of the restraining effect of the tamper (§ 1.52) and the weapon casing, the mass of fissionable material will begin to expand rapidly. The time at which this expansion commences is called the "explosion time." Since the expansion permits neutrons to escape more readily, the self-sustaining chain reaction soon ends, although an appreciable proportion of the fissionable material remains unchanged. Some fissions will continue as a result of neutron capture, but the amount of energy released at this stage is relatively small.

1.47 To summarize the foregoing discussion, it may be stated that because the fission process is accompanied by the instantaneous liberation of neutrons, it is possible, in principle, to produce a self-sustaining chain reaction accompanied by the rapid release of large amounts of energy. 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 many thousands of tons of TNT. This is the basic principle of nuclear fission weapons.

Critical Size of Nuclear Fission Weapon

1.48 It was mentioned above that some of the neutrons produced in fission are lost by escape from the fissionable material or by capture therein by 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.

1.49 The escape of neutrons occurs at the exterior of the uranium (or plutonium) material. The rate of loss by escape will thus be determined by 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, therefore, dependent upon the mass. By increasing the volume of the fissionable material, the ratio of the surface area to the mass is decreased; consequently, the loss of neutrons by escape relative to their formation by fission is decreased.

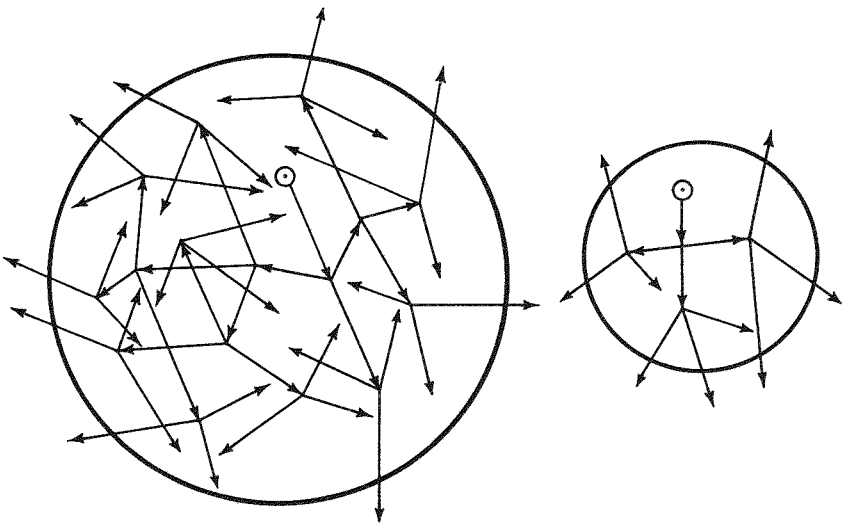

Figure 1.50. Effect of increased size of fissionable material in reducing the proportion of neutrons lost by escape.

1.50 The situation may be understood by reference to Fig. 1.50 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. 1.50 that a much greater fraction of the neutrons is lost from the smaller than from the larger sphere.

1.51 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.

1.52 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. Moreover, elements of high density, which make good reflectors for neutrons of high energy, provide inertia, thereby delaying expansion of the exploding material. The action of the reflector is then like the familiar tamping in blasting operations. As a consequence of its neutron reflecting and inertial properties, the "tamper" permits the fissionable material in a nuclear weapon to be used more efficiently.

Attainment of Critical Mass

1.53 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 detonation, a nuclear weapon 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.

1.54 Two general methods have been described for bringing about a nuclear exposion, 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.

1.55 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 compressing the fissionable material, i.e., by increasing its density, the rate of production of neutrons by fission is increased relative to the rate of loss by escape. A self-sustaining

chain reaction may then become possible with the same mass that was subcritical in the uncompressed state.

1.56 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. The surface to volume ratio of this compressed mass is then such as to make it supercritical. The introduction of neutrons from a suitable source can now initiate a chain reaction leading to an explosion.

Fission Products

1.57 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, so that about 80 different fragments are produced. There are some variations in the nature of the fission fragment nuclei and in their properties, depending on the particular substance undergoing fission and on the energy of the neutrons causing fission. For example, when uranium-238 undergoes fission as a result of the capture of neutrons of very high energy released in certain fusion reactions (§ 1.16) the products are somewhat different, especially in their relative amounts, from those formed from uranium-235 by ordinary fission neutrons.

1.58 Regardless of their origin, most, if not all, of the approximately 80 fission fragments 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 (§ 1.26). 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.

1.59 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.

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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.[4] Something like 200 or more different isotopes of 36 light elements, from zinc to terbium, have been identified among the fission products.

1.60 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.

1.61 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 that the decrease in the total radiation intensity from the fission products can be calculated approximately 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. 1.61. 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.

1.62 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 § 1.46, 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 expelled 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.

1.63 Because of their greater mass and charge, alpha particles are much less penetrating than beta particles or gamma rays of the

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

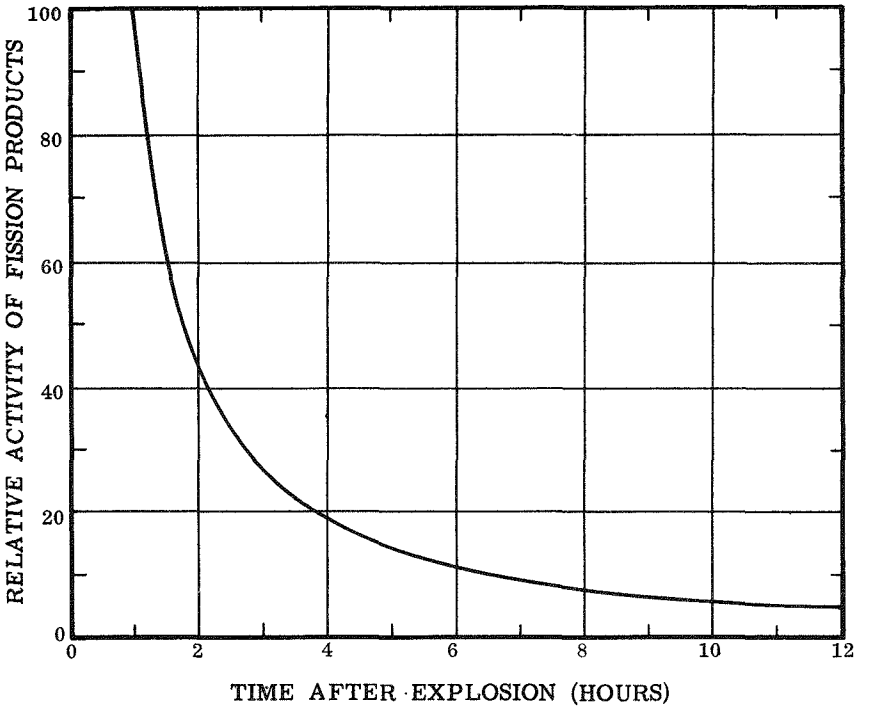

Figure 1.61. Rate of decay of fission products after a nuclear explosion (activity is taken as 100 at 1 hour after the detonation).

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 fission residues does 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

1.64 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.

1.65 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.

1.66 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; these are:

$$H^2+H^2=He^3+n+3.2 \text{ Mev}$$
$$H^2+H^2=H^3+H^1+4.0 \text{ Mev}$$
$$H^3+H^2=He^4+n+17.6 \text{ Mev}$$
$$H^3+H^3=He^4+2n+11.3 \text{ Mev},$$

where He is the symbol for helium and n(mass=1) represents a neutron. The energy liberated in each case is given in million electron volt (Mev) units. In comparing the energy released in these fusion reactions with that produced in fission, it will be noted that, as a result of the first three reactions given above, five deuterium nuclei, with a total mass of 10 units, will liberate 24.8 Mev upon fusion. On the other hand, in the fission process, e.g., of uranium-235, a mass of 235 units will produce a total of about 200 Mev of energy (§ 1.39). Weight for weight, therefore, the fusion of deuterium nuclei would produce nearly three times as much energy as the fission of uranium or plutonium.

1.67 In order to make the nuclear fusion reactions take place, temperatures of the order of several million degrees are necessary. The only practical 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 device, 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.

1.68 It will be observed that in three of the fusion reactions given in § 1.66, neutrons are produced. Because of their small mass, these neutrons carry off most of the reaction energy; consequently, they have sufficient energy to cause fission of uranium-238 nuclei. As stated earlier, this process requires neutrons of high energy. It is possible, therefore, to make use of the thermonuclear neutrons by surrounding the fusion weapon with a blanket of ordinary uranium. The high-energy neutrons are then captured by uranium-238 nuclei; the latter undergo fission, thereby contributing to the overall energy yield of the explosion, and also to the residual nuclear radiations arising from the fission products. In general, the energy released in the explosion of a thermonuclear weapon originates in roughly equal amounts from fission and fusion processes.

Thermal Radiation

1.69 The observed phenomena associated with a nuclear explosion and the effects on men and materials are largely affected by the thermal radiation and its interaction with the surroundings. It is desirable, therefore, to consider the nature of these radiations somewhat further. Thermal radiations belong in the broad category of what are known as "electromagnetic radiations." These are a kind of wave motion resulting from oscillating electric charges and their associated magnetic fields. Ordinary visible light is the most familiar kind of electromagnetic radiation, and all such radiations travel through the air (or, more exactly, a vacuum) at the same velocity, namely, the velocity of light, 186,000 miles per second. Electromagnetic radiations range from the very short wave length (or very high frequency) gamma rays (§ 1.25) and X-rays, through the invisible ultraviolet to the visible region, and then to the infrared and radar and radio waves of relatively long wave length (and low frequency).

1.70 The approximate wave length and frequency regions occupied by the different kinds of electromagnetic radiations are indicated in Fig. 1.70. The wave length λ in centimeters and the frequency ν in waves (or cycles) per second are related by $\lambda\nu=c$, where c is the velocity of light, 3.00×10^{10} cm per second. According to Planck's theory, the energy of the corresponding "quantum" (or unit) of

energy, carried by the "photon," i.e., the postulated particle (or atom) of radiation, is given by

$$E\ (\text{ergs}) = h\nu = \frac{hc}{\lambda} = \frac{1.99\times10^{-16}}{\lambda\ (\text{cm})}, \tag{1.70.1}$$

where h is a universal constant equal to 6.62×10^{-27} erg-second. The energy quantum values for the various electromagnetic radiations are included in Fig. 1.70; the results are expressed either in Mev, i.e., million electron volt, in kev, i.e., kilo (or thousand) electron volt, or in ev, i.e., electron volt, units. These are obtained from equation (1.70.1) by writing it in the form

$$E\ (\text{Mev}) = \frac{1.24\times10^{-10}}{\lambda\ (\text{cm})}. \tag{1.70.2}$$

It is seen that the energy of the radiations decreases from left to right in the figure, i.e., as the wave length increases and the frequency decreases.

1.71 The radiation energy for unit volume of matter in temperature equilibrium is given by

$$E\ (\text{radiation}) = 7.6\times10^{-15}\ T^4\ \text{ergs per cm}^3,$$

where T is the temperature in degrees Kelvin. At the temperature of a conventional chemical explosion, e.g., 5,000° K, the radiation energy density is then less than 1 erg per cm^3, compared with roughly 10^8 ergs per cm^3 for the material energy, i.e., kinetic energy and internal (electronic, vibrational, and rotational) energy. Hence, as indicated in §1.21, the radiation energy is a very small proportion of the total energy. In a nuclear explosion, on the other hand, where temperatures of several tens of million degrees are reached, the radiation energy density will be of the order of 10^{16} ergs per cm^3, whereas the material energy is in the range of 10^{14} to 10^{15} ergs per cm^3. It has been estimated that in a nuclear explosion some 80 percent of the total energy may be present as radiation energy.

1.72 Not only does the radiation energy density increase with temperature but the rate of its emission as thermal radiation increases correspondingly. For materials at temperatures of a few thousand degrees Kelvin, the energy is radiated slowly, with the greatest part in the ultraviolet, visible, and infrared regions of the electromagnetic

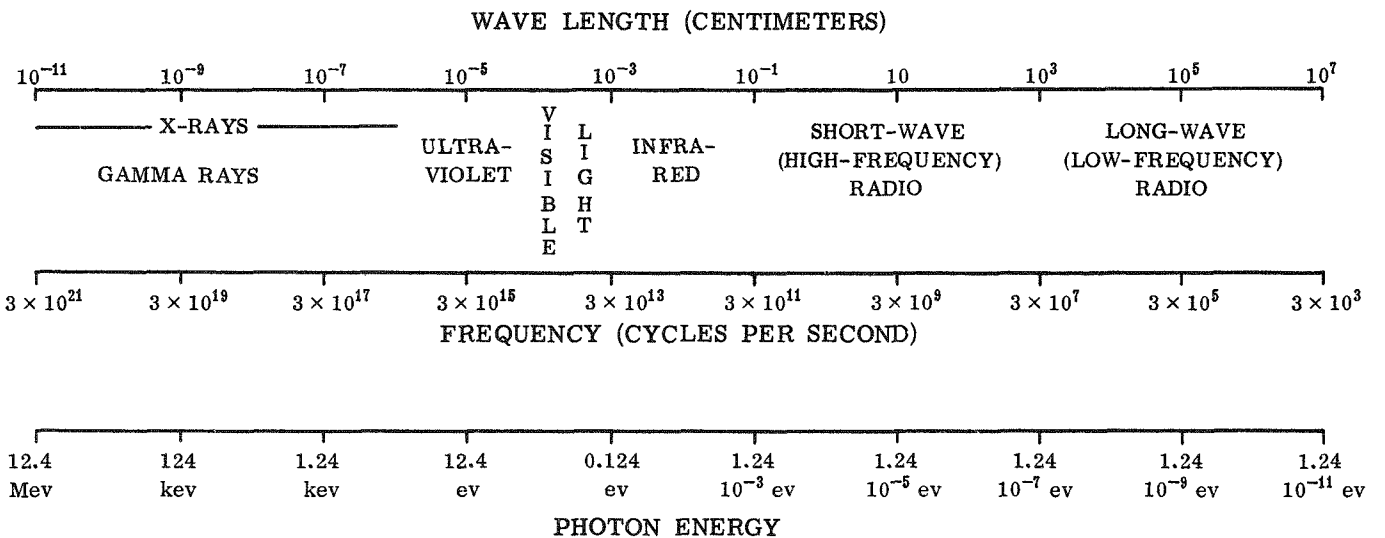

Figure 1.70. Wave lengths, frequencies, and energies of electromagnetic radiations.

spectrum (Fig. 1.70). But at the temperatures of a nuclear explosion not only is the radiation energy emitted very rapidly, but most of this energy is in the spectral region with wave lengths shorter than the ultraviolet, as will be seen in Chapter VII. In fact, under these conditions, about 60 or 70 percent of the total (material and radiation) energy is radiated as X-rays.[5]

1.73 When a nuclear weapon explodes, temperature equilibrium is rapidly established in the residual material. Something like 80 percent of the fission energy other than that associated with the residual radiation, i.e., about 70 percent of the total, appears as primary thermal radiation, most of which consists of soft X-rays. The primary thermal radiation is absorbed by the air in the vicinity of the explosion, as described below, and is then re-radiated. It is this (secondary) radiation which is the thermal radiation of immediate interest.[6]

1.74 When a nuclear detonation occurs in the air, where the atmospheric pressure (and density) is near to sea-level conditions, the soft X-rays in the primary thermal radiation are completely absorbed within a distance of a few feet. Some of the radiations are degraded to lower energies, e.g., into the ultraviolet region, but most of the energy is converted into kinetic and internal energy of the oxygen and nitrogen atoms and molecules in the air. In other words, much of the energy of the primary thermal radiation serves to heat the air immediately surrounding the nuclear burst. It is in this manner that the fireball is formed. Part of the energy is then re-radiated at a lower temperature from the fireball and the remainder is converted into shock (or blast) energy, as will be seen in Chapter II. This explains why only about 30 to 40 percent of the fission energy is received at a distance as thermal radiation energy in an air burst, although the primary thermal radiation may constitute as much as 70 percent of the total. Furthermore, because the secondary thermal radiation is emitted at a lower temperature, it lies mainly in the region of the spectrum with longer wave lengths, i.e., ultraviolet, visible, and infrared.

1.75 In the event of a burst at high altitudes, where the air density is low, the soft X-rays travel long distances before they are degraded and absorbed. At this stage, the available energy is spread throughout such a large volume that most of the atoms and molecules

[5] X-rays are frequently distinguished as "hard" or "soft." The latter have longer wave lengths and lower energies, and they are more easily absorbed than hard X-rays. They are, nevertheless, radiations of high energy compared with ultraviolet or visible light.

[6] It is sometimes referred to as the "prompt thermal radiation" because only that which is received within a few seconds of the explosion is significant as a hazard.

in the air cannot get very hot. Although the total energy emitted as thermal radiation in a high-altitude explosion is greater than for an air burst closer to sea level, about half is re-radiated so slowly by the heated air that it has no great significance as a cause of damage. The remainder, however, is radiated very much more rapidly, i.e., in a shorter time interval, than is the case at lower altitudes. A shock wave is generated from a high-altitude burst, but at distances of normal practical interest it produces a smaller pressure increase than from an air burst of the same yield.

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CHAPTER II

DESCRIPTIONS OF NUCLEAR EXPLOSIONS

INTRODUCTION

2.01 A number of characteristic phenomena, some of which are visible whereas others are not directly apparent, are associated with nuclear explosions. Certain aspects of these phenomena will depend on the type of burst, i.e., air, high-altitude, surface, or subsurface, as indicated in Chapter I. This dependence arises from direct and secondary interactions of the output of the exploding weapon with its environment, and leads to variations in the distribution of the energy released, particularly among blast, shock, and thermal radiation. In addition, the design of the weapon can also affect the energy distribution. Finally, meteorological conditions, such as temperature, humidity, wind, precipitation, and atmospheric pressure, and even the nature of the terrain over which the explosion occurs, may influence some of the observed effects. Nevertheless, the gross phenomena associated with a particular type of nuclear explosion, namely, air, surface, underwater, underground, or high-altitude burst, remain unchanged. It is such phenomena that are described in this chapter.

2.02 The descriptions of explosions at very high altitudes as well as those in the air nearer to the ground refer mainly to nuclear devices with energies in the vicinity of 1-megaton TNT equivalent. For underwater bursts, the information is based on the detonations of a very few weapons with roughly 20 kilotons of TNT energy in shallow and moderately deep water. Indications will be given of the results to be expected for explosions of other yields. As a general rule, however, the basic phenomena for a burst in a particular environment are not greatly dependent upon the energy of the explosion. In the following discussion it will be supposed, first, that a typical air burst takes place at such a height that the fireball, even at its maximum, is well above the surface of the earth. The modifications, as well as the

special effects, resulting from a surface burst and for one at very high altitudes will be included. In addition, some of the characteristic phenomena associated with underwater and underground nuclear explosions will be described.

DESCRIPTION OF AIR AND SURFACE BURSTS

The Fireball

2.03 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, and other weapon parts are raised to extremely high temperatures, similar to those in the center of the sun. The maximum temperature attained by the fission weapon residues is several tens of million degrees, which may be compared with a maximum of 5,000° C (or 9,000° F) in a conventional high-explosive weapon. Because of 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 weapon, tremendous pressures will be produced. These pressures are probably over a million times the atmospheric pressure, i.e., of the order of many millions of pounds per square inch.

2.04 Within less than a millionth of a second of the detonation of the weapon, the extremely hot weapon residues radiate large amounts of energy, mainly as invisible X-rays, which are absorbed within a few feet in the surrounding (sea-level) atmosphere (§ 1.73). This leads to the formation of a hot and highly luminous, spherical mass of air and gaseous weapon residues which is the fireball referred to in § 1.29; a typical fireball accompanying an air burst is shown in Fig. 2.04. The surface brightness decreases with time, but after about a millisecond,[1] the fireball from a 1-megaton nuclear weapon would appear to an observer 50 miles away to be many times more brilliant than the sun at noon. In several of the nuclear tests made at low altitudes 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. This was not the result of direct (line of sight) transmission, but rather of scattering and diffraction, i.e., bending, of the light rays by particles of dust and

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

possibly by moisture in the atmosphere. However, high-altitude bursts in the megaton range have been seen directly as far as 700 miles away.

2.05 The surface temperatures of the fireball, upon which the brightness (or luminance) depends, do not vary greatly with the total energy yield of the weapon. Consequently, the observed brightness of the fireball in an air burst is roughly the same, regardless of the amount of energy released in the explosion. Immediately after its formation, the fireball begins to grow in size, engulfing the surrounding

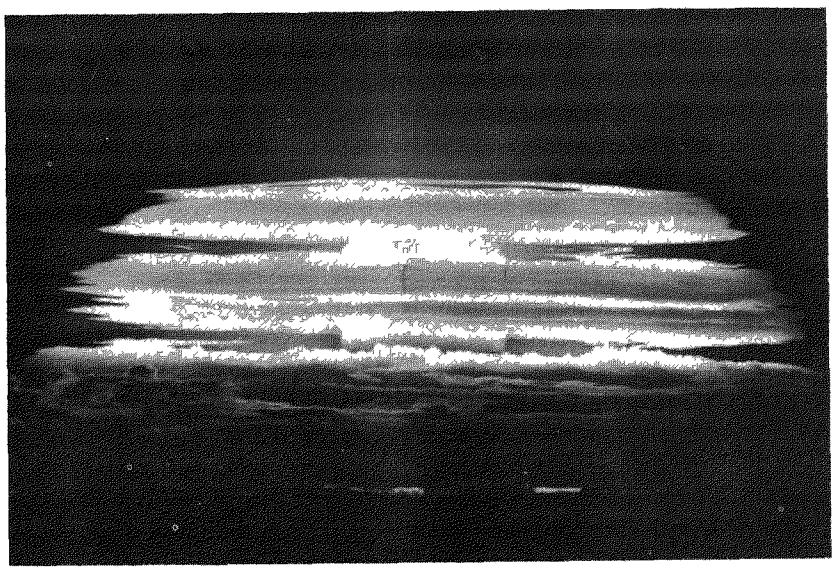

Figure 2.04. Fireball from an air burst in the megaton energy range, photographed from an altitude of 12,000 feet at a distance of about 50 miles. The fireball is partially surrounded by the condensation cloud (see § 2.47).

air. This growth is accompanied by a decrease in temperature because of the accompanying increase in mass. At the same time, the fireball rises, like a hot-air balloon. Within seven-tenths of a millisecond from the detonation, the fireball from a 1-megaton weapon is about 440 feet across, and this increases to a maximum value of about 7,200 feet in 10 seconds. It is then rising at a rate of 250 to 350 feet per second. After a minute, the fireball has cooled to such an extent that it no longer emits visible radiation. It has then risen roughly 4.5 miles from the point of burst.

The Radioactive Cloud

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

2.07 Quite early in the ascent of the fireball, cooling of the outside by radiation and the drag of the air through which it rises frequently brings about a change in shape. The roughly spherical form becomes a toroid (or doughnut), although this shape and its associated motion are often soon hidden by the radioactive cloud and debris. As it

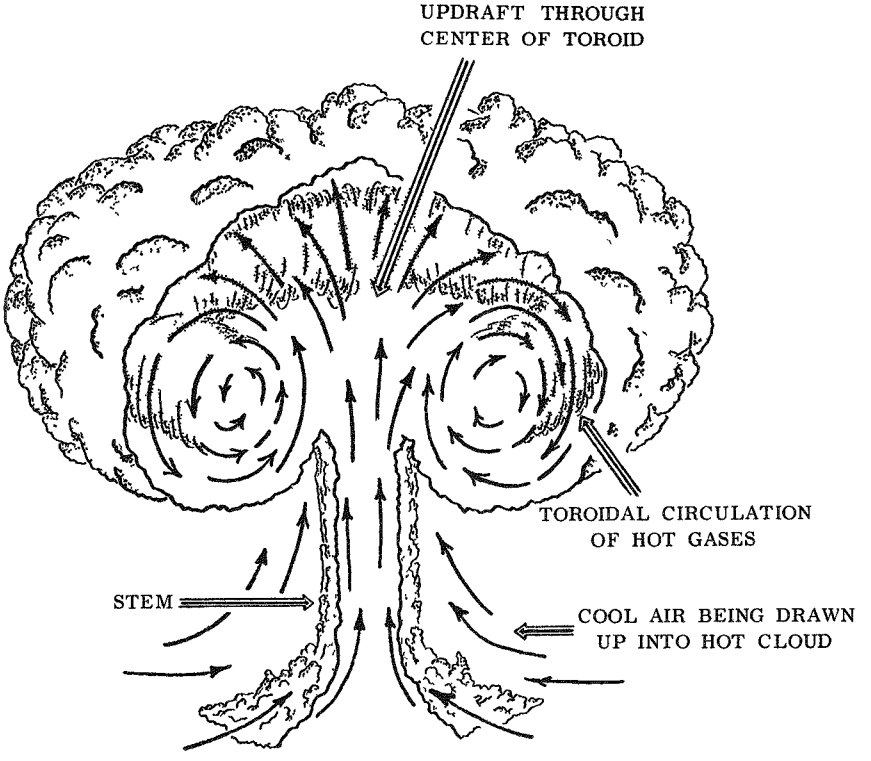

Figure 2.07a. Cutaway showing artist's conception of toroidal circulation within the radioactive cloud from a nuclear explosion.

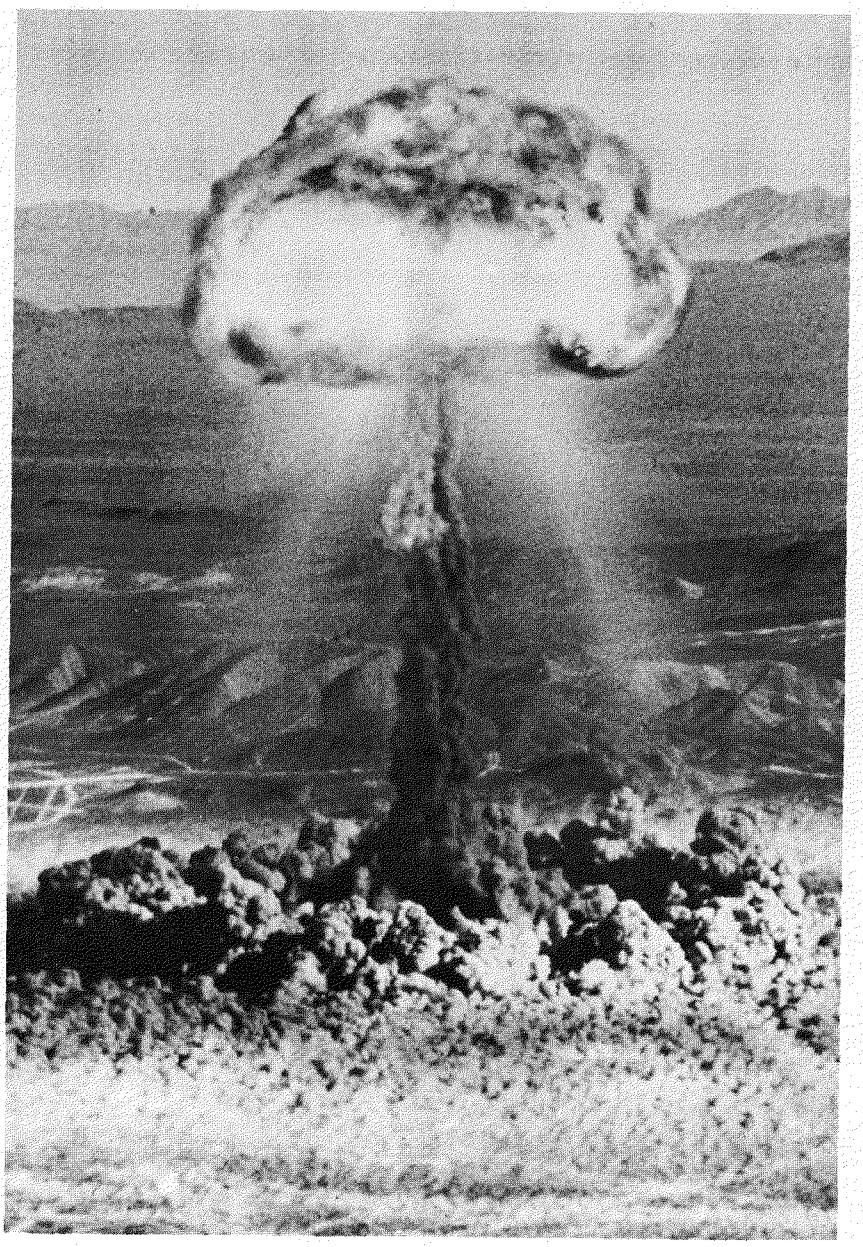

Figure 2.07b. Low air burst showing toroidal fireball and dirt cloud.

ascends, the toroid undergoes a violent, internal circulatory motion as shown in Fig. 2.07a. The formation of the toroid is usually observed in the lower part of the visible cloud, as may be seen in the lighter, i.e., more luminous, portion of Fig. 2.07b. During the course of the rapid ascent of the fireball, the toroidal motion slows and may be dissipated completely as the cloud rises toward its maximum height. In megaton explosions, the motion continues even after the maximum height is attained.

2.08 The color of the radioactive cloud 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 fireball. These result from the chemical interaction of nitrogen, oxygen, and water vapor in the air at the existing high temperatures and under the influence of the nuclear radiations. As the fireball cools and condensation occurs, the color of the cloud changes to white, mainly due to the water droplets as in an ordinary cloud.

2.09 Depending on the height of burst of the nuclear weapon and the nature of the terrain below, a strong updraft with inflowing winds, called "afterwinds", is produced in the immediate vicinity. These afterwinds can cause varying amounts of dirt and debris to be sucked up from the earth's surface into the radioactive cloud (Fig. 2.07b).

2.10 In an air burst with a moderate (or small) amount of dirt and debris drawn up into the cloud, only a relatively small proportion of the dirt particles will become contaminated with radioactivity. This is because the particles do not mix intimately with the weapon residues in the cloud at the time when the fission products are still vaporized and about to condense. In the case of a burst near the land surface, however, large quantities of dirt and other debris are drawn into the cloud at early times. Good mixing then occurs during the initial phases of cloud formation and growth. Consequently, when the vaporized fission products condense they do so on the foreign matter, thus forming highly radioactive particles (§ 2.23).

2.11 At first the rising mass of weapon 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 weapon 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 weapon. An approximate indication of the rate of rise of the cloud from a 1-megaton explosion 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 approximately 260 miles per hour. These values should be regarded as rough averages only, and large deviations may be expected in different circumstances.

2.13 The eventual height reached by the radioactive cloud depends upon the heat energy of the weapon, and upon the atmospheric conditions, e.g., moisture content and stability. The greater the

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

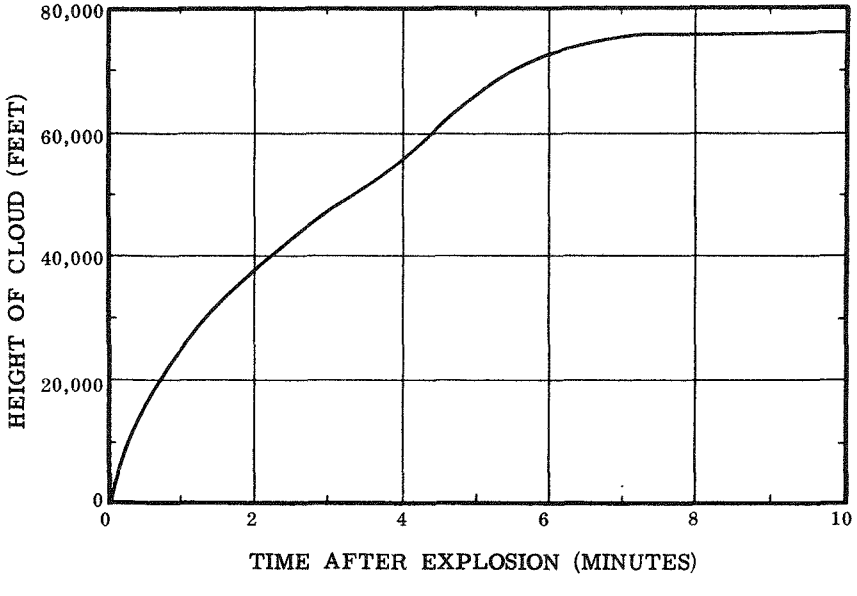

Figure 2.12. Height of cloud top above burst height at various times after a 1-megaton explosion for a moderately low air burst.

amount of heat generated the greater will usually be the upward thrust due to buoyancy and so the greater will be the distance the cloud ascends. The maximum height attained by the radioactive cloud is strongly influenced by the tropopause, i.e., the boundary between the troposphere below and the stratosphere above, assuming that the cloud attains the height of the tropopause.[2]

2.14 When the cloud reaches the tropopause, there is a tendency for it to spread out laterally, i.e., sideways. But if sufficient energy remains in the radioactive cloud at this height, a portion of it will penetrate the tropopause and ascend into the more stable air of the stratosphere.

2.15 The cloud attains its maximum height after about 10 minutes

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.

[2] The tropopause is the boundary between the troposphere and the relatively stable air of the stratosphere. It varies with season and latitude, ranging from 25,000 feet near the poles to about 55,000 feet in equatorial regions (§ 9.147)

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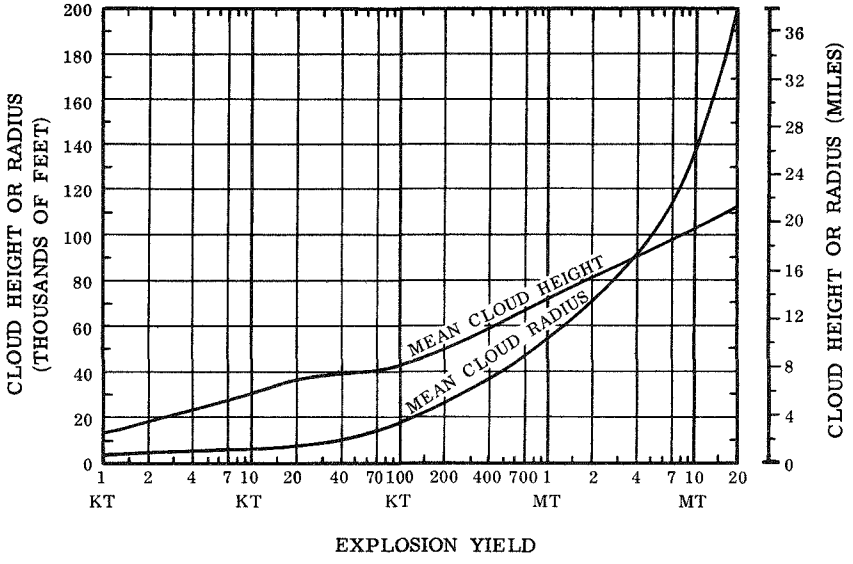

Figure 2.16. Average values of stabilized cloud height and radius as a function of explosion yield.

and is then said to be "stabilized." It continues to grow laterally, however, to produce the mushroom shape that is characteristic of nuclear explosions (Fig. 2.15). The cloud may continue to be visible for about an hour or more before being dispersed by the winds into the surrounding atmosphere where it merges with natural clouds in the sky.

2.16 The dimensions of the stabilized cloud formed in a nuclear explosion depend on the meteorological conditions, which vary with time and place. Approximate average values of cloud height and radius (at about 10 minutes after the explosion), attained in bursts at or near the earth's surface, for conditions most likely to be encountered in the continental United States, are given in Fig. 2.16 as a function of the energy yield of the explosion. The flattening of the height curve in the range of about 20- to 100-kilotons TNT equivalent is due to the effect of the tropopause in slowing down the cloud rise. For yields below about 15 kilotons the heights indicated are distances above the burst point but for higher yields the values are above sea level. For land surface bursts, the maximum cloud height is somewhat less than given by Fig. 2.16 because of the mass of dirt and debris carried aloft by the explosion.

2.17 For yields below about 20 kilotons, the radius of the stem of the mushroom cloud is about half the cloud radius. With increasing yield, however, the ratio of these dimensions decreases, and for yields in the megaton range the stem may be only one-fifth to one-tenth as wide as the cloud. For clouds which do not penetrate the tropopause the base of the mushroom head is, very roughly, at about one-half the altitude of the top. For higher yields, the broad base will probably be in the vicinity of the tropopause. There is a change in cloud shape in going from the kiloton to the megaton range. A typical cloud from a 10-kiloton air burst would reach a height of 30,000 feet with the base at about 15,000 feet; the horizontal extent would also be roughly 15,000 feet. For an explosion in the megaton range, however, the horizontal dimensions are greater than the total height (cf. Fig. 2.16).

Characteristics of a Surface Burst

2.18 Since many of the phenomena and effects of a nuclear explosion occurring on the earth's surface are similar to those associated

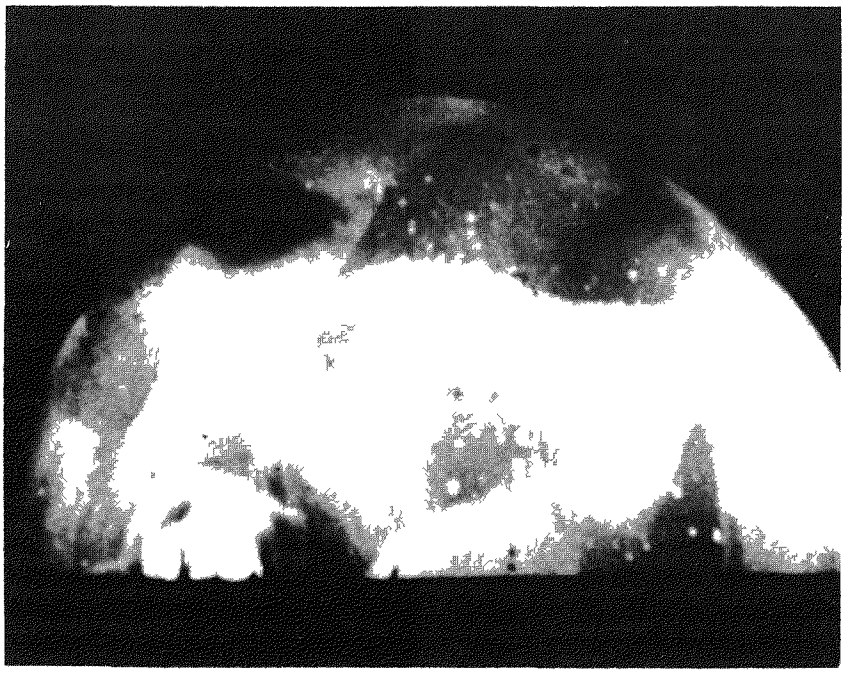

Figure 2.18a Fireball formed by a nuclear explosion in the megaton energy range near the earth's surface. The maximum diameter of the fireball was 3¼ miles

with an air burst, it is convenient before proceeding further to refer to some of the special characteristics of the former. In a surface burst, the fireball, in its rapid initial growth, will touch the surface of the earth (Fig. 2.18a). 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 fireball. It has been estimated that, if

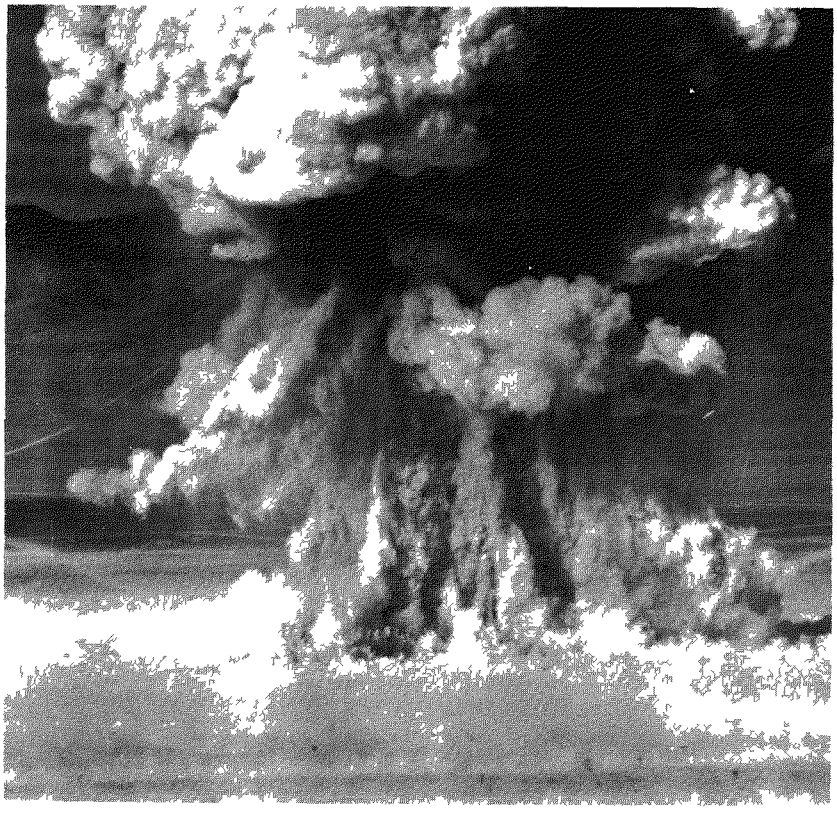

Figure 2.18b. Formation of dirt cloud in surface burst.

only 1 percent of the energy of a 1-megaton weapon is spent in this manner, something like 4,000 tons of vaporized soil material will be added to the normal constituents of the fireball. In addition, the strong afterwinds at the earth's surface will cause large amounts of dirt, dust, and other particles to be sucked up as the fireball rises (Fig. 2.18b).

2.19 An important difference between a surface burst and an air burst is, consequently, that in the surface burst the radioactive 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 fireball cools to the much larger debris particles which have been raised by the afterwinds. The exact composition of the cloud will, of course, depend on the nature of the surface materials and the extent of their contact with the fireball.

2.20 For a surface burst associated with a moderate amount of debris, such as has been the case in several test explosions in which the weapons 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 radioactive cloud reaches a height of several miles before spreading out abruptly into a mushroom shape.

2.21 The vaporization of dirt and other material when the fireball 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 weapon is exploded and with the character of the soil, as well as with the energy of the explosion. It is believed that for a 1-megaton weapon there would be no appreciable crater formation unless detonation occurs at an altitude of 450 feet or less.

2.22 If a nuclear weapon is exploded near the surface of the water, large amounts of water will be vaporized and carried up into the radioactive cloud. For example, if it is supposed, as in § 2.18, that 1 percent of the energy of the 1-megaton weapon is expended in this manner, about 20,000 tons of water will be converted into vapor. When the cloud reaches high altitudes this will condense to form water droplets, similar to those in an ordinary atmospheric cloud.

The Fallout

2.23 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 and other radioactive residues 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 weapon 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 explosion 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.[3]

2.24 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 weapon, 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 surface materials are sucked into the cloud, the contaminated particles become widely dispersed. The magnitude of the hazard from fallout will then be far less than if the explosion were a surface burst. Thus at Hiroshima and Nagasaki, where approximately 20-kiloton devices were exploded 1,850 feet above the surface, casualties due to fallout were completely absent.

2.25 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 15-megaton thermonuclear device tested at Bikini Atoll on March 1, 1954—the BRAVO shot of Operation CASTLE—the ensuing fallout caused substantial contamination over an area of more than 7,000 square miles. The contaminated region was roughly cigar-shaped and extended more than 20 statute miles upwind and over 320 miles downwind. The width in the crosswind direction was variable, the maximum being over 60 miles (§ 9.100)

2.26 The meteorological conditions which determine the shape, extent, and location of the fallout pattern from a nuclear explosion are the height of the tropopause, atmospheric winds, and the occurrence of precipitation. For a given explosion energy yield, type of burst, and tropopause height, the fallout pattern is affected mainly by the directions and speeds of the winds over the fallout area, from the earth's surface to the top of the stabilized cloud, which may be as high as 100,000 feet. As will be seen later, not only the space variations of the atmospheric winds but also their time variations, from the time of burst until the particles reach the ground, perhaps several hours later, affect the fallout pattern following a nuclear explosion.

[3] Another 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.

2.27 It should be understood that the fallout is a gradual phenomenon extending over a period of time. In the BRAVO explosion, for example, 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 radioactive 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 cloud cannot be seen. Nevertheless, the area of contamination which presents the most serious hazard generally results from the fallout of visible particles. The sizes of these particles range from that of fine sand, i.e., approximately 100 microns [4] in diameter, or smaller, in the more distant portions of the fallout area, to pieces about the size of a marble, i.e., roughly 1 cm or 0.4 inch in diameter, close to the point of burst.

2.28 Particles in this size range will have arrived on the ground within one day after the explosion, and will not have traveled too far, e.g., up to a few hundred miles, from the region of the shot, depending on the wind. Thus, the fallout pattern from particles of visible size will have been established within about 24 hours after the burst. This is referred to as "early fallout" and is also sometimes called "local" or "close-in" fallout. In addition, there is the deposition of very small particles which descend very slowly over large areas of the earth's surface. This is the "delayed fallout," also referred to as "world-wide fallout," to which residues from nuclear explosions of various types—air, high-altitude, surface, and shallow subsurface—may contribute (see Chapter IX).

2.29 Although the 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 fireball did not touch the surface of the ground, the early fallout would have been of insignificant proportions.

2.30 The general term "scavenging" is used to describe various processes resulting in the removal of radioactivity from the cloud and its deposition on the earth. One of these processes results from the entrainment in the cloud of quantities of dirt and debris sucked up in a surface (or near-surface) nuclear burst. The condensation of the fission product and other radioactive vapors on the particles and their subsequent relatively rapid fall to earth leads to a certain degree of scavenging.

[4] A micron is a one-millionth part of a meter, i.e., 10^{-6} meter, or about 0.00004 (or 4×10^{-5}) inch.

2.31 Another scavenging process, which can occur at any time in the history of the radioactive cloud, is that due to rain falling through the weapon debris and carrying contaminated particles down with it. This is one mechanism for the production of "hot spots," i.e., areas on the ground of much higher activity than the surroundings, in both early and delayed fallout patterns. Since rains generally originate from atmospheric clouds at heights below about 20,000 feet, it is only in this region that scavenging by rain is likely to take place.

The Blast Wave

2.32 At a fraction of a second after the explosion, a high-pressure wave develops and moves outward from the fireball (Fig. 2.32). This is the shock wave or blast wave, mentioned in § 1.01 and to be con-

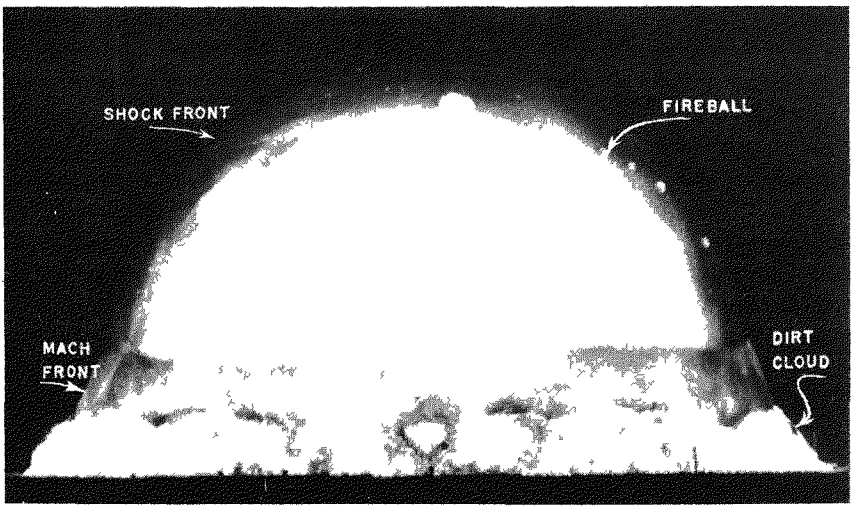

Figure 2.32. The faintly luminous shock front seen just ahead of the firebal soon after breakaway.

sidered subsequently in more detail, which is the cause of much destruction accompanying an air burst. The front of the blast wave, i.e., 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 weapon 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 fireball

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.

2.33 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 wave fronts fuse. This fusion phenomena 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 blast wave front.

2.34 For an air burst of a 1-megaton nuclear weapon at an altitude of 6,500 feet, the Mach effect will begin approximately 4.5 seconds after the explosion, in a rough circle at a radius of 1.3 miles from ground zero.[5] The overpressure on the ground at the blast wave front at this time is about 16 pounds per square inch, so that the total air pressure is more than double the normal atmospheric pressure.[6]

2.35 At first the height of the Mach front is small, but as the blast wave front continues to move outward, the height increases steadily. At the same time, however, the overpressure, like that in the original (or direct) 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 weapon is 10 miles from ground zero, the overpressure will have decreased to roughly 1 pound per square inch.

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

2.37 It should be noted that there are strong transient winds associated with the passage of the shock (and Mach) front. These blast winds (§ 3.07) are very much stronger than the ground wind (or afterwind) due to the updraft caused by the rising fireball (§ 2.09) which occurs at a later time. The blast winds may have peak veloci-

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[5] The term "ground zero" refers to the point on the earth's surface immediately below (or above) the point of detonation. For a burst over (or under) water, the corresponding point is generally called "surface zero." In some publications, ground zero is called the "hypocenter" of the explosion.

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

ties of several hundred miles an hour fairly near to ground zero; even at more than 6 miles from the explosion of a 1-megaton nuclear weapon, the peak velocity will be greater than 70 miles per hour. It is evident that such strong winds can contribute greatly to the blast damage resulting from the explosion of a nuclear weapon.

Thermal Radiation from an Air Burst

2.38 Immediately after the explosion, the weapon residues emit the primary thermal radiation (§ 1.72). Because of the very high temperatures, much of this is in the form of X-rays which are absorbed within a layer of a few feet of air; the energy is then re-emitted from the fireball as thermal radiation consisting of ultraviolet, visible, and infrared rays. Due to certain phenomena occurring in the fireball (see § 2.98 *et seq.*), the surface temperature undergoes a curious change. The temperature of the interior falls steadily, but the apparent surface temperature of the fireball 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. 2.113). 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 for air (and surface) bursts, although the duration times of the pulses increase with the energy yield of the explosion.

2.39 Corresponding to the two surface-temperature pulses, there are two pulses of emission of thermal radiation from the fireball (Fig. 2.39). In the first pulse, which lasts about a tenth part of a second for a 1-megaton explosion, the surface temperatures are mostly very high. As a result, much of the radiation emitted by the fireball during this pulse is in the ultraviolet region. Although ultraviolet radiation can cause skin burns, in most circumstances following an ordinary air burst the first pulse of thermal radiation is not a significant hazard in this respect, 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. Furthermore, it appears that the ultraviolet radiation from the first pulse could cause significant effects on the human skin only within ranges at which other thermal radiation effects are much more serious. It should be mentioned, however, that although the first radiation pulse may be disregarded as a source of skin burns, it is

capable of producing permanent or temporary effects on the eyes, especially of individuals who happen to be looking in the direction of the explosion.

2.40 In contrast to the first pulse, the second radiation pulse may last for several seconds, e.g., about 10 seconds for a 1-megaton explosion; it carries about 99 percent of the total thermal radiation energy. Since the temperatures are lower than in the first pulse, most of the rays reaching the earth consist of visible and infrared

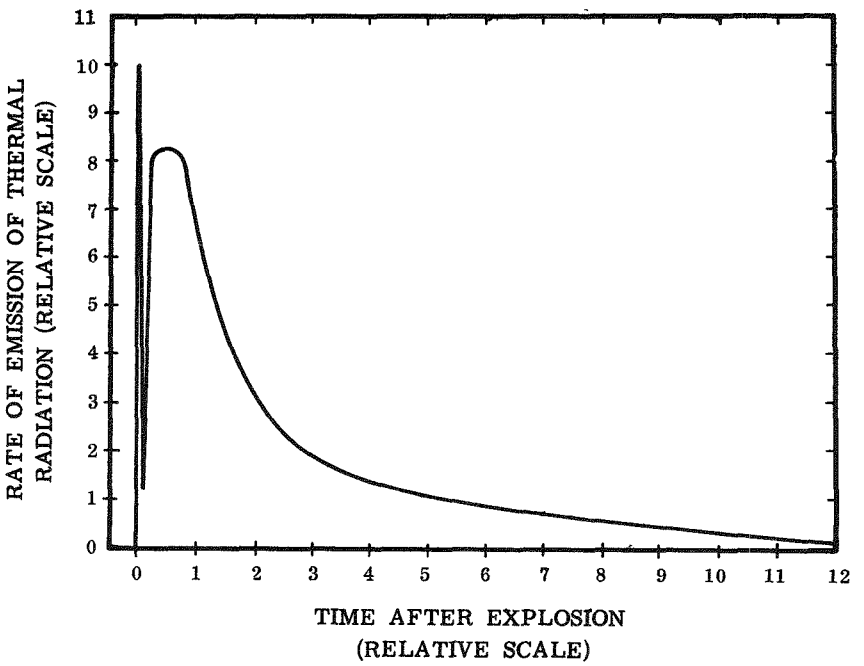

Figure 2.39. Emission of thermal radiation in two pulses in an air burst.

(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, and of eye effects at even greater distances, from the explosion of a 1-megaton weapon. For weapons 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 from an Air Burst

2.41 As stated in Chapter I, the explosion of a nuclear weapon 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. These are referred to as the "prompt nuclear radiations" because they are produced simultaneously with the nuclear explosion. Some of the neutrons liberated in fission are immediately captured and others undergo "scattering collisions" with various nuclei present in the weapon. These processes are frequently accompanied by the instantaneous emission of gamma rays. In addition, many of the escaping neutrons undergo similar interactions with atomic nuclei of the air, thus forming an extended source of gamma rays around the burst point. 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 weapon.

2.42 The initial nuclear radiation is generally defined as that emitted from both the fireball and the radioactive 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 fission products and other radioactive species in the rising cloud. It should be noted that the alpha and beta particles present in the initial radiation 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 radioactive cloud.

2.43 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 radioactive 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.

2.44 The foregoing arguments are based on the characteristics of a 20-kiloton nuclear weapon. For a detonation 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 weapon 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 explosion.

2.45 Neutrons are the only significant nuclear radiations produced directly in the thermonuclear reactions mentioned in § 1.66. 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 weapon. Those neutrons absorbed by fissionable species may lead to the liberation of more neutrons as well as to the emission of gamma rays. In addition, the capture of neutrons in nonfission reactions is usually accompanied by gamma rays. It is seen, therefore, that the initial radiations from an explosion 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 weapon in which all the energy release is due to fission, but for present purposes the difference may be disregarded.

Other Nuclear Explosion Phenomena

2.46 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 explosion. Soon after the detonation, a violet-colored glow may be observed, particularly at night or in dim daylight, at some distance from the fireball. This glow may persist for an appreciable length of time, being distinctly visible near the head of the radioactive 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.

2.47 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.

2.48 The condensation cloud which was observed in the ABLE Test at Bikini in 1946 is shown in Fig. 2.48. Since the device 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 formed some way ahead of the fireball. The reason is

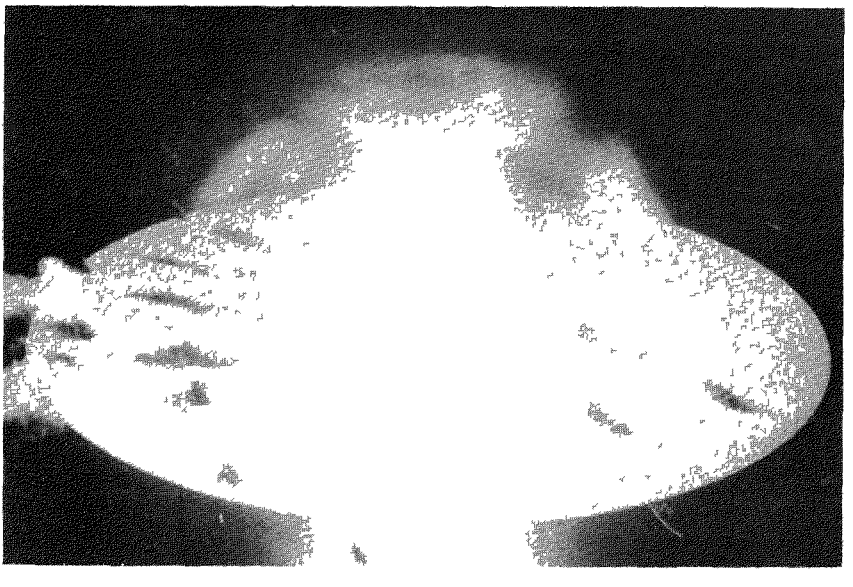

Figure 2.48. Condensation cloud formed in an air burst over water.

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 to that required for condensation to occur, the blast wave front has moved still further away, as is apparent in Fig. 2.48, where the disk-like formation on the surface of the water indicates the passage of the shock wave.

2.49 The relatively high humidity of the air makes the conditions for the formation of the condensation cloud 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. 2.49, and then disappeared.

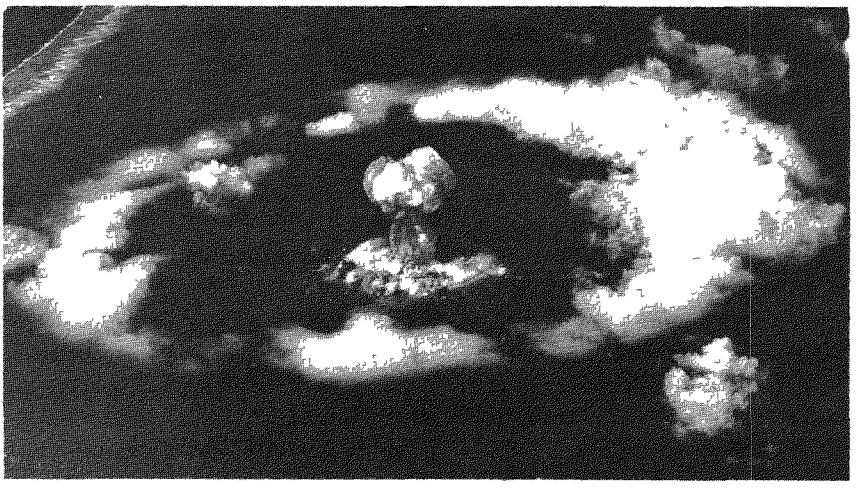

Figure 2.49. Late stage of the condensation cloud in an air burst over water.

2.50 Since the Wilson condensation cloud forms after the fireball 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 fireball. 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

2.51 The more important aspects of the description given above of a nuclear explosion in the air are summarized in a series of drawings, Figs. 2.51 a, b, c, d, and e, which are presented at the end of this chapter (pp. 87 to 91). In these figures, a 20-kiloton TNT equivalent detonation is assumed to take place at an altitude of 1,760 feet, and a 1-megaton burst at 6,500 feet. Because of the operation of certain simple rules, called scaling laws (see Chapter III), it is possible to

represent times and distances for these two different explosion energies on one set of drawings. The specified heights of burst for the two cases were chosen because it is expected that the conditions would be such as to lead to the maximum blast damage to an average city. The figures show the chronological development of the various phenomena associated with the air bursts defined above.

2.52 It should be noted that the drawings are schematic only, and do not represent what can be observed. All the eye is likely to see, if not blinded by the brilliance, is the fireball and the radioactive 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 HIGH-ALTITUDE BURST

Introduction

2.53 Nuclear devices were exploded at high altitudes during the summer of 1958 as part of the HARDTACK test series in the Pacific Ocean and the ARGUS operation in the South Atlantic Ocean. In the HARDTACK series, two high-altitude bursts, with energy yields in the megaton range, were set off in the vicinity of Johnston Island, 700 miles southwest of Hawaii. The first device, named TEAK, was detonated on August 1, 1958 (Greenwich Civil Time) at an altitude of 252,000 feet, i.e., nearly 50 miles. The second, called ORANGE, was exploded at an altitude of 141,000 feet, i.e., nearly 27 miles, on August 12, 1958 (GCT).

2.54 The ARGUS operation was not intended as a test of nuclear weapons or their destructive effects. It was an experiment designed to provide information on the trapping of electrically charged particles in the earth's magnetic field. The operation consisted of a series of three high-altitude nuclear detonations, each having a yield from 1 to 3 kilotons TNT equivalent. The burst altitudes were all about 300 miles.

High-Altitude Burst Phenomena

2.55 The TEAK and ORANGE high-altitude nuclear explosions created spectacular visible effects both locally and at great distances.

These effects were observed from Johnston Island and its vicinity, close to the explosion, and at remote points such as Hawaii and the Samoan Islands. In addition, the detonations caused widespread disturbances in that portion of the upper atmosphere known as the ionosphere, and this affected the propagation of radio waves and other similar electromagnetic radiations of relatively long wave lengths. This subject is treated more fully in Chapter X.

2.56 The TEAK burst was accompanied by a sharp and bright flash of light which was visible in the sky above the horizon in Hawaii. Because of the weak interaction of the thermal and nuclear radiations and the kinetic energy of the fission products with the ambient, low-density atmosphere, the fireball which developed grew very rapidly in size (see § 2.120 *et seq.*). In 0.3 second, its diameter was already 11 miles and it increased to 18 miles in 3.5 seconds. The fireball also

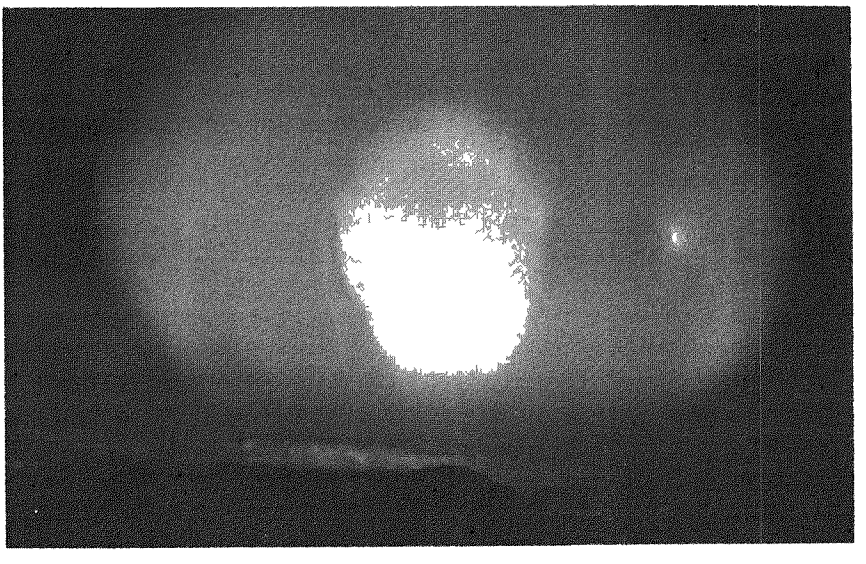

Figure 2.56. Fireball and red luminous spherical wave formed after the TEAK high-altitude shot. (The photograph was taken from Hawaii, 780 miles from the explosion.)

ascended with great rapidity, the initial rate of rise being about a mile per second. Surrounding the fireball was a very large red luminous spherical wave, apparently produced by passage of a shock front through the low-density air (Fig. 2.56).

2.57 At about a minute or so after the detonation, the TEAK fireball had risen to a height of over 90 miles, and it was then directly

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(line-of-sight) visible from Hawaii, over 700 miles away. The rate of rise of the fireball was estimated to be some 3,300 feet per second and it was expanding horizontally at a rate of about 1,000 feet per second. The large red luminous sphere was observed for a few minutes; at roughly 6 minutes after the explosion it was nearly 600 miles in diameter.

2.58 An interesting visible effect of the TEAK shot was the creation of an "artificial aurora." Within a second or two after the burst time a brilliant aurora appeared from the bottom of the fireball, and purple streamers were seen to spread toward the north. About a minute after the detonation, an aurora was observed at Apia, in the Samoan Islands, more than 2,000 miles from the point of burst, although at no time was the fireball in direct view. The formation of the aurora is attributed to the motion along the lines of the earth's magnetic field of beta particles (electrons), emitted by the radioactive fission fragments.

2.59 The ORANGE shot created a fireball almost spherical in shape. It grew in size much more slowly than that from the TEAK burst, which was at a higher altitude and, consequently, at lower atmospheric density. In general, the fireball behavior was in agreement with the somewhat stronger interaction of the various radiations and kinetic energy with the ambient air at higher density than in the TEAK shot. As seen from Hawaii, the ORANGE explosion produced a bright flash in the sky above the horizon lasting for a fraction of a second. About a minute later, a grayish-white radioactive cloud was observed low on the horizon, but it disappeared within 4 minutes.

2.60 Because of the natural cloud cover over Johnston Island at the time of burst, direct observation of the ORANGE fireball was not possible from the ground. However, such observations were made from aircraft flying above the low clouds. The auroras were less marked than from the TEAK shot, but an aurora lasting 17 minutes was again seen from Apia. Blast data were obtained at Johnston Island for the two high-altitude bursts. The maximum pressures were less than would have been expected from an ordinary air burst at the same respective distances. Thermal radiation measurements were made on the earth's surface in connection with the TEAK shot, and the results were found to be in agreement with expectation (§ 7.109). A special feature of the high-altitude explosions is the extreme brightness of the fireball which is visible at great distances and is capable of producing effects on the eyes over large areas (§ 11.72).

DESCRIPTION OF UNDERWATER BURSTS

Shallow Underwater Explosion Phenomena

2.61 There are certain characteristic phenomena associated with an underwater nuclear explosion, the details varying with the energy yield of the weapon, 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 mainly on the observations made at the BAKER test at Bikini in 1946. In this test, a 20-kiloton nuclear weapon was detonated well below the surface of the lagoon which was about 200 feet deep. These conditions may be regarded as corresponding to a shallow underwater explosion.

2.62 In an underwater nuclear detonation, a fireball is formed, but it is smaller than in the case of an air burst. At the BAKER test the water in the vicinity of the explosion was illuminated by the fireball. The distortion caused by the water 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 persisted for a few thousandths of a second, but it disappeared as soon as the bubble of hot, high-pressure gases (or vapors) and steam constituting the fireball reached the water surface. At this time, the gases were expelled and cooled, so that the fireball was no longer visible.

2.63 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.

2.64 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. 2.64). 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

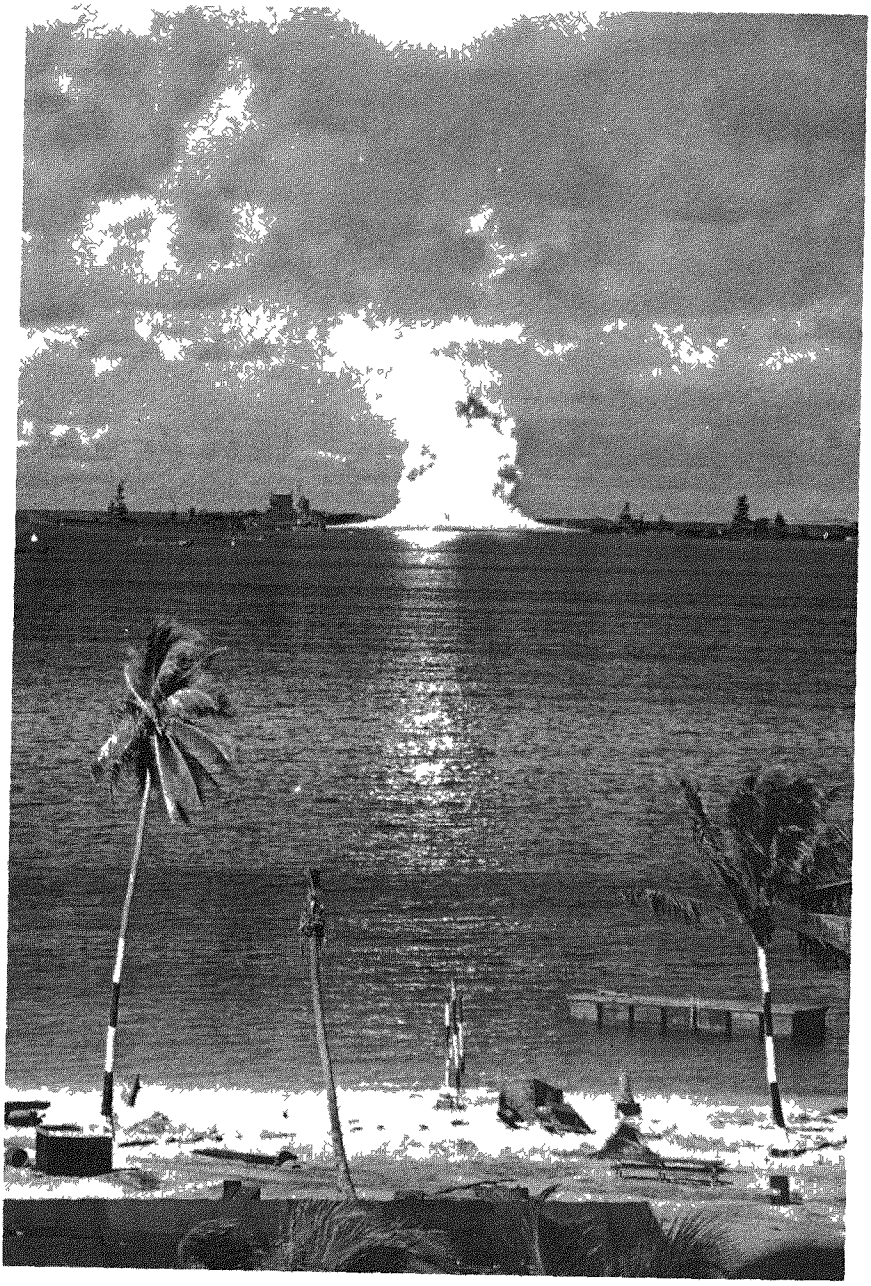

Figure 2.64. The "spray dome" formed over the point of burst in a shallow underwater explosion.

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 depend upon the energy of the explosion, and upon its depth below the water surface.

2.65 If the depth of burst is not too great, the bubble remains essentially intact until it rises to the surface of the water. At this point the steam, fission gases, and debris 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. 2.65a). 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" or "plume." The radioactive contents of the bubble are vented through this hollow column and may form a cauliflower-shaped cloud at the top (Fig. 2.65b).

2.66 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 maximum height attained by the hollow column, through which the gases vented, could not be estimated exactly because the upper part was surrounded by the radioactive cloud (Fig. 2.66). 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.

2.67 The cauliflower-shaped cloud, which concealed part of the upper portion of the column, contained some of the fission products and other weapon 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 this cloud, was found on the decks of ships some distance from the burst. The cloud was roughly 6,000 feet across and utimately rose to a height of nearly 10,000 feet before being dispersed. This is considerably less than the height attained by the radioactive cloud in an air burst.

2.68 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

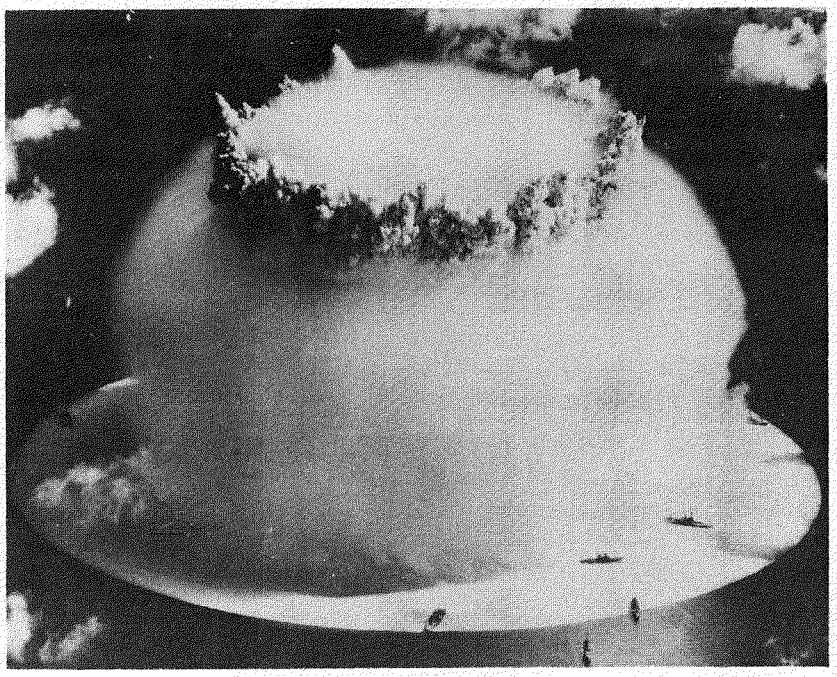

Figure 2.65a. The condensation cloud formed after a shallow underwater explosion. (The "slick," due to the shock wave, can be seen on the water surface.)

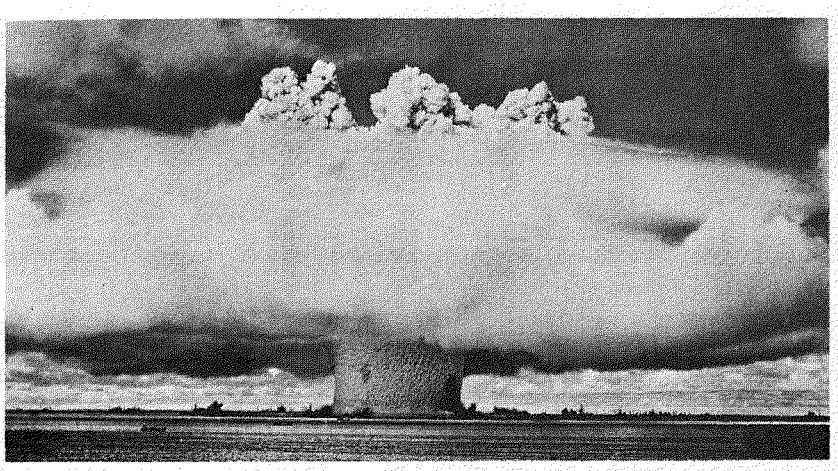

Figure 2.65b. Formation of the hollow column in a shallow underwater explosion, the top is surrounded by a late stage of the condensation cloud.

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.

2.69 It has been observed that certain underwater and water

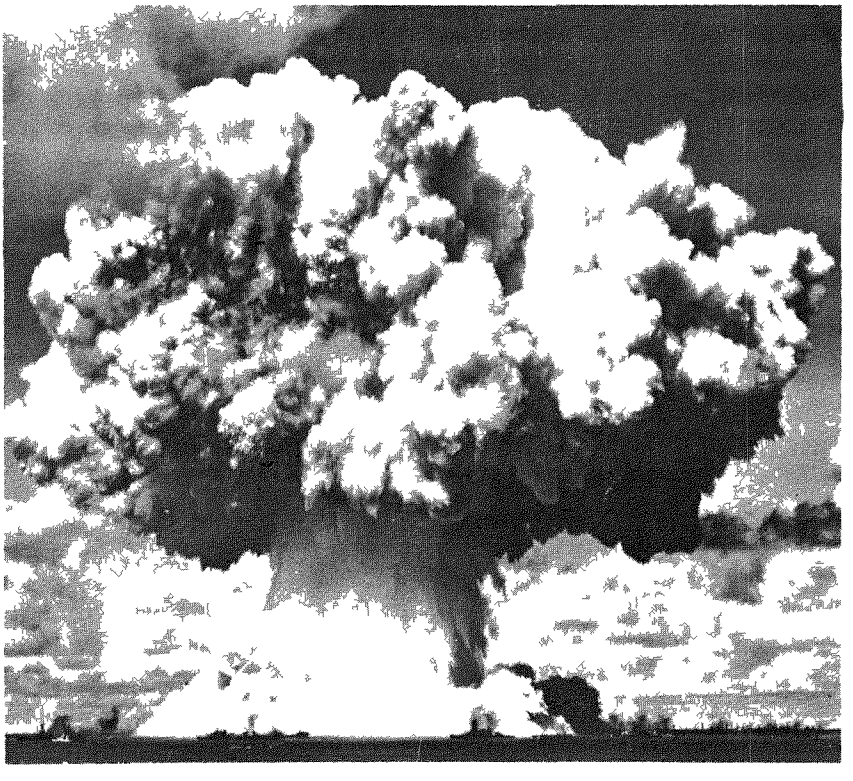

Figure 2.66. The radioactive cloud and first stages of the base surge following a shallow underwater burst. Water is beginning to fall back from the column into the lagoon.

surface bursts have caused unexpectedly serious flooding of nearby beach areas, the depth of inundation being sometimes twice as high as the approaching water wave. The extent of inundation is related in a complex manner to a number of factors which include the energy yield of the explosion, the depth of burst, the depth of the water, the composition and contour of the bottom, and the angle of incidence of the approaching wave.

The Visible Base Surge

2.70 As the column (or plume) 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 66). 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

2.71 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 radioactive cloud and other clouds in the sky (Fig 2 71)

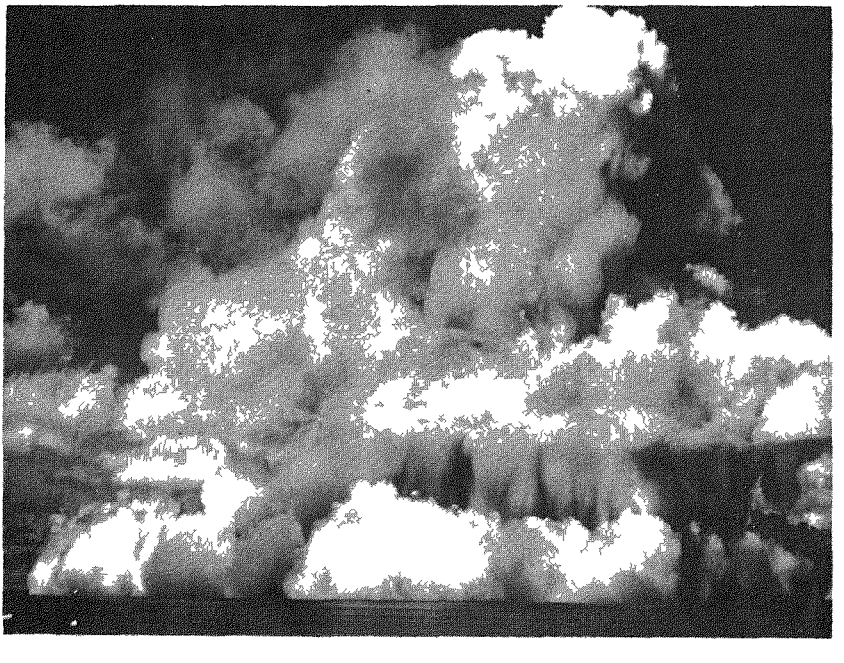

Figure 2 71 The development of the base surge following a shallow underwater explosion

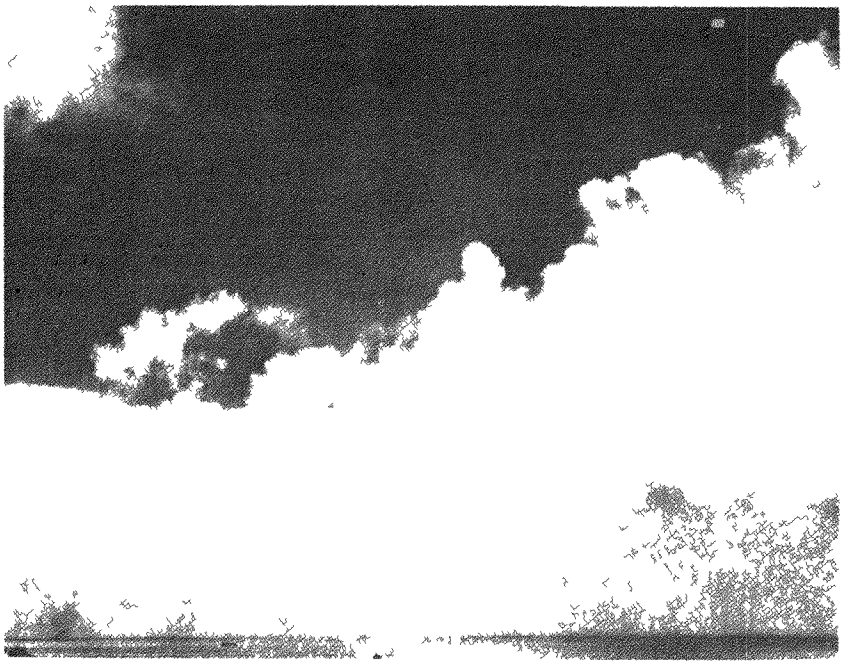

Figure 2 72. Final stage in the development of the base surge.

2.72 After about 5 minutes, the base surge had the appearance of a mass of stratocumulus clouds which eventually reached a thickness of several thousand feet (Fig. 2.72). 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 radioactive cloud.

2.73 The necessary conditions for the formation of a base surge have not been definitely established, although it is reasonably certain that no base surge would accompany bursts at great depths. The underwater test shots upon which the present analysis is based have all created both a visible and an invisible (§ 2.74) base surge. The only marked difference between the phenomena at the various tests is that at Bikini BAKER there was an airborne cloud, evidently composed of fission debris and steam. The other shots, which were at somewhat greater depths, produced no such cloud. The whole of the plume fell back into the surface of the water where the low-lying base surge cloud was formed.

The Radioactive Base Surge

2.74 From the weapons effects standpoint, the importance of the base surge lies in the fact that it is likely to be highly radioactive because of the fission (and other) residues present either at its inception, or dropped into it from the radioactive 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). The fission debris is suspended in the form of very small particles that occupy the same volume as the visible base surge at early times, that is, within the first 3 or 4 minutes. However, when the small water droplets which make the base surge visible evaporate and disappear, the radioactive particles and gases remain in the air and continue to move outwards as an invisible radioactive base surge. There may well be some fallout or rainout on to the surface of the water (or a ship or shore station) from the radioactive base surge, but in many cases it is expected to pass over without depositing any debris. Thus, according to circumstances, there may or may not be radioactive contamination on the surfaces of objects in the vicinity of a shallow underwater nuclear burst.

2.75 The radioactive base surge continues to expand in the same manner as would have been expected had it remained visible. It drifts downwind either as an invisible, doughnut-shaped cloud or possibly as an invisible, low-lying disc type of formation with no hole in the center. The length of time this base surge remains radioactive will depend on the energy yield of the explosion, the burst depth, and the nearness of the sea bottom to the point of burst. In addition, weather conditions will control depletion of debris due to rainout and diffusion by atmospheric winds. As a general rule, it is expected that there will be a considerable hazard from the radioactive base surge within the first 5 to 10 minutes after an underwater explosion and a decreasing hazard for half an hour or more.

2.76 The proportion of the residual nuclear radiation that remains in the water or that is trapped by the falling plume and returns immediately to the surface will be determined by the location of the burst and the depth of the water, and perhaps also by the nature of the bottom material. However, even though as much as 90 percent of the fission product and other radioactivity could be left behind in the water, the base surge, both visible and invisible, could still be extremely radioactive in its early stages.

Thermal and Nuclear Radiations in Underwater Burst

2.77 Essentially all the thermal radiation emitted by the fireball while it is still submerged is absorbed by the surrounding water. When the hot steam and 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.

2.78 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 vents, 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, radioactive cloud, and base surge, all three of which are formed within a few seconds of the burst, will contribute to the initial effects.

2.79 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

2.80 The series of drawings in Figs. 2.80a, b, c, d, and e, which are shown on pages 92 to 96, at the end of this chapter, 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.

Deep Underwater Explosion Phenomena

2.81 Because the effects of a deep underwater nuclear explosion are largely of military interest, the phenomena will be described in general terms and in less detail than for a shallow underwater burst.

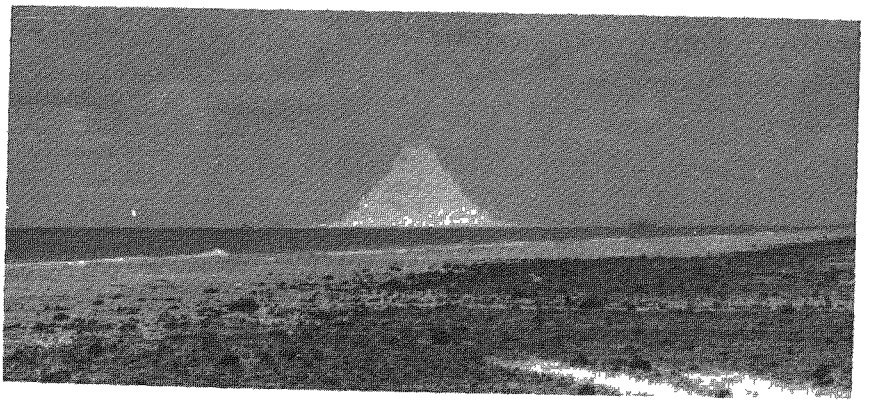

Figure 2.82a. Spray dome observed 5.3 seconds after explosion in deep water

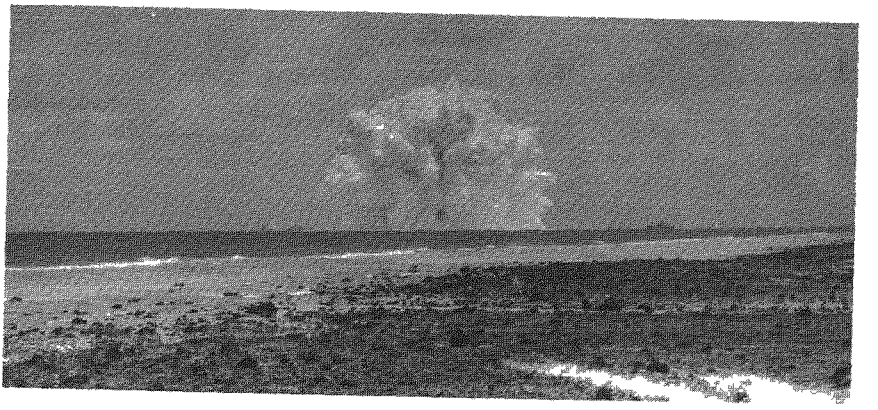

Figure 2.82b. Plume observed 11.7 seconds after explosion in deep water.

Figure 2.82c. Formation of base surge at 45 seconds after explosion in deep water.

The more important observations made at the WAHOO shot of Operation HARDTACK in 1958, when a nuclear weapon was detonated at a depth of 500 feet in deep water, will be summarized here.

2.82 The spray dome formed by the explosion rose to a height of 900 feet above the surface of the water (Fig. 2.82a). Shortly after the maximum height was attained, the hot gas and steam bubble burst through the dome, throwing out multiple plumes in all directions; the highest plumes reached an elevation of 1,700 feet (Fig. 2.82b). There was no airborne radioactive cloud, such as was observed in the shallow underwater BAKER shot. The collapse of the plumes created a visible base surge extending out to a distance of over 2½ miles downwind and reaching a maximum height of about 1,000 feet (Fig. 2.82c). This base surge traveled outward at an initial speed of nearly 75 miles per hour, but decreased within 10 seconds to less than 20 miles per hour.

2.83 There was little evidence of the fireball in the WAHOO shot, because of the depth of the burst, and only a small amount of thermal radiation escaped. The initial nuclear radiation was similar to that from a shallow underwater burst, but there was no lingering airborne radioactive cloud from which fallout could occur. The radioactivity was associated with the base surge while it was visible and also after the water droplets had evaporated. The invisible, radioactive base surge continued to expand and moved in the downwind direction. The deposited residual nuclear radiation was light and very little radioactivity was found on the surface of the water.

2.84 The hot bubble formed by the underwater nuclear detonation undergoes a series of pulsations, i.e., successive expansions and contractions, as it rises toward the surface. During the contraction phases some of the steam in the bubble condenses and part of the radioactive debris is removed by the liquid water droplets formed. When the bubble expands, however, and some of the water evaporates again, some of the radioactivity may return to the bubble. Hence, the radioactivity level of the base surge may be affected by the phase of the bubble when it breaks through the water surface. The activity levels of the radioactive base surge may thus be expected to vary widely, and although the initial dose rates may be very high, their duration is expected to be short.

DESCRIPTION OF UNDERGROUND BURSTS

Shallow Underground Explosion Phenomena

2.85 When a nuclear weapon is exploded under the ground, a fireball is formed consisting of extremely hot gases at high pressures,

including vaporized earth and weapon 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

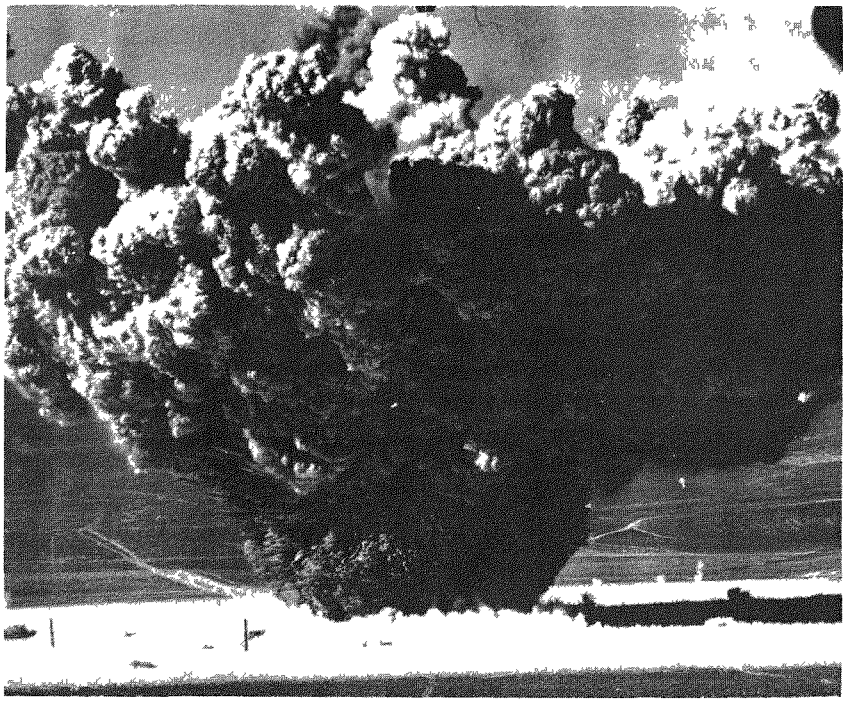

Figure 2.85. Shallow underground burst.

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. 2.85). Because of the large amount of material removed by the explosion, a crater of considerable size was left in the ground.

2.86 It is estimated from tests made in Nevada that, if a 1-megaton weapon were dropped from the air and penetrated underground in sandy soil to a depth of 50 feet before exploding, the resulting crater would be about 300 feet deep and nearly 1,400 feet across. This means that approximately 10 million tons of earth 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 weapon. As they descend to earth, the finer particles of soil may initiate a base surge, as will be described below.

2.87 The rapid expansion of the bubble of hot, high-pressure gases formed in the underground burst initiates a shock wave in the earth. This has a similar effect on a seismograph some distance away as an earthquake of moderate intensity. But, apart from the fact that the disturbances may originate at different depths, an underground nuclear explosion and an earthquake differ in an important respect. Theoretically, an explosion should produce an outward motion in all directions, whereas most earthquakes involve a sliding movement which should cause outward motion in some directions and inward motion in others. However, the actual motions do not always conform to these expectations.

2.88 As in an underwater burst, part of the energy released by the weapon in an underground explosion may appear 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 weapon before detonation occurs, the smaller is the proportion of the shock energy that escapes into the air. If the explosion is fully contained there is, of course, no blast wave formed.

Base Surge and Fallout

2.89 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 underwater Bikini BAKER test. For example, the early stages of a base surge formation can be seen in Fig. 2.89, which resembles Fig. 2.71 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 explosion. It is believed that a dry sandy terrain would be particularly conducive to base surge formation in an underground burst.

2.90 The radioactive cloud resulting from an uncontained underground explosion will inevitably include 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

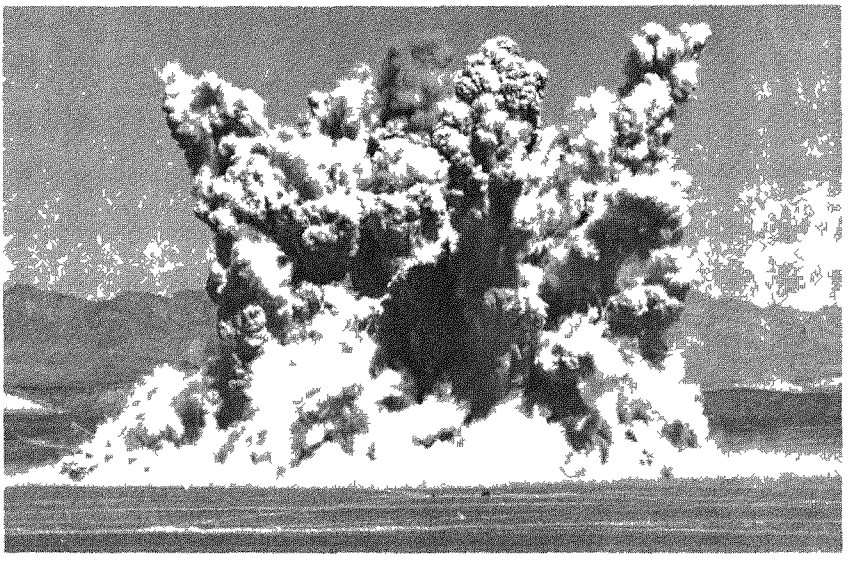

Figure 2 89. Base surge formation in a shallow underground burst

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 in Underground Burst

2.91 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.

2.92 For the same reasons as were given in § 2.79 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

2.93 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. 2.93 a, b, c, and d. For convenience, these are given on pages 97 to 100 at the end of the chapter.

Deep Underground Explosion Phenomena

2.94 A deep underground explosion is one occurring at such a depth that there is little or no venting of the weapon debris through the surface of the ground. The following description is based on the observations associated with the RAINIER event of Operation PLUMBBOB in 1957, in which a 1.7-kiloton TNT equivalent nuclear device was detonated at a depth of 790 feet below the surface in a medium referred to geologically as "tuff." All of the radioactivity as well as the heat energy were contained in the ground. The phenomena can best be described in terms of four phases having markedly different time scales.

2.95 First, the energy of the nuclear explosion, which took place in a chamber 6 ft by 6 ft by 7 ft in dimensions, was released in less than a one-millionth part of a second, i.e., less than 1 microsecond. As a result, the pressure in the chamber rose to several million atmospheres within a few microseconds and the temperature reached about a million degrees. In the second (hydrodynamic) stage, which was of a few hundredths of a second duration, the chamber expanded under the influence of the tremendous pressures to produce a spherical cavity 62 feet in radius. At this stage the cavity was lined with a shell of molten rock about 4 inches thick. The shock from the explosion crushed the rock to a radius of 130 feet and fractured it to 180 feet. The shock continued outward, its amplitude decreasing with increasing distance until it became attenuated. Seismic signals were detected out to distances of several hundred miles and a weak signal was recorded in Alaska.

2.96 In the next phase, lasting for a period of seconds to minutes, the molten material flowed down the walls and collected at the

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bottom of the cavity. Here it froze to form a glassy mass which contained 65 to 80 percent of the total radioactivity of the fission products; the remainder was distributed throughout the crushed zone. The third stage ended when the roof collapsed, thus enlarging the chamber upward for a distance of about 400 feet. The temperature then dropped as a result of expansion of the gases and the introduction of colder rock and other material. In the final (or long-term) stage, the heat gradually diffused outward and the radioactive material decayed in the usual manner.

2.97 Records, obtained at stations located 110 to 350 miles from the test site, showed that the seismic signal of the RAINIER shot was equivalent to that from an earthquake of magnitude 4.06 on the conventional Gutenberg-Richter scale; this would be described as a "minor" earthquake. Such a disturbance, originating from a movement of the earth's crust, should be perceptible to individuals as far as 60 miles from the epicenter. However, of the observers located 2½ miles from ground zero at the time of the RAINIER detonation, only a very few felt any ground motion.

SCIENTIFIC ASPECTS OF NUCLEAR EXPLOSION PHENOMENA [7]

Introduction

2.98 The events which follow the very large and extremely rapid energy release in a nuclear explosion are mainly the consequences of the interaction of the kinetic energy of the fission fragments and the thermal radiations with the medium surrounding the explosion. The exact nature of these interactions, and hence the directly observable and indirect effects they produce, that is to say, the nuclear explosion phenomena, are dependent on such properties of the medium as its temperature, pressure, density, and composition. It is the variations in these factors in the environment of the nuclear detonation that account for the different types of response associated with air, high-altitude, surface, and subsurface bursts, as described earlier in this chapter.

2.99 Immediately after the explosion time, the temperature of the weapon material is several tens of million degrees and the pressures are estimated to be many million atmospheres. As a result

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

of numerous inelastic collisions part of the kinetic energy of the fission fragments is converted into internal and radiation energy. Some of the electrons are removed entirely from the atoms, whereas others are raised to higher energy (or excited) states while still remaining attached to the nuclei. Within an extremely short time, perhaps a hundredth of a microsecond or so, the weapon residues consist essentially of completely and partially stripped atoms, many of the latter being in excited states, together with the corresponding free electrons. The system then immediately emits electromagnetic (thermal) radiation, the nature of which is determined by the temperature. Since this is of the order of several tens of million degrees, most of the energy will be in the soft X-ray region (§ 1.72, see also § 7.80).

2.100 The primary thermal radiation leaving the exploding weapon is absorbed by the atoms and molecules of the surrounding medium. Consequently the medium is heated and the resulting fireball re-radiates part of its energy as thermal radiation which lies mainly in the ultraviolet, visible, and infrared regions of the spectrum. The remainder of the energy contributes to the shock wave formed in the surrounding medium in the manner to be described below. Ultimately, essentially all the thermal radiation (and shock wave energy) is absorbed and appears as heat, although it may be dissipated over a large area. In a dense medium such as earth or water, the degradation and absorption occur within a short distance from the explosion, but in air the thermal radiation may travel considerable distances. The actual behavior depends on the air density, as will be seen later.

2.101 There is another mechanism, in addition to the one just described, for the transfer of part of the kinetic energy of the fission fragments to the surroundings. This arises from what is called "hydrodynamic coupling" of the explosion energy with the ambient medium. Because of the very high pressure within the exploding weapon, the residue, consisting of fission products and all other weapon materials, moves outward from the center of the explosion at a very high velocity. The random kinetic energy of the individual atoms, etc., is thus being converted into directed mass energy, that is, energy of motion of the mass of residues. After a few microseconds nearly all of the debris is contained in a moderately thin shell of high density called the "hydrodynamic front." Its initial temperature is about a million degrees and it is traveling at a speed of several hundred miles per second. When the hydrodynamic front reaches the ambient medium it acts like a fast-moving piston. Energy is thus transferred to the medium by impulse, and a compression wave, which rapidly becomes a steep-

fronted shock wave, as shown in Fig. 1.01, moves outward. The mass energy of the weapon debris is thus transferred to the surroundings as blast and shock.

2.102 It will be apparent from the foregoing descriptions that the kinetic energy of the fission fragments, constituting some 85 percent of the total energy released (§ 1.22), distributes itself between thermal radiation, on the one hand, and shock and blast, on the other hand, in proportions depending largely on the nature of the ambient medium. The higher the density of the latter, the greater the extent of the coupling between it and the hydrodynamic front of the exploding nuclear weapon. Consequently, when a burst takes place in a medium of high density, e.g., water or earth, a larger percentage of the kinetic energy of the fission fragments is converted into shock and blast energy than is the case in a less dense medium, e.g., air. At very high altitudes, on the other hand, where the air pressure is extremely low, only a small proportion of the kinetic energy of the fission fragments may appear in the shock wave. In any event, the form and amount in which this radiation is received at a distance from the explosion will also be dependent on the nature of the intervening medium.

Development of the Fireball in an Air Burst

2.103 The transfer of energy by radiation within a hot gas, e.g., from the hot interior to the cooler exterior of the fireball, takes place in the following manner. First, an atom, molecule, or ion absorbs a photon of the radiation (§ 1.70) and is thereby converted into a high-energy (or excited) state. The atom or other particle remains in the excited state for a short time and then reverts to its lower energy (or ground) state by the re-emission of a photon. This photon then moves off in a random direction with the velocity of light; it may then be captured by another atom, molecule, etc., and again re-emitted, and so on. The energy carried by the photon is thus transferred from one point to another within the gas.

2.104 If the mean free path of the radiation, i.e., the average distance a photon travels between interactions, is large in comparison with the dimensions of the gaseous volume, the transfer of energy from the hot interior to the cooler exterior of the gas will occur more rapidly than if the mean free path is small. This is because, in their outward motion through the gas, the photons with short mean free paths will be absorbed and re-emitted several times. At each re-emission the photon moves away in a random direction, and so the

effective rate of transfer of energy in the outward direction will be less than for a photon of long mean free path which undergoes little or no absorption and re-emission.

2.105 In the earliest stage of the expansion of the weapon residues the temperature is extremely high and the mean free path of the radiation is long compared to the dimensions of the volume of expanding residues. Consequently, the transfer of energy by radiation takes place rapidly within the mass of hot gas and the temperature throughout the material is uniform. This mass is therefore referred to as the "isothermal sphere" and represents the early stages of the fireball. Provided the ambient air is cold and has an appreciable density, the soft X-rays and ultraviolet radiation constituting the major part of the thermal radiation emanating from the isothermal sphere are absorbed or degraded in energy within a short distance. The surrounding air thus becomes extremely hot, with the result that the dimensions of the fireball increase rapidly.

2.106 At first, the shock front (§ 2.101) lags behind the radiation front, i.e., the surface of the fireball, because the mean free path of the radiation in the hot gas is so long that transfer of energy by radiation is more rapid than by mass motion. As the fireball expands and the energy is deposited in an ever increasing volume (and mass) of air, the temperature within the isothermal sphere falls. As a result, the mean free path of the radiation decreases and transfer of energy by radiation becomes less rapid. The shock front then begins to advance faster than the radiation front and soon the two coincide. The shock front continues to advance more rapidly than the radiation front and moves ahead of it at the time when the temperature of the isothermal sphere has fallen to about 300,000° C (540,000° F). This phenomenon is called "hydrodynamic separation." For a 20-kiloton explosion it occurs at about 0.1 millisecond (10^{-4} second) after the burst time when the fireball radius is roughly 40 feet.

2.107 As the shock front moves ahead of the isothermal sphere it causes a tremendous compression of the ambient air and the temperature is thereby increased to an extent sufficient to render the air incandescent. The fireball 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 high, temperature. The surface of separation between the very hot core and the somewhat cooler outer layer is the radiation front.

2.108 The phenomena described above are represented schematically in Fig. 2.108; qualitative temperature profiles are shown at the

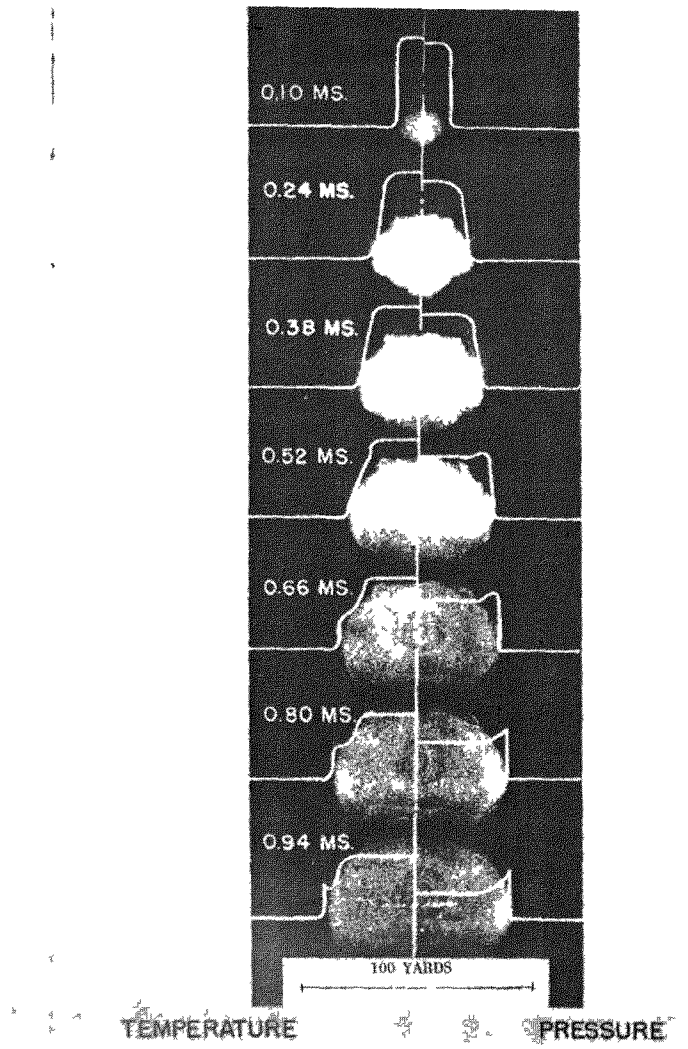

Figure 2.108. Variation of temperature and pressure in the fireball. (Times and dimensions apply to a 20-kiloton explosion.)

left and pressure profiles at the right of a series of photographs of the fireball at various intervals after the detonation of a 20-kiloton weapon. In the first picture, at 0.1 millisecond, the temperature is shown to be uniform within the fireball and to drop abruptly at the

exterior, so that the condition is that of the isothermal sphere. Subsequently, as the shock front begins to move ahead of the isothermal sphere, the temperature is no longer uniform, as indicated by the more gradual fall near the outside of the fireball. Eventually, two separate temperature regions form. The outer region absorbs the radiation from the isothermal sphere in the center and so the latter cannot be seen. The photographs, therefore, show only the exterior surface of the fireball.

2.109 From the shapes of the curves at the right of Fig. 2.108, the nature of the pressure changes in the fireball can be understood. In the isothermal stage the pressure is uniform throughout and drops sharply at the outside, but after a short time, when the shock front has separated from the isothermal sphere, the pressure near the surface is greater than in the interior 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 shock front. It will be noted, incidentally, from the photographs, that the surface of the fireball, which has hitherto been somewhat uneven, has now become sharply defined.

2.110 For some time the fireball continues to grow in size at a rate determined by the propagation of the shock front in the surrounding air. During this period the temperature of the shocked air decreases steadily so that it becomes less opaque. Eventually, it is transparent enough to permit the much hotter and still incandescent interior of the fireball, i.e., the isothermal sphere, to be seen through the faintly visible shock front (see Fig. 2.32). The onset of this condition at about 0.015 second after the detonation of a 20-kiloton weapon, for example, is referred to as the "breakaway."

2.111 Following the breakaway, the visible fireball 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 to 1 second after the detonation of a 20-kiloton nuclear weapon, is shown in Fig. 2.111. 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 rather one that falls off with time. Nevertheless, the marked decrease in the rate at which the fireball grows after breakaway is apparent from the subsequent flattening of the curve.

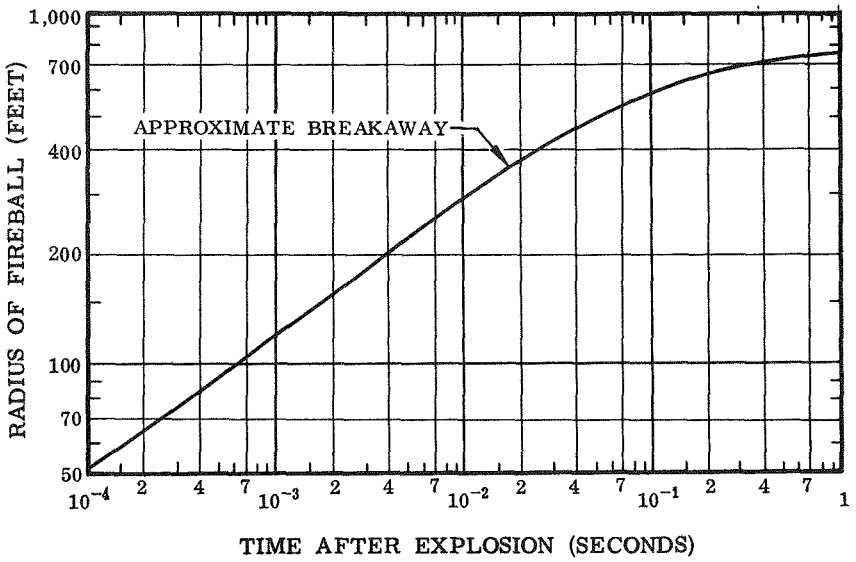

Figure 2.111. Variation of radius of luminous fireball with time in a 20-kiloton explosion.

Temperature of the Fireball

2.112 As indicated earlier, the interior temperature of the fireball decreases steadily, but the apparent surface temperatures, which influences the emission of thermal radiation, decreases to a minimum and then increases to a maximum before the final steady decline. This behavior is related to the fact that at high temperatures air both absorbs and emits thermal radiation very readily, but as the temperature falls below a few thousand degrees, the ability to absorb and radiate decreases.

2.113 From about the time the fireball temperature has fallen to 300,000° C, when the shock front begins to move ahead of the isothermal sphere, until close to the time of the first temperature minimum (§ 2.38), the expansion of the fireball is governed by the laws of hydrodynamics. It is then possible to calculate the temperature of the shocked air from the measured shock velocity, i.e., the rate of growth of the fireball. The variation of the temperature of the shock front with time, obtained in this manner, is shown by the full line from 10^{-4} to 10^{-2} second in Fig. 2.113, for a 20-kiloton explosion. However, photographic and spectroscopic observations of the surface brightness

of the advancing shock front, made from a distance, indicate the much lower temperatures represented by the broken curve in the figure. The reason for this discrepancy is that both the nuclear and thermal radiations emitted in the earliest stages of the detonation interact in depth with the gases of the atmosphere ahead of the shock front to produce ozone, nitrogen dioxide, nitrous acid, etc. These substances are strong absorbers of radiation coming from the fireball, so that the brightness observed some distance away corresponds to a temperature considerably lower than that of the shock front.

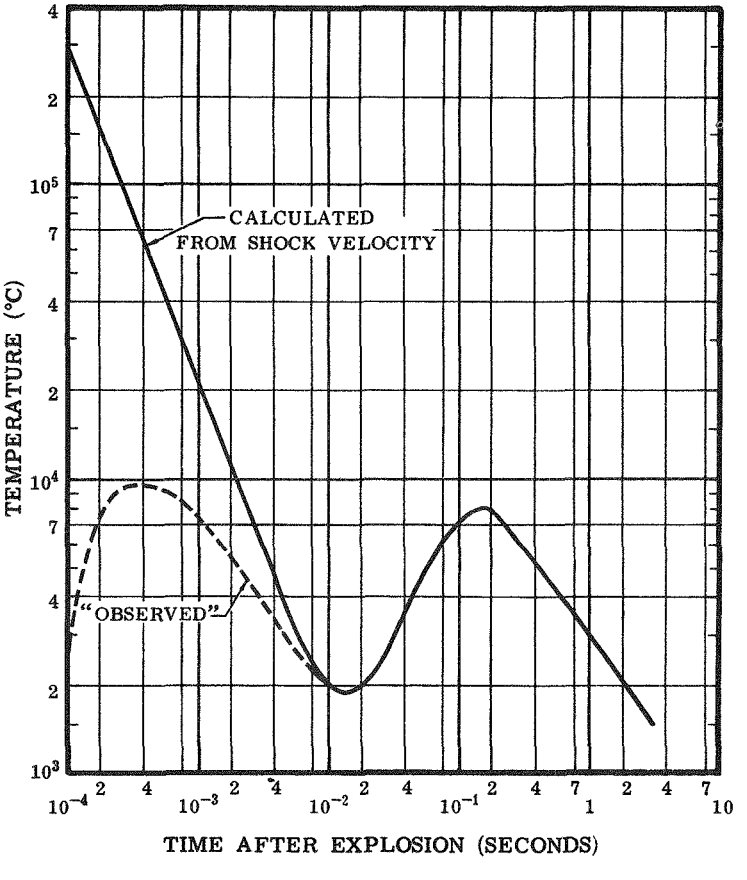

Figure 2.113. Variation of apparent fireball surface temperature with time in a 20-kiloton explosion.

2.114 As long as the temperature of the shock front is above a few thousand degrees, the air is opaque to the radiation from the isothermal sphere, and so the latter cannot be seen. The rate at which the shock front emits (and absorbs) radiation is determined by its temperature and radius. The temperature at this time is considerably lower than that of the isothermal sphere but the radius is larger. However, as the temperature of the shocked air approaches 1,800° C it absorbs (and radiates) less readily. Thus the shock front becomes increasingly transparent to the radiation from the isothermal sphere and there is a gradual unmasking of the still hot isothermal sphere, representing breakaway (§ 2.110).

2.115 As a result of this unmasking of the isothermal sphere, the apparent surface temperature of the fireball then increases (Fig. 2.113), after passing through the temperature minimum at about 1,800° C attributed to the shock front. This minimum, representing the end of the first thermal pulse, occurs at about 11 milliseconds (0.011 second) after the explosion time for a 20-kiloton weapon. Subsequently, as the apparent surface temperature continues to increase from the minimum, radiation from the fireball is emitted directly from the hot interior (or isothermal sphere), largely unimpeded by the cooled air in the shock wave ahead of it, so that energy is radiated more rapidly than before. The apparent surface temperature increases to a maximum of about 7,700° C (14,000° F), and this is followed by a steady decrease over a period of seconds as the fireball cools and ceases to radiate appreciably. It is during the second pulse that the major part of the thermal radiation is emitted in an air burst, the rate of emission being greatest when the surface temperature is at the maximum.

2.116 The curves in Figs. 2.111 and 2.113 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 maximum radius. The time of thermal minimum increases with the energy yield, a good approximation for an air burst being given by the scaling law

$$t_{\min} \approx 0.0025\ W^{1/2},$$

where $t_{\min}$ is the time in seconds and W is in kilotons TNT equivalent. The observed breakaway time is slightly later than that of apparent surface temperature minimum for the same energy. The time at which the maximum temperature occurs in an air burst is related to the explosion energy, except perhaps for very high yields, by

$$t_{\max} \approx 0.032\ W^{1/2},$$

so that it is longer than the time to the minimum by a factor of more than ten. For contact surface bursts, the respective times are greater by 30 percent or so. It should be noted that, although the times vary with the energy yield, the respective minimum and maximum radiating surface temperatures are essentially independent of the explosion energy.

Size of Fireball

2.117 The size of the fireball increases with the energy yield of the explosion. Because of the complex interaction of hydrodynamic and radiation factors, the radius of the fireball at the thermal minimum is not very different for air and surface bursts of a given yield. The relationship between the average radius and the yield is then given approximately by

$$R \text{ (at thermal minimum)} \approx 90\ W^{0.4},$$

where R is the fireball radius in feet and W is the explosion yield in kilotons TNT equivalent. The breakaway phenomenon, on the other hand, is determined almost entirely by hydrodynamic considerations, so that a distinction should be made between air and surface bursts. For an air burst the radius of the fireball is given by

$$R \text{ (at breakaway) for air burst} \approx 110\ W^{0.4}. \qquad (2.117.1)$$

In the case of a contact surface burst, i.e., in which the exploding weapon is actually on the surface, blast wave energy is reflected back from the surface into the fireball (§ 2.33) and W in equation (2.117.1) should probably be replaced by $2W$, where W is the actual yield. Hence, for a contact surface burst,

$$R \text{ (at breakaway) for contact surface burst} \approx 145\ W^{0.4}. \qquad (2.117.2)$$

For surface bursts in the transition range between air bursts and contact bursts, the radius of the fireball at breakaway is somewhere between the values given by equations (2.117.1) and (2.117.2). The size of the fireball is not well defined in its later stages, but as a rough approximation the maximum radius may be taken to be about twice that at the time of breakaway (cf. Fig. 2.111).

2.118 Related to the fireball size is the question of the height of burst at which early (or local) fallout ceases to be a serious problem. As a guide, it may be stated that this is very roughly related to the weapon yield by

$$H \text{ (maximum for local fallout)} \approx 180\ W^{0.4}, \qquad (2.118.1)$$

where H feet is the maximum value of the height of burst for which there will be appreciable local fallout. This expression is plotted in Fig. 2.118. For an explosion of 1,000 kilotons, i.e., 1 megaton yield, it can be found from Fig. 2.118 or equation (2.118.1) that significant local fallout is probable for heights of burst less than about 2,900 feet. It should be emphasized that the heights of burst estimated in this manner are approximations only, with probable errors of ± 30 percent. Furthermore, it must not be assumed that if the burst height exceeds the value given by equation (2.118.1) there will definitely be no local fallout. The amount, if any, may be expected, however, to be small enough to be tolerable under emergency conditions.

High-Altitude Bursts

2.119 For nuclear detonations at heights up to about 100,000 feet, the density of air is such that the distribution of the explosion energy remains almost unchanged, approximating that described in § 1.22, e.g., about 45 to 55 percent (of the fission energy) appears as blast and shock and 30 to 40 percent is received as thermal radiation. At greater altitudes, this distribution begins to change noticeably with increasing height of burst, a smaller proportion of the energy appearing as blast. It is for this reason that the level of 100,000 feet has been chosen for distinguishing between air bursts and high-altitude bursts. There is, of course, no sharp change in behavior at this elevation, and so the definition of a high-altitude burst as being at a height above 100,000 feet is somewhat arbitrary. Although there is a progressive decline in the blast energy with increasing height of burst above 100,000 feet, the proportion of the explosion energy received as effective thermal radiation on the ground does not at first change appreciably. This is due to the interaction of the primary thermal radiation with the surrounding air and its subsequent emission in a different spectral region, as explained below. At still higher altitudes, the effective thermal radiation received on the ground decreases and is, in fact, less than at an equal distance from an air burst of the same total yield (§ 7.25).

2.120 When a nuclear explosion occurs at a very high altitude, the low density of the air affects the development of the fireball phenomena in several ways. The probability of interaction of the primary thermal radiation, i.e., the thermal X-rays, with atoms and molecules in the air is markedly decreased, so that the photons have long mean free paths and travel greater distances, on the average, before they are absorbed or degraded into a different form of energy. The volume of the atmosphere in which the energy of the radiation is deposited,

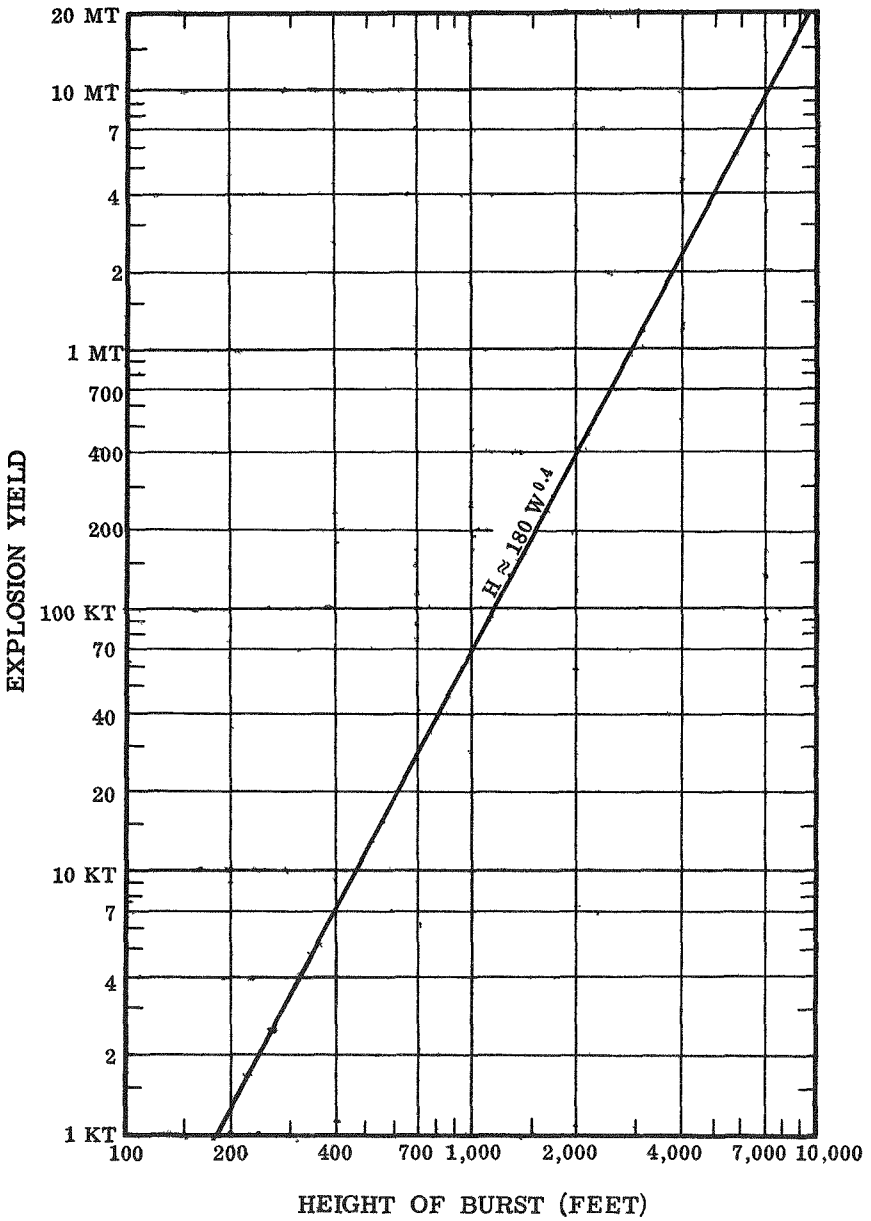

Figure 2.118. Approximate maximum height of burst for appreciable local fallout.

over a period of a millisecond or so, may extend for many miles, the dimensions increasing with the altitude burst. The first interaction of the X-rays with the air is to produce a strong flash of light, called

"flourescence radiation," lasting perhaps a microsecond, This light, which is intense in the ultraviolet and visible regions, is similar to that observed in electrical discharges through air in the laboratory; it consists predominantly of emission from excited neutral and ionized molecules of nitrogen.

2.121 Most of the X-ray energy is absorbed in the large volume of air which has a considerable mass, in spite of its low density. Consequently, the fireball temperatures, although of the order of 10,000° C (18,000° F) or more, are much lower than for an explosion at sea-level densities. Various excited atoms and ions are formed in the air, as a result of interaction with the thermal X-rays, and the radiation re-emitted by these species represents the thermal radiation observed at a distance. About half of the absorbed energy is emitted in this manner in less than a second from a megaton-range explosion at an altitude of about 250,000 feet and constitutes the main pulse of thermal radiation. The remainder of the thermal energy is radiated so slowly that it can be ignored as a significant effect.

2.122 A qualitative comparison of the rate of arrival of thermal radiation energy at a distance from the burst point as a function of time for a megaton-range explosion at high altitude and in a sea-level atmosphere is shown in Fig. 2.122. It is seen, as mentioned above, that in the high-altitude burst there is only a single pulse of relatively short duration. Not only is the pulse shorter and more intense than in a normal air burst, but it is richer in ultraviolet radiation. This is because of the decreased formation of ozone, oxides of nitrogen, and nitrous acid (§ 2.113) which absorb strongly in this spectral region.

2.123 Because the primary thermal radiation energy in a high-altitude burst is deposited in a much larger volume of air, the energy per unit volume available for the development of the shock front is less than in an air burst. Furthermore, the shock wave is slow to form, so that in the meantime the fireball radiates a large fraction of its energy. Consequently the shock front does not become hot enough to be opaque at times sufficiently early to mask the radiation front and cause an apparent temperature minimum as in the case of an air burst. Thus, with increasing height, a series of changes take place in the thermal pulse phenomena; the surface temperature minimum becomes less pronounced and eventually disappears, so that the thermal radiation is emitted in a single pulse. It is for this reason that the TEAK high-altitude shot was accompanied by a single bright flash of light of short duration (§ 2.56).

2.124 Although the energy density in the atmosphere as the result of a high-altitude burst is small compared with that from an air burst of the same yield, a shock wave is ultimately produced in the

upper atmosphere. For example, disturbance of the ionosphere in the vicinity of Hawaii after the TEAK shot indicated that a shock wave was being propagated at that time at an average speed of about 4,200 feet per second. The formation of the large red, luminous sphere, several hundred miles in diameter, surrounding the fireball, has been attributed to the electronic excitation of oxygen atoms by the energy of the blast wave. Soon after excitation, the excess energy is emitted as visible radiation toward the red end of the spectrum (6,300 and 6,364 A).

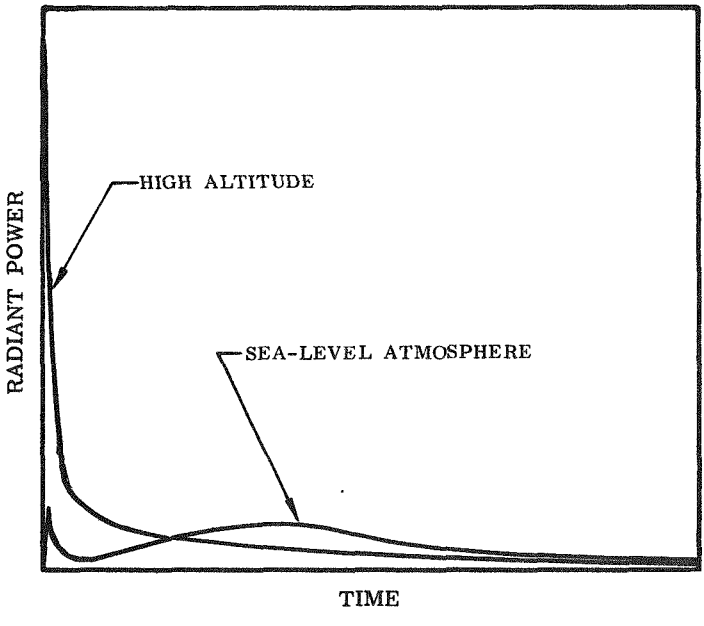

Figure 2.122. Qualitative comparison of rates of arrival of thermal radiation at a given distance from high-altitude and sea-level bursts.

2.125 The formation of auroras and the disturbances in the ionosphere which affect the transmission of radio (and similar) waves are caused by electrically charged particles produced directly or indirectly as a result of the nuclear explosion. It is well known that the ionosphere, which is that part of the atmosphere above an altitude of about 40 miles, plays an important part in the propagation of certain radio waves over long distances. The ability of the ionosphere to reflect these waves is dependent upon normal variations in the electron density at different levels. The neutrons and gamma rays present in the initial nuclear radiation and the beta particles

and gamma rays from the fission residues, as well as the thermal X-rays, are capable of producing ionization, i.e., forming ions and electrons, by interaction with the oxygen and nitrogen in the atmosphere. Hence, a nuclear explosion is accompanied by a large increase in the electron density (or concentration). In the event of an air burst at moderate altitude, the electrons are promptly removed by attachment to neutral molecules or by recombination with ions; consequently, although radio signals in the immediate vicinity of the explosion will be affected, there will be little interference with radio communications in general. For a burst at high altitudes, however, the electrons can remain free for a longer time in the low-density air, thus causing a significant disturbance of the normal ionospheric electron densities. As a result there may be a "black-out" of radio signals over a large area for several hours. In some circumstances the earth's magnetic field contributes to the situation, as will be described below.

2.126 The auroral effects associated with high-altitude nuclear explosions are primarily due to the beta particles emitted by the fission products when they undergo radioactive decay. The earth's magnetic field exerts forces on charged particles so that they are largely constrained to travel in helical (spiral) paths along the field lines. When the beta particles formed in a nuclear detonation and trapped in this manner enter the upper atmosphere, they cause electronic excitation (and ionization) of the atoms and molecules in the air. The excess energy is then re-emitted as visible radiation characteristic of the aurora.

2.127 The remote auroras, such as those observed at Apia following the TEAK and ORANGE shots, arise from the fact that the earth behaves like a magnetic dipole, i.e., it has two (one north and one south) poles. Hence every line of force reaches the earth at two points, called "conjugate points," one north of the magnetic equator and the other south of it. For the lines of force passing through the TEAK and ORANGE points of burst, the near conjugate point, in the northern hemisphere, is somewhat to the northeast of Johnston Island whereas the more remote conjugate point, in the southern hemisphere, is to the northwest of Apia. Hence, the charged particles spiraling about the earth's magnetic lines of force will enter the atmosphere near these two locations and these are where the auroras may be expected to form (Fig. 2.127). Since it takes a very short time—no more than a fraction of a second—for the beta particles to travel along the field lines from the point of burst to the southern conjugate point, the aurora was seen at Apia at almost the same time as that observed from Johnston Island.

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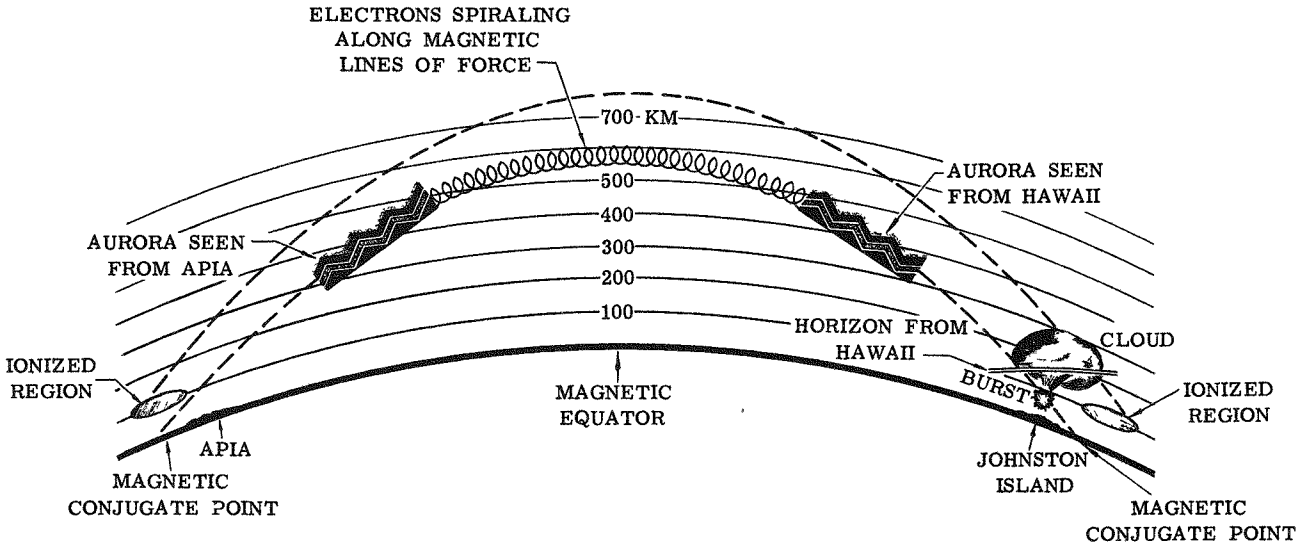

Figure 2.127. Phenomena associated with high-altitude explosions.

2.128 For bursts at sufficiently high altitudes, the fission product ions move along the earth's lines of force and are mostly brought to rest at altitudes of about 70 miles near the conjugate points. There they continue to decay and so act as a stationary source of beta particles. On the other hand, the neutral fission products remaining in the vicinity of the burst point emit beta particles which travel toward the conjugate points along the lines of force. However, when they enter a region where the strength of the earth's magnetic field increases, as it does near the conjugate points, a small proportion of the beta particles are turned back (or reflected), so that they travel back and forth a number of times before they are eventually captured.

2.129 In actual fact, the interactions of the ionized and neutral particles and radiations from a nuclear explosion with the earth's magnetic field and with the atmosphere are more complicated than outlined above. For example, in addition to the motion of the charged particles along the field lines, there is a tendency for them to move across the lines wherever the magnetic field strength is not uniform. This results in an eastward (longitudinal) drift around the earth superimposed on the back and forth spiral motion between regions near the conjugate points. Furthermore, the general behavior is strongly affected by the altitude at which the nuclear burst occurs. These and other related matters are discussed more fully in Chapter X.

Nuclear Explosions and the Weather

2.130 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.

2.131 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. Furthermore, 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.

2.132 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 weapon 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.

2.133 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 weapon 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 test explosions of nuclear devices, since these were not accompanied by large fires.

2.134 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 radioactive 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 radioactive cloud directly associated with the explosion.

2.135 The amount of ionization produced by the radioactive material, even for a high-energy nuclear explosion, is believed to be insufficient to cause any significant disturbance of general atmospheric

conditions. It appears improbable, therefore, that the ionization accompanying a nuclear explosion can affect the weather, although it may produce auroral effects and interfere with radio transmission.

2.136 The dust raised in severe volcanic eruptions, such as that at Krakatoa 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 Krakatoa eruption. Moreover, 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.

2.137 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.

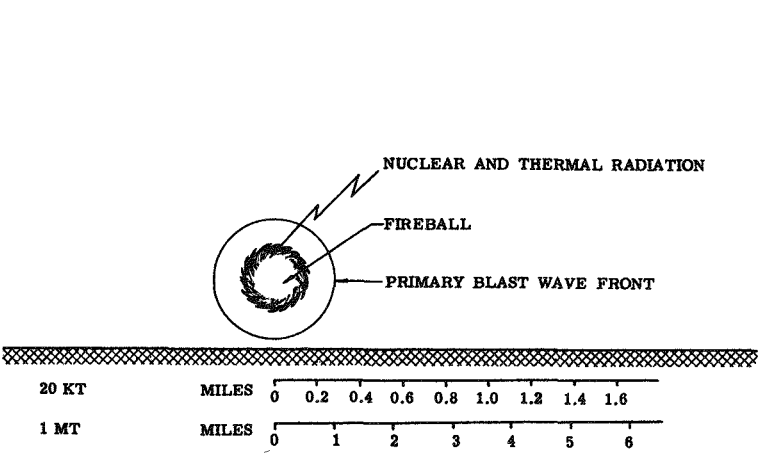

Figure 2.51a. Chronological development of an air burst; 0.5 second after 20-kiloton detonation; 1.8 seconds after 1-megaton detonation.

CHRONOLOGICAL DEVELOPMENT OF AIR BURST

Immediately following the detonation of a nuclear weapon in the air, an intensely hot and luminous (gaseous) fireball is formed. Because of 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) which 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 fireball 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 blast wave front in the air is seen to be well ahead of the fireball, about 800 feet for the 20-kiloton explosion and roughly half a mile for the 1-megaton detonation.

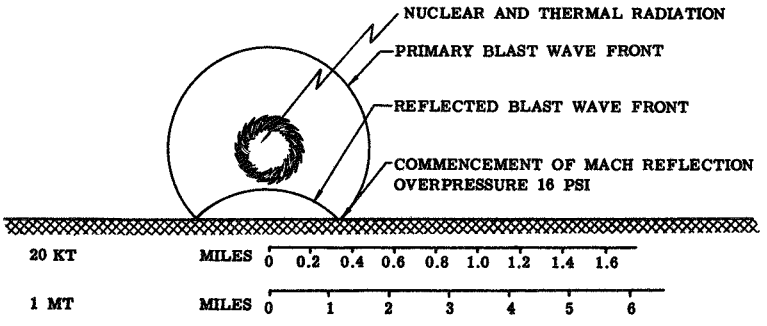

Figure 2.51b. Chronological development of an air burst; 1.25 seconds after 20-kiloton detonation; 4.6 seconds after 1-megaton detonation.

When the primary air blast wave from the explosion strikes the ground, another blast wave is produced by reflection. At a certain distance from ground zero, which depends upon the height of burst and the energy yield of the weapon, the primary and reflected wave 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 the air bursts at the given heights are as follows:

Explosion yield	*Height of burst (feet)*	*Time after detonation (seconds)*	*Distance from ground zero (miles)*
20 kilotons	1, 760	1. 25	0. 35
1 megaton	6, 500	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 fireball.

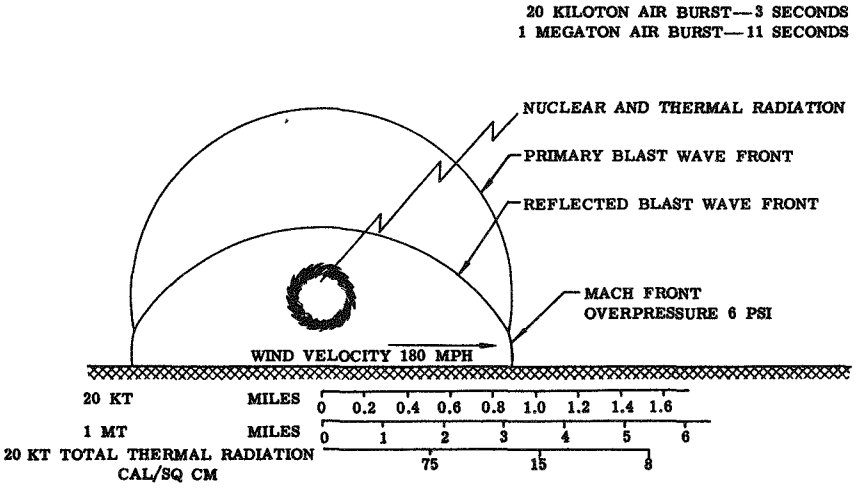

Figure 2.51c. Chronological development of an air burst; 3 seconds after 20-kiloton detonation; 11 seconds after 1-megaton detonation.

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	*Height of burst (feet)*	*Time after detonation (seconds)*	*Distance from ground zero (miles)*	*Height of stem (feet)*
20 kilotons	1, 760	3	0. 87	185
1 megaton	6, 500	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 from the weapon residues in the rising fireball continue to reach the ground. But after 3 seconds from the detonation of a 20-kiloton weapon, 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, at 1,760 feet, are shown on the scale at the bottom of the figure (for further details, see Chapter VII). Appreciable amounts of thermal radiation are still received 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.

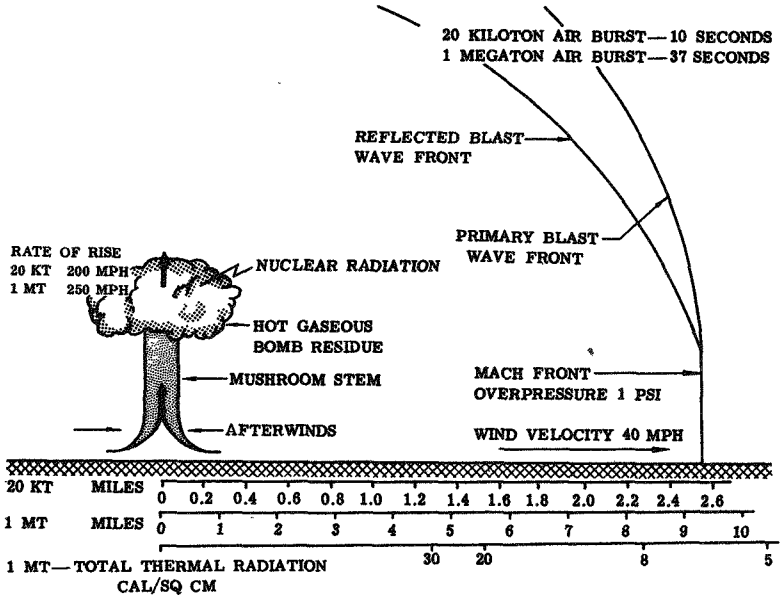

Figure 2.51d. Chronological development of an air burst; 10 seconds after 20-kiloton detonation; 37 seconds after 1-megaton detonation.

At 10 seconds after a 20-kiloton explosion at an altitude of 1,760 feet the Mach front is over 2½ miles from ground zero, and 37 seconds after a 1-megaton detonation at 6,500 feet, 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. There will be slight damage to many structures, including doors and window frames ripped off, roofs cracked, and plaster damaged. Glass will be broken at overpressures down to ½ pound per square inch. 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 fireball 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. For moderately low air bursts, these winds will raise dirt and debris from the earth's surface to form the stem of what will eventually be the characteristic mushroom cloud.

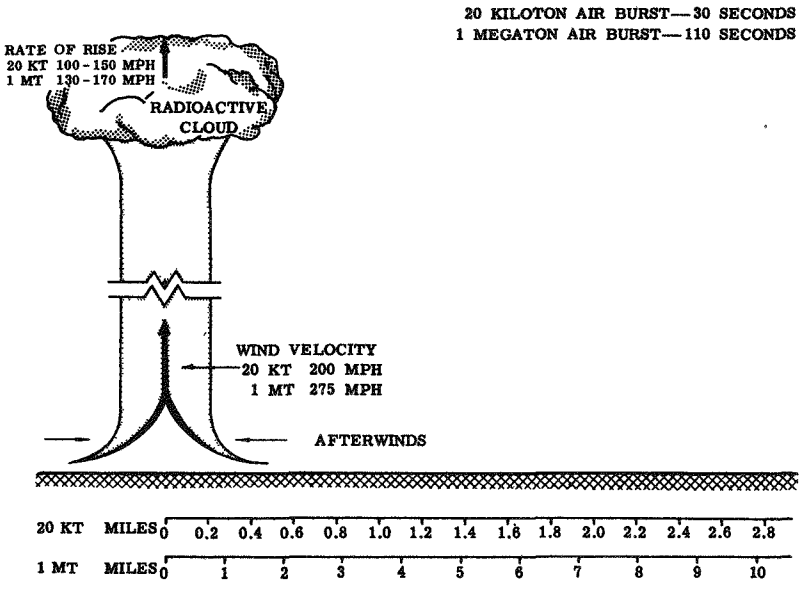

Figure 2.51e. Chronological development of an air burst; 30 seconds after 20-kiloton detonation; 110 seconds after 1-megaton detonation.

The hot residue of the weapon continues to rise and at the same time it expands and cools. As a result, the vaporized fission products and other weapon residues condense to form a cloud of highly radioactive particles. The afterwinds have velocities of 200 or more miles per hour, and for a sufficiently low burst they will 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. After about 10 minutes, the maximum heights attained by the clouds will be about 7 miles and 14 miles, respectively. Ultimately, the particles in the cloud will be dispersed by the wind and, unless there is precipitation, there will usually be no early (or local) fallout. Only if the height of burst is less than about 600 feet for a 20-kiloton and 3,000 feet for a 1-megaton explosion would appreciable early fallout be expected.

Although the 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.

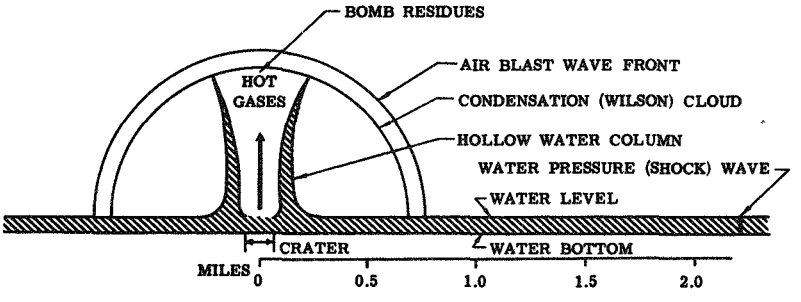

Figure 2.80a. Chronological development of a 100-kiloton shallow underwater burst: 2 seconds after detonation.

CHRONOLOGICAL DEVELOPMENT OF SHALLOW UNDERWATER BURST

When a nuclear weapon is exploded under the surface of water, a bubble of intensely hot gases and steam 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 weapon 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 and steam 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 blast wave has passed, a dome-shaped cloud of condensed water droplets, called the condensation cloud, may form for a second or two. Although this phenomenon is impressive, 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.

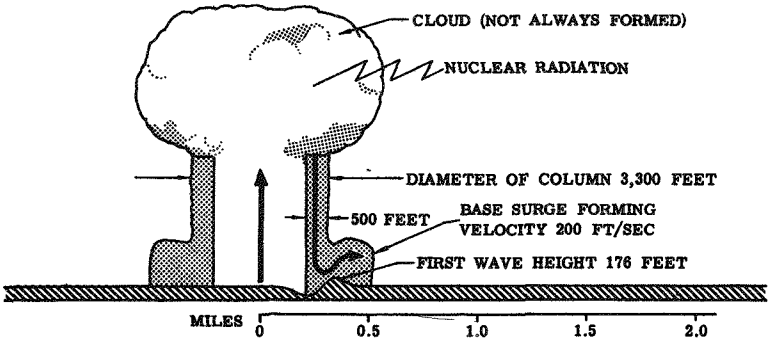

Figure 2.80b. Chronological development of a 100-kiloton shallow underwater burst: 12 seconds after detonation.

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 weapon residues venting through the hollow central portion condense and spread out to form the cauliflower-shaped 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). For underwater bursts at certain depths, the radioactive cloud may not be formed, although there will generally be a base surge.

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.

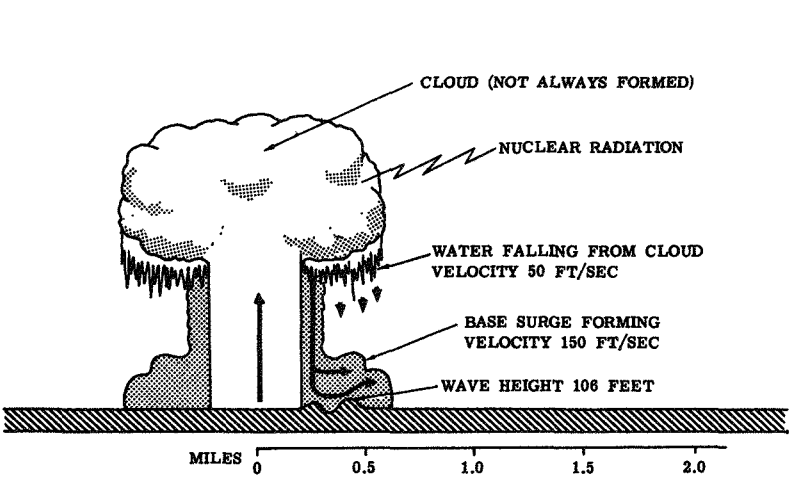

Figure 2.80c. Chronological development of a 100-kiloton shallow underwater burst: 20 seconds after detonation.

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 radioactive cloud, if it is formed. The initial rate of fall is about 50 feet per second. The diameter of the column 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.

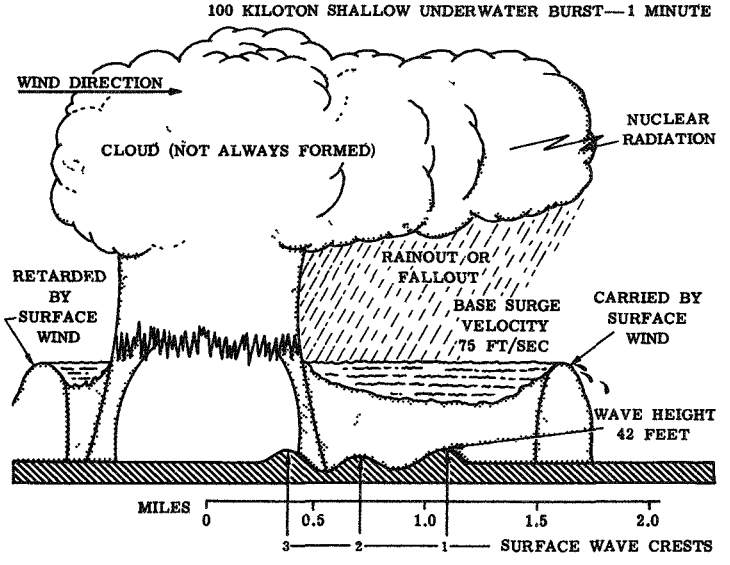

Figure 2.80d. Chronological development of a 100-kiloton shallow underwater burst: 1 minute after detonation.

At 1 minute after the underwater burst, the water falling from the radioactive cloud reaches the surface, forming a region of primary cloud fallout. There is consequently a continuous ring of water and spray between the cloud, if one has formed, 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 present in 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.

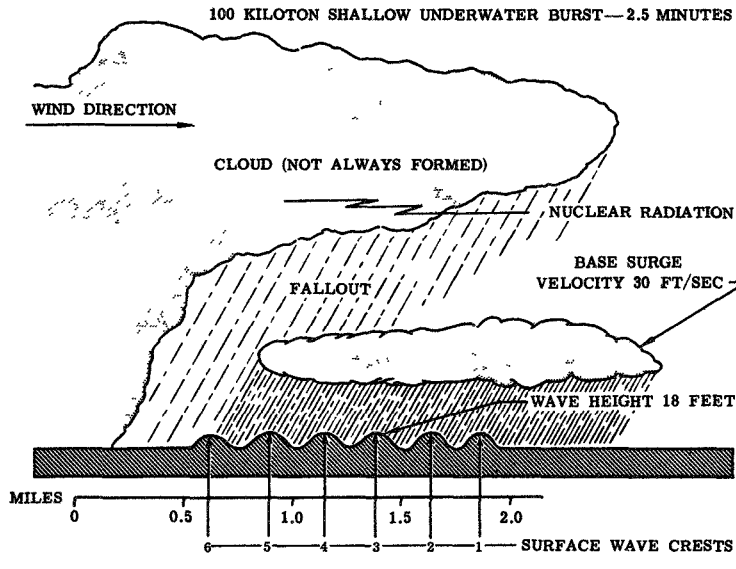

Figure 2.80e. Chronological development of a 100-klloton shallow underwater burst: 2.5 minutes after detonation.

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 effective spread of the visible base surge cloud at 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. Due 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 radioactive 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.

After 4 or 5 minutes, the visible base surge will begin to disappear as the water droplets evaporate. However, radioactive particles will still be present and will spread out in the form of the invisible base surge.

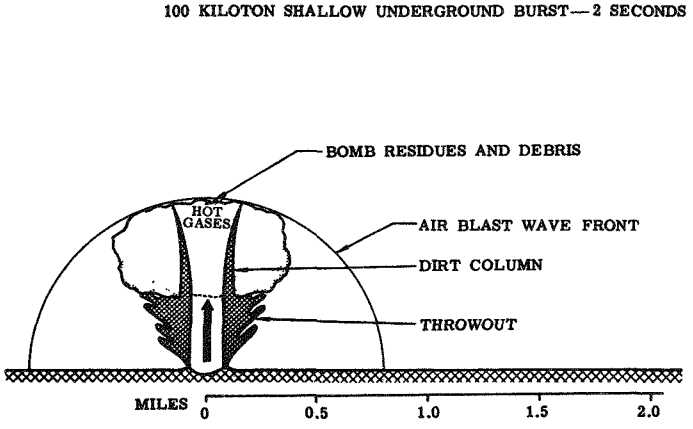

Figure 2.93a. Chronological development of a 100-kiloton shallow underground burst: 2.0 seconds after detonation.

CHRONOLOGICAL DEVELOPMENT OF UNDERGROUND BURST

When a nuclear explosion occurs at a shallow depth underground, the fireball breaks through the surface of the earth within a fraction of a second of the instant of detonation. 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 weapon 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 blast wave in the air. At 2 seconds after the explosion, the blast wave front in air is about ¾ mile from surface zero.

100 KILOTON SHALLOW UNDERGROUND BURST—9 SECONDS

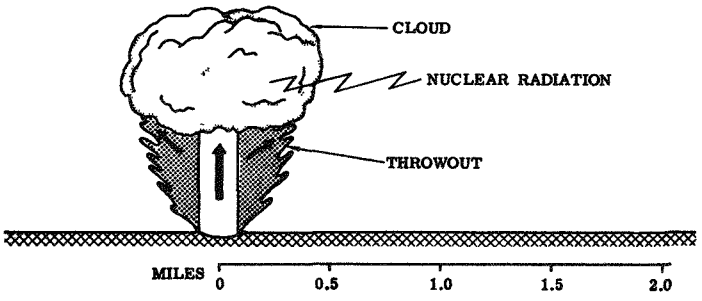

Figure 2.93b. Chronological development of a 100-kiloton shallow underground burst: 9.0 seconds after detonation.

The radioactive 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.

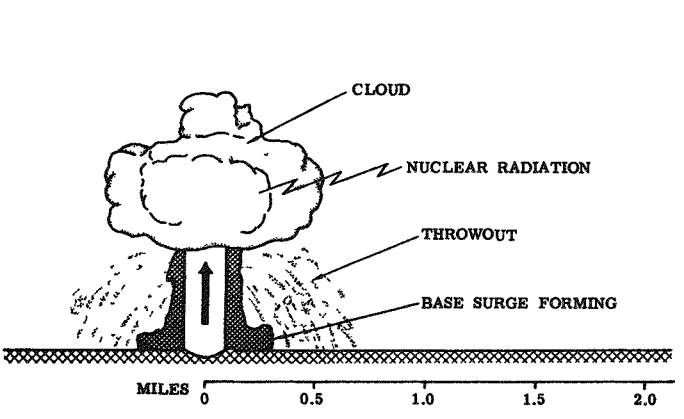

Figure 2 93c Chronological development of a 100-kiloton shallow underground burst: 45 seconds after detonation.

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 would be particularly conducive to base surge formation.

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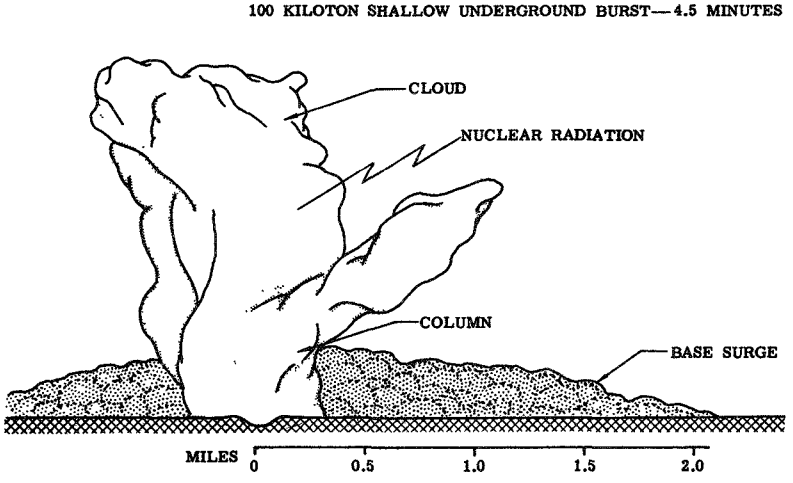

Figure 2.93d. Chronological development of a 100-kiloton shallow underground burst: 4.5 minutes after detonation.

The base surge increases in height and area and soon begins to merge with the radioactive cloud of weapon 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.

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*These documents may be obtained for a small charge from Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C.

CHAPTER III

AIR BLAST PHENOMENA

CHARACTERISTICS OF THE BLAST WAVE IN AIR

Development of the Blast Wave

3.01 Most of the material damage caused by an air burst nuclear weapon 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.

3.02 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 blast wave (or 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.

3.03 As already seen in Chapter II, the expansion of the intensely hot gases at extremely high pressures in the fireball causes a blast wave to form in the air, moving outward at high velocity. The main characteristic of this wave is that the pressure rises very sharply 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. 3.03 for an ideal (instantaneously rising) shock front. It is seen that, prior to breakaway (§ 2.110),

pressures at the shock front are about twice as high as those in the interior of the fireball which are of considerable magnitude.

3.04 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. 3.04, which shows the overpressures at six successive times, indicated by the numbers 1, 2, 3, 4, 5, and 6. In the

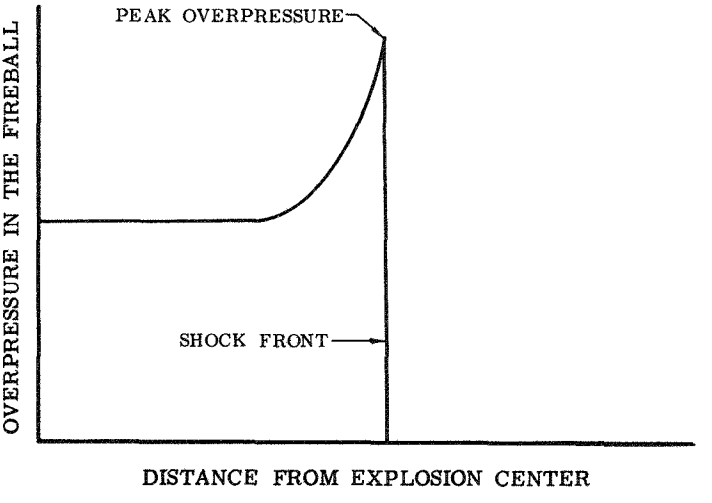

Figure 3.03. Variation of overpressure with distance in the fireball.

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, so that an "underpressure" rather than an overpressure exists.

3.05 During the negative (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, which is somewhat longer than the positive phase, the pressure has essentially returned to

ambient. The peak values of the underpressure are generally small compared with the peak overpressures, the former having a maximum of about 4 pounds per square inch below the ambient pressure. With increasing distance from the explosion, both peak values decrease, the positive more rapidly than the negative, but they do not approach equality until the peak pressures have decayed to a very low level.

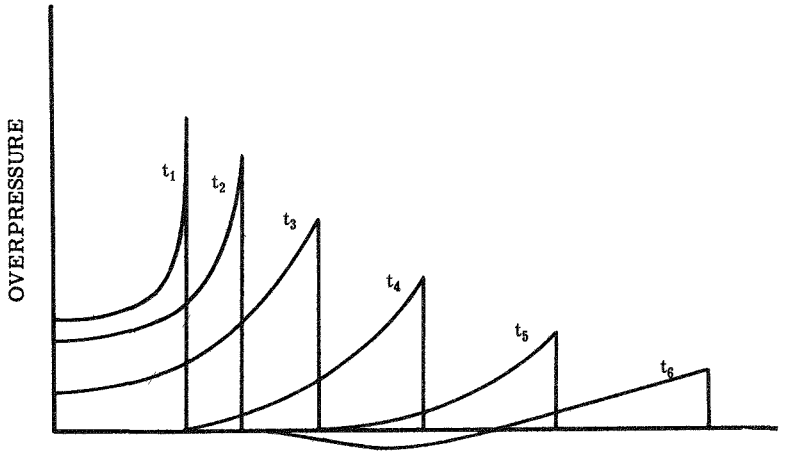

Figure 3.04. Variation of overpressure with distance at successive times.

Variation of Blast Overpressure with Time

3.06 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. 3.06. 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.

3.07 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 (ideal) shock front arrives, the pressure will suddenly increase to a large value, i.e., to the peak overpressure referred to earlier. In Fig. 3.06 the numeral 1 represents the time of the explosion, and 2 indicates the time of arrival of the shock front. At the

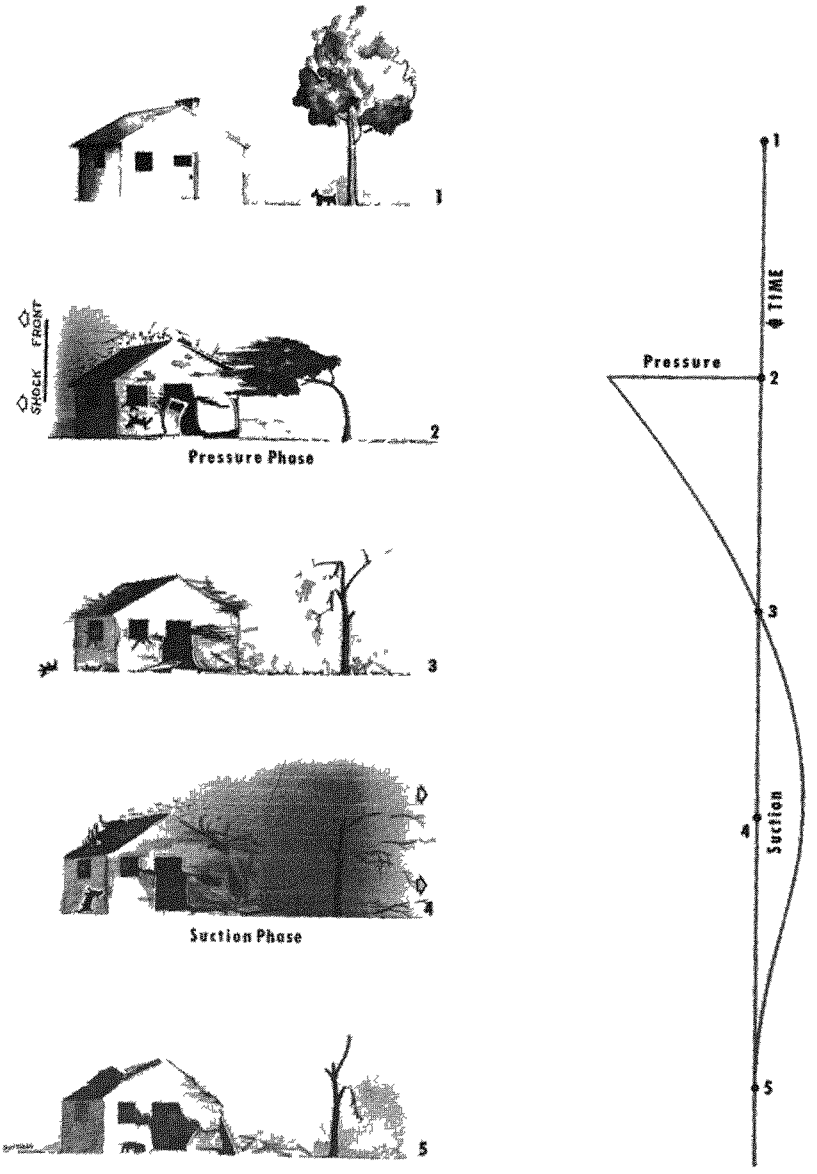

Figure 3.06. Variation of pressure with time at a fixed location and effect of blast wave passing over a structure.

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.

3.08 Following the arrival of the shock front, the pressure falls rapidly and at the time corresponding to the point 3 in Fig. 3.06 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 2 to 4 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.

3.09 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. 3.06, 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, e.g., large windows which are poorly held against outward motion, brick veneer, and plaster walls may be dislodged by trapped air at normal pressure. But since the maximum underpressure is generally smaller than the peak overpressure at the shock front, less damage occurs during the negative than in the positive phase of the blast wave. As the negative phase passes, the pressure at first decreases below ambient and then it 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 proportional to the square of the wind velocity and to the density of the air behind the shock front. Both of these quantities may be related to the overpressure under ideal conditions at the wave front by certain equations, which will be given later (see § 3.49). For very strong shocks the dynamic pressure is larger than the overpressure, but below 70 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 for an ideal shock front in air at sea level are given in Table 3.11.

TABLE 3.11

OVERPRESSURE, DYNAMIC PRESSURE, AND WIND VELOCITY IN AIR AT SEA LEVEL FOR AN IDEAL SHOCK FRONT

Peak overpressure (pounds per square inch)	*Peak dynamic pressure (pounds per square inch)*	*Maximum wind velocity (miles per hour)*
200	330	2, 080
150	223	1, 778
100	123	1, 414
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 usually different. This may be seen from Fig. 3.12 which indicates how the two pressures vary in the course of the first few seconds or so following arrival of the shock front. In the case illustrated, the peak overpressure is about 5 pounds per square inch, so that the peak dynamic pressure is close to 0.7 pound per square inch; at different values of the peak overpressure the relative positions of the two curves will, of course, be different, in accordance with the data in Table 3.11.

3.13 When the shock front reaches the given point, both the overpressure and the dynamic pressure increase almost immediately from zero to their maximum values and then decrease. The dynamic pressure (and wind velocity) will fall to zero somewhat later than the

overpressure because of the momentum of the air in motion behind the shock front, but for purposes of estimating damage the difference is not significant. During the negative (or underpressure) 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 phase is generally small compared to that in the positive phase.

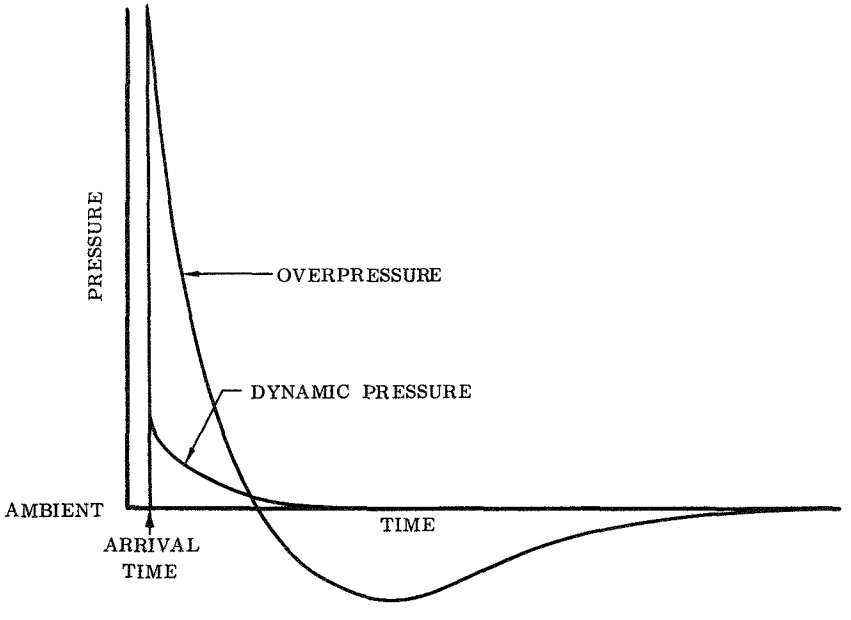

Figure 3.12. Variation of overpressure and dynamic pressure with time at a fixed location in the low-pressure region.

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; 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 pressure at the 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 above that the transient wind velocity decays to zero at a somewhat later time than the end of the overpressure positive phase. Consequently, the duration of the positive dynamic pressure phase may exceed that of the positive overpressure phase by varying amounts depending on the pressure level involved. However, positive dynamic pressures existing after the overpressure positive phase has ended are so low that they can be disregarded. Therefore the period of time over which the positive dynamic pressure is effective may be taken as essentially the positive phase duration of the overpressure. The same considerations apply to the respective negative phases.

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 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. In the first stage the wave 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.

3.18 When such reflection occurs, an individual or object precisely at the surface will experience a single pressure increase, 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 peak reflected pressure (§§ 3.50, 3.71) 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, is depicted in Fig. 3.18 for an ideal shock front. 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 except on the surface.

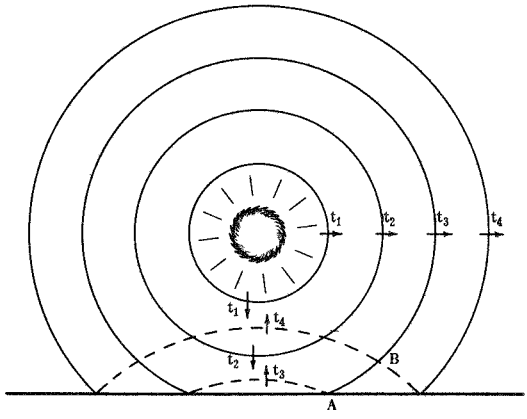

Figure 3.17. Reflection of blast wave at the earth's surface in an air burst; t_1 to t_4 represent successive times.

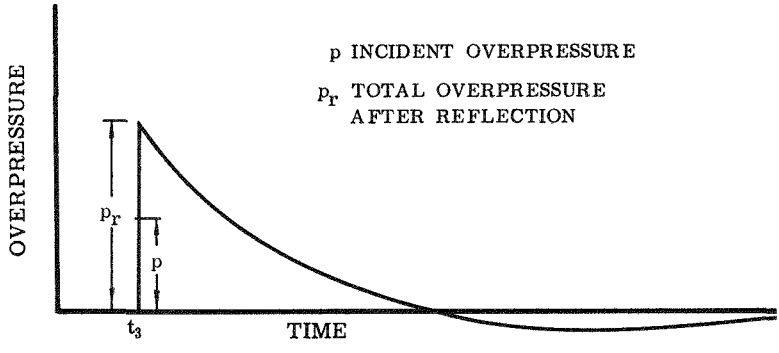

Figure 3.18. Variation of overpressure with time at a point on the surface in the region of regular reflection.

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 (Fig. 3.19). This situation can be illustrated by considering the point B in Fig. 3.17, which is also in the regular

[1] For an explanation of the term "ground zero," see § 2.34.

reflection region. When the incident wave front reaches this point, at time t_3, the reflected wave is still some distance away. There will, consequently, be a short interval before the reflected wave reaches the point above the surface at time t_4. Between t_3 and t_4, 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, it may be necessary to consider 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.

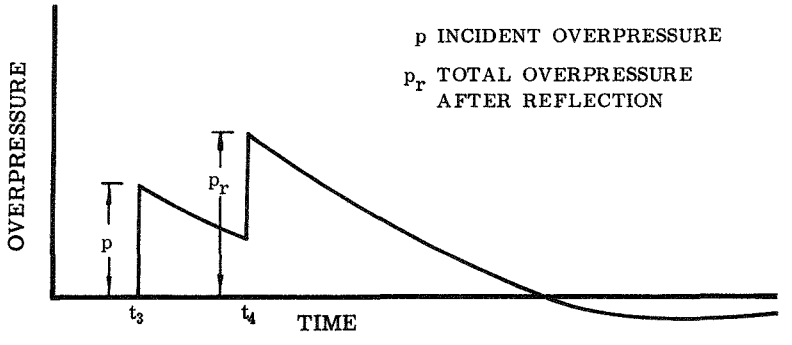

Figure 3.19. Variation of overpressure with time at a point above the surface in the region of regular reflection.

The Mach Effect

3.20 The foregoing discussion concerning the delay between the arrival of the incident and reflected wave 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 wave 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 wave front moves faster than the incident wave and, under certain conditions, eventually overtakes it so that the two wave fronts fuse to produce a single front. 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 waves 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 overtaking, the incident wave. At the stage represented by Fig. 3.21c, the reflected wave near the ground has overtaken and fused with the incident wave to form a single front called the "Mach stem." The point at which the incident wave, reflected wave, and Mach fronts meet is called the "triple point." [2]

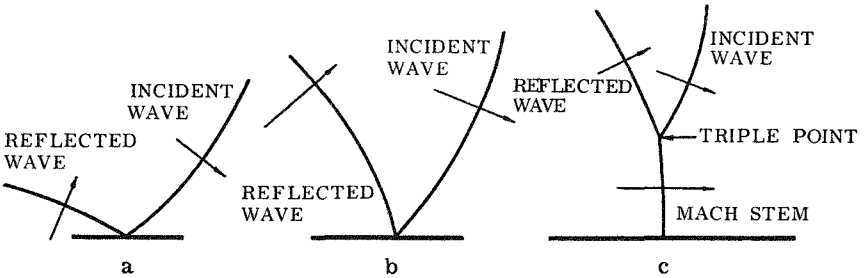

Figure 3.21. Fusion of incident and reflected waves and formation of Mach stem.

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 wave is the same as that previously described for blast waves 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. 3.06.

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 pressure increases 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 weapon is detonated at the surface, i.e., in a contact surface burst, only a single merged wave develops. Consequently, only one pressure increase will be observed either on or above the ground.

[2] At any instant the so-called "triple point" is not really a point, but a horizontal circle with its center on the vertical line through the burst point; it appears as a point on a drawing, such as Fig. 3.21c.

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 pressure increase is experienced in the Mach region below the triple point as compared to the 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.

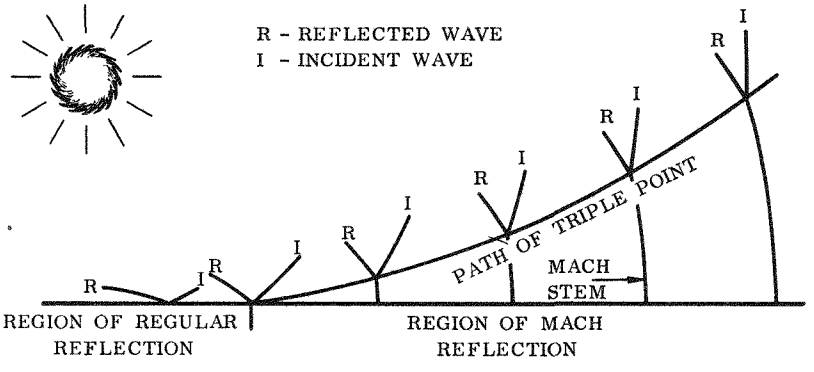

Figure 3.22. Outward motion of the blast wave near the surface in the Mach region.

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. Provided the height of burst is not too great, the Mach stem forms at increasing distances from ground zero as the height of burst increases for a given yield, and also as the yield decreases at a specified height of burst. For moderate heights of burst Mach fusion occurs at a distance from ground zero approximately equal to the burst height. As the height of burst is increased, the distance from ground zero at which the Mach effect commences exceeds the burst height by larger and larger amounts.

Height of Burst and Blast Damage

3.26 The height of burst and energy yield (or power) 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, or as the energy yield for a given height of burst increases, 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 VI.

3.27 Because of the relation between height of burst and energy of the explosion, the air blast phenomena to be expected on the ground from a weapon of large yield detonated at a height of several thousand feet will approach those of a near surface burst. On the other hand, explosions of weapons of smaller energy yields at these same or even lower levels will have the characteristics of air bursts. A typical example of the latter situation is found in the nuclear explosion which occurred over Nagasaki, Japan, in World War II when a weapon having a yield of approximately 20 kilotons of TNT equivalent was detonated at a height of about 1,850 ft. By means of certain rules, called "scaling laws," which are described in the technical section of this chapter (§ 3.55), it is found that to produce similar blast phenomena at ground distances proportional to the heights of burst, for a 1-kiloton weapon the height of burst would have to be roughly 680 feet and for a 1-megaton explosion about 6,800 feet. In these three cases, the Mach stem formation would occur at distances from ground zero that are not very different from the respective heights of burst.

3.28 It should be noted that there is no single optimum height of burst, with regard to blast effects, for any specified explosion yield because the chosen burst height will be determined by the nature of the target. As a rule, strong (or hard) targets will require the equivalent of a low air burst or a surface burst. For weaker targets, which are destroyed or damaged at relatively low overpressures or dynamic pressures, the height of burst may be raised to increase the damage areas, since the required pressures will extend to a larger range than for a low air or surface burst.

3.29 The variation of blast characteristics with distance from ground zero for air bursts occurring at different heights are most conveniently represented by what are called "height of burst" curves. Such curves have been prepared for various blast wave properties, e.g., peak overpressure, peak dynamic pressure, time of arrival, and positive phase duration, and will be presented and discussed later (§ 3.63 *et seq.*). Values of these (and other) properties can be determined from the curves, by application of appropriate scaling factors, for any explosion yield and height of burst.

Contact Surface Burst

3.30 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 at successive times, t_1 through t_4, in Fig. 3.30. 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 blast wave front may be assumed to be vertical for most structures, with both overpressure and dynamic pressure decaying at different rates behind the wave (shock) front as previously described. The transient winds behind the wave front near the surface are essentially horizontal.

MODIFICATION OF AIR BLAST PHENOMENA

Terrain Effects

3.31 Large hilly land masses tend to increase air blast effects in some areas and to decrease them in others. The change in peak overpressure appears to depend on the slope angle and on the actual value of the pressure. The increase (or "spike") in peak overpressure which occurs at the base of a hill is attributable to the reflection of the blast wave by the front slope. This spike tends to broaden or lengthen with time as the wave travels up the hill. However, a reduction in peak overpressure occurs as the blast wave moves over the crest and down the back slope. The pressure at the wave front does not rise instantaneously, as in an ideal shock wave (see Fig. 3.06), but somewhat more gradually, although the behavior soon becomes normal as the blast wave proceeds down the hill. In

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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.

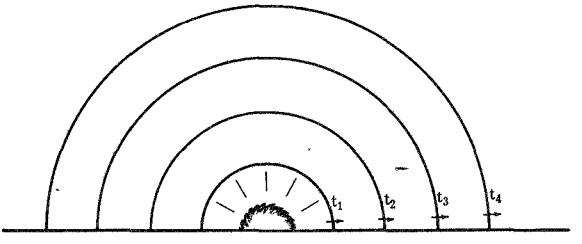


Figure 3.30. Blast wave from a contact surface burst; incident and reflected waves coincide.

3.32 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 in Chapter IV that blast waves can easily bend (or diffract) around apparent obstructions.

3.33 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.

3.34 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 difficult to predict.

Meteorological Conditions

3.35 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. Meteorological conditions, however, can sometimes either enlarge or contract the area over which light structural damage would normally be expected. For example, window breakage and noise have been experienced hundreds of miles from the burst point. Such phenomena, which have been observed with large TNT detonations as well as nuclear explosions, are caused by the bending back to the earth of the blast wave by the atmosphere.

3.36 Four general circumstances which lead to this effect are known. The first is a temperature inversion near the earth's surface, where the temperature increases with the height above ground; this may arise either from night-time cooling of the ground surface by the radiation of heat or from a mass of warm air moving over a relatively cold surface. The result is that the overpressures on the ground are higher than would be expected in a standard atmosphere. Conversely, when unstable conditions prevail, and the temperature decreases with altitude, as in the afternoon or in tropical climates, the blast wave is bent away from the ground. The overpressure then decays faster with distance than under isothermal conditions.

3.37 The second situation arises when there are high-speed winds aloft. If a decrease in air temperature at increasing altitude, such as usually occurs in the daytime, is combined with an upper wind whose speed exceeds 3 miles per hour for each 1,000 feet of altitude, the blast wave will be refracted (or bent) back to the ground. This usually occurs with jet-stream winds, where maximum velocities are found between 25,000- and 50,000-feet altitudes. These conditions may cause several "rays" to converge into a sharp focus at one location on the ground, and the concentration of blast energy there will greatly exceed the value that would otherwise occur at that distance. The first (or direct striking) focus from a jet stream duct may be at 20 to 50 miles from the explosion. Since the blast energy is reflected from the ground and is again bent back by the atmosphere, the focus may be repeated at regularly spaced distances. In the explosion of a 20-kiloton weapon at the Nevada Test Site, this effect caused windows to break 75 to 100 miles away.

3.38 Bending of blast waves can also be produced by a layer of relatively warm air, called the ozonosphere, at a height of 20 to 30

miles. In these levels winds blow from the west in winter and from east in summer, enhancing blast pressures and noise at downwind distances from 70 to 150 miles (first direct strike). Reflections from the ground, and subsequent refractions by the ozonosphere, cause the usual repeat focus pattern. Focusing of this type has resulted in the breakage of windows on the second ground strike at 285 miles from a 17-kiloton nuclear explosion. Large explosions have been distinctly heard at even greater distances.[3]

3.39 The fourth condition is brought about by the very high temperatures in the ionosphere above an altitude of 60 miles. Generally, sounds returned by the ionosphere are heard usually in the opposite direction from the principal ozonosphere signals and at ranges beyond 120 miles from a burst. Downwind of the ozonosphere channel the strike range of ionospheric signals is extended, whereas it is shortened upwind. Moreover, since most of the blast wave energy is absorbed in passing through the extremely low air densities at such high altitudes, no damage has been reported from ionospheric signals. However, in traveling through low-pressure air, the waves tend to behave like shocks and give very sharp pressure rises, although they are of small amplitude. Even when returned to ground level by refraction they are easily heard as sharp cracks and pops.

Effect of Altitude

3.40 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.

3.41 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 § 3.59), 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

[3] The situations described here and in § 3.39 could also be considered as temperature inversions.

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 small, and since most surface targets are at lower altitudes, it is rarely necessary to make the corrections.

3.42 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 ambient conditions at the target altitude are used to evaluate the correction factor referred to above when the target is at an appreciable elevation above sea level.

Surface Effects

3.43 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. For example, the nature of the reflecting surface and its roughness may affect peak pressures in the blast wave as well as the formation and growth of the Mach stem. On the whole, these mechanical effects on the blast wave are small and have little influence on overall damage. The results presented later in the present chapter are for approximately ideal (or "nearly-ideal") surface conditions. However, if the surface is dusty or has heat-absorbing properties, the character of the blast wave may be modified by the formation of an auxiliary wave, called a "precursor," that precedes the main incident wave. This phenomenon, which is associated with non-ideal behavior, is discussed more fully in § 3.72 *et seq.*

3.44 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 dusty areas, the blast wave may pick up enough dust to increase the dynamic pressure over the values normally corresponding to the overpressure in an ideal blast wave. There may also be an increase in the velocity of air particles in the blast wave due to precursor action. Consequently, the effect on structures which are damaged mainly by dynamic pressure will be correspondingly increased, especially in regions where the precursor is strong.

Ground Shock from Air Blast

3.45 Another aspect of the blast wave problem is the possible effect of an air burst on underground structures as a result of the transfer of some of the blast wave energy into the ground. A minor oscillation of the surface is experienced and a ground shock is produced. The strength of this shock at any point is determined by the overpressure in the blast wave immediately above it. For large overpressures with long positive-phase duration, the shock will penetrate some distance into the ground, but blast waves which are weaker and of shorter duration are attenuated more rapidly. 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 Chapter VI.

3.46 For high air bursts, where relatively large blast pressures are not expected at ground level, the effects of ground shock induced by air blast will be negligible. But if the overpressure at the surface is large, there may be damage to buried structures. However, even if the structure is strong enough to withstand the effect of the ground shock, the sharp jolt resulting from the impact of the shock wave can cause injury to occupants and damage to loose equipment. Certain public utilities, such as sewer pipes and drains made of relatively rigid materials and located at shallow depths, in areas where the air blast pressure is high, may be damaged by earth movement, but relatively flexible metal pipe will not normally be affected. In the case of a surface burst when cratering occurs, the situation is quite different, as will be seen in Chapter VI.

TECHNICAL ASPECTS OF BLAST WAVE PHENOMENA [4]

Properties of the Blast Wave

3.47 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. The basic relationships among the properties of a blast wave, having a sharp front at which there is a sudden pressure discontinuity, i.e., a true (or ideal) shock front, 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.

3.48 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 overpressure. For a contact surface burst, when there is but a single hemispherical (fused) wave, as stated in § 3.30, 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.

3.49 The shock velocity, U, is expressed by

$$U=c_0\left(1+\frac{\gamma+1}{2\gamma}\cdot\frac{p}{P_0}\right)^{1/2},$$

where c_0 is the ambient speed of sound (ahead of the shock front), p is the peak overpressure (behind the shock front), P_0 is the ambient pressure (ahead of the shock), and γ is the ratio of the specific heats of the medium, i.e , air. If γ is taken as 1.4, which is the value at moderate temperatures, the equation for the shock velocity becomes

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

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

The particle velocity (or peak wind velocity behind the shock front), u, is given by

$$u=\frac{c_0 p}{\gamma P_0}\left(1+\frac{\gamma+1}{2\gamma}\cdot\frac{p}{P_0}\right)^{-1/2}$$

so that for air

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

The density, ρ, of the air behind the shock front is related to the ambient density, ρ_0, by

$$\frac{\rho}{\rho_0}=\frac{2\gamma P_0+(\gamma+1)p}{2\gamma P_0+(\gamma-1)p}$$

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

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 the relation

$$q=\frac{p^2}{2\gamma P_0+(\gamma-1)p}$$

$$=\frac{5}{2}\cdot\frac{p^2}{7P_0+p} \tag{3.49.1}$$

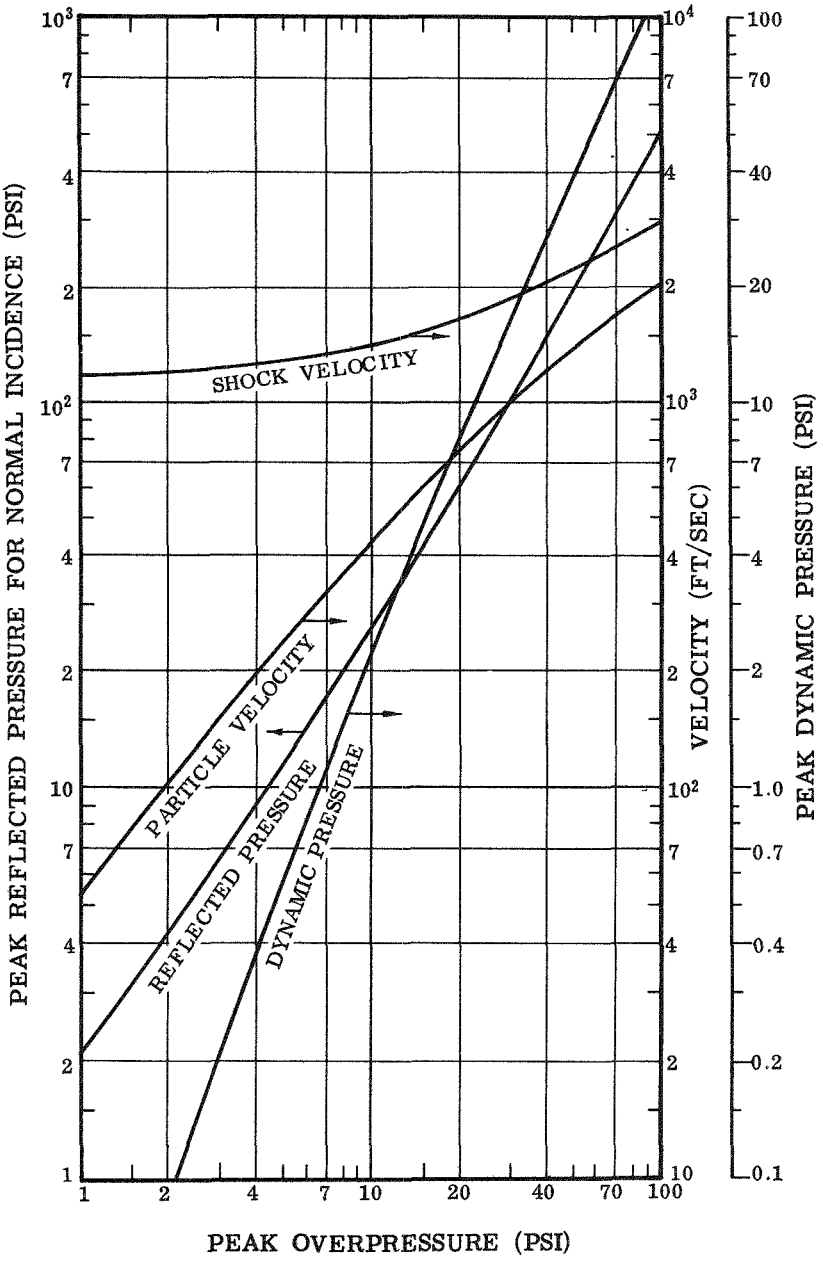
between the peak dynamic pressure in air and the peak overpressure and ambient pressure. The variations of shock velocity, particle (or peak wind) velocity, and peak dynamic pressure with the peak overpressure at sea level, as derived from the foregoing equations, are shown graphically in Fig. 3.49.

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

$$p_r=2p+(\gamma+1)q, \tag{3.50.1}$$

and using equation (3.49.1) for air, this becomes

$$p_r=2p\left(\frac{7P_0+4p}{7P_0+p}\right). \tag{3.50.2}$$



ure 3.49. Relation of ideal blast wave characteristics at the shock front to peak overpressure.

It can be seen from equation (3.50.2) that the value of p_r approaches $8p$ for very large values of the incident overpressure and dynamic pressure (strong shocks), and tends toward $2p$ for small overpressures and small dynamic pressures (weak shocks). It is evident from equation (3.50.1) that the increase in the reflected overpressure above the expected value of twice the incident value, i.e., $2p$, is due to the dynamic (or wind) pressure. The reflected overpressure arises from the change of momentum when the moving air changes direction as a result of striking the surface. A curve showing the variation of the instantaneous (peak) reflected pressure, with the peak incident overpressure, for normal incidence, is included in Fig. 3.49.

3.51 The equations in § 3.49 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. Provided the peak overpressure is low, e.g., about 10 pounds per square inch or less, the variation of the overpressure behind the shock front with time at a given point can be represented to a good approximation by the simple empirical equation

$$p(t)=p\left(1-\frac{t}{t_+}\right)e^{-t/t_+}, \tag{3.51.1}$$

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. In the event of the interaction of the blast wave with a structure, this equation is used to determine the air blast loading as a function of time for low overpressures.

3.52 Strictly speaking, the rate of decay of the normalized overpressure behind the shock front is a function of the peak overpressure. This may be expressed mathematically by a series of exponential equations similar in form to equation (3.51.1). A set of such equations is represented graphically in Fig. 3.52, which shows the "normalized overpressure," i.e., the value relative to the peak overpressure, as a function of the "normalized time," i.e., the time relative to the duration of the positive phase, for various peak overpressure values. These have been developed by the numerical integration of the differential equations of gas motion for a spherical blast wave in air.

3.53 For low values of the peak dynamic pressure, the variation with time behind the shock front may be expressed, with fair accuracy, by an empirical expression similar to equation (3.51.1); thus,

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

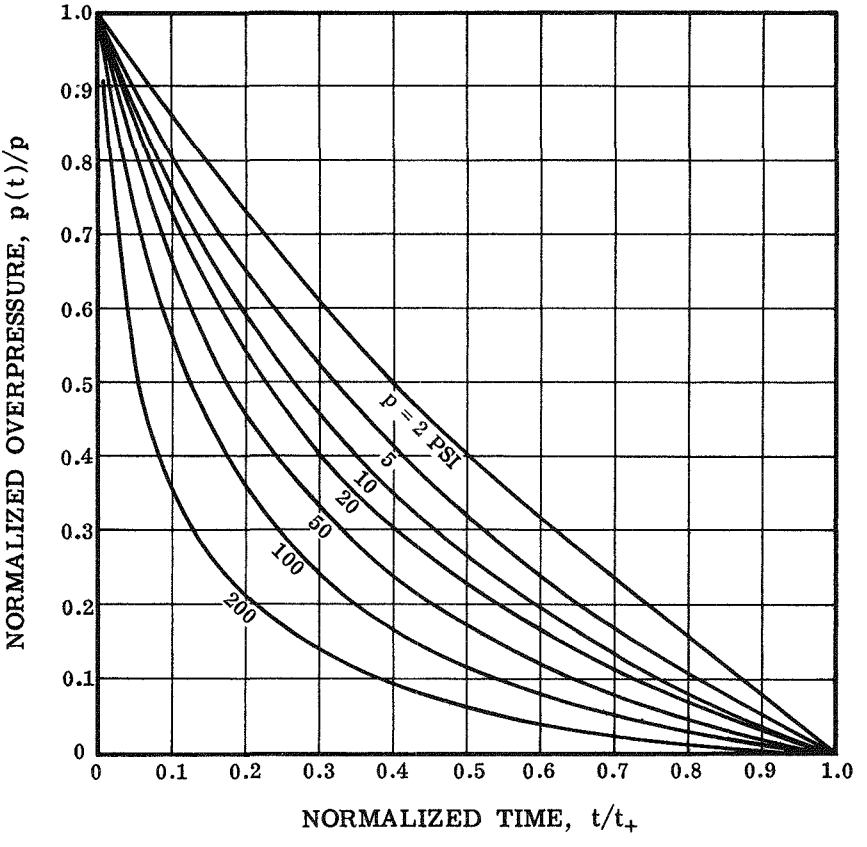


Figure 3.52. Rate of decay of pressure with time for various values of the peak overpressure.

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. However, as is the case with the overpressure, the rate of decrease of the normalized dynamic pressure is dependent on the overpressure. This is shown by the curves in Fig. 3.53 which are for several indicated values of the peak overpressure. The time in this figure is normalized with respect to the duration of the dynamic pressure positive phase which is somewhat longer than that for the overpressure (§§3.16, 3.69).

3.54 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 (per unit

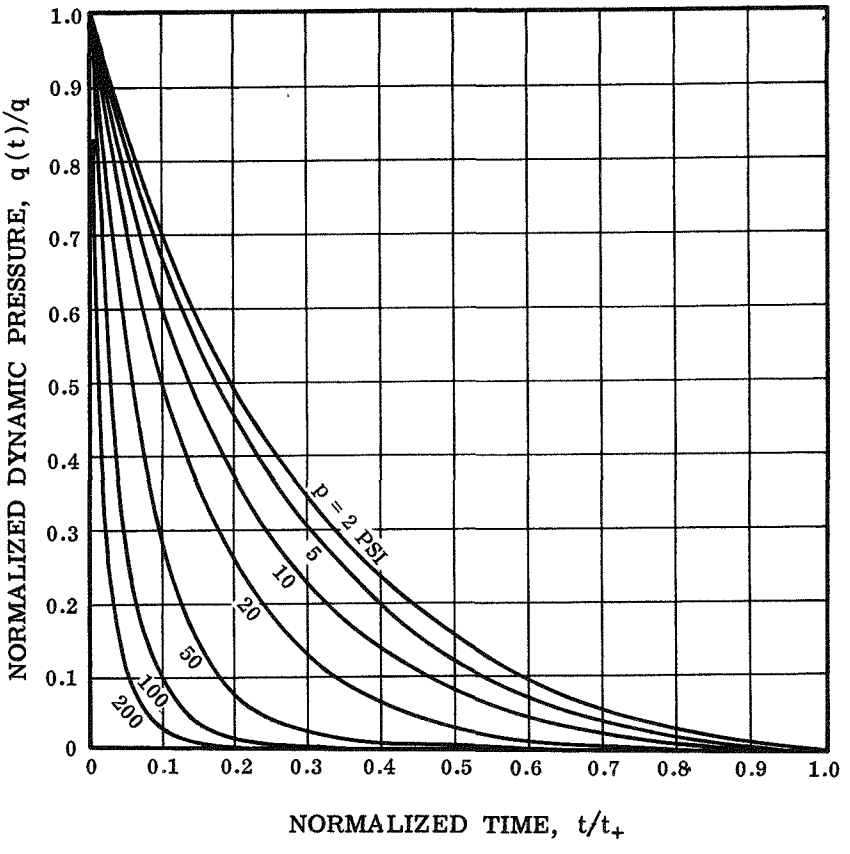


Figure 3.53. Rate of decay of dynamic pressure with time for various values of the peak overpressure.

area) may be defined as the total area under the overpressure-time curve, such as those shown in Fig. 3.52. The positive phase overpressure impulse (per unit area), I, may then be represented mathematically by

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

where $p(t)$ may be expressed analytically for low overpressures by means of equation (3.51.1). The positive phase dynamic impulse can be defined by a similar expression in which $q(t)$ replaces $p(t)$.

Scaling Laws

3.55 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 explosion. Then, with the aid of the scaling laws, the values for an explosion of any specified energy can be readily determined for a particular height of burst.

3.56 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_1 is the distance (or slant range) from a reference explosion of W_1 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

$$\frac{D}{D_1}=\left(\frac{W}{W_1}\right)^{1/3}. \tag{3.56.1}$$

As stated above, the reference explosion is conveniently chosen as having an energy yield of 1 kiloton, so that $W_1=1$. It follows, therefore, from equation (3.56.1) that

$$D=D_1\times W^{1/3}, \tag{3.56.2}$$

where D_1 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 (3.56.2).

3.57 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_1 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

$$d=d_1\times W^{1/3}. \qquad (3.57.1)$$

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

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

$$\frac{t}{t_1}=\frac{d}{d_1}=\left(\frac{W}{W_1}\right)^{1/3} \qquad \text{and} \qquad \frac{I}{I_1}=\frac{d}{d_1}=\left(\frac{W}{W_1}\right)^{1/3},$$

where t_1 represents arrival time or positive phase duration and I_1 is the impulse for a reference explosion of energy W_1, and t and I refer to any explosion of energy W; as before, d_1 and d are distances from ground zero. If W_1 is taken as 1 kiloton, then the various quantities are related as follows:

$$t=t_1\times W^{1/3} \text{ at a distance } d=d_1\times W^{1/3}$$

and

$$I=I_1\times W^{1/3} \text{ at a distance } d=d_1\times W^{1/3}.$$

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

Altitude Corrections

3.59 The data presented (§ 3.49 *et seq*) for the characteristic properties of a blast wave are strictly applicable to a homogeneous atmosphere at sea level. For bursts up to about 5,000 feet altitude this condition holds, at least approximately, and the scaling equations given above may be used. If it is required to determine the air blast parameters at altitudes where the ambient atmospheric conditions are appreciably different from those at sea level, then the correction factor referred to in § 3.41 must be applied.

3.60 The general relationships which take into account the fact 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 in a sea-level atmosphere, are as follows. For the overpressure,

$$p=p_1\frac{P}{P_0},$$

where p is the overpressure at altitude and p_1 is that at sea-level. The corrected value of distance for the new overpressure level is then given by

$$d=d_1W^{1/3}\left(\frac{P_0}{P}\right)^{1/3},$$

and for arrival time or positive phase duration at this new distance by

$$t=t_1W^{1/3}\left(\frac{P_0}{P}\right)^{1/3}\left(\frac{T_0}{T}\right)^{1/2}.$$

For impulse at altitude, the appropriate relationship is

$$I=I_1W^{1/3}\left(\frac{P}{P_0}\right)^{2/3}\left(\frac{T_0}{T}\right)^{1/2}.$$

It should be understood that the foregoing expressions are applicable when the altitude at the observation point (or target) does not differ by more than a few thousand feet from that at the point of burst. If the altitudes differ considerably, the situation is more complicated, as noted in § 3.42.

3.61 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 §§ 3.57 and 3.58, 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 indicated previously, for bursts at elevations within 5,000 feet or so above sea level, the corrections will be small.

3.62 The scaling laws for altitude given above can be used provided the proportion of the explosion energy appearing as blast is approximately the same as at sea level. At heights of burst in excess of 100,000 feet (about 20 miles), however, the percentage of blast energy decreases (§2.119). The mechanism of shock formation apparently changes, too, at these altitudes, so that the scaling laws are no longer

applicable. In general, blast effects on the ground are determined by the energy yield of the explosion and the altitude of burst, both of which affect the amount of energy appearing in the blast wave and its subsequent propagation down through the nonhomogeneous atmosphere. For a 1-megaton weapon exploded 30 miles above the surface, the peak overpressures on the ground are expected to be less than 0.1 pound per square inch, compared with 0.4 pound per square inch at a distance of 30 miles from a burst at a height of 1 mile.

Standard Curves and Calculations of Blast Wave Properties

3.63 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 "height of burst" 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, and positive phase duration with distance from ground zero for various heights of burst over a nearly-ideal surface. Similar curves may also be constructed for other blast wave parameters, but the ones presented here are generally considered to be the most useful. They apply to urban targets as well as to a wide variety of other approximately ideal situations.

3.64 From the curves given below 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 again be mentioned that the data represent the behavior of the blast wave under nearly-ideal 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 IV for the determination of blast damage to be expected under various conditions.

3.65 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. 3.65 is provided; this gives the values of cube roots ($n=0.33$) required in the application of the scaling laws.[5]

3.66 The variations of peak overpressure and dynamic pressure with distance from ground zero for a 1-kiloton TNT equivalent con-

[5] Values of $W^{0.3}$, i.e., for $n=0.3$, are also included because they are used in Chapter VI.

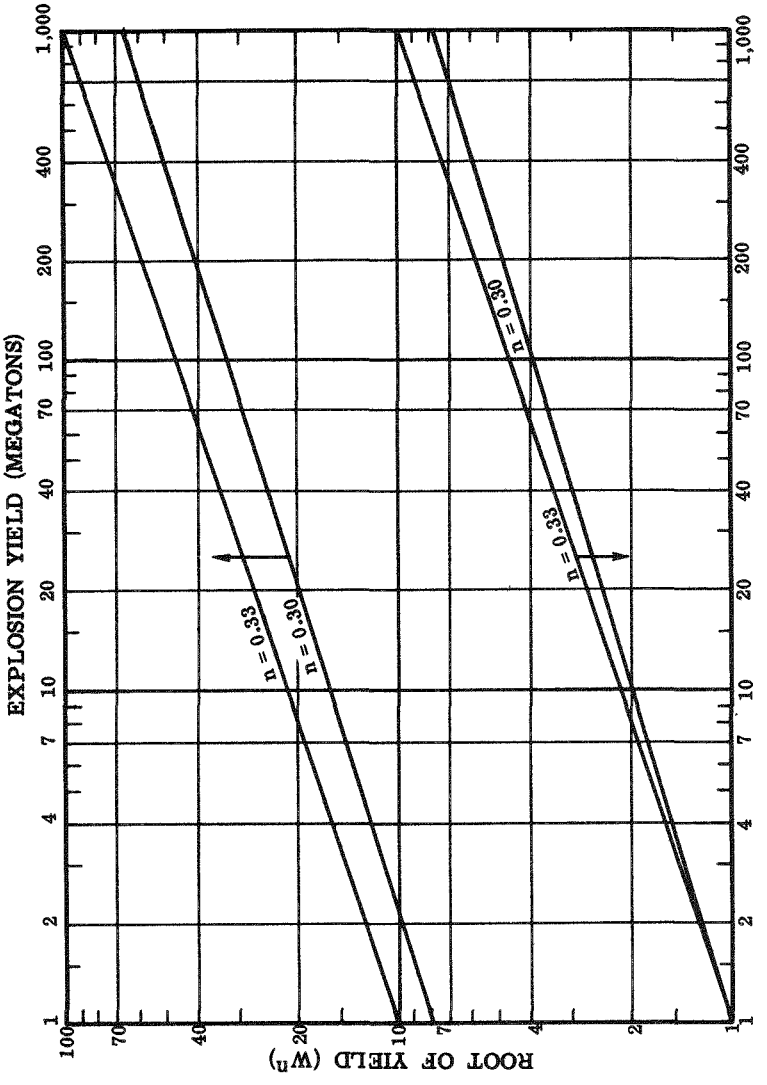


Figure 3.65. Values of $W^{0.33}$ ($W^{1/3}$) and $W^{0.3}$ for use in scaling calculations.

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tact surface burst in a standard sea-level atmosphere are represented by the full curves in Fig. 3.66. The approximate range of the overpressure which may be expected under varying atmospheric conditions is indicated by the broken curves; the pressures will be higher than average if there is an inversion, i.e., air temperature increases with height above the ground, but they will be lower than average in an unstable atmosphere with no inversion, i.e., normal lapse rate.

3.67 The curves in Fig. 3.67a (high-pressure range) and Fig. 3.67b (low-pressure range) show the variation of peak overpressure, for a 1-kiloton air burst, with distance from ground zero as a function of the height of burst. The presence of a pronounced "knee" in the curves in the Mach region means that, for any given overpressure, there is an optimum burst height that maximizes the distance from ground zero at which this overpressure is experienced. The corresponding data for any other explosion energy yield may be obtained by use of the scaling laws. It will be noted that values of the ground distance for specific levels of peak overpressure in Fig. 3.66 may be derived from Figs. 3.67a and 3.67b by assuming the burst height to be zero, i.e., corresponding to a contact surface burst. Similar curves can be obtained for any height of burst by drawing a horizontal line across the figure at the desired burst height and reading off ground distances for specific values of the blast wave parameter.

3.68 The family of curves in Fig. 3.68 indicate the variation of the horizontal component of the peak dynamic pressure along the surface with distance from ground zero and height of burst for a 1-kiloton air burst in a standard sea-level atmosphere for nearly-ideal surface conditions. By assuming a height of burst of zero, the peak dynamic pressures in Fig. 3.66 for a surface burst are obtained.

3.69. The dependence of the positive phase duration of the overpressure and of the dynamic pressure on the distance from ground zero and on the height of burst is shown by the curves in Fig. 3.69; the values for the dynamic pressure duration are in parentheses. As in the other cases, the results apply to a 1-kiloton explosion in a standard sea-level atmosphere for a nearly-ideal surface. It will be noted, as mentioned earlier, that for a given detonation and location, the duration of the positive phase of the dynamic pressure is longer than that of the overpressure.

3.70 The curves in Figs. 3.70 a and b give the time of arrival of the shock front on the ground at various distances from ground zero as a function of the height of burst for a 1-kiloton explosion under the usual conditions of a sea-level atmosphere and a nearly-ideal surface.

3.71 The peak overpressures in Figs. 3.66, 3.67 a and b are those that would be observed at or near the surface of the ground after reflection has taken place. These peak values are considered to be the side-on overpressures (§ 4.07, footnote) to be used in determining target loading and response. However, further reflection is possible at the front face of a structure when it is struck by the blast wave. The magnitude of the reflected pressure $p_{r(\alpha)}$ depends on the side-on pressure p and the angle, α, between blast wave front and the struck surface (Fig. 3.71a). The values of the ratio $p_{r(\alpha)}/p$ as a function of angle of incidence for various indicated side-on pressures are given in Fig. 3.71b. It is seen that for normal incidence, that is when $\alpha=0°$, the ratio $p_{r(\alpha)}/p$ is approximately 2 at low overpressures and increases with the overpressure (§ 3.50). The curves in Fig. 3.71b are particularly applicable in the Mach region where an essentially vertical shock front moving radially strikes a reflecting surface such as the front wall of a structure (see Fig. 4.08).

The Precursor

3.72 The foregoing results have referred to blast wave conditions which are ideal or nearly ideal, so that the Rankine-Hugoniot equations are applicable (§ 3.47). In certain circumstances, however, the physical character of the surface may be such as to produce a non-ideal situation. As a result of intense thermal radiation from the nuclear explosion impinging on a heat-absorbing surface, such as desert, coral, or asphalt, a hot layer of air, referred to as a "thermal layer," is produced. The thermal layer, which often includes smoke, dust, and other particulate matter, forms before the arrival of the blast wave from an air burst, and interaction of the wave with the heated layer may affect the reflection process to a considerable extent. For appropriate combinations of explosion energy yield, low burst height, and heat-absorbing surfaces, an auxiliary blast wave, called a "precursor," will form and move ahead of the main incident wave for a limited distance. Severe modifications of the usual blast wave characteristics may occur within the precursor region. In particular, the pressure at the wave front increases more gradually but to a lower peak value than in a true shock wave, and the decay with distance is abnormal. Furthermore, the normal Rankine-Hugoniot relations at the shock front no longer apply. For these reasons, the precursor region is said to be non-ideal.

3.73 It should be noted that precursor formation is not to be expected over non-dusty and heat-reflecting surfaces, such as concrete, snow, ice, or water. Furthermore, thermal effects on the blast wave appear to be small for surface bursts and for high air bursts, regardless of yield and the type of surface. Consequently, it is believed that in many situations, especially in urban areas, nearly-ideal blast wave conditions would prevail.

(Text continued on page 148.)

The curves in Fig. 3.66 show the variation of peak overpressure and peak dynamic pressure with distance for a 1 KT surface burst in a standard sea-level atmosphere.

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

$$d = d_1 \times W^{1/3},$$

where, for a given peak overpressure or dynamic pressure, d_1 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. 3.65 the cube root of 1000 is 10. From Fig. 3.66, a peak overpressure of 2 psi occurs at a distance of 2,500 feet from a 1 KT surface burst. Therefore, for a 1 MT surface burst,

$$d = d_1 \times W^{1/3} = 2{,}500 \times 10 = 25{,}000 \text{ feet} = 4.7 \text{ miles.} \quad \textit{Answer.}$$

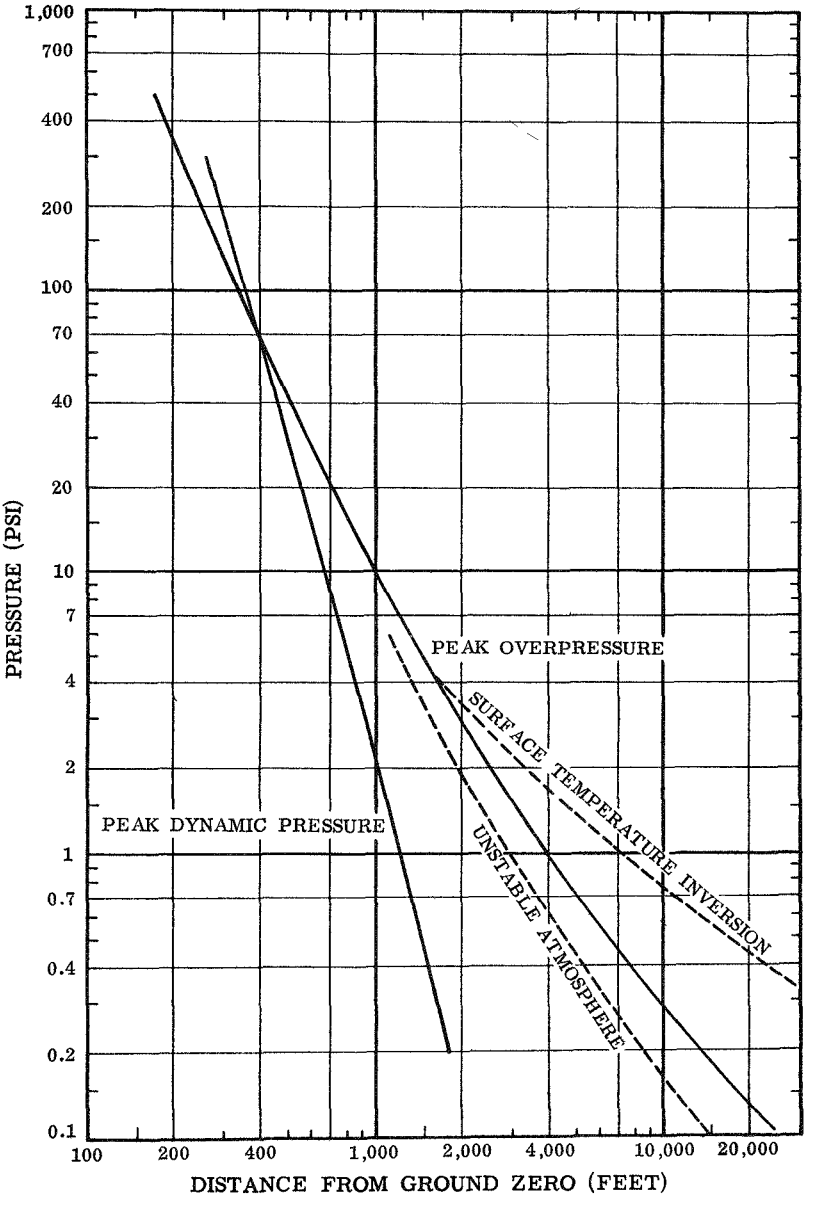

Figure 3.66. Peak overpressure and peak dynamic pressure for 1-kiloton surface burst.

The curves in Fig. 3.67a show peak overpressures on the ground in the high-pressure range as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The dashed line separates the regular reflection region from the Mach region and indicates where the triple point is formed (§ 3.20 *et seq.*). The data are considered appropriate to nearly-ideal target conditions. Surface influences are discussed in §§ 3.43, 3.44, and 3.72.

Scaling. The height of burst and the distance from ground zero to which a given peak overpressure extends scale as the cube root of the yield, i.e.,

$$\frac{d}{d_1}=\frac{h}{h_1}=W^{1/3},$$

where, for a given peak overpressure, d_1 and h_1 are distance from ground zero and height of burst for 1 KT, and d and h are the corresponding distance and height of burst for W KT.

Example

Given: An 80 KT detonation at 2,580 feet.

Find: The distance to which 50 psi extends.

Solution: The corresponding height of burst for 1 KT is

$$h_1=\frac{h}{W^{1/3}}=\frac{2{,}580}{(80)^{1/3}}=600 \text{ feet.}$$

From Fig. 3.67a, an overpressure of 50 psi extends to 215 feet for a 600-foot burst height for a 1 KT weapon. The corresponding distance for 80 KT is

$$d=d_1W^{1/3}=215\times(80)^{1/3}=925 \text{ feet.} \quad \textit{Answer}$$

The procedure to be used for calculating the peak overpressure at a specified distance is given on the page facing Fig. 3.68.

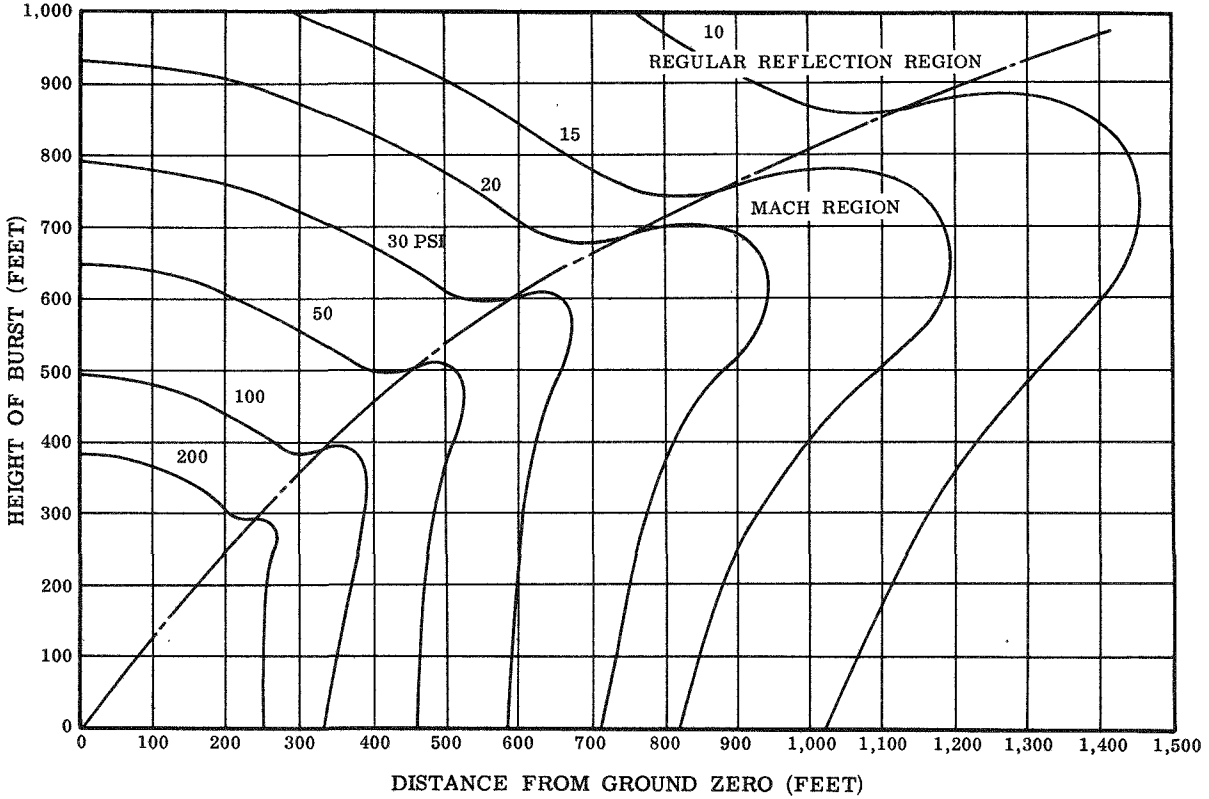

Figure 3.67a. Peak overpressures on the ground for a 1-kiloton burst (high-pressure range).

The curves in Fig. 3.67b show peak overpressures on the ground in the low-pressure range as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The broken line separates the regular reflection region from the Mach region and indicates where the triple point is formed (§ 3.20 *et seq.*). The data are considered appropriate for nearly-ideal target conditions. Surface influences are discussed in §§ 3.43, 3.44, and 3.72.

Scaling. The height of burst and the distance from ground zero to which a given peak overpressure extends scale as the cube root of the yield, i.e.,

$$\frac{d}{d_1}=\frac{h}{h_1}=W^{1/3},$$

where, for a given peak overpressure, d_1 and h_1 are the distance from ground zero and height of burst for 1 KT, and d and h are the corresponding distance and height of burst for W KT.

Example

Given: An 80 KT detonation at 2,580 feet.
Find: The distance to which 4 psi extends.
Solution: The corresponding height of burst for 1 KT is

$$h_1=\frac{h}{W^{1/3}}=\frac{2{,}580}{(80)^{1/3}}=600 \text{ feet.}$$

From Fig. 3.67b, 4 psi extends to 2,300 feet for a 600-foot burst height for a 1 KT weapon. The corresponding distance for 80 KT is

$$d=d_1W^{1/3}=2{,}300\times(80)^{1/3}=9{,}900 \text{ feet.} \quad \textit{Answer.}$$

The procedure to be used for calculating the peak overpressure at a specified distance is given on the page facing Fig. 3.68.

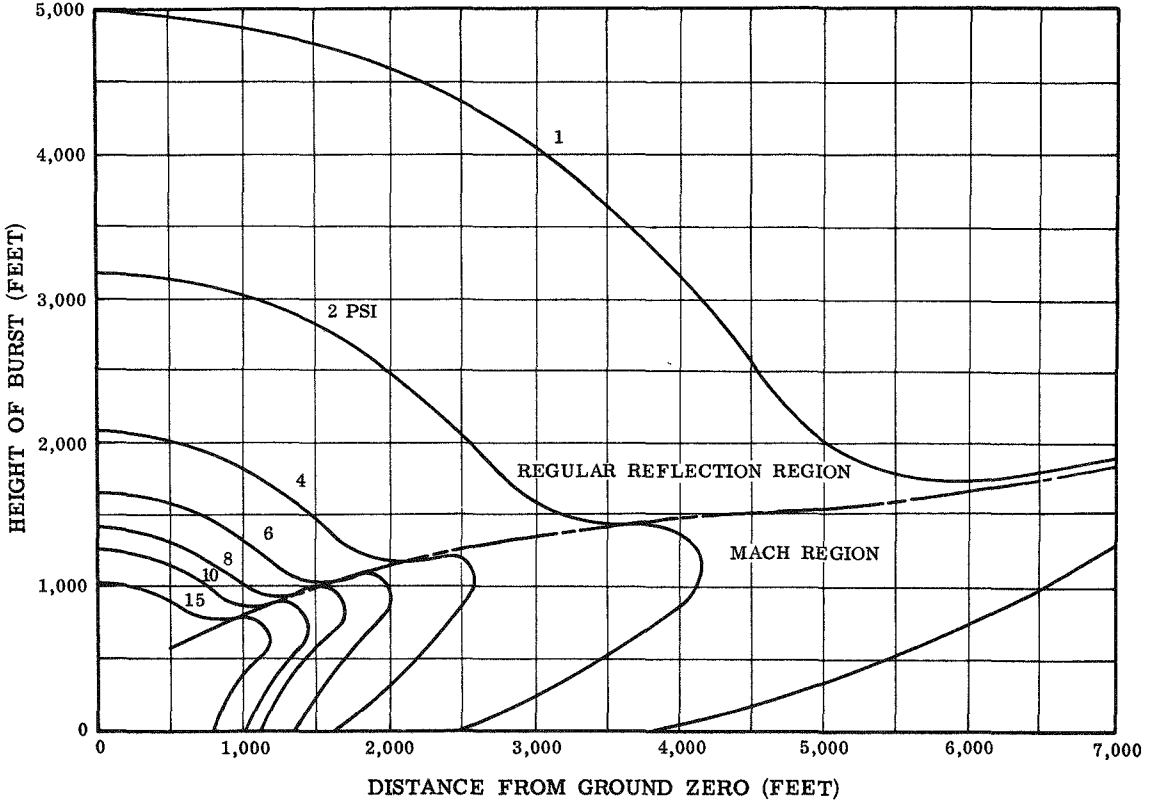

Figure 3.67b. Peak overpressures on the ground for 1-kiloton burst (low-pressure range).

The curves in Fig. 3.68 show the horizontal component of peak dynamic pressure on the ground as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The data are considered appropriate for nearly-ideal target conditions. Surface influences are discussed in §§ 3.43, 3.44, and 3.72.

Scaling. The height of burst and range to which a given peak dynamic pressure value extends scale as the cube root of the yield, i.e.,

$$\frac{d}{d_1}=\frac{h}{h_1}=W^{1/3},$$

where, for a given peak dynamic pressure, h_1 and d_1 are the height of burst and distance from ground zero for 1 KT, and h and d are the corresponding height of burst and distance for W KT.

Example

Given: A 160 KT burst at a height of 3,000 feet.

Find: The horizontal component of peak dynamic pressure on the ground at a range of 6,000 feet.

Solution: The corresponding height of burst for 1 KT is

$$h_1=\frac{h}{W^{1/3}}=\frac{3{,}000}{(160)^{1/3}}=550 \text{ feet.}$$

The corresponding range for 1 KT is

$$d_1=\frac{d}{W^{1/3}}=\frac{6{,}000}{(160)^{1/3}}=1{,}110 \text{ feet.}$$

From Fig. 3.68, at a range of 1,110 feet and a burst height of 550 feet, the horizontal component of the peak dynamic pressure is approximately 3 psi. *Answer.*

The procedure to be used for calculating the distance to which a given peak dynamic pressure extends is given on the pages facing Figs. 3.67 a and b.

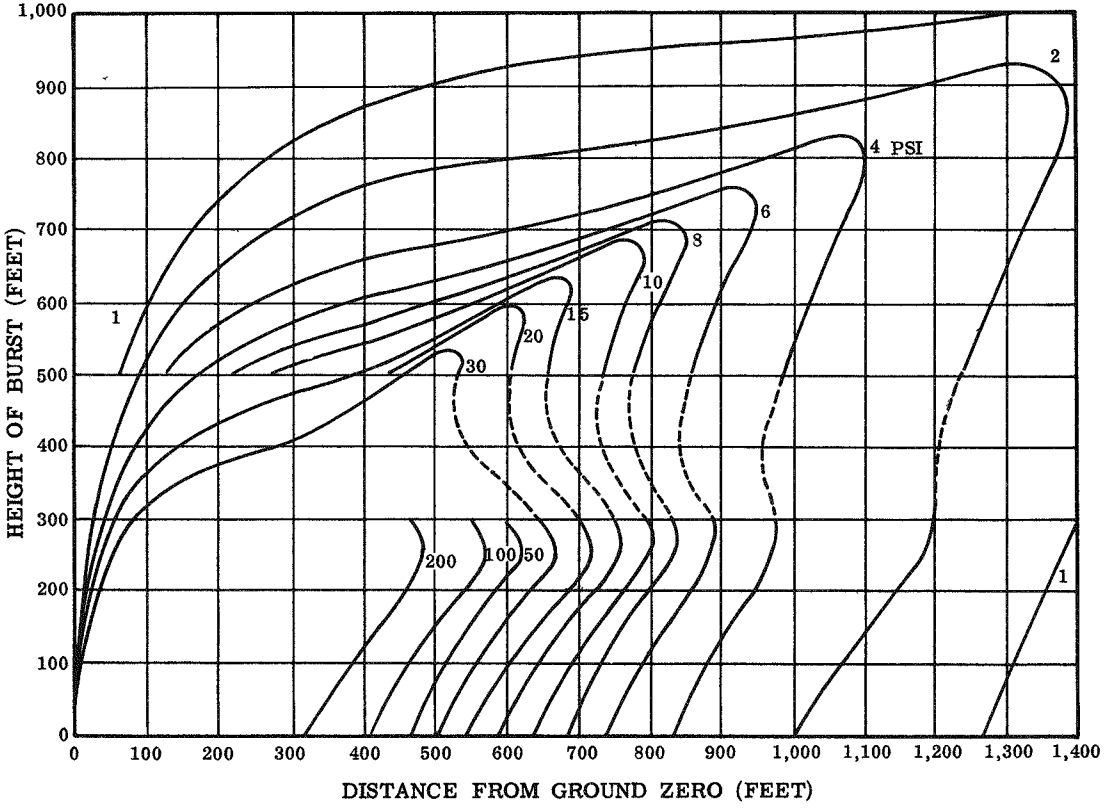

Figure 3.68. Horizontal component of peak dynamic pressure for 1-kiloton burst.

The curves in Fig. 3.69 show the duration on the ground of the positive phase of the overpressure and of the dynamic pressure (in parentheses) as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The curves are considered appropriate for nearly-ideal surface conditions.

Scaling. The required relationships are

$$\frac{d}{d_1}=\frac{h}{h_1}=\frac{t}{t_1}=W^{1/3},$$

where d_1, h_1, and t_1 are the distance from ground zero, the height of burst, and duration, respectively, for 1 KT; and d, h, and t are the corresponding distance, height of burst, and duration for W KT.

Example

Given: A 160 KT explosion at a height of 3,000 feet.

Find: The positive phase duration on the ground of (*a*) the overpressure, (*b*) the dynamic pressure at 4,000 feet.

Solution: The corresponding height of burst for 1 KT is

$$h_1=\frac{h}{W^{1/3}}=\frac{3{,}000}{(160)^{1/3}}=550 \text{ feet},$$

and the corresponding distance from ground zero is

$$d_1=\frac{d}{W^{1/3}}=\frac{4{,}000}{(160)^{1/3}}=740 \text{ feet}.$$

(*a*) From Fig. 3.69, the positive phase duration of the overpressure for 1 KT at 740 feet from ground zero and a burst height of 550 feet is 0.18 second. The corresponding duration of the overpressure positive phase for 160 KT is, therefore,

$$t=t_1W^{1/3}=0.18\times(160)^{1/3}=1.0 \text{ second.} \quad \textit{Answer}$$

(*b*) From Fig. 3.69, the positive phase duration of the dynamic pressure for 1 KT at 740 feet from ground zero and a burst height of 550 feet is 0.34 second. The corresponding duration of the dynamic pressure positive phase for 160 KT is, therefore,

$$t=t_1W^{1/3}=0.34\times(160)^{1/3}=1.8 \text{ second.} \quad \textit{Answer}$$

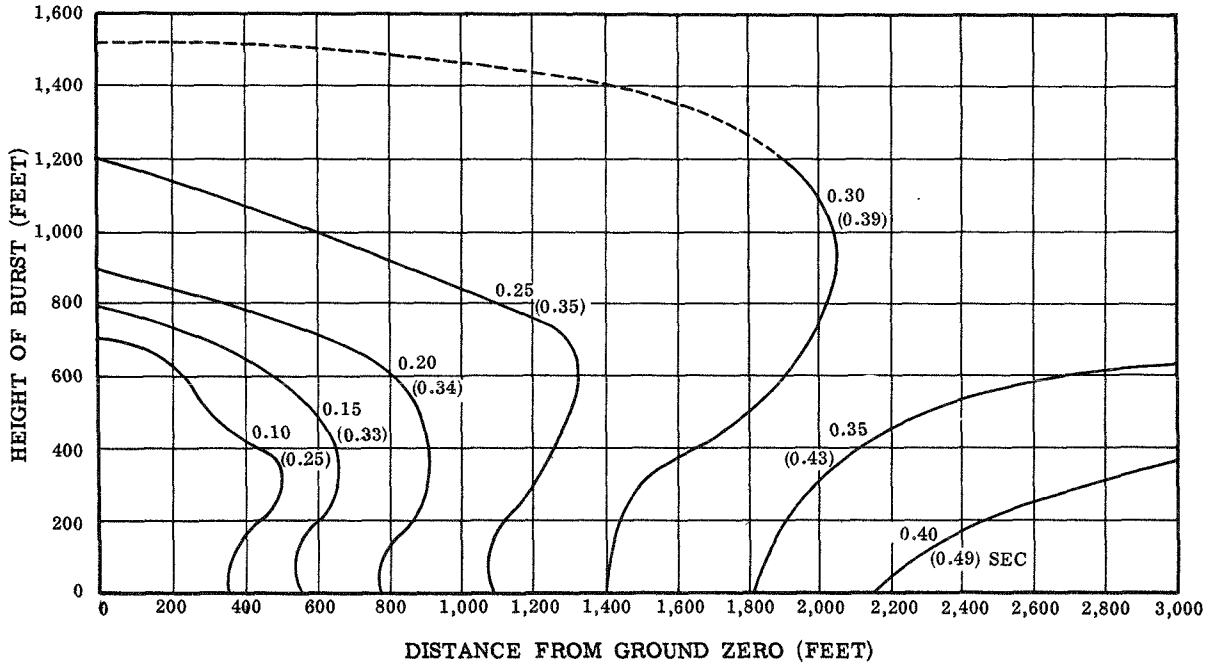

Figure 3.69. Positive phase duration on the ground of overpressure and dynamic pressure (in parentheses) for 1-kiloton burst.

The curves in Figs. 3.70 a and b give the time of arrival of the blast wave on the ground as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The curves are considered appropriate for nearly-ideal surface conditions.

Scaling. The required relationships are

$$\frac{d}{d_1}=\frac{h}{h_1}=\frac{t}{t_1}=W^{1/3},$$

where d_1, h_1, and t_1 are the distance from ground zero, height of burst, and time of arrival, respectively, for 1 KT; and d, h, and t are the corresponding distance, height of burst, and time for W KT.

Example

Given: A 1 MT explosion at a height of 5,000 feet.

Find: The time of arrival of the blast wave at a distance of 10 miles from ground zero.

Solution: The corresponding burst height for 1 KT is

$$h_1=\frac{h}{W^{1/3}}=\frac{5{,}000}{(1{,}000)^{1/3}}=500 \text{ feet.}$$

The corresponding distance from ground zero for 1 KT is

$$d_1=\frac{d}{W^{1/3}}=\frac{5{,}280\times 10}{(1{,}000)^{1/3}}=5{,}280 \text{ feet.}$$

From Fig. 3.70b, at a height of burst of 500 feet and a distance of 5,280 feet from ground zero, the arrival time is 4.0 seconds for 1 KT. The corresponding arrival time for 1 MT is

$$t=t_1W^{1/3}=4.0\times(1{,}000)^{1/3}=40 \text{ seconds.} \quad \textit{Answer}$$

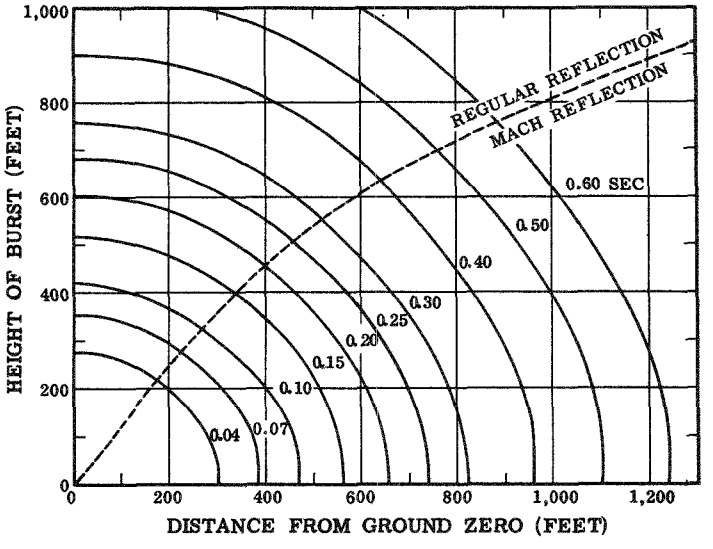

Figure 3.70a. Arrival times on the ground of blast wave for 1-kiloton burst (early times).

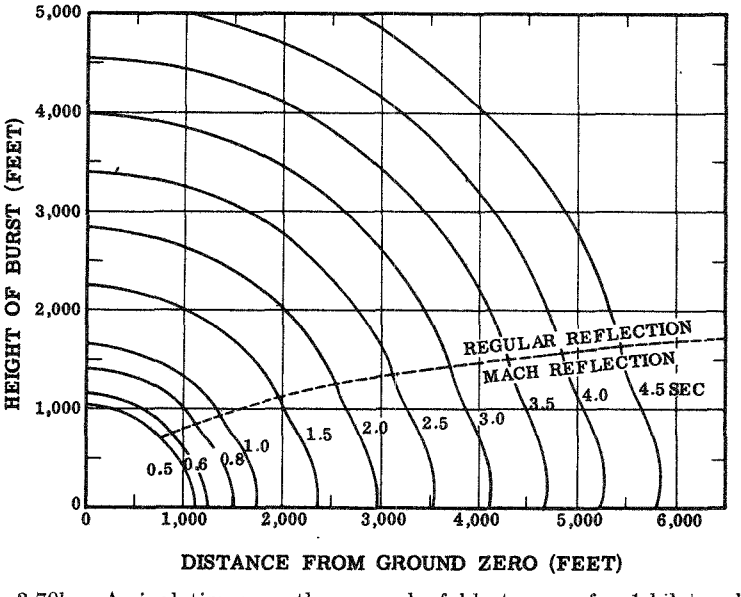

Figure 3.70b. Arrival times on the ground of blast wave for 1-kiloton burst (late times).

The reflected overpressure ratio $p_{r(\alpha)}/p$ is plotted in Fig. 3.71b as a function of the angle of incidence of the blast wave front for various values of the peak (side-on) overpressure. The curves apply to a wave front striking a reflecting surface, such as a wall of a structure.

$p_{r(\alpha)}$ = reflected blast wave overpressure for any given angle of incidence (psi).
p = initial peak incident overpressure (psi)
α = angle between the blast wave front and the reflecting surface (degrees)

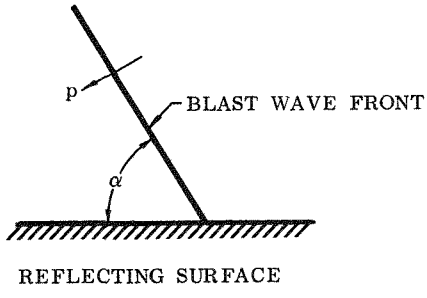

Figure 3.71a. Angle of incidence (α) of blast wave with reflecting surface.

Example

Given: A shock wave of 30 psi initial peak overpressure striking a surface at an angle of 35°.

Find: The reflected shock wave overpressure.

Solution: From Fig. 3.71b the reflected overpressure ratio, $p_{r(\alpha)}/p$, for 30 psi and an angle of incidence of 35° is 3.2; hence, $p_{r(35°)} = 3.2p = 3.2 \times 30 = 96$ psi. *Answer*

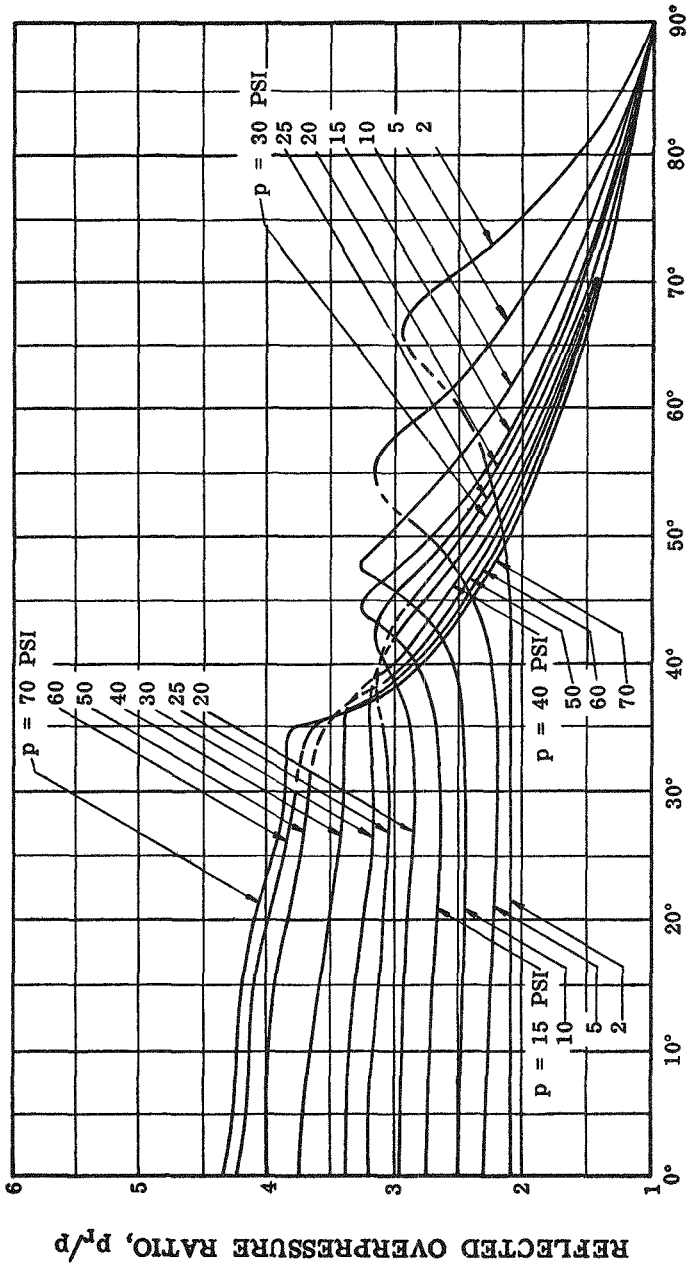

Figure 3.71b. Reflected overpressure ratio as function of angle of incidence for various side-on overpressures.

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(Text continued from page 134.)

3.74 For this reason, the height of burst curves for various air blast parameters presented earlier apply to nearly-ideal surface conditions. These curves are considered to be the most representative for general use. However, it should be noted that empirical data obtained in the precursor region for low air bursts at the Nevada Test Site may reflect the non-ideal behavior of the blast wave with regard to both phenomena and damage. Under such circumstances the peak values of overpressure and dynamic pressure do not obey equation (3.49.1). In fact, the overpressure wave form may be irregular and show a slow rise to a peak value somewhat less than that expected for nearly-ideal conditions. Consequently, the peak value of reflected pressure on the front face of an object struck by the blast wave may not exceed the peak value of the incident pressure by more than a factor of two instead of the much higher theoretical factor for an ideal shock front as given by equation (3.50.2). Similarly, the dynamic pressure wave form may also be irregular, but the peak value may be several times that computed from the measured peak overpressure by the Rankine-Hugoniot relations for the reasons given in §3.44. Damage to and displacement of targets which are affected by the dynamic pressure may thus be considerably greater in the non-ideal precursor region for a given value of peak overpressure than under nearly-ideal conditions.

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CHAPTER IV

AIR BLAST LOADING AND TARGET RESPONSE

INTERACTION OF BLAST WAVE WITH STRUCTURES

Introduction

4.01 The phenomena associated with a blast wave in air have been treated in the preceding chapter. On the basis of the information developed, consideration will now be given to the interaction of the air blast with a target and the factors affecting the response of the target. Criteria of damage to targets of different types will be discussed and relationships given between the damage and the distances over which such damage may be expected from nuclear weapons of various yields. In addition, quantitative methods of computing structural loads and their duration will be outlined.

4.02 The general conclusions concerning the expected effects of nuclear explosions on various targets are summarized in the form of nomographs (Figs. 4.58 a and b). 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 given here are considered to be the most representative for the average situations that might be encountered in actual target complexes.

Air Blast Loading

4.03 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. Furthermore, 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 this type is, of course, greatly dependent upon circumstances.

4.04 Direct damage to structures attributable 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.

4.05 For an air burst, the direction of propagation of the incident blast wave will be towards the ground at ground zero. In the regular reflection region, where the direction of propagation of the blast wave is not parallel to the horizontal axis of the structure, the forces exerted upon structures will also have a considerable downward component (prior to passage of the reflected wave) due to the reflected pressure build-up on the horizontal surfaces. Consequently, in addition to the horizontal loading, as in the Mach region (§ 3.24), there will also be initially an appreciable downward force. This tends to cause crushing toward the ground, e.g., dished-in roofs, in addition to distortion due to translational motion.

4.06 The discussion of air blast loading for aboveground structures in the Mach region given in the sections which follow is based on the assumption that the situation is essentially ideal and that the blast wave behaves normally, in accordance with theoretical considerations. For convenience, the treatment will be somewhat arbitrarily divided into two parts: one deals with "diffraction loading," which is determined mainly by the peak overpressure in the blast wave, and the other with "drag loading," in which the dynamic pressure is the significant property. However, it is important to remember that all structures are subjected simultaneously to both types of loading, since the overpressure and dynamic pressure cannot be separated, although for certain structures one may be more important than the other.

Diffraction Loading

4.07 When the front of an air blast 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 wave front. The actual pressure attained is determined by various factors, such as the peak overpressure of the incident blast wave and the angle between the direction of motion of the wave and the face of the building (§3.71). As the wave front moves forward, the reflected overpressure on the face drops rapidly to that produced by the blast wave without reflection,[1] plus an added drag force due to the wind (dynamic) pressure. 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 the side walls and the roof. The front wall, however, is still subjected to wind pressure, although the back wall is shielded from it.

4.08 The developments described above are illustrated in a simplified form in Figs. 4.08 a, b, c, d, e;[2] this shows, in plan, successive stages of a building without openings which is being struck by an air blast wave moving in a horizontal direction. In Fig. 4.08a the wave front is seen approaching the structure with the direction of motion perpendicular to the face of the building exposed to the blast. In Fig. 4.08b the wave has just reached its front face, producing a high reflected overpressure. In Fig. 4.08c the blast wave has proceeded about halfway along the building and in Fig. 4.08d the wave has passed the back side of the structure. The pressure on the front face has dropped to some extent while the pressure is building up on the back face as the blast wave diffracts around the structure. Finally, when, the wave front has passed, as in Fig. 4.08e, approximately equal air pressures are exerted on the side walls and roof of the structure. A pressure difference between front and back faces, due to the wind forces, will persist, however, during the whole positive phase of the blast wave. 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. 4.08 f, g, h, and i).

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[1] 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.

[2] A more detailed treatment is given later in this chapter.

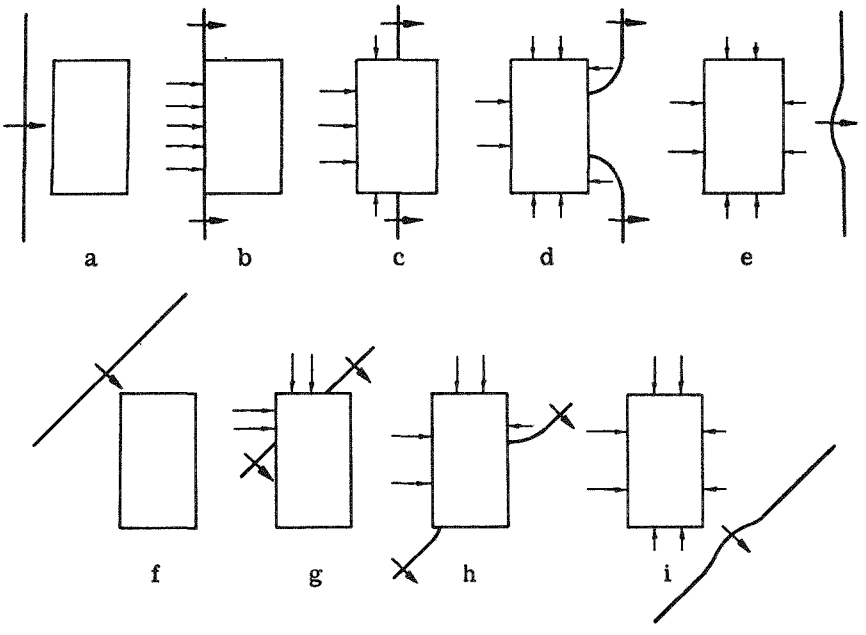

Figure 4.08. Stages in the diffraction of a blast wave by a structure without openings (plan view).

4.09 The pressure differential between the front and back faces will have its maximum value when the blast wave has not yet completely surrounded the structure. In this case, as well as that shown in Figs. 4.08 b through d, such a pressure differential will produce a lateral (or translational) force tending to cause the structure to deflect and thus move bodily, usually 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 also important in determining the response, as will be seen later.

4.10 When the blast wave has engulfed the structure (Fig. 4.08e or 4.08i), the pressure differential is small, and the loading is due almost entirely to the drag pressure[3] exerted on the front face. The actual pressures on all faces of the structure are in excess of the ambient atmospheric pressure and will remain so, although decreasing

[3] The drag pressure is the product of the dynamic pressure and the drag coefficient (§4.69).

steadily, until the positive phase of the blast wave has ended. Hence, the diffraction loading on a structure without openings is eventually replaced by an inwardly directed pressure, i.e., a compression or squeezing action, combined with the dynamic pressure of the blast wave. In a structure with no openings, the loading will cease only when the overpressure drops to zero.

4.11 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 assumed so far, the duration of the diffraction loading will be very roughly the time required for the wave front to move from the front to the back of the building, although wind loading will continue for a longer period. 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 about one-tenth of a second, but the squeezing and the wind loading will continue for a longer period. For thin structures, e.g., telegraph or utility poles and smokestacks, the diffraction period is so short that the corresponding loading is negligible.

4.12 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. Furthermore, 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

4.13 During the whole of the overpressure positive phase duration (and for a short time thereafter) a structure will be subjected to the dynamic pressure loading or drag loading caused by the transient winds behind the blast wave front. In the case of non-ideal (precursor) conditions, a dynamic pressure loading of varying strength may exist prior to the maximum overpressure (diffraction) loading. 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.

4.14 Except at high blast pressures, 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 only for a small fraction of a second, even for a large structure, as seen above.

4.15 It is the effect of the duration of the 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 weapon will prove to be more destructive than a conventional one, especially for buildings which respond to drag loading. This is because the blast wave is of much shorter duration for a high-explosive weapon, e.g., a few hundredths of a second. As a consequence of the increased length of the positive phase of the blast wave from weapons of high energy yield, such devices cause more destruction than might be expected from the peak overpressures alone.

Structural Characteristics and Air Blast Loading

4.16 In analyzing the response to blast loading, either quantitatively, by the use of mathematical procedures, 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.

4.17 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.

4.18 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 Fig. 3.71b).

4.19 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 blast 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.

4.20 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 projected area, the loading on a telephone pole or a smokestack will be less than on an I-beam.

4.21 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.

4.22 For structures which are fundamentally of the drag type, or which rapidly become so because of loss of siding, 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 the peak dynamic pressure. Consequently, for a given peak dynamic pressure, an explosion 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

4.23 The range (or area) within 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 was shown in Chapter III, there are scaling rules which relate the distance at which a given peak overpressure is attained in the blast wave to the weapon yield. 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 the yield on the range (or area) within which a particular type of damage is sustained can be readily calculated.

4.24 Assuming equivalent heights of burst, in the sense discussed in §3.27 (see also §3.57), 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.

4.25 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 the peak dynamic pressure. The greater the energy of the weapon, the farther will be the distance from the explosion at which the peak dynamic pressure has a specific value and the longer will be the duration of the positive phase. Since there is increased drag damage with increased duration at a given pressure, the same damage will extend to lower dynamic pres-

sure levels. 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 the energy of the explosion, 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

4.26 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.

4.27 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 column connections, the redundancy of supports, and the amount of diagonal bracing in the structure. Some of these factors will be examined subsequently. If the building does not have the same strength along both axes, then orientation with respect to the burst should also be considered.

4.28 The strongest structures are heavily framed steel and reinforced-concrete buildings, particularly those designed to be earthquake resistant, whereas the weakest are probably certain shed-type industrial structures having light frames and long beam spans. Some kinds of lightly-built and open-frame construction also fall into the latter category, but well-constructed frame houses have greater strength than these sheds.

4.29 The resistance to blast of structures having load-bearing, masonry walls (brick or concrete block), 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 their strength.

Structural Design

4.30 Except for those regions in which fairly strong earthquake shocks may be expected, most structures in the United States are designed to withstand only the lateral loadings produced by 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.

4.31 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, often 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

4.32 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 suddenly after passing their elastic (yield) loading.

4.33 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, some deformation is permanent, but there is no failure. Only when the stress reaches the "ultimate strength" does failure, i.e., breakage, occur.

4.34 Ideally, a structure which is to suffer little damage from blast should have as much ductility 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. One of the problems 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.

4.35 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. Structural steel has the further advantage of a higher yield point (or elastic limit) under dynamic than under static loading, the increase being roughly 25 to 30 percent for some steels.

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

DESCRIPTION OF DAMAGE FROM AIR BLAST

Damage Classification

4.37 For the purposes of the subsequent discussion, damage to structures or objects has been divided into three categories as follows:

Severe Damage

A degree of damage that precludes further use of the structure or object for its intended purpose without essentially complete reconstruction. For a structure or building, collapse is generally implied.

Moderate Damage

A degree of damage to principal members that precludes effective use of the structure or object for its intended purpose unless major repairs are made.

Slight Damage

A degree of damage to buildings resulting in broken windows, slight damage to roofing and siding, blowing down of light interior partitions, and slight cracking of curtain walls in buildings. For other structures, the nature of light damage is described in Tables 4.38a and 4.38b.

Damage to Structures Above Ground

4.38 The detailed nature of the damage in the severe, moderate, and light categories, as defined above, to various structures are given in Tables 4.38a and 4.38b. For convenience, the information is divided into two groups. Table 4.38a is concerned with structures of the type that are primarily affected by the blast wave during the diffraction phase, so that the peak overpressure is the factor which largely determines the damage. In Table 4.38b are the data for structures which are primarily affected by drag (or wind) loading, so that both the peak dynamic pressure and the duration of the positive phase of the blast wave are important. The damage ranges for structures of various types from weapons of different yields are given later in Fig. 4.58a.

4.39 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 4.39. 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 side-on blast overpressures for panels that face ground zero. For panels that are oriented so that there are no reflected pressures thereon, the side-on pressures must be doubled.

TABLE 4.38a

DAMAGE TO TYPES OF STRUCTURES PRIMARILY AFFECTED BY BLAST WAVE OVERPRESSURE DURING THE DIFFRACTION PHASE

Description of structure	Description of damage		
	Severe	Moderate	Light
Multistory reinforced concrete building with reinforced concrete walls, blast resistant design for 30 psi in Mach region from 1 MT; no windows.	Walls shattered, severe frame distortion, incipient collapse.	Walls breached or on the point of being so, frame distorted. Entranceways damaged, doors blown in or jammed, extensive spalling of concrete.	Some cracking of concrete walls and frame.
Multistory reinforced concrete building with concrete walls, small window area; 3 to 8 stories.	Walls shattered, severe frame distortion, incipient collapse.	Exterior walls badly cracked, interior partitions badly cracked or blown down. Structural frame permanently distorted, extensive spalling of concrete.	Windows and doors blown in, interior partitions cracked.
Multistory wall-bearing building, brick apartment house type; up to 3 stories.	Bearing walls collapse, resulting in total collapse of structure.	Exterior walls badly cracked, interior partitions badly cracked or blown down.	Windows and doors blown in, interior partitions cracked.
Multistory wall-bearing-building, monumental type; up to 4 stories.	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 the structure may receive only moderate damage.	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; 1 or 2 stories.	Frame shattered so that for the most part collapsed.	Wall framing cracked, roof badly damaged, interior partitions blown down.	Windows and doors blown in, interior partitions cracked.

DAMAGE TO LIGHT-WEIGHT, EARTH COVERED AND BURIED STRUCTURES

4.40 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 flying debris. The depth of earth cover above the structure would usually

TABLE 4.38b

DAMAGE TO TYPES OF STRUCTURES PRIMARILY AFFECTED BY DYNAMIC PRESSURE DURING THE DRAG PHASE

Description of structure	Description of damage		
	Severe	Moderate	Light
Light steel frame industrial building, single story, with up to 5 ton crane capacity. Lightweight, low strength walls fail quickly.	Severe distortion or collapse of frame.	Some to major distortion of frame, cranes (if any) not operable until repairs made.	Windows and doors blown in, light siding ripped off.
Heavy steel frame industrial building, single story, with 25–50 ton crane capacity. Lightweight, low strength walls fail quickly.	Severe distortion or collapse of frame.	Some distortion to frame, cranes not operable until repairs made.	Windows and doors blown in, light siding ripped off.
Heavy steel frame industrial building, single story, with 60–100 ton crane capacity. Lightweight, low strength walls fail quickly.	Severe distortion or collapse of frame.	Some distortion to frame, cranes not operable until repairs made.	Windows and doors blown in, light siding ripped off.
Multistory steel frame office type building, 3–10 stories (earthquake resistant construction). Lightweight, low strength walls fail quickly.	Severe frame distortion, incipient collapse.	Frame distorted moderately, interior partitions blown down.	Windows and doors blown in, light siding ripped off, interior partitions cracked.
Multistory steel frame office type building, 3–10 stories (nonearthquake resistant construction) Lightweight, low strength walls fail quickly.	Severe frame distortion, incipient collapse.	Frame distorted moderately, interior partitions blown down.	Windows and doors blown in, light siding ripped off, interior partitions cracked.
Multistory reinforced concrete frame office type building, 3–10 stories (earthquake resistant construction). Lightweight, low strength walls fail quickly.	Severe frame distortion, incipient collapse.	Frame distorted moderately, interior partitions blown down. Some spalling of concrete.	Windows and doors blown in, light siding ripped off, interior partitions cracked.
Multistory reinforced concrete frame office type building, 3–10 stories (nonearthquake resistant construction). Lightweight, low strength walls fail quickly.	Severe frame distortion, incipient collapse.	Frame distorted moderately, interior partitions blown down. Some spalling of concrete.	Windows and doors blown in, light siding ripped off, interior partitions cracked.
Highway truss bridges, spans 150–250 ft.	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, slight distortion of some bridge components.
Railroad truss bridges, spans 150–250 ft.	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, slight distortion of some bridge components.
Highway and railroad truss bridges, spans 250–500 ft.	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, slight distortion of some bridge components.

TABLE 4.39

CONDITIONS OF FAILURE OF PEAK OVERPRESSURE-SENSITIVE ELEMENTS

Structural element	Failure	Approximate side-on 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 in. or 12 in. thick (not reinforced).	Shearing and flexure failures	7.0–8.0
Wood siding panels, standard house constuction.	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 in. or 12 in. thick (not reinforced).	Shattering of the wall	2.0–3.0

be determined by the degree of protection from nuclear radiation required at the design overpressure or dynamic pressure (see Chapter VIII).

4.41 The usual method of providing earth cover for surface or "cut-and-cover" semiburied structures is to build an earth mound over the portion of the structure that is above the normal ground level. If the slope of the earth cover is chosen properly the blast reflection factor is reduced and the aerodynamic shape of the structure is improved. This results in a considerable reduction in the applied translational forces. An additional benefit of the earth cover is the stiffening or resistance to deformation that the earth provides to flexible structures by the buttressing action of the soil.

4.42 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 the depth of burial to the span to be large enough for any benefit to be derived from soil arching (see § 4.44). For ratios of depth of burial to span between 0.25 and 3.0 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.

4.43 The lateral blast pressures exerted on the vertical faces of a shallow buried structure have been found to be as low as 15 percent of the blast pressure on the roof in dry, well-compacted, silty soils.

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For most soils, however, this lateral blast pressure is likely to be somewhat higher and may approach 100 percent of the roof blast 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.

4.44 Underground structures, buried at such a depth that the ratio of the burial depth to the span approaches (or exceeds) a value of 3.0, 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.

4.45 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 and direction of the blast wave. In Table 4.45 are given the limiting values of the peak overpressure required to cause various degrees of damage to two types of shallow buried 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 blast wave.

4.46 An illustration of severe damage to a 10-gage corrugated steel-arch, earth-covered, surface structure is shown in Fig. 4.46. It

TABLE 4.45

DAMAGE CRITERIA FOR SHALLOW BURIED STRUCTURES

Type of structure	Damage type	Peak overpressure	Nature of damage
		psi	
Light, corrugated steel arch, surface structure (10-gage corrugated steel with a span of 20–25 ft), central angle of 180° with 5 ft of earth cover at the crown.*	Severe	45–60	Collapse.
	Moderate	40–50	Large deformations of end walls and arch, also major entrance door damage.
	Light	30–40	Damage to ventilation and entrance door.
Buried concrete arch with a 16 ft span and central angle of 180°; 8 in. thick with 4 ft of earth cover at the crown.	Severe	220–280	Collapse.
	Moderate	160–220	Large deformations with considerable cracking and spalling.
	Light	120–160	Cracking of panels, possible entrance door damge.

*In the case of arched structures reinforced with ribs, the collapse pressure is higher depending on the number of ribs.

Figure 4 46 Severe damage to earth-covered surface corrugated steel structure

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.

Damage to Land Transportation Equipment

4 47 The general types of land transportation equipment considered here include civilian motor-driven vehicles 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 4.47. The corresponding ranges as a function of explosion yield are represented graphically in Fig. 4.58b.

TABLE 4.47

DAMAGE CRITERIA FOR LAND TRANSPORTATION EQUIPMENT

Description of equipment	Damage	Nature of damage
Motor equipment (cars and trucks).	Severe	Gross distortion of frame, large displacements, outside appurtenances (door and hoods) torn off, need rebuilding before use.
	Moderate	Turned over and displaced, badly dented, frames sprung, need major repairs.
	Light	Glass broken, dents in body, possibly turned over, immediately usable.
Railroad rolling stock (box, flat, tank, and gondola cars).	Severe	Car blown from tracks and badly smashed, extensive distortion, some parts usable.
	Moderate	Doors demolished, body damaged, frame distorted, could possibly roll to repair shop.
	Light	Some door and body damage, car can continue in use.
Railroad locomotives (Diesel or steam).	Severe	Overturned, parts blown off, sprung and twisted, major overhaul required.
	Moderate	Probably overturned, can be towed to repair shop after being righted, need major repairs.
	Light	Glass breakage and minor damage to parts, immediately usable.
Construction equipment (bulldozers and graders).	Severe	Extensive distortion of frame amd crushing of sheet metal, extensive damage to tracks and wheels.
	Moderate	Some frame distortion, overturning, track and wheel damage.
	Light	Slight damage to cabs and housing, glass breakage.

DAMAGE TO PARKED TRANSPORT AIRCRAFT

4.48 Aircraft are relatively vulnerable to air blast effects associated with nuclear detonations. 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 drag forces due to wind (dynamic) pressure 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.

4.49 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 debris. 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.

4.50. The various damage categories for parked transport airplanes, light liaison airplanes, and helicopters are outlined in Table 4.50 together with the approximate overpressures at which the damage may be expected to occur. The estimated ranges for the different types of damage can be obtained by using the overpressure values in conjuction with the height of burst curves presented in Chapter III. The aircraft are considered to be parked in the open at random orientation with respect to the point of burst. It should be mentioned that the data are based on tests in which aircraft were exposed to detonations with yields in the kiloton range. For megaton yields, the longer duration of the positive phase of the blast wave may result in some increase in damage over that estimated from small-yield explosions at the same overpressure level. This increase is likely to be significant at pressures producing severe damage, but will probably be less important for moderate and light damage conditions. Since quantitative data are not available concerning the effect of detonations of high yield on aircraft, no allowance for it has been made in Table 4.50.

TABLE 4.50

DAMAGE CRITERIA FOR PARKED AIRCRAFT

Damage type	Nature of damage	Overpressure	
			psi
Severe	Major (or depot level) maintenance required to restore aircraft to operational status.	Transport airplanes	3
		Light liaison craft	2
		Helicopters	3
Moderate	Field maintenance required to restore aircraft to operational status.	Transport airplanes	2
		Light liaison craft	1
		Helicopters	1.5
Light	Flight of the aircraft not prevented, although performance may be restricted.	Transport airplanes	1
		Light liaison craft	0.5
		Helicopters	0.5

4.51 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. 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

4.52 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 is given in Chapter V, and the general conclusions may be summarized here. Masts, spars, radar antennas, stacks, electrical equipment, and other light objects are especially sensitive to air blast particularly to the dynamic pressure. 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.

4.53 The degrees of damage to merchant type vessels are described in Table 4.53, and the damage-distance relationships are included in Fig. 4.58b. Illustrations of the destruction caused to ships by air blast from a nuclear explosion are presented in Chapter V.

Damage to Utilities

4.54 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 in § 6.24. Damage to structures, such as power stations, pumping stations, and storage tanks may be inferred from the information given earlier in the section on aboveground structures (§ 4.38 *et seq.*). Essentially, power lines are damaged if some (or all) of the poles are blown down, but they are otherwise undamaged. Lines extending radially from ground zero are less susceptible to damage than those running at right angles to this direction. In general, utility lines suffer either severe or light damage, since the lines are either blown down and require extensive repair or they remain in place and need little repair.

TABLE 4.53

DAMAGE CRITERIA FOR SHIPPING FROM AIR BLAST

Damage type	Nature of damage
Severe	The ship is either sunk or is damaged to the extent of requiring rebuilding.
Moderate	The ship is immobilized and requires extensive repairs, especially to shock-sensitive components or their foundations, e.g., propulsive machinery, boilers, and interior equipment.
Light	The ship may still be able to operate, although there will be damage to electronic, electrical, and mechanical equipment.

DAMAGE TO FORESTS

4.55 The detailed characteristics of the damage to forest stands resulting from a nuclear explosion will depend on a variety of conditions, e.g., deciduous or coniferous trees, degree of foliation of the trees, natural or planted stands, and favorable or unfavorable growing conditions. A general classification of forest damage, applicable in most cases, is given in Table 4.55. Trees are primarily sensitive to the drag forces from a blast wave and so it is of interest that the damage in an explosion is similar to that resulting from a strong, steady wind; the velocities of such winds that would produce comparable damage are included in the table.

TABLE 4.55

DAMAGE CRITERIA FOR FORESTS

Damage type	Nature of damage	Equivalent steady wind velocity (*miles per hour*)
Severe	Up to 90 percent of trees blown down; remainder denuded of branches and leaves. (Area impassable to vehicles and very difficult on foot.)	130–140
Moderate	About 30 percent of trees blown down; remainder have some branches and leaves blown off. (Area passable to vehicles only after extensive clearing.)	90–100
Light	Very few trees blown down; some leaves and branches blown off. (Area passable to vehicles.)	60–80

4.56 The distances from ground zero within which severe damage would be experienced by an average forest stand, for a given yield, can be derived from Fig. 4.58b. The results apply, in particular, to unimproved coniferous forests which have developed under unfavorable

growing conditions and to most deciduous forests in the temperate zone when foliation is present. Improved coniferous forests, with trees of uniform height and a smaller average tree density per acre, are more resistant to blast than are unimproved forests which have grown under unfavorable conditions. A forest of defoliated deciduous trees is also somewhat more blast resistant than is implied by the data in Fig. 4.58b.

Damage to Storage Tanks

4.57 The prediction of damage to POL (petroleum, oil, lubricant) storage tanks due to blast loading is based upon extensive analytical work supported by limited shock tube data and model testing with high explosives. It appears that the chief cause of failure is the lifting of the tank from its foundation. This results in plastic deformation and yielding of the joint between the side and bottom so that leakage can occur. Severe damage is regarded as that damage which is associated with loss of the contents of the tank by leakage. Apart from the loss of the tank's contents, the leakage can lead to secondary effects, such as the development of fires. If failure by lifting does not occur, it is expected that there will be little, if any, loss of liquid from the tank as a consequence of sloshing. There is apparently no clear cut overall structural collapse which initially limits the usefulness of the tank. In Figs. 4.57 a and b there are presented the peak overpressure levels required for severe damage, as defined above, to POL storage tanks satisfying American Petroleum Institute standards; Fig. 4.57a is applicable to nuclear explosions of from 1 to 500 kilotons energy yield and Fig. 4.57b to yields of 500 kilotons or more. By using the data in Figs. 4.57 a and b and the overpressure curves in Chapter III, it is possible to determine the radii of damage for various yields and heights of burst.

Damage-Distance Relationships

4.58 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, relationships have been developed between the yield of an explosion, the distance from ground zero, and the degree of damage, as already defined, that would be expected for a variety of objects and structures. The results are presented in the form of nomographs in Figs. 4.58 a and b. The data refer to air bursts with the height of burst chosen so that it maximizes the radius of

(Text continued on page 176.)

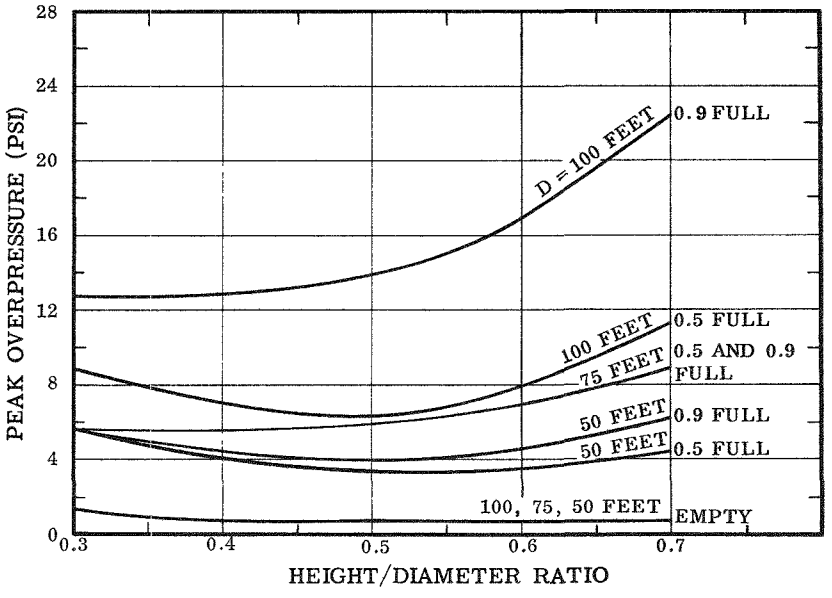

Figure 4.57a. Peak overpressures for severe blast damage to floating- or conical-roof tanks for explosions from 1 to 500 kilotons.

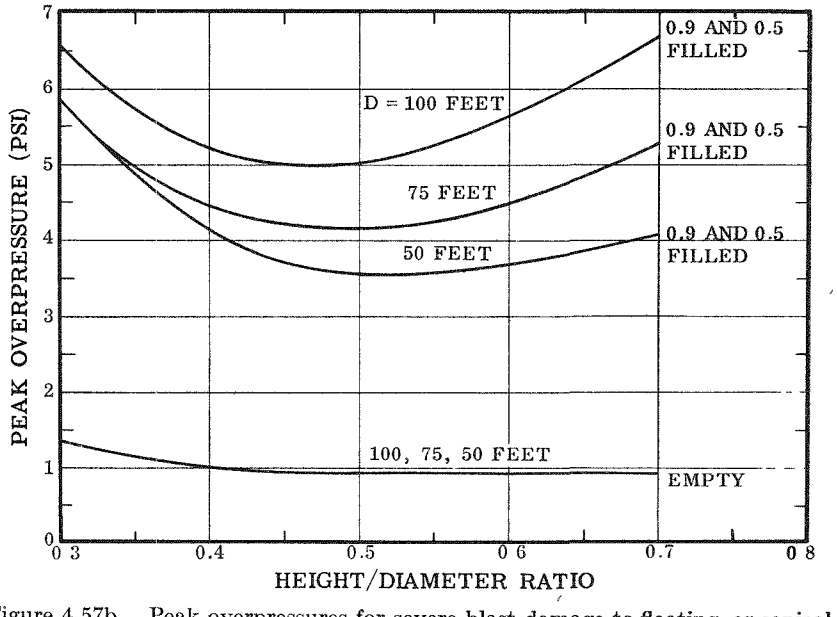

Figure 4.57b. Peak overpressures for severe blast damage to floating- or conical-roof tanks from explosions of 500 kilotons or more.

TYPES OF STRUCTURES

1. Wood-frame building.
2. Multistory, wall-bearing buildings, brick apartment house type.
3. Multistory, wall-bearing buildings, monumental type.
4. Multistory, blast-resistant design, reinforced-concrete buildings.
5. Multistory, reinforced-concrete buildings, with concrete walls and small window area.
6. Highway truss bridges of 150 to 250 foot span (blast normal to longitudinal bridge axis).
7. Multistory, reinforced-concrete, frame office type buildings, earthquake resistant.
8. Light steel-frame industrial buildings.
9. Heavy steel-frame industrial buildings (25 to 50 ton crane).
10. Heavy steel-frame industrial buildings (60 to 100 ton crane).
11. Railroad truss bridges of 150 to 250 foot span (blast normal to longitudinal bridge axis).
12. Multistory, reinforced-concrete frame office type buildings.
13. Highway and railroad truss bridges of 250 to 400 foot spans (blast normal to longitudinal bridge axis).
14. Multistory, steel-frame office type buildings.
15. Multistory, steel-frame office type buildings, earthquake resistant.

For a surface burst multiply the range by three-quarters.

Example:

Given: Wood-frame building (Type 1). A 1 MT weapon is burst (*a*) at the optimum height, (*b*) at the surface.

Find: The ranges from ground zero for severe and moderate damage.

Solution: (*a*) From the point 1 (at the right) draw a straight line to 1 MT on the severe damage scale and another to 1 MT on the moderate damage scale. The intersections of these lines with the range scale give the required solutions for the optimum burst height; thus,

Range for severe damage = 29,000 feet. *Answer.*

Range for moderate damage = 34,000 feet. *Answer.*

(*b*) For a surface burst the respective ranges are three-quarters those obtained above; hence,

Range for severe damage = 22,000 feet. *Answer.*

Range for moderate damage = 26,000 feet. *Answer.*

(The values have been rounded off to two significant figures, since greater precision is not warranted.)

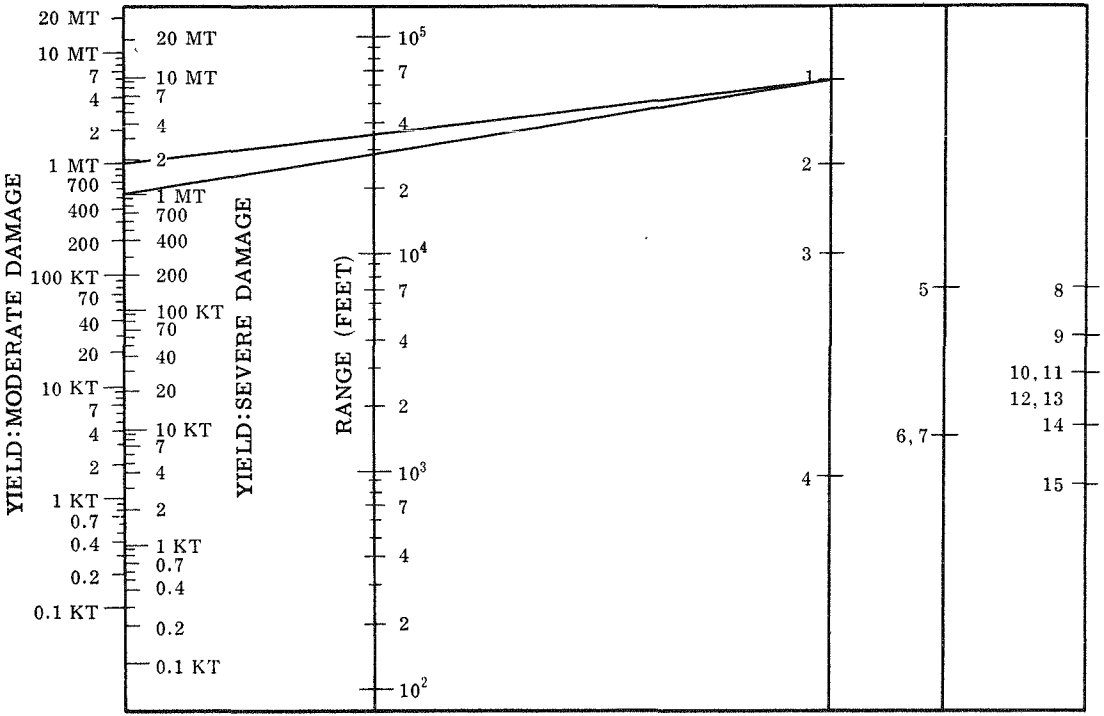

Figure 4.58a. Damage-distance relationships for structures of various types.

TARGETS

1. Truck mounted engineering equipment (unprotected).
2. Earth moving engineering equipment (unprotected).
3. Transportation vehicles.
4. Boxcars, flatcars, full tank cars, and gondola cars (side-on orientation).
5. Locomotives (side-on orientation).
6. Telephone lines (radial).
7. Telephone lines (transverse).
8. Average forest stand.
9. Boxcars, flatcars, full tank cars, and gondola cars (end-on orientation).
10. Locomotives (end-on orientation).
11. Merchant shipping.

Subscript "m" refers to moderate damage and subscript "s" refers to severe damage.

For a surface burst multiply the range by three-quarters for Items 1 through 8. For Items 9, 10, and 11, the ranges are the same for a surface burst as for the optimum burst height.

Example:

Given: A transportation type vehicle (Item 3). A 10 KT weapon is burst at (*a*) the optimum height, (*b*) at the surface.

Find: The range from ground zero for severe and moderate damage.

Solution: (*a*) Draw straight lines from the points 3_s and 3_m, at the right, to 10 KT on the yield scale at the left. The intersection of these lines with the range scale give the solutions for severe and moderate damage, respectively, for the optimum burst height; thus,

Range for severe damage=1,900 feet. *Answer.*

Range for moderate damage=2,900 feet. *Answer.*

(*b*) For a surface burst the ranges in this case are three-quarters those obtained above, thus,

Range for severe damage=1,400 feet. *Answer.*

Range for moderate damage=2,200 feet. *Answer.*

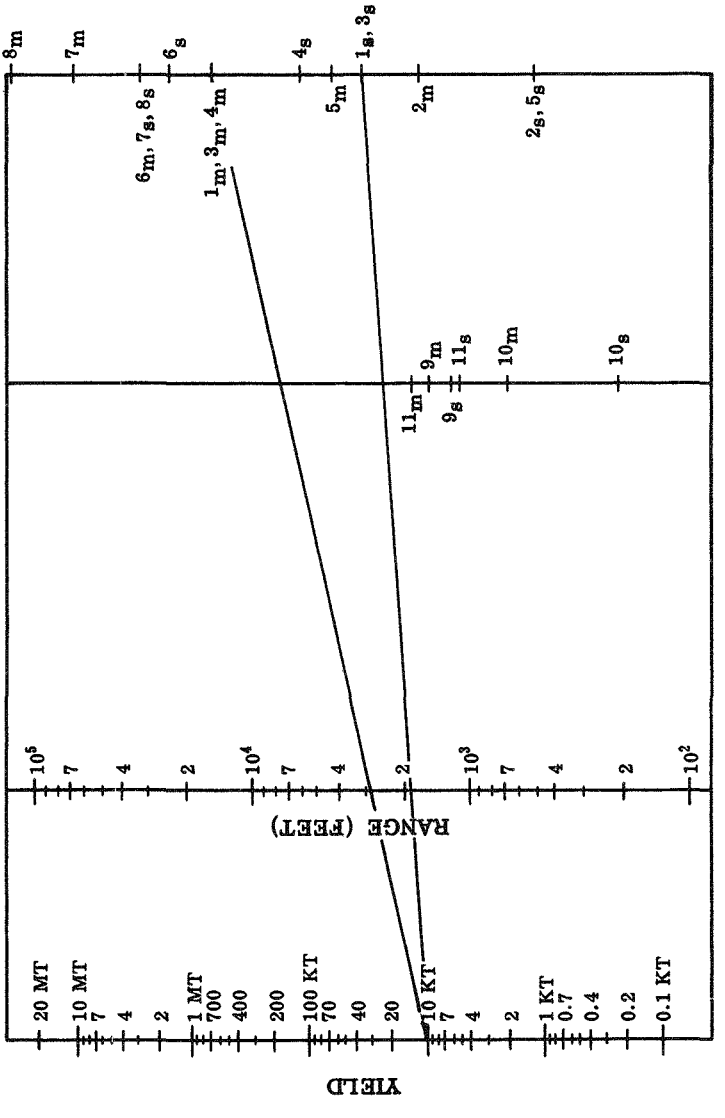

Figure 4.58b. Damage-distance relationships for various targets.

(Text continued from page 170.)

damage for the particular target being considered and is not necessarily the same from one target to another. The procedures for converting the distances for an air burst to those for a surface burst of the same yield are given in the descriptive material accompanying the figures. Examples illustrating the use of the nomographs are also included.

4.59 Except for blast-resistant structures and bridges, slight damage to all targets can be expected at the range at which 1 pound per square inch overpressure occurs. For the blast-resistant structure described in Table 4.38a, an overpressure of 10 pounds per square inch should be used to estimate the distance for slight damage. Slight damage to bridges can be expected at the range at which 0.6 pound per square inch dynamic pressure occurs.

4.60 The data presented in Figs. 4.58a and b are for certain average target conditions. These presuppose 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 in certain areas and local enhancement of damage in others); and (3) the structures have average characteristics (that is, they are of average size and strength and that orientation of the target with respect to the burst is no problem, i.e., that the ratio of loading to resistance is relatively the same in all directions from the target). 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. The ranges obtained from the nomographs are accurate to within ± 20 percent over all conditions presented.

4.61 It should also be mentioned that the damage charts do not take into consideration the possibility of fire. Generally speaking, except for fabric surfaces of aircraft, 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 severe or moderate damage fires may start because of disrupted gas and electric utilities. In some cases, as in Hiroshima (§7.75), 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. 4.58 a and b are used to estimate the damage to a particular city or target area.

INTERACTION OF OBJECTS WITH AIR BLAST[4]

Development of Blast Loading

4.62 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 the 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.

4.63 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.

4.64 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

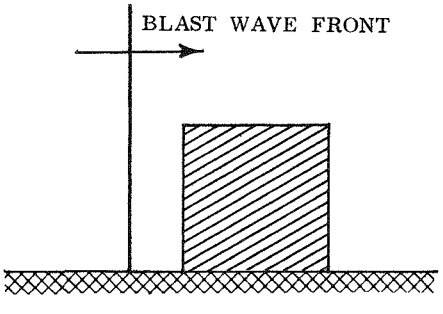

Figure 4.64. Blast wave approaching cube rigidly attached to ground.

when subjected to the loading. The blast wave (or shock) 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

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

are 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. 4.64).

4.65 As the blast wave strikes the front face of the cube, a reflection occurs producing reflected pressures which may be from two to eight times as great as the incident overpressure (§ 3.50). The blast wave then bends (or diffracts) around the cube exerting pressures on the sides and top of the object, and finally 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.

4.66 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

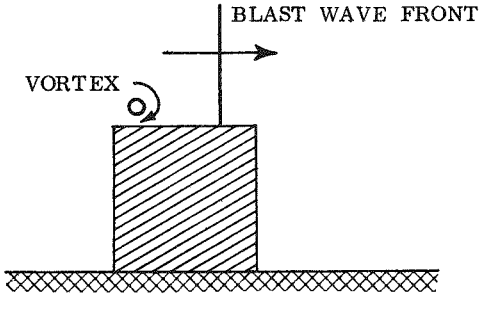

Figure 4.66. Blast wave moving over sides and top of cube.

and which travels along or near the surface behind the wave front (Fig. 4.66). 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 pressure here has a negative value.

4.67 When the blast wave reaches the rear of the cube, it diffracts around the edges, and travels down the back surface (Fig. 4.67). 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 wave front as it 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.

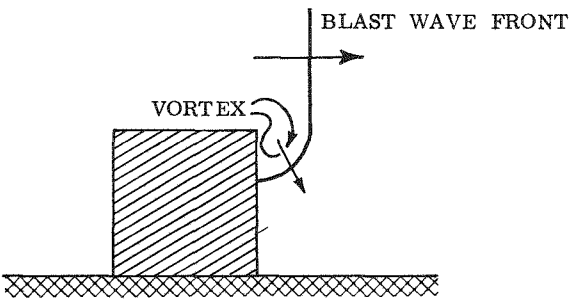

Figure 4.67. Blast wave moving down rear of cube.

4.68 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, essentially 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.

4.69 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 wave 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 wave front (§ 3.51 *et seq.*).

4.70 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

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the 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

4.71 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 and no loading has reached the rear face.

4.72 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.

4.73 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.

4.74 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 loading becomes increasingly important. For classification purposes, objects are often described as "diffraction targets" or "drag targets," as mentioned earlier, 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

4.75 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.

4.76 The drag coefficient, i.e., the ratio of the drag pressure to the dynamic pressure (§ 4.69), 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.

4.77 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

4.78 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.

4.79 The blast wave characteristics which need to be known and their symbols are summarized in Table 4.79. 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 and height of burst, are also indicated.

TABLE 4.79

BLAST WAVE CHARACTERISTICS FOR DETERMINATION OF LOADING

Property	*Symbol*	*Source*
Peak overpressure	p	Figs. 3.66 and 3.67 a and b.
Time variation of overpressure	$p(t)$	Fig. 3.52.
Peak dynamic pressure	q	Fig. 3.68.
Time variation of dynamic pressure	$q(t)$	Fig. 3.53.
Reflected overpressure	p_r	Fig. 3.71b.
Duration of positive phase	t_+	Fig. 3.69.
Blast front (shock) velocity	U	Fig. 3.49.

CLOSED BOX-LIKE STRUCTURE

4.80 A closed box-like structure may be represented simply by a parallelepiped, as in Fig. 4.80, having a length L, height H, and breadth B. In this category will fall structures with a flat roof and walls of

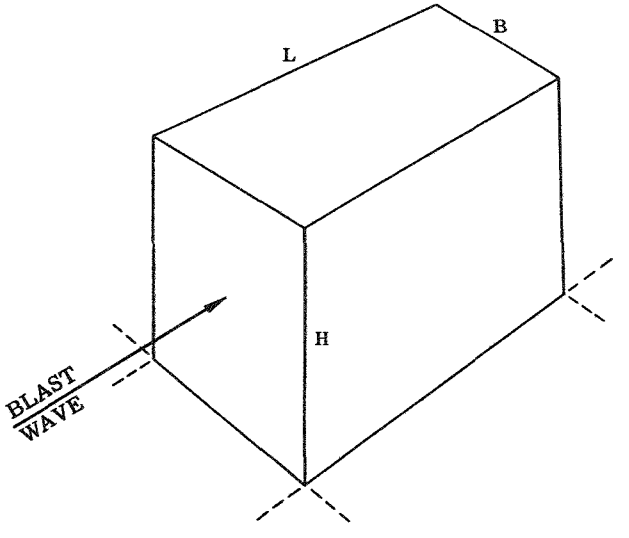

Figure 4.80. Representation of closed box-like structure.

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 existing before the arrival of the blast wave, 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*).

4.81 (*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. 4.81). 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 $B/2$, 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. 4.81.

4.82 (*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

$$p_a=p\left(\frac{L}{2U}\right)+C_d q\left(\frac{L}{2U}\right),$$

the drag coefficient on the sides and top of the structure being given in Table 4.82. The loading thus increases from zero at $t=0$ to the value p_a at the time L/U, as shown in Fig. 4.82. After this time the pressure at any time t is given by

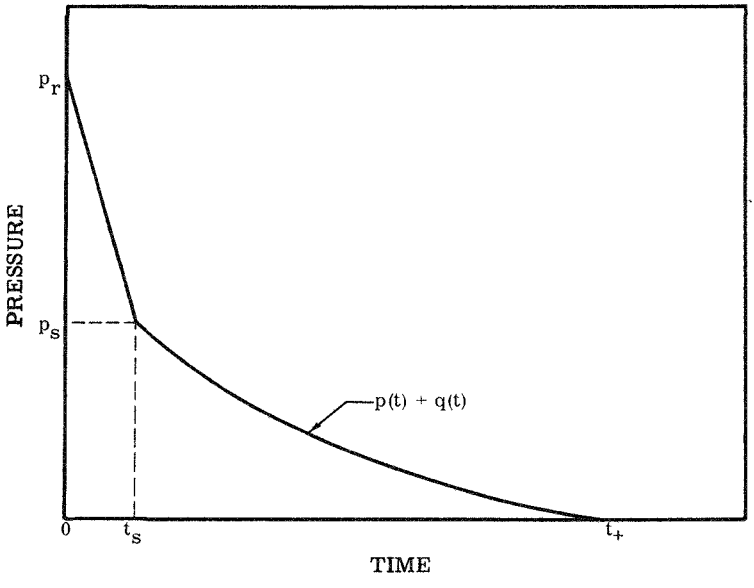

Figure 4.81. Average front face loading of closed box-like structure.

$$\text{Pressure at time } t = p\left(t-\frac{L}{2U}\right)+C_d q\left(t-\frac{L}{2U}\right),$$

where t lies between L/U and $t_+ + L/2U$, as seen in Fig. 4.82. The overpressure and dynamic pressure, respectively, are the values at the time $t-L/2U$.

TABLE 4.82

DRAG COEFFICIENTS FOR ABOVEGROUND RECTANGULAR STRUCTURES

Dynamic pressure	*Drag coefficient (side, top, and back)*
0–25 psi	−0.4
25–50 psi	−0.3
50–130 psi	−0.2

4.83 (*c*) *Average Loading on Back Face.*—The shock front arrives at the back face at time L/U, but it requires an additional time, $4S/U$,

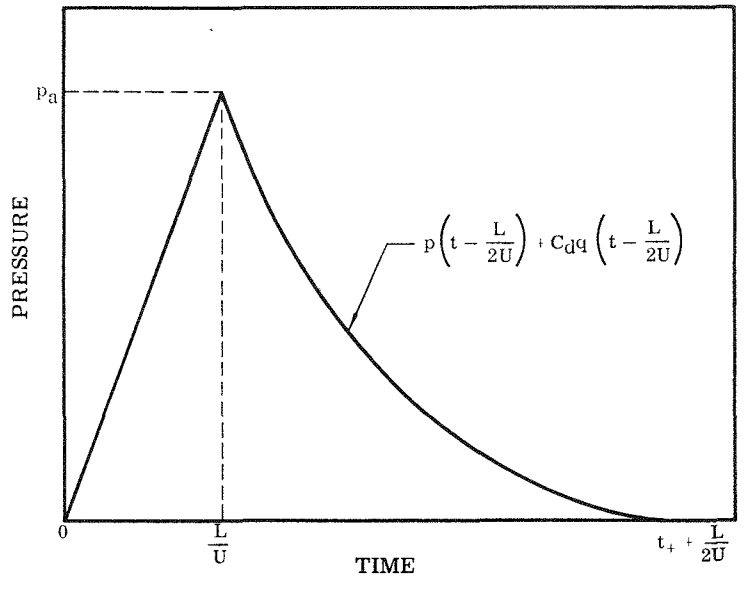

Figure 4.82. Average side and top loading of closed box-like structure.

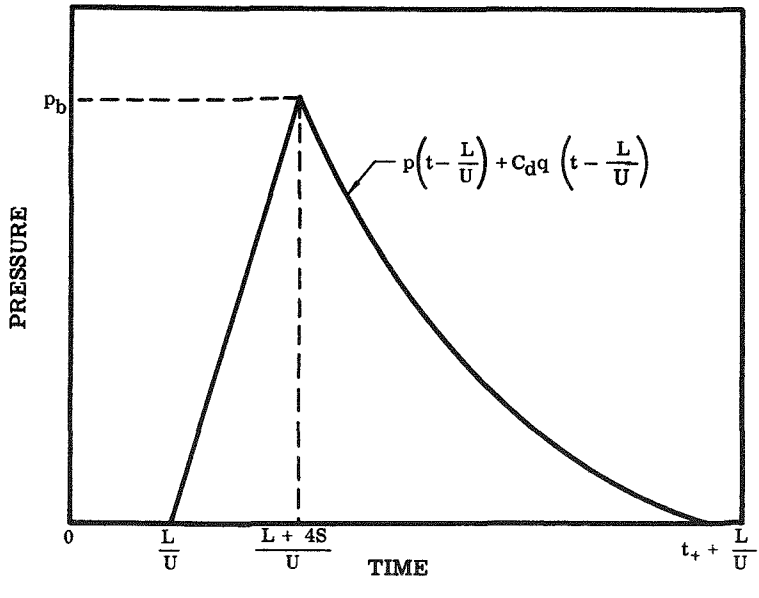

Figure 4.83. Average back face loading of closed box-like structure.

for the pressure to build up to the value p_b (Fig. 4.83). Here, as before, S is equal to H or $B/2$, whichever is the smaller. The drag coefficient on the back face is given in Table 4.82 and the pressure at any time after p_b is attained is represented by

$$\text{Pressure at time } t = p\left(t - \frac{L}{U}\right) + C_d q\left(t - \frac{L}{U}\right),$$

where t lies between $(L + 4S)/U$ and $t_+ + L/U$, as seen in Fig. 4.83.

4.84 (*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. 4.84. The left-hand diagram gives the individual front and back loading curves, as derived from Figs. 4.81 and 4.83, 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.

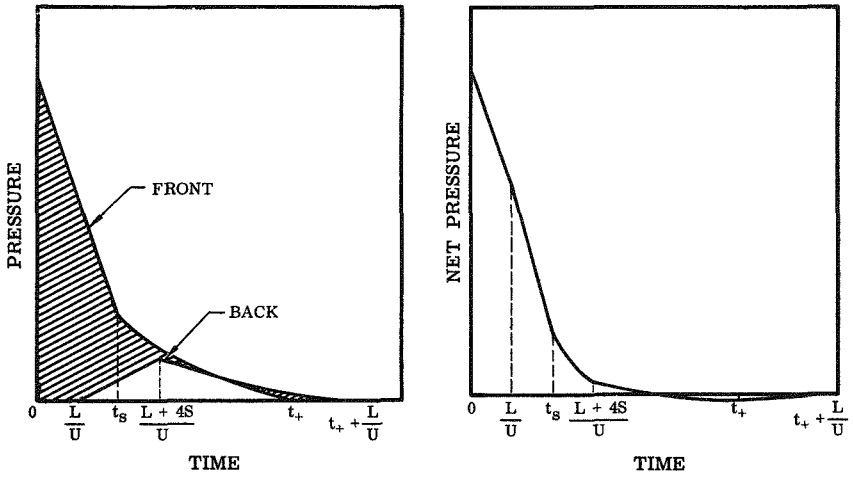

Figure 4.84. Net horizontal loading of closed box-like structure.

Partially Open Box-Like Structure

4.85 Such a structure is one in which the front and back walls have about 30 percent of openings or window area and no interior partitions to influence the passage of the blast wave. 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.

4.86 (*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.

4.87 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. 4.87.

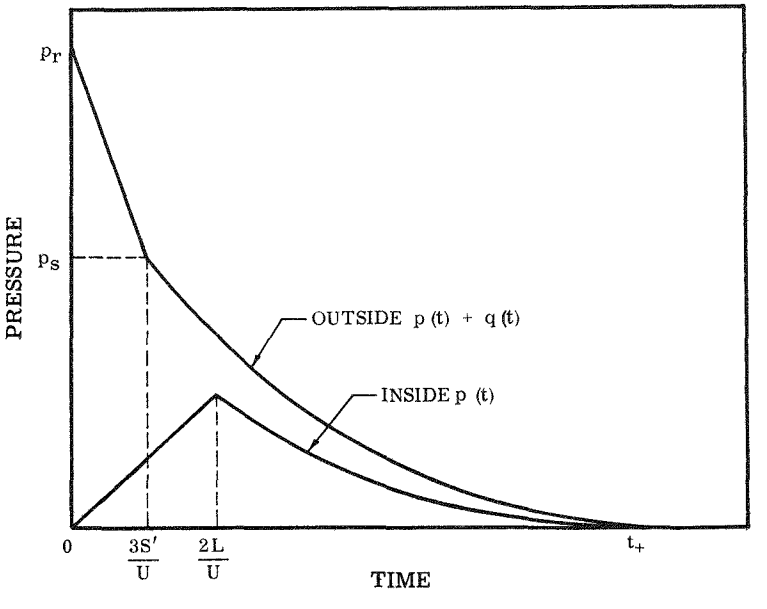

Figure 4.87. Average front face loading of partially open box-like structure.

4.88 (*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. 4.88.

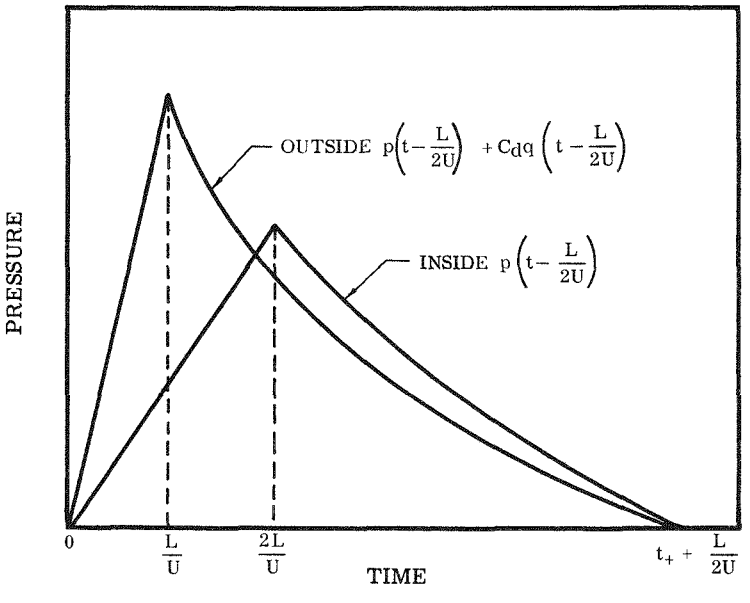

Figure 4.88. Average side and top loading of partially open box-like structure.

4.89 (*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. 4.89).

4.90 (*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

4.91 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

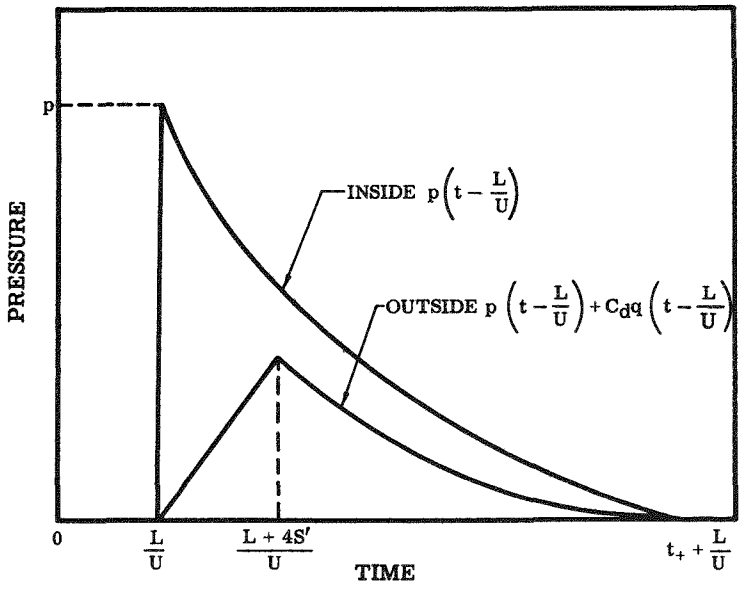

Figure 4.89. Average back face loading of partially open box-like structure.

structure. Steel-frame office buildings, with a majority of the wall area of glass, and industrial buildings, with asbestos, light steel, or aluminum panels, quickly become open frame structures after the initial impact of the blast wave.

4.92 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.

4.93 Another difficulty in the treatment of open frame structures arises in the computations 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, as shown below in Fig. 4.95.

4.94 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 1.5. 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 multipled by area, on an individual member is thus given by

$$F \text{ (member)} = C_d q(t) A_i,$$

where C_d is 1.5 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 ΣA_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 $A = \Sigma A_i$.

4.95 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. 4.95. 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

4.96 The following treatment, which is limited to peak overpressures of less than 25 pounds per square inch, is applicable to structures having a circular cross section, such as telephone poles and

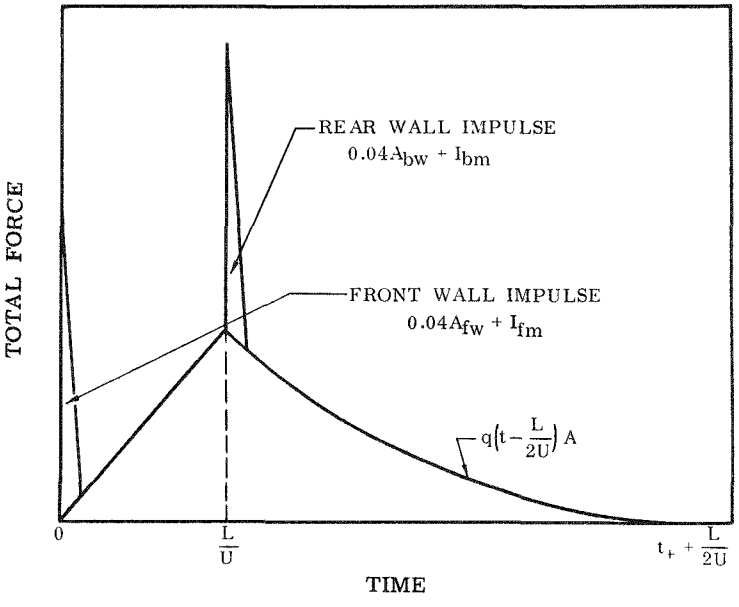

Figure 4.95. Net horizontal loading of an open frame structure.

smokestacks. It can also be applied to arched structures with semicircular cross sections, such as quonset huts and, as a rough approximation, to dome-shaped or spherical structures.

4.97 The discussion presented here is for a cylindrical (or semicylindrical) structure with the direction of propagation of the blast perpendicular to the axis of the cylinder. The pressure-time curves to be developed are those for arched structures with a semicircular cross section. The results can be applied to a cylindrical structure, since it consists of two such semicylinders with identical loading on each half. The general situation is then as depicted in Fig. 4.97; H is the height of the arch (or the radius of the cylinder) and z represents any point on the surface. The angle between the horizontal (or springing line) and the line joining z to the center of curvature of the semicircle is indicated by α; and X, equal to $H(1-\cos\ \alpha)$, is the horizontal distance, in the direction of propagation of the blast wave, between the bottom of the arch and the arbitrary point z.

4.98 When an ideal blast wave impinges on the flat surface of a structure, the pressure rises instantaneously to the reflected value and then it soon drops to the stagnation pressure (§4.65). On curved surfaces, however, vortex formation occurs just after reflection, so that there may be a temporary sharp drop before the stagna-

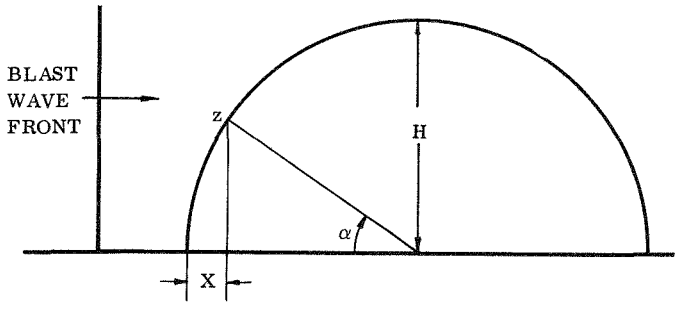

Figure 4.97. Representation of a typical semicircular arched structure.

tion pressure is reached. A generalized representation of the variation of the pressure with time at any point, z, is shown in Fig. 4.98. The blast wave front strikes the base of the arch at time $t=0$ and the time of arrival at the point z, regardless of whether it is on the front or back half, is X/U. The overpressure then rises sharply, in the time interval t_1, to the reflected value, p_1, so that t_1 is the rise time. Vortex formation causes the pressure to drop to p_2, and this is followed

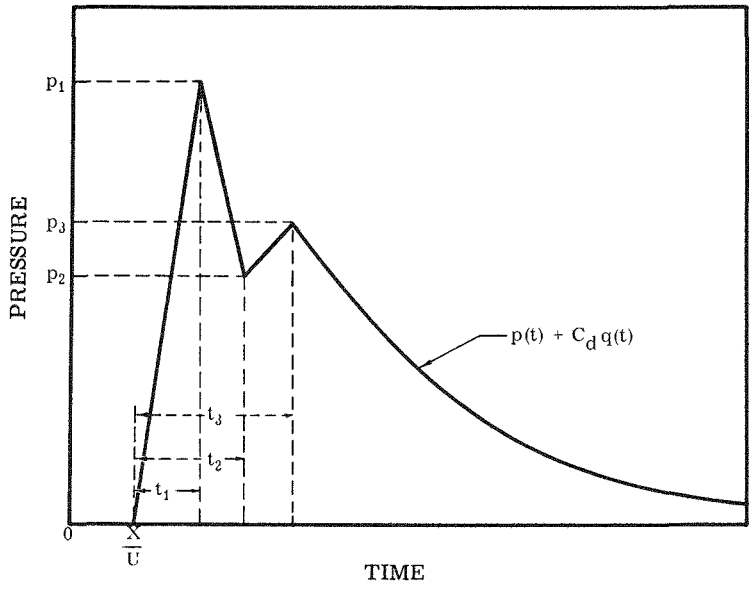

Figure 4.98. Typical pressure variation at a point on an arched structure subjected to a moving blast wave.

by an increase to p_3, the stagnation pressure; subsequently, the pressure, which is equal to $p(t)+C_d q\ (t)$, where C_d is the appropriate drag coefficient, decays in the normal manner.

4.99 The dependence of the pressures p_1 and p_2 and the drag coefficient C_d on the angle α is represented in Fig. 4.99; the pressure values are expressed as the ratios to p_r, where p_r is the ideal reflected pressure for a flat surface. When α is zero, i.e., at the base of the arch, p_1 is identical with p_r, but for larger angles it is less. The rise time t_1 and the time intervals t_2 and t_3, corresponding to vortex formation and attainment of the stagnation pressure, respectively, after the blast wave reaches the base of the arch, are also given in Fig. 4.99, in terms of the time unit H/U. The rise time is seen to be zero for the front half of the arch, i.e., for α between 0° and 90°, but it is finite and increases with α on the back half, i.e., for α between 90° and 180°. The times t_2 and t_3 are independent of the angle α.

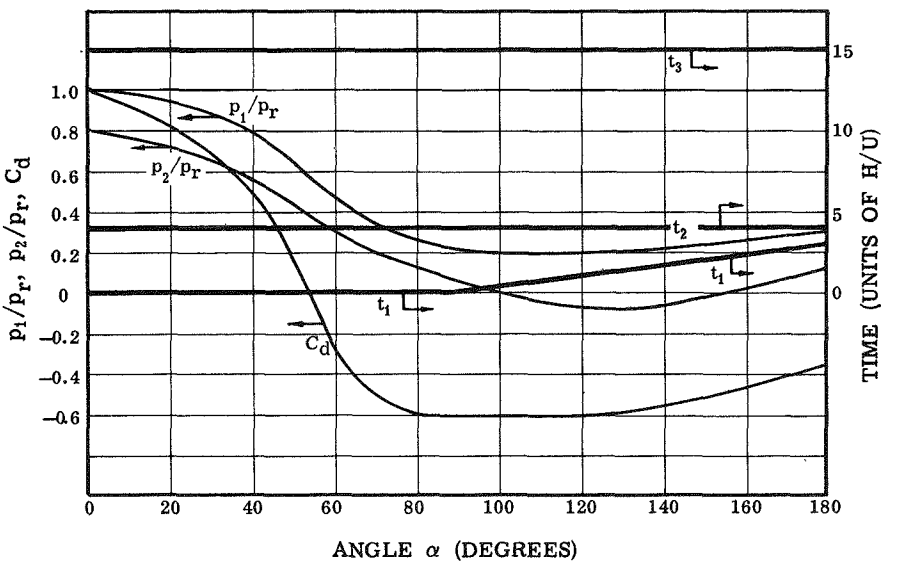

Figure 4.99. Variation of pressure ratios, drag coefficient, and time intervals for an arched structure.

4.100 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.

4.101 In the approximate procedure for determining the net loading, the overpressure loading during the diffraction stage is considered to be equivalent to an initial impulse equal to $p_r A(2H/U)$, where A is the projected area normal to the direction of the blast propagation. It will be noted that $2H/U$ 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 25 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. 4.101, 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 (§4.94) with C_d equal to 0.2.

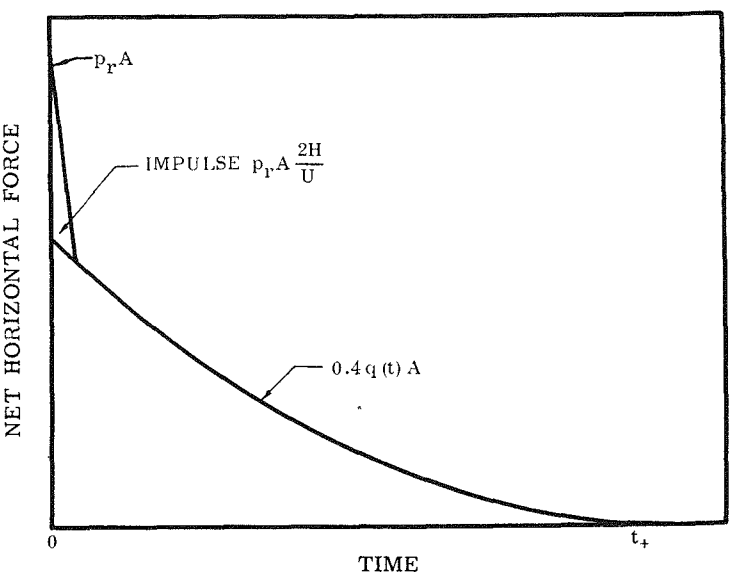

Figure 4.101. Approximate equivalent net horizontal force loading on semi-cylindrical structure.

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*These documents may be obtained for a small charge from the Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C.

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CHAPTER V

STRUCTURAL DAMAGE FROM AIR BLAST

INTRODUCTION

General Observations

5.01 The two preceding chapters have dealt with general principles of air blast and its effect on structures. In the present chapter, the actual damage to buildings of various types, bridges, utilities, and vehicles caused by nuclear explosions will be described. 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.

5.02 Before proceeding with detailed accounts 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. In the former case, the combination of high peak overpressure, high wind (or dynamic) pressure, and longer duration of the positive (compression) phase of the blast wave results in "mass distortion" of buildings, similar to that produced by earthquakes and hurricanes. An ordinary explosion will usually damage only part of a large structure, but the blast from a nuclear weapon can surround and destroy whole buildings in addition to causing localized structural damage.

5.03 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 by the crushing action of the blast wave.

5.04 Many buildings, which 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.

5.05 A highly important consequence of the tremendous power of the nuclear explosion was 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 second-

Figure 5.05. Debris after the nuclear explosion at Hiroshima.

ary damage to structures and utilities, and numerous casualities even in the lightly damaged areas. In addition, the large quantities of debris resulted in the blockage of streets, thus making rescue and fire-fighting operations extremely difficult (Fig. 5.05).

5.06 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.

5.07 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. The peak overpressure and dynamic pressure values given in most cases are those estimated for the particular detonation (in Japan) or test (in Nevada) for weapons with energy yields in the kiloton range. For megaton weapons, however, there may be some reduction in the dynamic pressure required to produce the same effect for drag-type targets (§ 5.74 *et seq.*).

STRUCTURES AND THEIR CONTENTS

Residential Structures

5.08 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

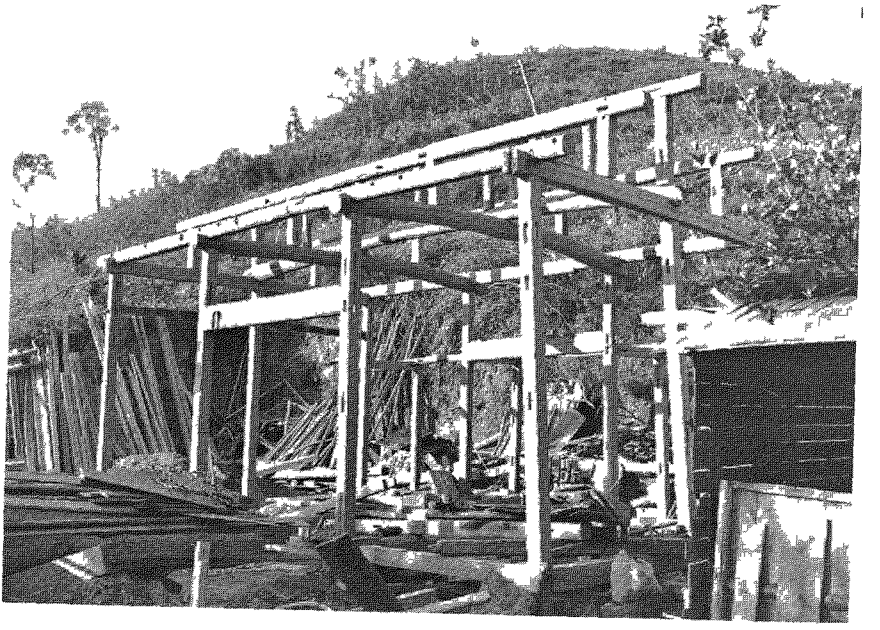

Figure 5 08 Upper photo Wood-frame building, 1 0 mile from ground zero at Hiroshima Lower photo Frame of residence under construction, showing small tenons

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 overall weakening (Fig. 5.08).

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

5.10 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 16 kilotons. In the test of May 5, 1955, the explosion took place on a 500-foot tower and the yield was close to 29 kilotons. In each case, air pressure measurements made possible a correlation, where it was justified, between the blast damage and the peak overpressure.

5.11 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.

Two-Story, Wood-Frame House: 1953 Test

5.12 In the 1953 test, two essentially identical houses, of a type 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. 5.12). 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 chances of fire were greater, whereas asphalt shingles were used for the other house. There were no utilities of any kind.

Figure 5 12 Wood-frame house before a nuclear explosion, Nevada Test Site

5.13 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 blast, was 1.7 and the dynamic pressure 0.5 pounds per square inch. Here par-

tial destruction only was expected, so that the test might provide data for structural improvements.

5 14 Some indication of the blast damage suffered by the dwelling nearer to the explosion can be obtained from Fig. 5 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.

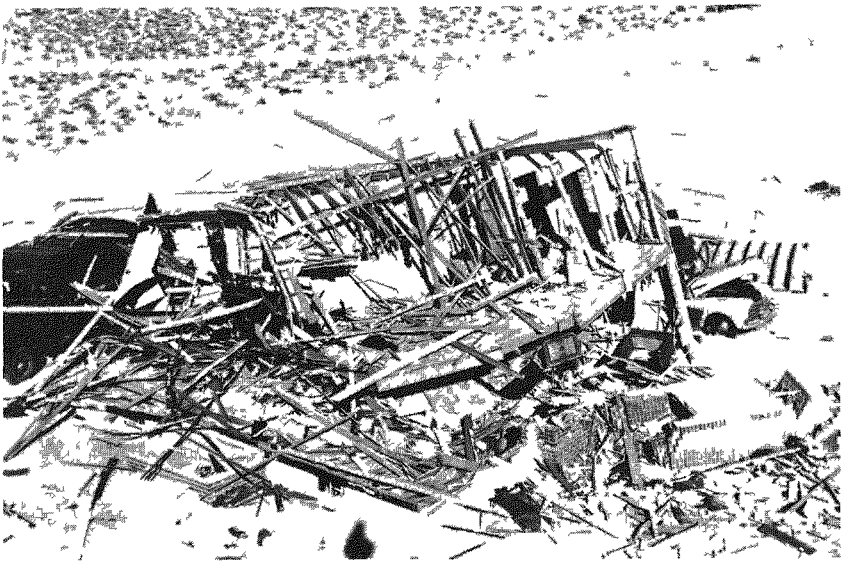

Figure 5.14. Wood-frame house after a nuclear explosion (5 psi overpressure).

5.15 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.

5.16 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. 5.16). Personnel in the main and upper floors would have suffered injuries ranging from minor cuts from glass fragments to possible fatal injuries from flying debris or as a result of translational displacement of the body as a whole. Some damage would also result to the furnishings and other contents of the house. 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.

Figure 5.16. Wood-frame house after a nuclear explosion (1.7 psi overpressure).

5.17 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. 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.

5.18 Principal damage to the first floor system consisted of broken joists. Breakages originated chiefly 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.

5.19 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.

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

Two-Story, Wood-Frame House: 1955 Test

5.21 Based upon the results described above, certain improvements in design were incorporated in two similar wood-frame houses

Figure 5.22. Strengthened wood-frame house after a nuclear explosion (4 psi overpressure).

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.

5.22 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. 5.22). However, the superstructure was so badly damaged that it could not have been occupied without expensive repair which would not have been economically advisable.

5.23 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.

5.24 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. 5.24). 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.

5.25 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. 5.25). Although there were differences in detail, the overall 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.

5.26 In addition to the doors and windows, the framing of the house, especially that of the roof, suffered most severely from the

Figure 5 24 First floor joists of strengthened wood-frame house after a nuclear explosion (4 psi overpressure)

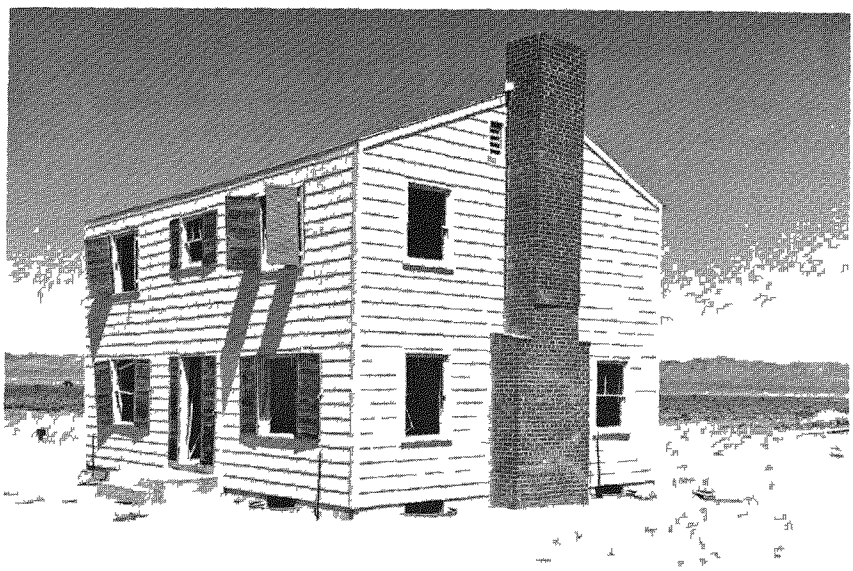

Figure 5 25 Strengthened wood-frame house after a nuclear explosion (2 6 psi overpressure)

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.

5.27 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. 5.27).

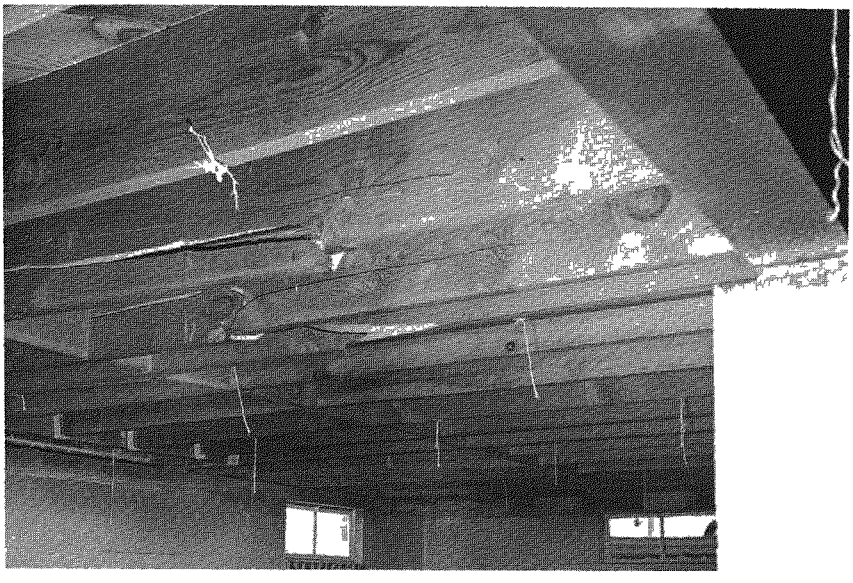

Figure 5.27. First floor joists of strengthened wood-frame house after a nuclear explosion (2.6 psi overpressure).

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

Two-Story, Brick-Wall-Bearing House

5.29 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. 5.29). 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.

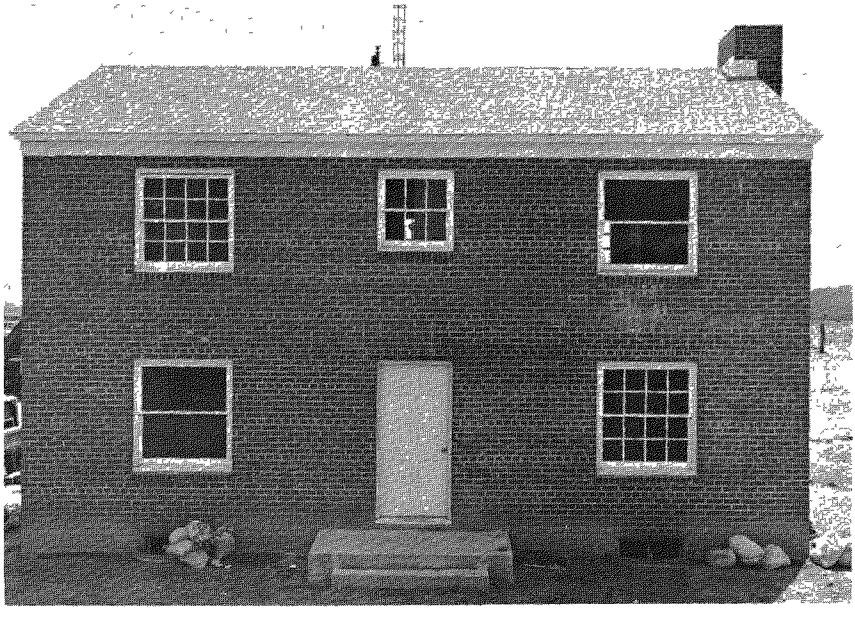

Figure 5.29. Unreinforced brick house before a nuclear explosion, Nevada Test Site.

5.30 At an incident overpressure of 5 pounds per square inch, the brick-wall house was damaged beyond repair (Fig. 5.30). 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.

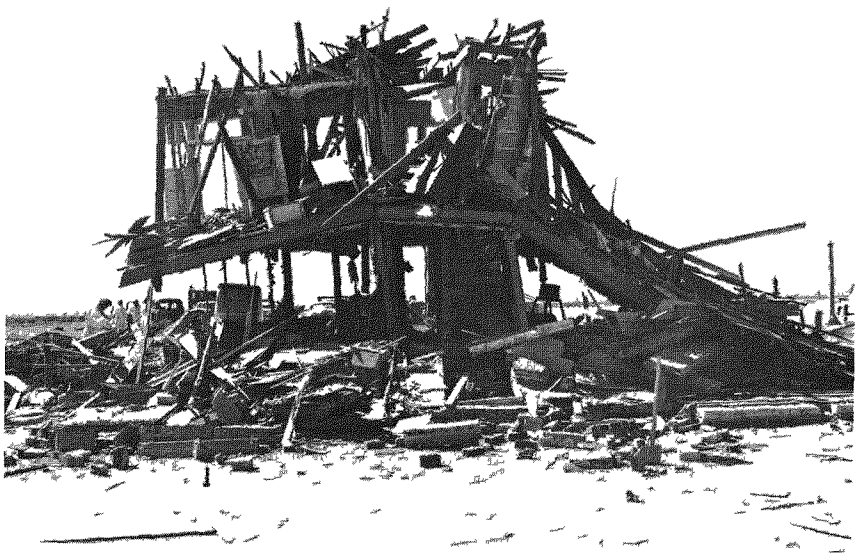

Figure 5 30 Unreinforced brick house after a nuclear explosion (5 psi over pressure)

Figure 5 31 Unreinforced brick house after a nuclear explosion (1 7 psi overpressure)

5.31 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. 5.31).

5.32 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 in 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.

5.33 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

5.34 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. 5.34).

5.35 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, although it was leaning away from the direction of the explosion (Fig. 5.35).

5.36 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.

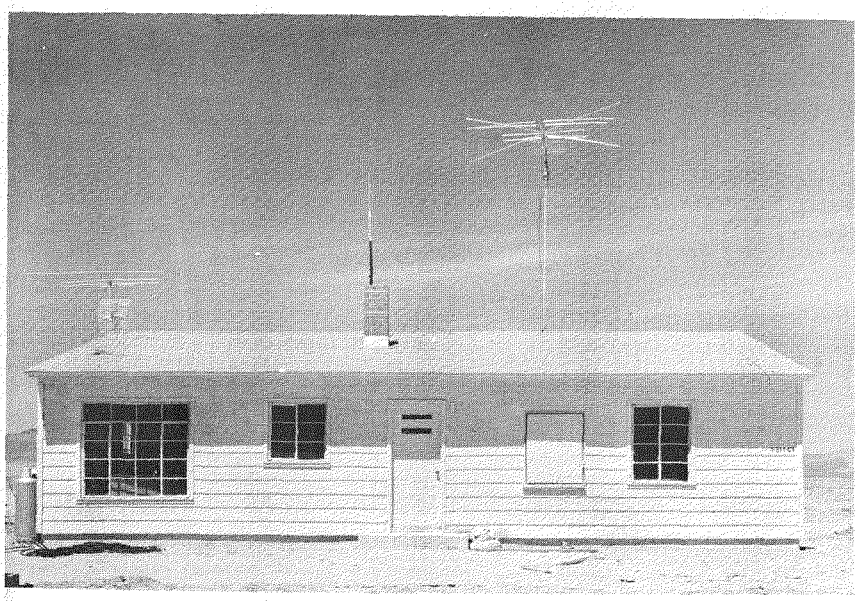

Figure 5.34. Rambler-type house before a nuclear explosion, Nevada Test Site. (Note blast door over bathroom window at right.)

Figure 5.35. Rambler-type house after a nuclear explosion (5 psi overpressure).

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One-Story, Precast Concrete House

5.37 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 overall design was such as to comply with the California code for earthquake-resistant construction (Fig. 5.37).

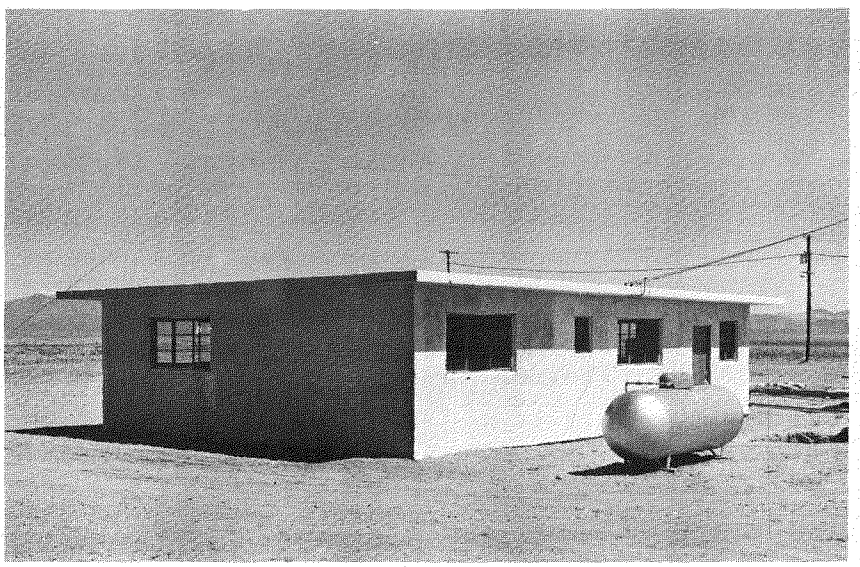

Figure 5.37. Reinforced precast concrete house before a nuclear explosion, Nevada Test Site.

5.38 This house stood up well, even at a peak overpressure of 5 pounds per square inch. By replacement of demolished or badly damaged doors and windows, it could have been made available for occupancy (Fig 5.38).

5.39 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

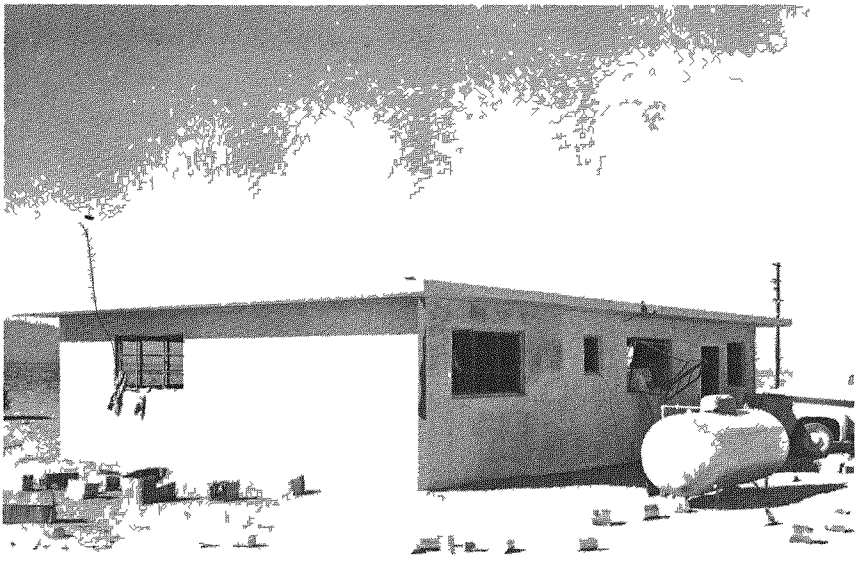

Figure 5 38 Reinforced precast concrete house after a nuclear explosion (5 psi overpressure). The LP-gas tank, sheltered by the house, is essentially undamaged

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.

5.40 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

5.41 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. 5.41).

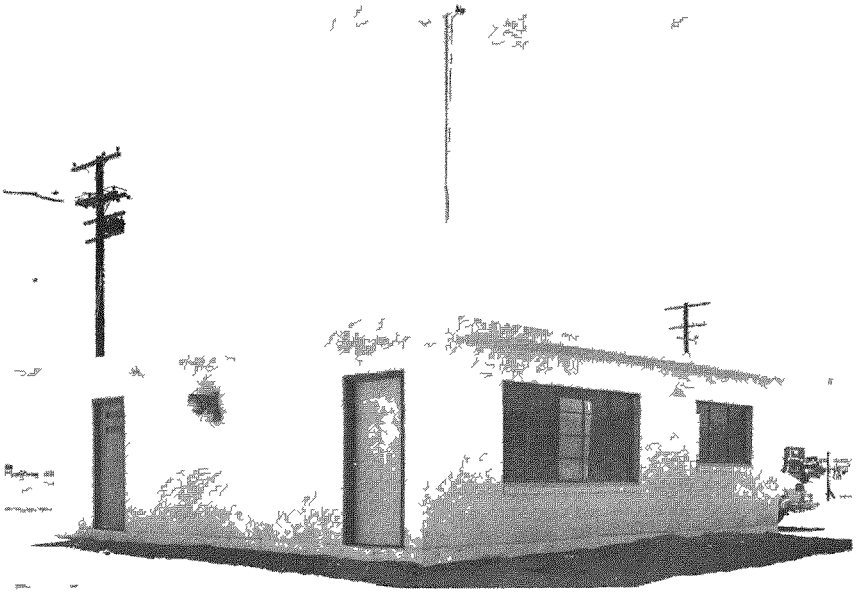

Figure 5 41 Reinforced masonry-block house before a nuclear explosion, Nevada Test Site

5.42 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. 5.42).

5.43 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 (see Fig. 5 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.

5.44 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 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 readily have been repaired.

Trailer-Coach Mobile Homes

5.45 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 dis-

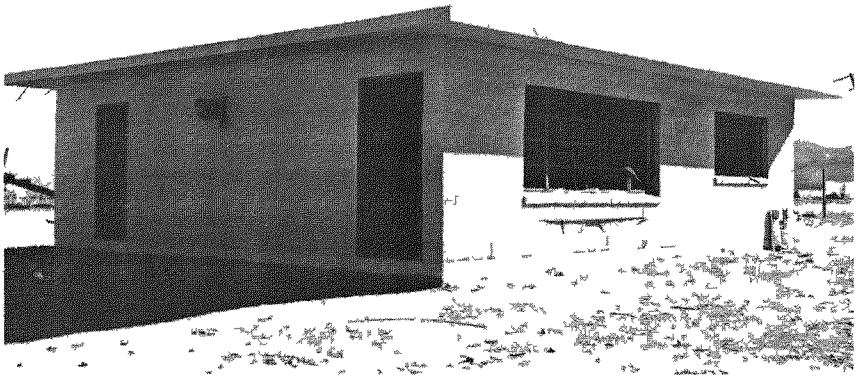

Figure 5 42 Reinforced masonry-block house after a nuclear explosion (5 psi overpressure)

tance 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.

5.46 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, because of different methods of construction, types of fastening, gage and design of die-formed metal, spacing of studs, and window sizes.

5.47 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.

5.48 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, improvising window coverings, and cleaning up the debris, all trailer-coaches could have been made habitable for emergency use.

5.49 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

5.50 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.

5.51 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.

5.52 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.

5.53 Containers made of soft materials, such as paper, polyethylene (plastic), or cardboard, were badly damaged by flying debris. 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

5.54 In Nagasaki there were many buildings of the familiar type, used for industrial purposes, consisting of a steel frame with roof and siding of corrugated sheet metal or of asbestos cement. In some 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.

5.55 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. 5.55 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 flexure, 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,

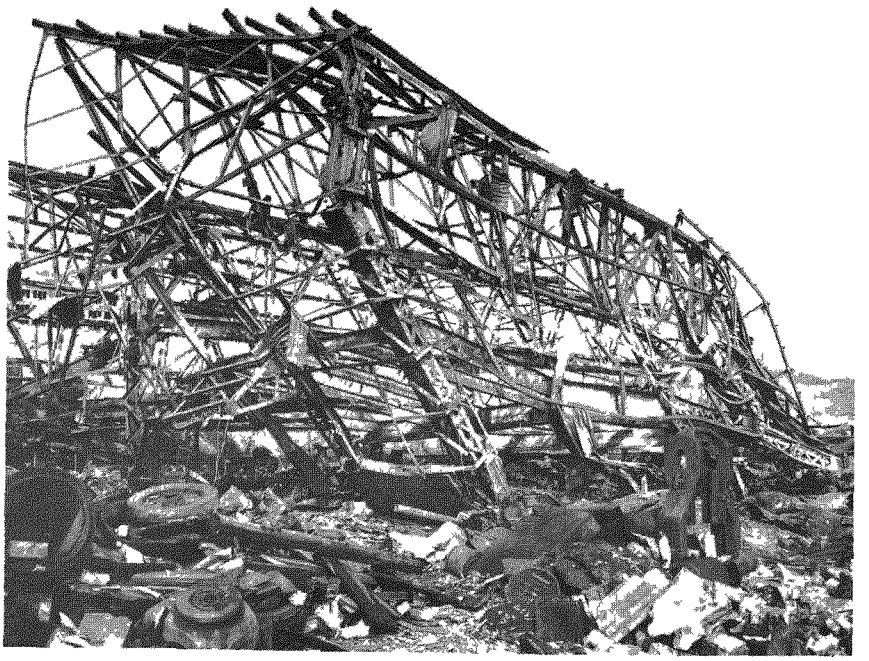

Figure 5 55a Industrial-type steel-frame building (0 35 mile from ground zero at Hiroshima) Wooden beams should be noted.

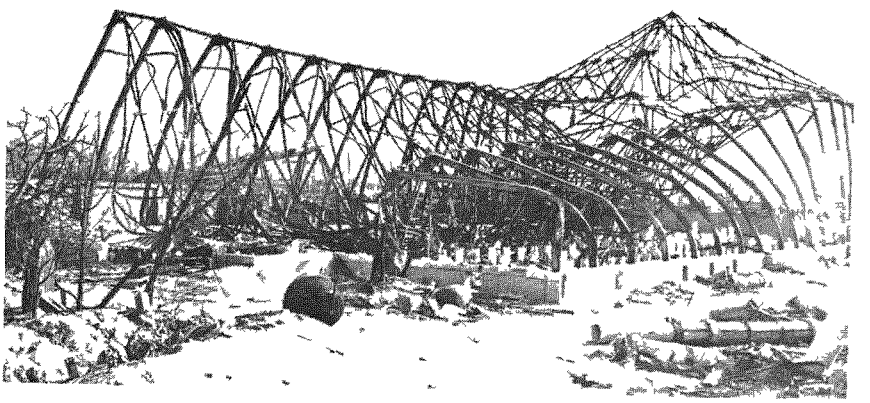

Figure 5 55b. Single story, light steel-frame building (0 8 mile from ground zero at Hiroshima), partially damaged by blast and further collapsed by subsequent fire.

complete collapse. Roof trusses were buckled by compression resulting from lateral blast loading on the side of the building facing the explosion.

5.56 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.

5.57 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.

5.58 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.

5.59 Damage to machine tools (Fig. 5.59) 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 belt-driven, so that the distortion of the building pulled the machine tool off its base, damaging or overturning it.

5.60 Smokestacks, especially those of reinforced concrete, proved to have considerable blast resistance (Fig. 5.60a). 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. 5.60b. 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

5.61 Three types of metal buildings of standard construction, such as are used for various commercial and industrial purposes, were exposed at peak overpressures of 3.0 and 1.3 pounds per square inch. The main objectives of the Nevada tests were to determine the blast

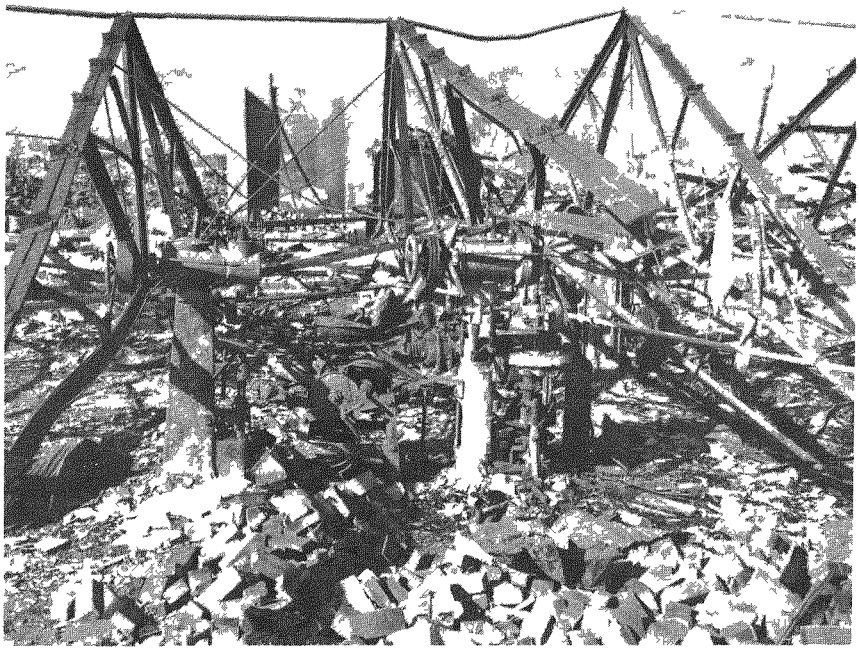

Figure 5 59. Damage to machine tools in steel-frame building (0.6 mile from ground zero at Hiroshima).

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

5.62 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. 5.62a) 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. On the side facing the explosion the deflection was about 1 foot at the eaves (Fig. 5.62b).

5.63 The aluminum-sheet panels were stripped from the front wall, together with most of their supporting girts and purlins. Girt and

Figure 5.60b. 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.

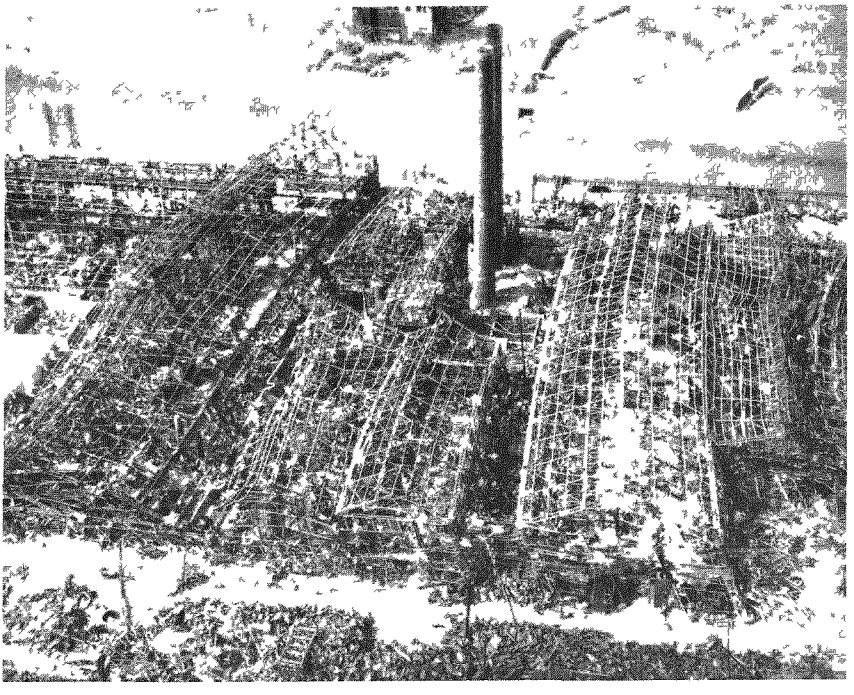

Figure 5.60a. Destroyed industrial area showing smokestacks still standing (0.51 mile from ground zero at Nagasaki).

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.

5.64 At a peak overpressure of 1.3 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.

5.65 As presently designed, structures of this type may be regarded as being repairable, provided they are not exposed to blast pressures

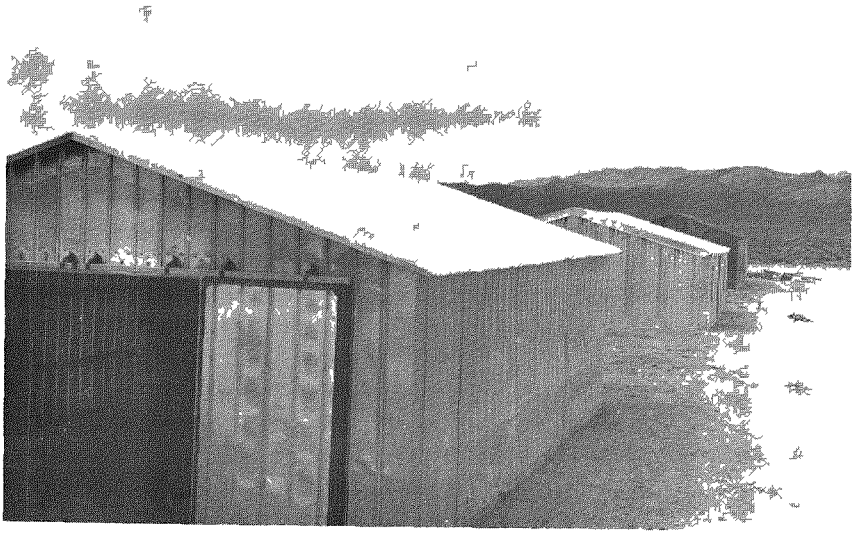

Figure 5 62a Rigid steel-frame building before a nuclear explosion, Nevada Test Site

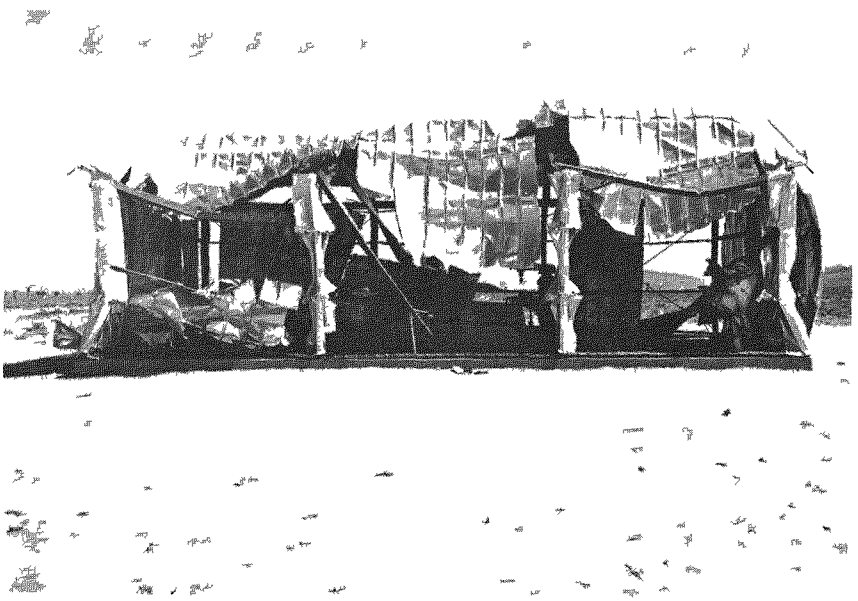

Figure 5 62b Rigid steel-frame building after a nuclear explosion (3 1 psi overpressure)

exceeding 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

5.66 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. 5.66a). The one subjected to 3.0 pounds per square inch overpressure (and a dynamic pressure of 0.2 pound per square inch) was completely demolished (Fig. 5.66b). 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.

5.67 Although damage at 1.3 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, the roof structure remained intact, except for some deflection near the center.

5.68 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

5.69 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. 5.69).

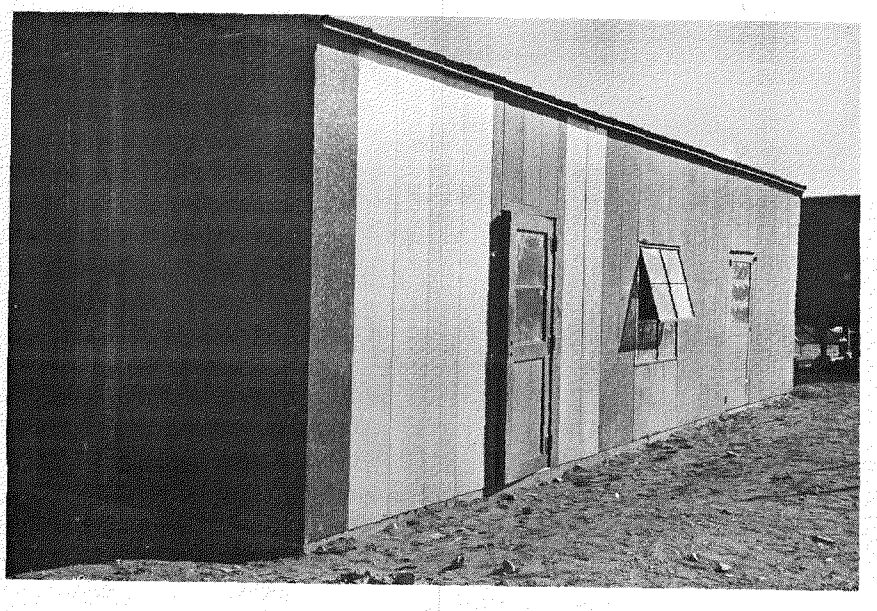

Figure 5.66a. Exterior of self-framing steel panel building before a nuclear explosion, Nevada Test Site.

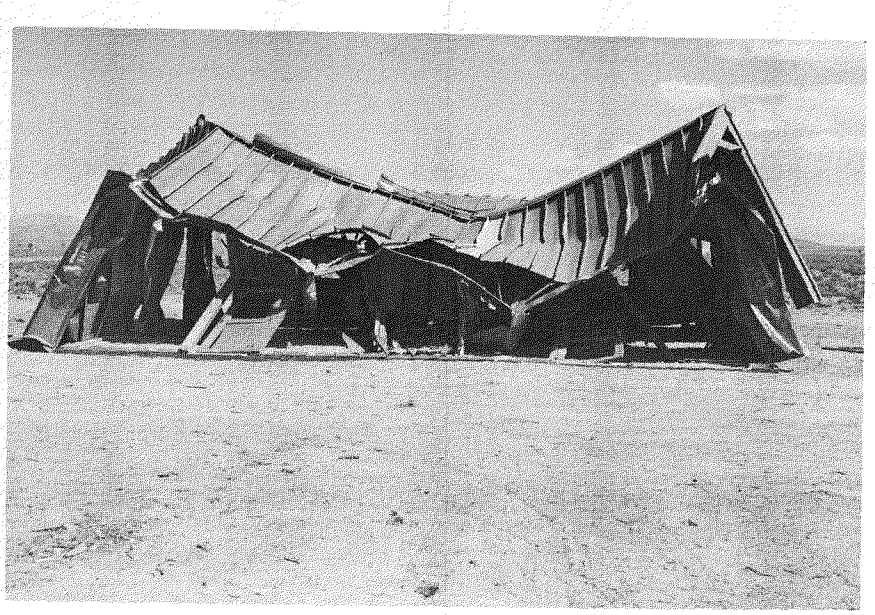

Figure 5.66b. Self-framing steel panel building after a nuclear explosion (3.1 psi overpressure).

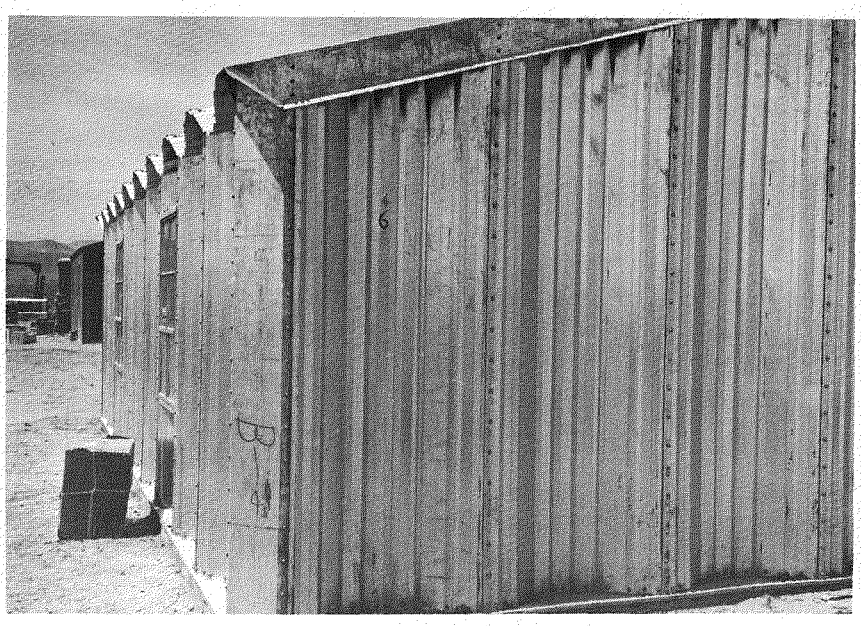

Figure 5.69. Self-framing corrugated steel panel building before a nuclear explosion, Nevada Test Site.

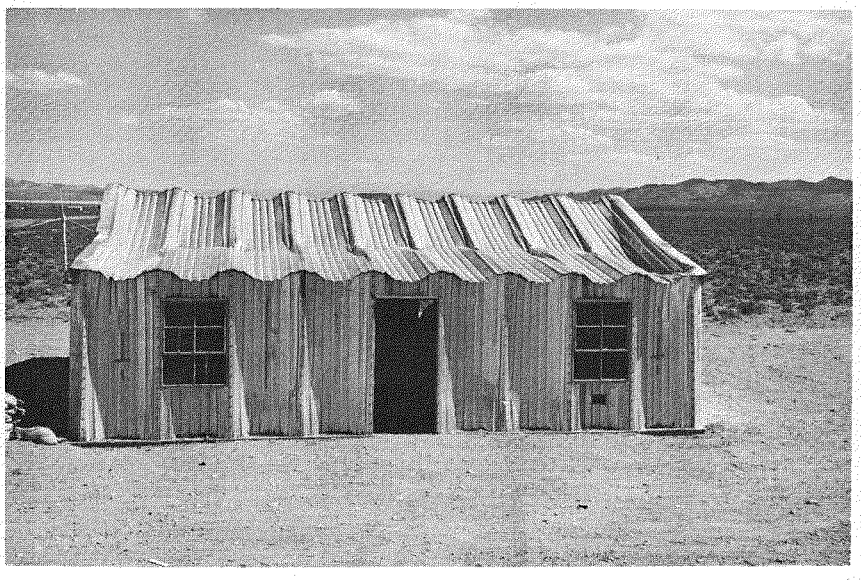

Figure 5.70. Self-framing corrugated steel panel building after a nuclear explosion (3.1 psi overpressure).

5.70 At a peak overpressure of 3.0 and a dynamic pressure of 0.2 pounds per square inch a structure of this type was 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 midsection, and the ridge line suffered moderate deflection. The rear slope of the roof appeared to be essentially undamaged (Fig. 5.70).

5.71 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.

5.72 Another building of this type, exposed to 1.3 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.

5.73 The corrugated steel, frameless structure proved to be the most blast-resistant 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.

Positive Phase Duration Tests

5.74 Tests were carried out at Nevada in 1955 and at Eniwetok in 1956 to investigate the effect of the difference in duration of the positive overpressure phase of a blast wave on damage. Typical-drag-type structures were exposed, at approximately the same overpressure, to nuclear detonations in the kiloton and megaton ranges. Two representative types of small industrial buildings were chosen for these tests. One had a steel frame covered with siding and roofing of a frangible material and was considered to be a drag-type structure (Fig. 5.74a). The other had the same steel frame and roofing, but it had concrete siding with a window opening of about 30 percent of the wall area; this was regarded as a semidrag structure (Fig. 5.74b).

5.75 In the Nevada tests, with kiloton yield weapons, the first structure was subjected to a peak overpressure of about 6.5 and a dynamic pressure of 1.1 pounds per square inch; the positive phase

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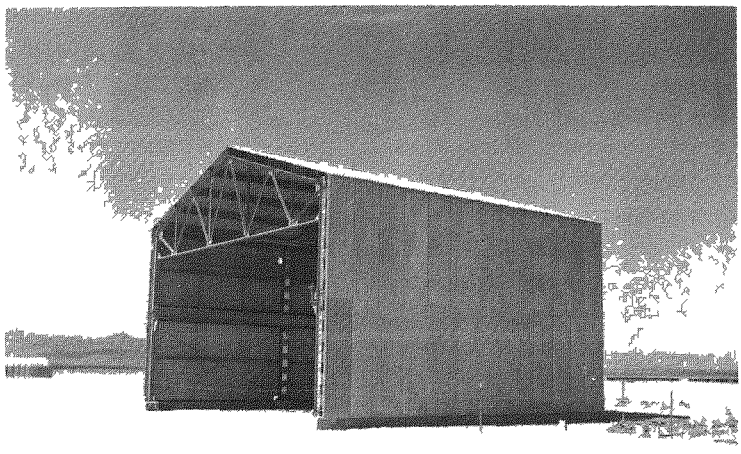

Figure 5 74a Steel-frame building with siding and roof of frangible material

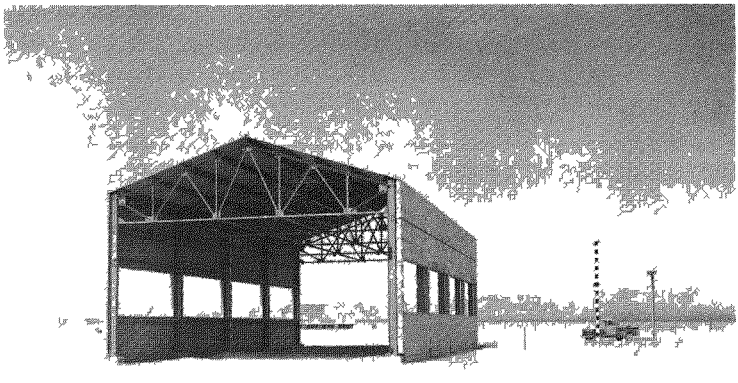

Figure 5 74b Steel-frame building with concrete siding and window openings of 30 percent of the wall area

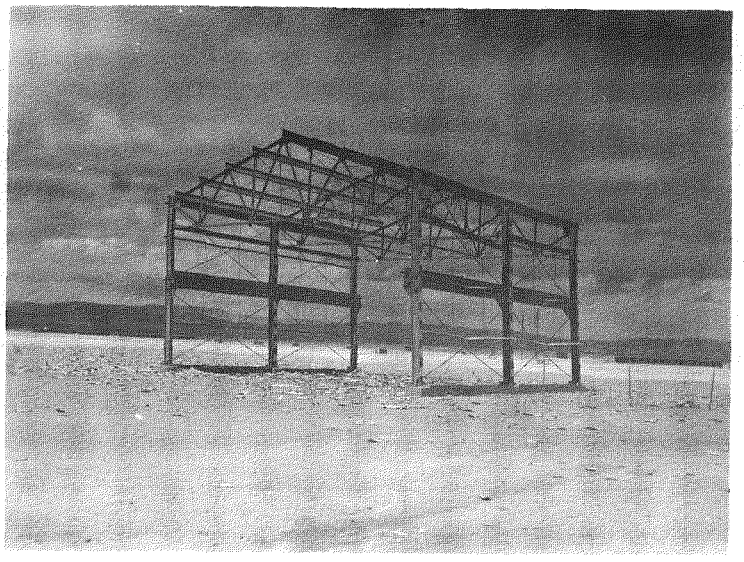

Figure 5.75. Structure in Figure 5.74a after exposure to 6.5 psi overpressure and 1.1 psi dynamic pressure; positive phase duration 0.9 second.

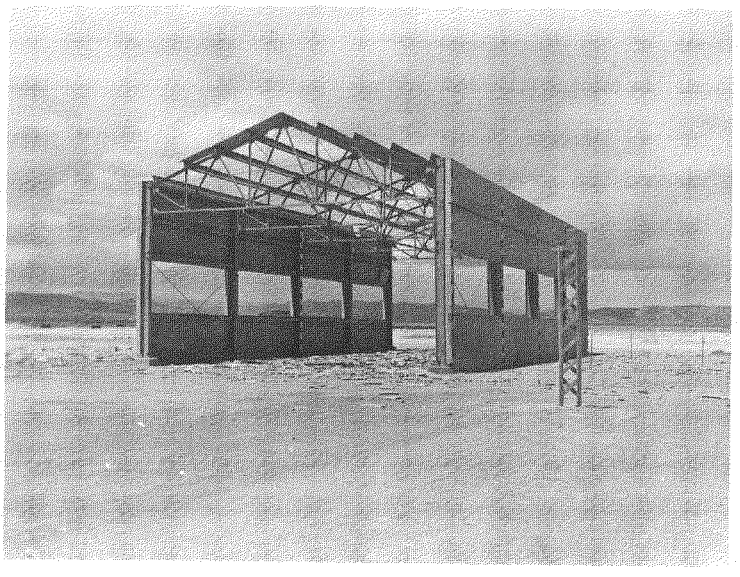

Figure 5.76. Structure in Figure 5.74b after exposure to 3.5 psi overpressure and 0.3 psi dynamic pressure; positive phase duration 1 second.

duration of the blast wave was 0.9 second. A permanent horizontal deflection of about 15 inches occurred at the top of the columns. The column anchor bolts failed, and yielding was found between the lower chord and column connections. The girts on the windward side were severely damaged and all of the siding was completely blown off (Fig. 5.75).

5.76 The second building, with the stronger siding, was exposed in Nevada to an overpressure loading of about 3.5 and a dynamic pressure of 0.3 pounds per square inch, with a positive phase duration of 1 second. Damage to this structure was small (Fig. 5.76). Although almost the whole of the frangible roof was blown off, the only other damage observed was a small yielding at some connections and column bases.

5.77 Structures of the same type were subjected to similar pressures in the blast wave from a megaton range explosion at Eniwetok; namely, an overpressure of 6.1 and a dynamic pressure of 0.6 pounds per square inch for the drag-type building, and 5 and 0.5 pounds per square inch, respectively, for the semi-drag structure; however, the positive phase now lasted several seconds as compared with about 1 second in the Nevada tests. Both structures suffered complete collapse (Figs. 5.77 a and b). Distortion and breakup occurred throughout, particularly of columns and connections. It was concluded, therefore, that damage to drag-sensitive structures can be enhanced, for a given peak pressure value, if the duration of the positive phase of the blast wave is increased.

Oil Storage Tanks

5.78 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 explosion 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 blast wave from the explosion was comparable to that of a 2- to 4-kiloton nuclear weapon. The serious fire hazard represented by the fuel stored in such tanks is obvious from Fig. 5.78a which shows both blast and fire destruction. Figure 5.78b indicates minor blast damage and some missile damage to the storage tank walls.

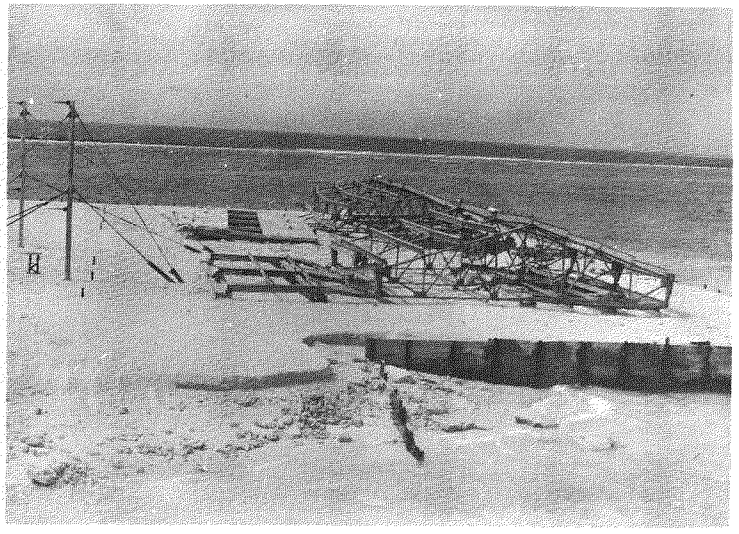

Figure 5.77a. Structure similar to Figure 5.74a after exposure to 6.1 psi overpressure and 0.6 psi dynamic pressure; positive phase duration several seconds.

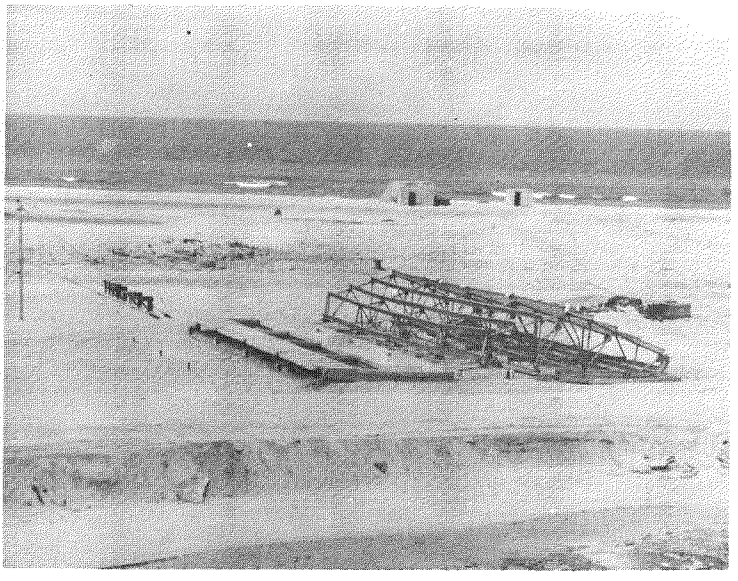

Figure 5.77b. Structure similar to Figure 5.74b after exposure to 5 psi overpressure and 0.5 psi dynamic pressure; positive phase duration several seconds.

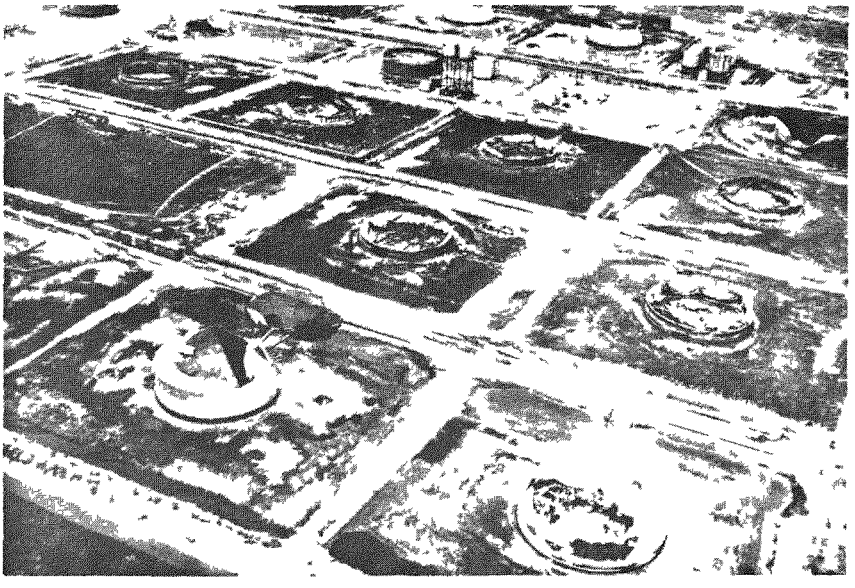

Figure 5.78a. General blast and fire damage at Texas City April 16–17, 1947; distance of foreground from detonation 0.65 mile

Figure 5.78b. Light missile and blast damage to oil tanks, 0.70 mile from detonation at Texas City April 16–17, 1947

Heavy-Duty Machine Tools

5.79 Some reference has been made above (§ 5.59) 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 infor-

mation 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. 5.79). 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.

5.80 Of the four machines, the three lighter ones were moved from their foundations and damaged quite badly (Fig. 5.80a). The fourth, weighing 12,000 pounds, which was considered as the only one to be actually of the heavy-duty type, survived (Fig. 5.80b). 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.

5.81 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 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.

5.82 Behind the two-story brick house in the overpressure region of 5 pounds per square inch (§ 5.30) 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. Moreover, 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.

5.83 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

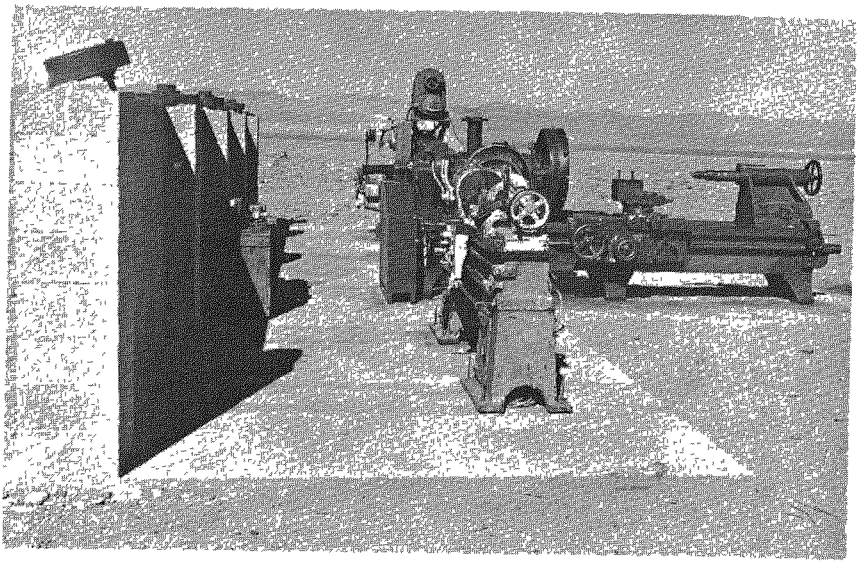

Figure 5.79. Machine tools behind masonry wall before a nuclear explosion, Nevada Test Site.

Figure 5.80a. Machine tools after a nuclear explosion (10 psi overpressure).

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 (§ 5 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.

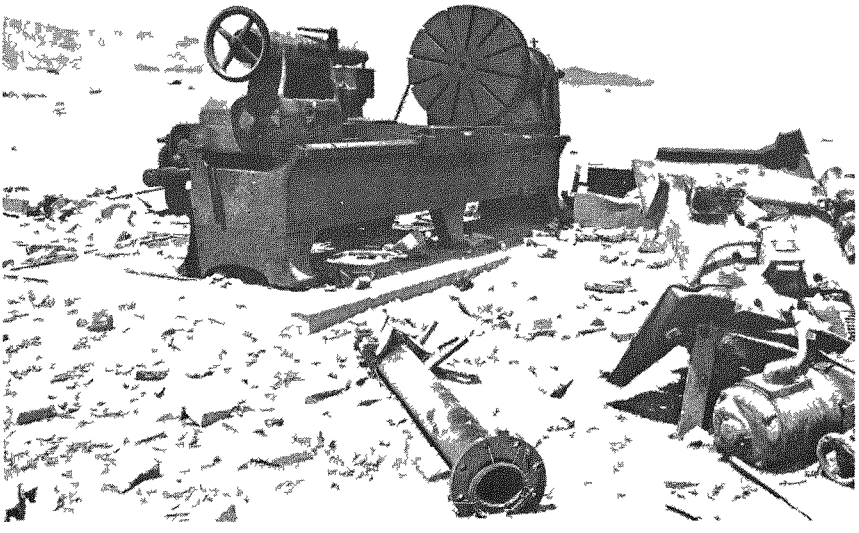

Figure 5 80b Heavy-duty lathe after a nuclear explosion (10 psi overpressure)

5.84 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 (§ 5.59). 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 and missiles produced in the tests was probably less than in the industrial buildings in Japan.

COMMERCIAL AND ADMINISTRATIVE STRUCTURES

Introduction

5.85 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

5.86 There were many multistory, reinforced-concrete frame 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. 5.86a. 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. 5.86b, at about the same distance from ground zero. This suffered more severely than the one of aseismic design.

5.87 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.

5.88 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. 5.88a) 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. At greater distances, from

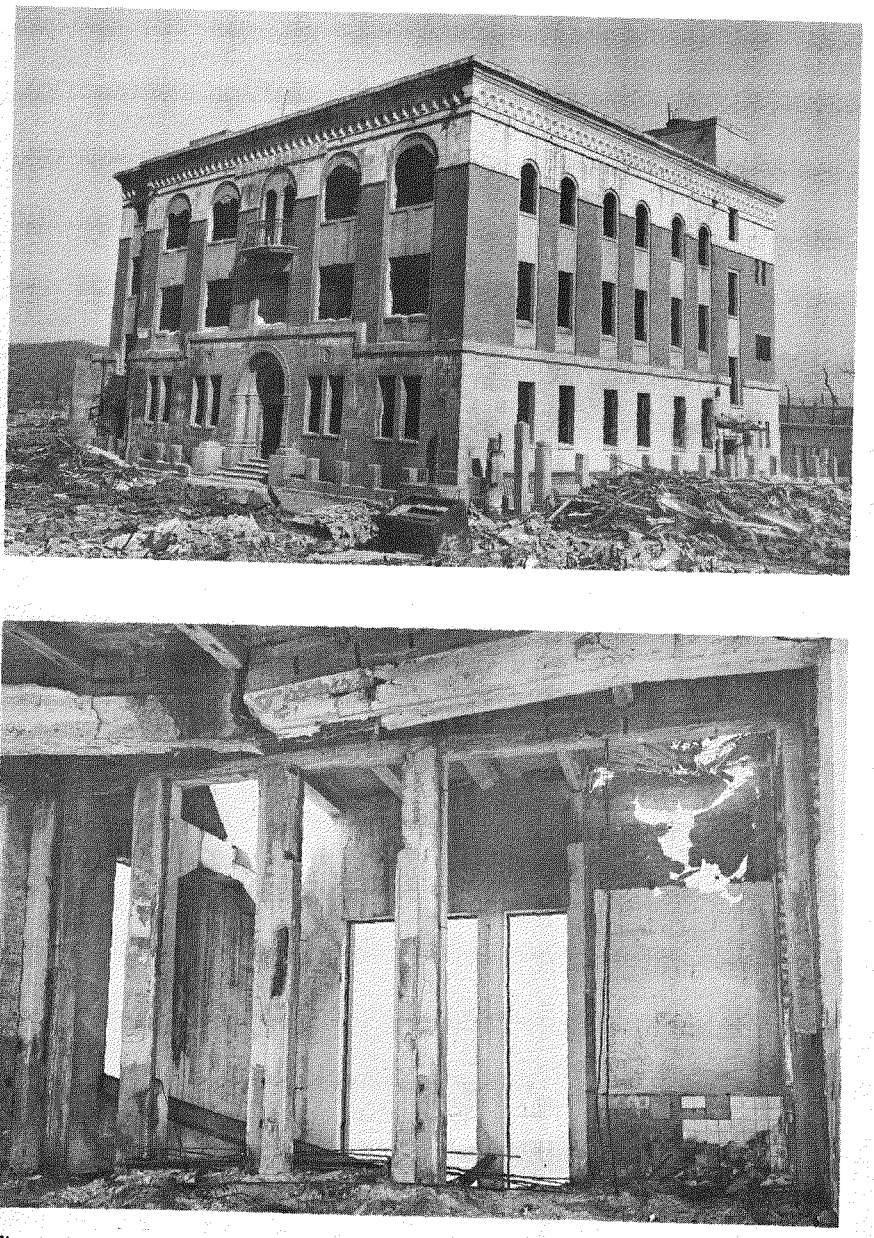

Figure 5.86a. Upper photo: Reinforced-concrete, aseismic structure; window fire shutters were blown in by blast and the interior gutted by fire (0.12 mile from ground zero at Hiroshima). Lower photo: Burned out interior of similar structure.

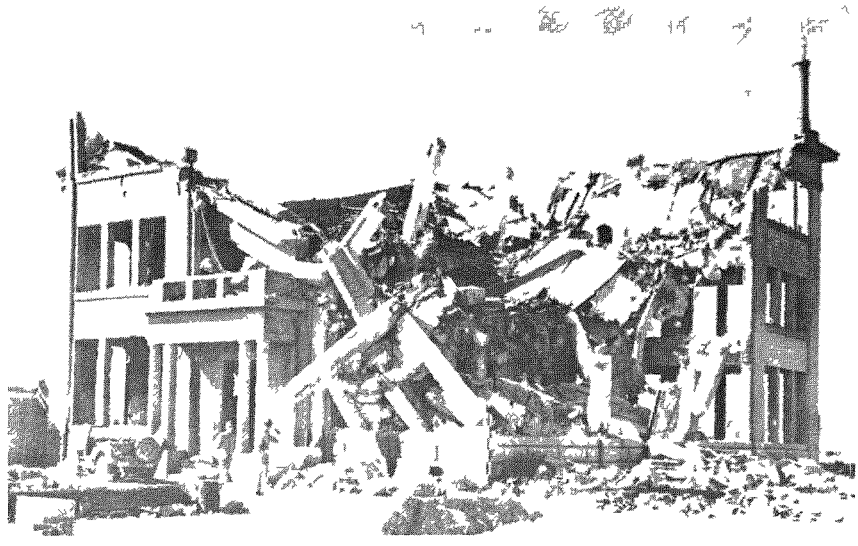

Figure 5.86b. Three-story, reinforced-concrete frame building; walls were 13-inch thick brick panel with large window openings (0 13 mile from ground zero at Hiroshima).

ground zero, especially in the region of Mach reflection, the consequences of horizontal loading were apparent (Figs. 5.88 b and c).

5.89 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. 5.89 a, 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.

5.90 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

5.91 There was apparently only one steel-frame structure having more than two stories in the Japanese cities exposed to nuclear ex-

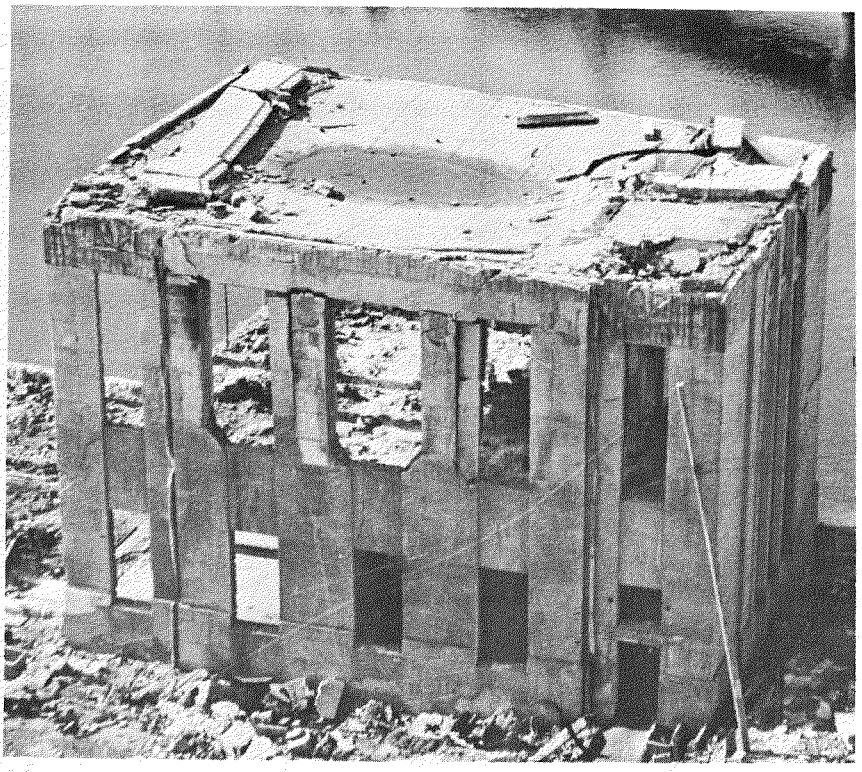

Figure 5.88a. Depressed roof of reinforced-concrete building (0.10 mile from ground zero at Hiroshima).

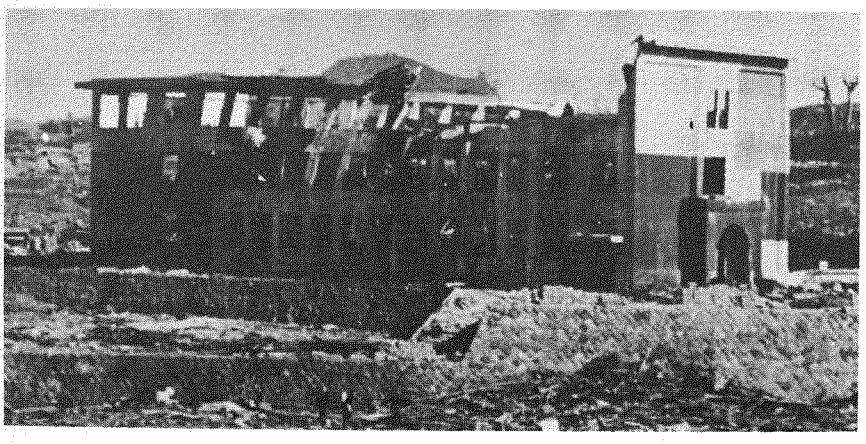

Figure 5.88b. Effects of horizontal loading on wall facing explosion (0.4 mile from ground zero at Nagasaki).

Figure 5.88c. 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.

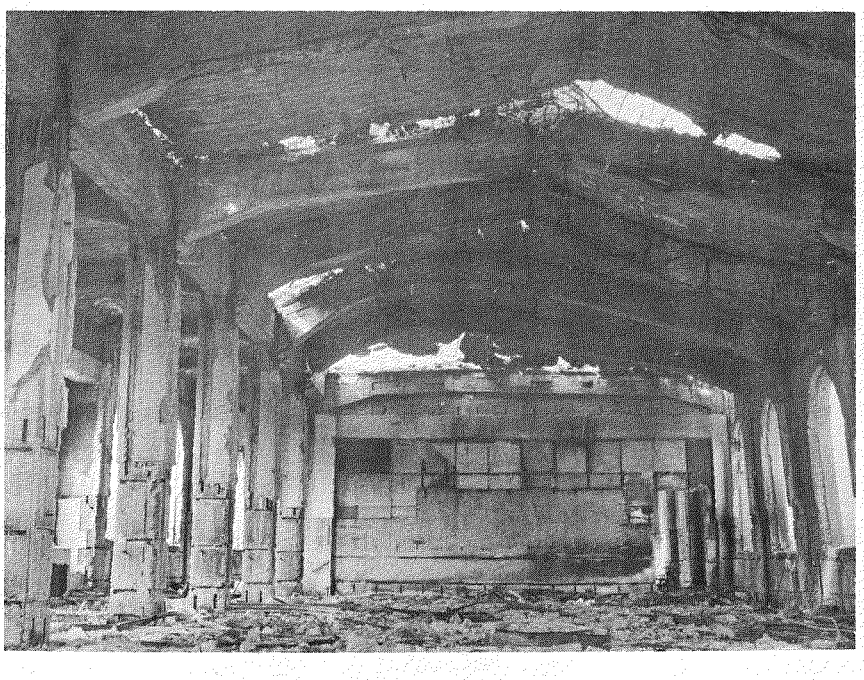

Figure 5.89a. Buckling and cracking of beams in reinforced-concrete building (0.32 mile from ground zero at Nagasaki).

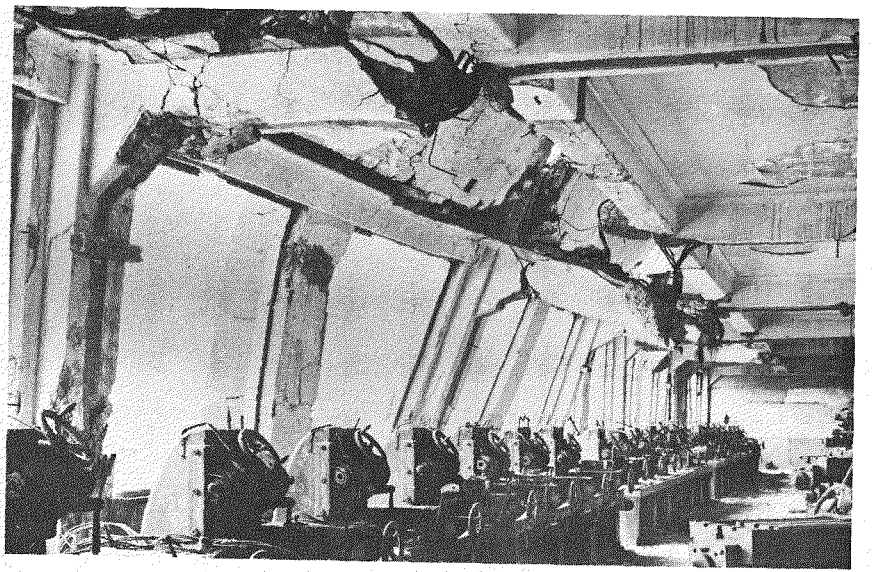

Figure 5.89b. Multistory reinforced-concrete frame building showing the failure of columns and girders (0.36 mile from ground zero at Nagasaki).

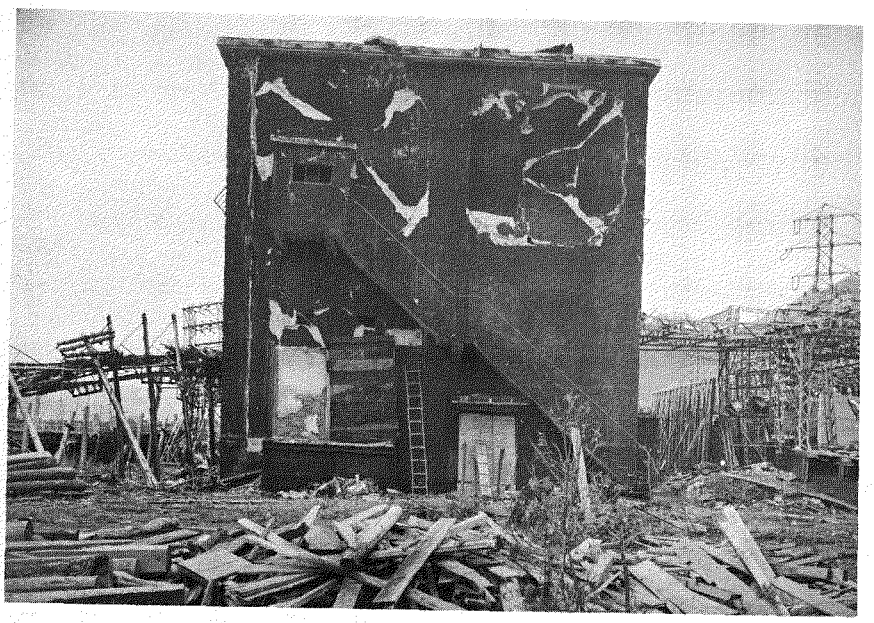

Figure 5.89c. Reinforced-concrete frame building showing crushed concrete panel walls on side facing explosion (0.68 mile from ground zero at Nagasaki).

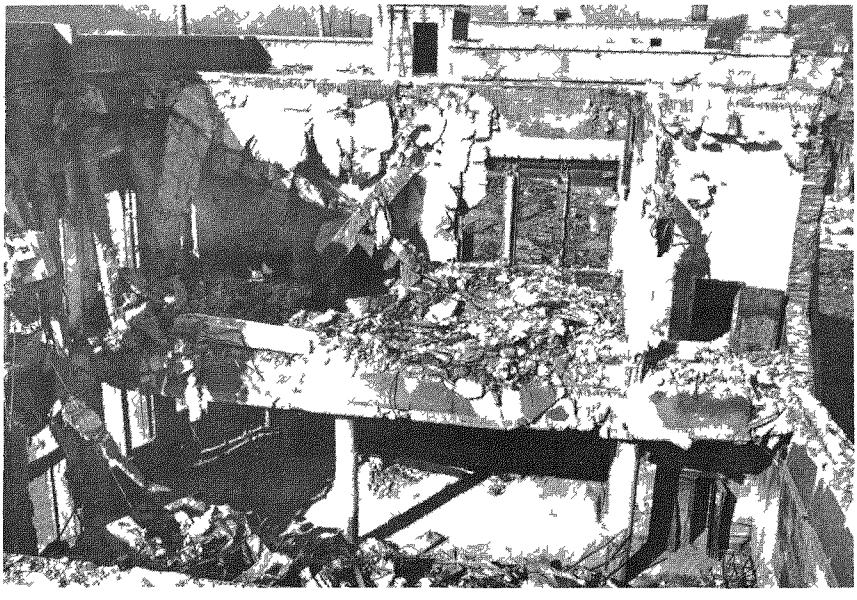

Figure 5 89d Reinforced-concrete building showing collapsed roof and floor slabs (0 10 mile from ground zero at Nagasaki)

plosions. This was a five-story structure in Nagasaki at a distance of 4,500 feet (0.85 mile) from ground zero (Fig. 5.91). 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.

5.92 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. 5 92 The heavy walls of the structure transmitted their loads to the steel frame, the columns of which collapsed.

Buildings With Load-Bearing Walls

5.93 Small structures with light load-bearing walls offered little resistance to the nuclear blast and, in general, collasped completely

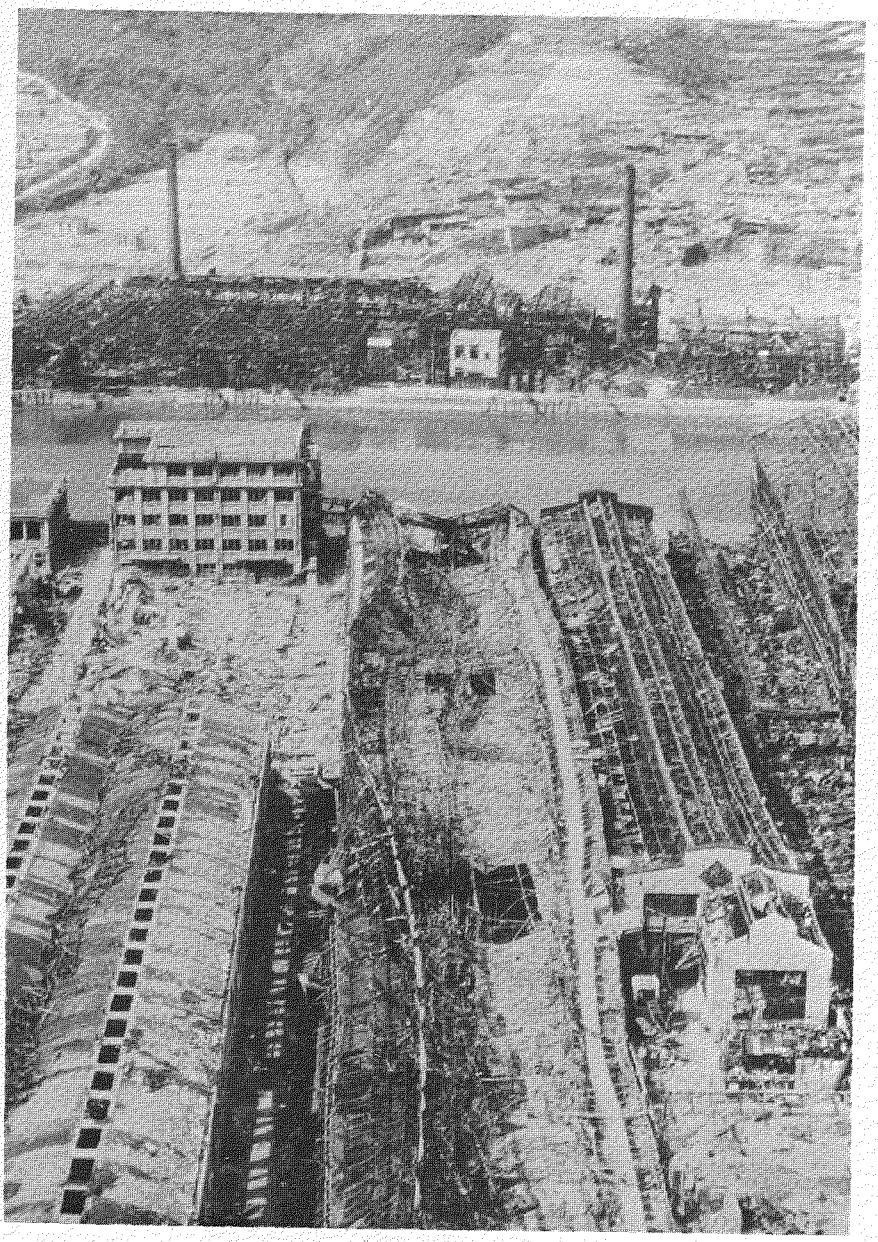

Figure 5.91. At left and back of center is a multistory, steel-frame building (0.85 mile from ground zero at Nagasaki).

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Figure 5 92 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

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 5 93 a 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.

Figure 5 93a. 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

Bridges

5.94 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. 5.94 a, b, and c). One bridge, only 270 feet from ground zero, i.e., about 2,100 feet from the point of explosion, 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, apparently as a result of reflection of the blast wave from the surface of the water below.

TRANSPORTATION

Streetcars and Automobiles

5.95 In Japan, trolley-car equipment was heavily damaged by both blast and fire, although the poles were frequently left standing

Figure 5 93b Heavy wall-bearing structure, the 28-inch thick exterior walls of brick with buttresses were shattered (0 34 mile from ground zero at Nagasaki)

(see Fig. 5.94b). Buses and automobiles were, in general, rendered inoperable by blast and fire as well as by damage caused by flying debris. 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. 5.95), but a similar vehicle at 6,000 feet (1 14 miles) suffered only minor damage.

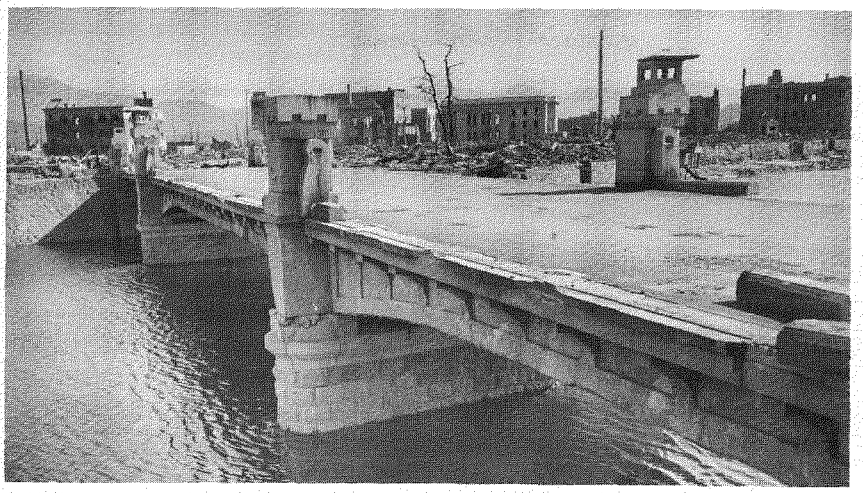

Figure 5.94a. Bridge with deck of reinforced concrete on steel-plate girders; outer girder had concrete facing (270 feet from ground zero at Hiroshima). The railing was blown down but the deck received little damage so that traffic continued.

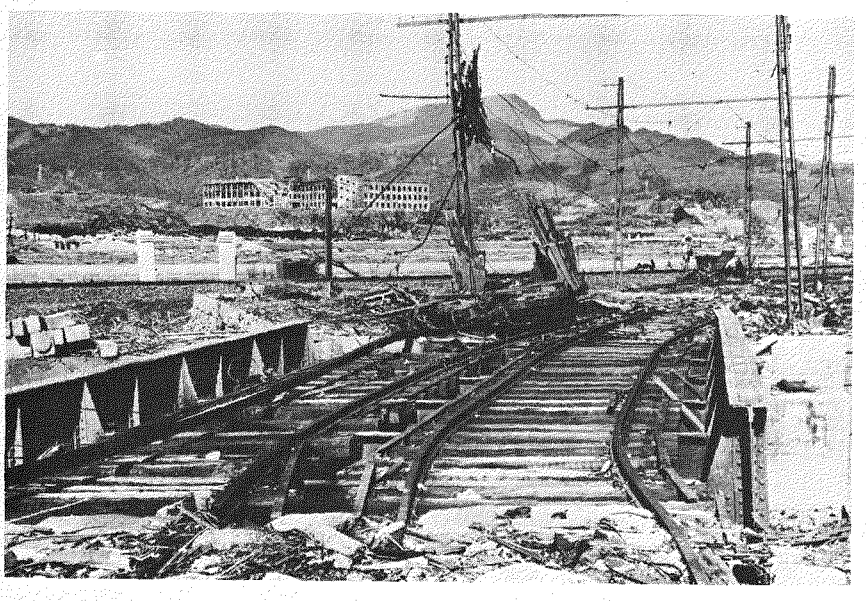

Figure 5.94b. A steel-plate girder, double-track railway bridge (0.16 mile from ground zero at Nagasaki). The plate girders were moved about 3 feet by the blast; the railroad tracks were bent out of shape and trolley cars were demolished, but the poles were left standing.

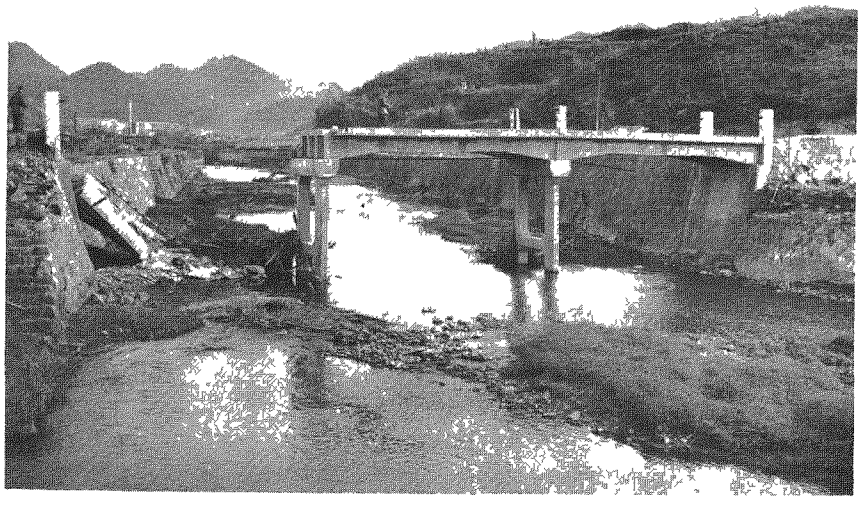

Figure 5.94c. A reinforced-concrete bridge with T-beam deck (0.44 mile from ground zero at Nagasaki). Part of deck was knocked off the pier and abutment by the blast, causing one span, 35 feet long, to drop into the river. The remainder of the bridge was almost undamaged.

5.96 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. In addition, allowance must be made for the effect of the blast wave precursor, described in §§ 3.43, 3.72. Hence, the damage radii cannot be determined from overpressure alone. The damage-distance nomograph in Fig. 4.58b takes these facts into account for average conditions. Some illustrations of the effects of a nuclear explosion on motorized vehicles are shown in Figs. 5.96 a, b, e, 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 overall damage was greater, the motors appeared to be intact.

Figure 5 95 General view at Nagasaki showing wrecked automobile in foreground (0 57 mile from ground zero)

Figure 5 96a 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 5.96b. Damage to automobile originally located behind wood-frame house (5 psi overpressure); the front of this car can be seen in Figure 5.14. Although badly damaged, the car could still be driven after the explosion.

Emergency Vehicles

5.97 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 overpressure 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 emphasized, however, that, as for automobiles, the overpressure is not the sole criterion of damage, as stated above.

5.98 The rescue truck at the 30 pounds 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 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 (Fig. 5.98). The earth-boring machine was knocked loose and was on its side, leaking gasoline and water. At the same location, shown to the left of the overturned truck in Fig. 5.98, was a

Figure 5 96c 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 5.96d Interior damage to bus shown above, caused by blast, displacement, and fire

heavy-duty electric utility truck, facing head-on to the blast. It had the windshield shattered, both doors and cab dished in, the hood partly blown off, and one tool-compartment door dished. There was, however, no damage to tools or equipment and the truck was driven away without any repairs being required.

5.99 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.

5.100 It may be concluded that vehicles designed for disaster and emergency operation are substantially constructed, so that they can withstand a 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.

Figure 5.98. Truck broadside to the blast wave (5 psi overpressure) overturned, electric utility truck in background head-on to blast was damaged but remained standing

Railroad Equipment

5.101 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 may be expected to receive relatively minor damage. At 4 pounds per square inch overpressure, the damage to a loaded wooden boxcar was more severe (Fig. 5.101a). 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. 5.101b). 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.

5.102 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

5.103 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 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.

5.104 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. 5.104a. The fuselage of this aircraft failed completely just aft of the wing. The skin of the fuselage, stabilizers, and engine cowling was severely buckled. Figure 5.104b shows damage to an aircraft oriented with its tail toward the burst and exposed to a blast of 2.4

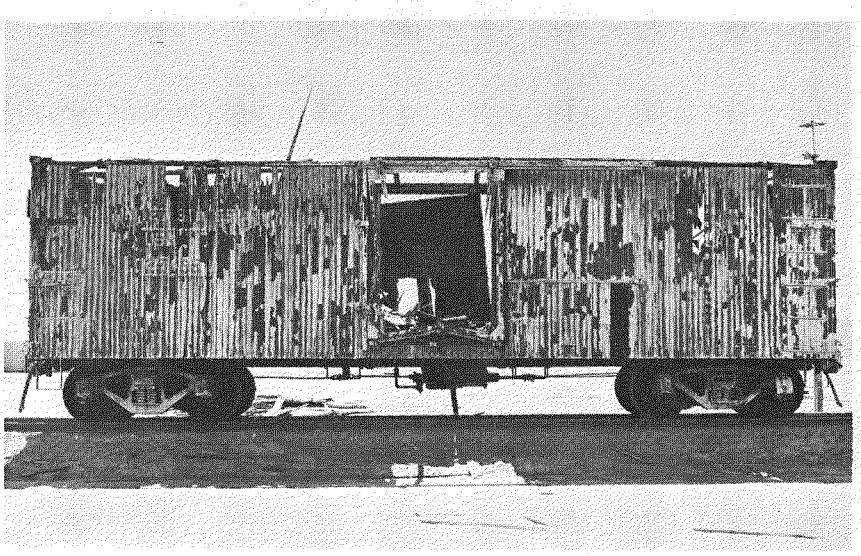

Figure 5.101a. Loaded wooden boxcar after a nuclear explosion (4 psi overpressure).

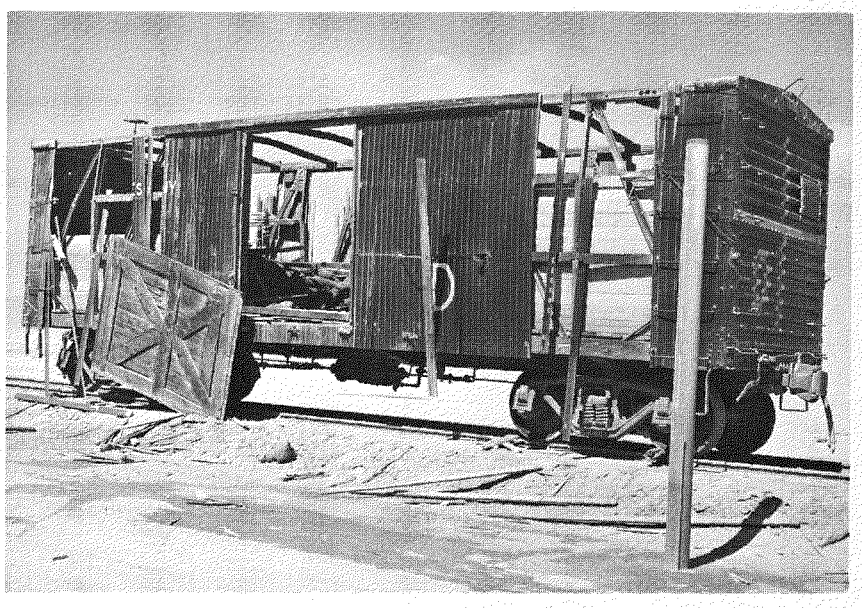

Figure 5.101b. Loaded wooden boxcar after a nuclear explosion (6 psi overpressure).

pounds per square inch peak overpressure. Skin was dished in on the vertical stablizer, horizontal stabilizers, wing surface above the flaps, and outboard wing sections. Vertical stabilizer bulkheads and the fuselage frame near the cockpit were buckled.

Shipping

5.105 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. 5.105 a 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).

5.106 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.

5.107 Closing of all exterior openings, prior to exposure to a nuclear explosion, will not safeguard light structures and shock-sensitive equipment (in the interior of the vessel) from serious damage. A reduction in damage intensity may be achieved by shock mounting.

5.108 Structures on the ships' decks were not protected and so were severely damaged by the air blast (Figs. 5.108 a 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.

UTILITIES AND COMMUNICATIONS

Electrical Distribution Systems

5.109 Because of the extensive damage caused by the nuclear explosions to the cities in Japan, the electrical distribution systems

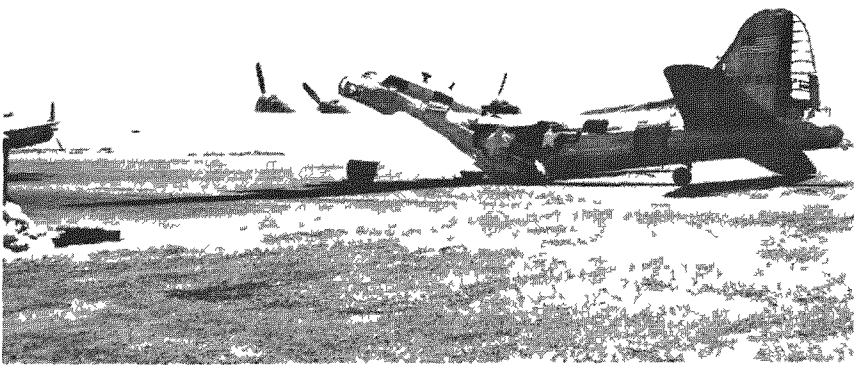

Figure 5.104a. Aircraft after side exposed to a nuclear explosion (3.6 psi overpressure).

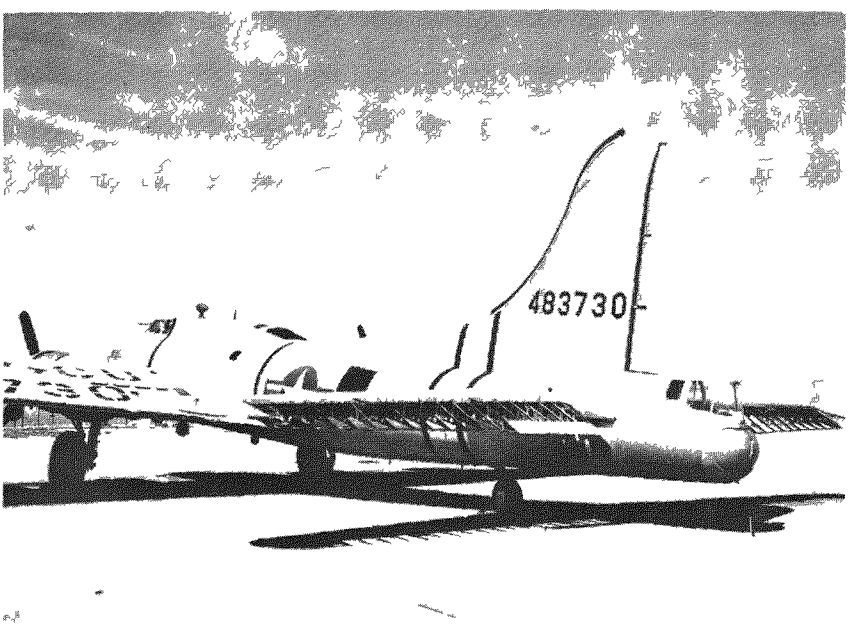

Figure 5.104b. Aircraft after tail exposed to a nuclear explosion (2 4 psi overpressure).

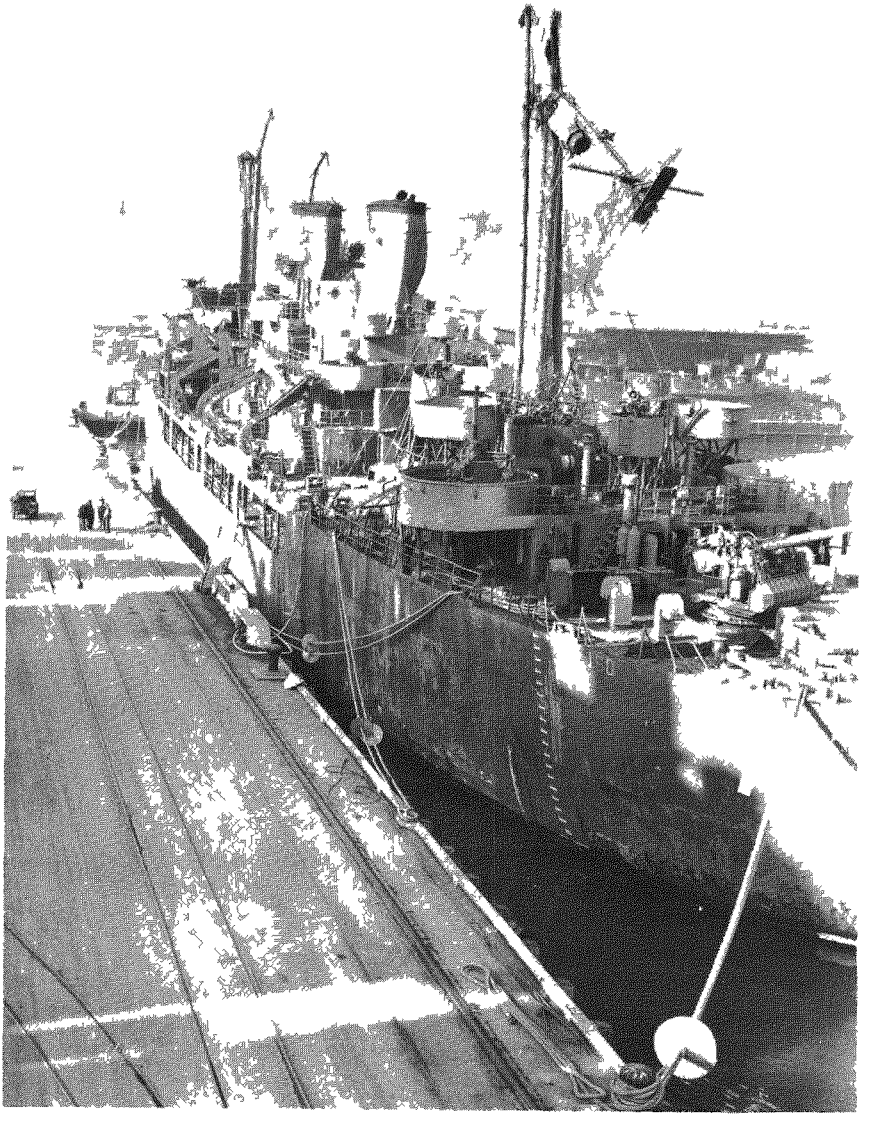

Figure 5 105a The U S S Crittenden after ABLE test, damage resulting was generally serious (0 47 mile from surface zero)

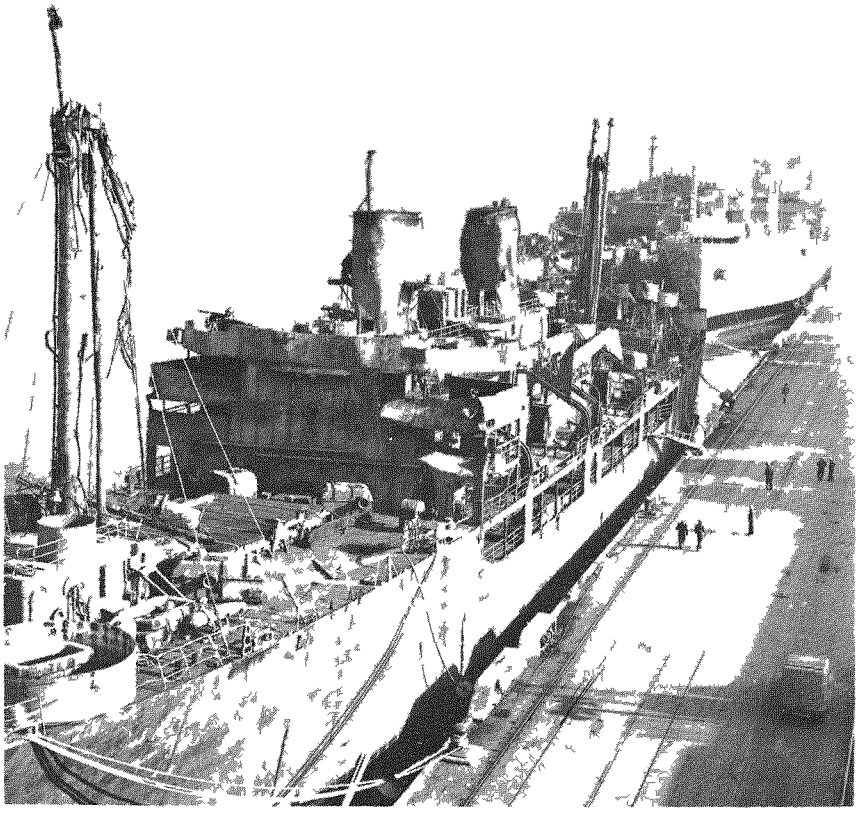

Figure 5 105b Major visible superstructure damage to U S S Crittenden, showing failure of the masting, crushing of the stacks, and damage to the bridge area

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. 5 109). 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.

5.110 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 blast pressure at which standard electrical equipment might be ex-

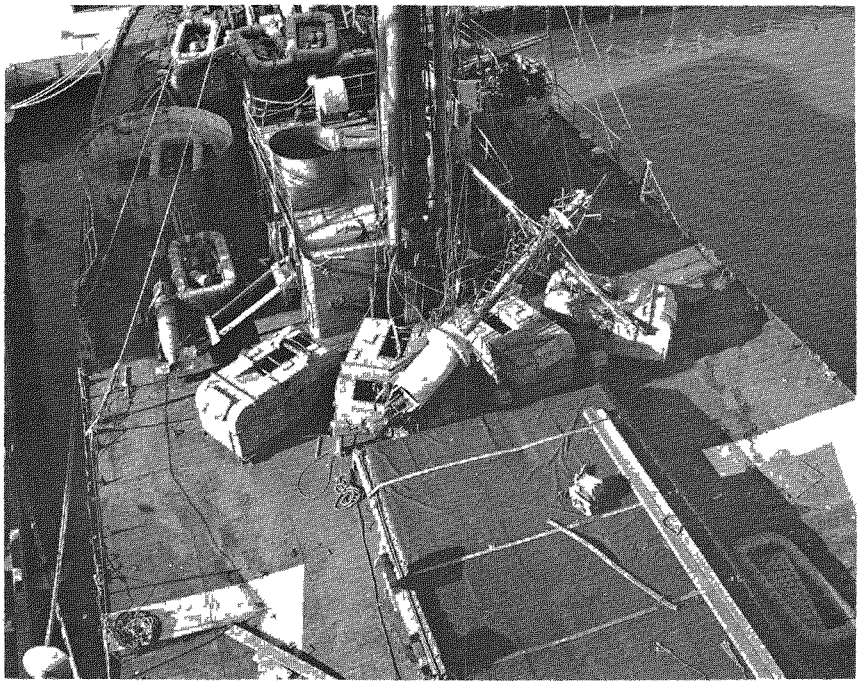

Figure 5.108a Damage to the forecastle of the U.S.S. Crittenden at the ABLE test.

pected 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 peak overpressure of about 5 and a dynamic pressure of 0.6 pounds per square inch and the other to 1.7 and 0.1 pounds per square inch, respectively. It will be recalled that at the lower overpressure, typical American residences would not be damaged beyond the possibility of further use.

5.111 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

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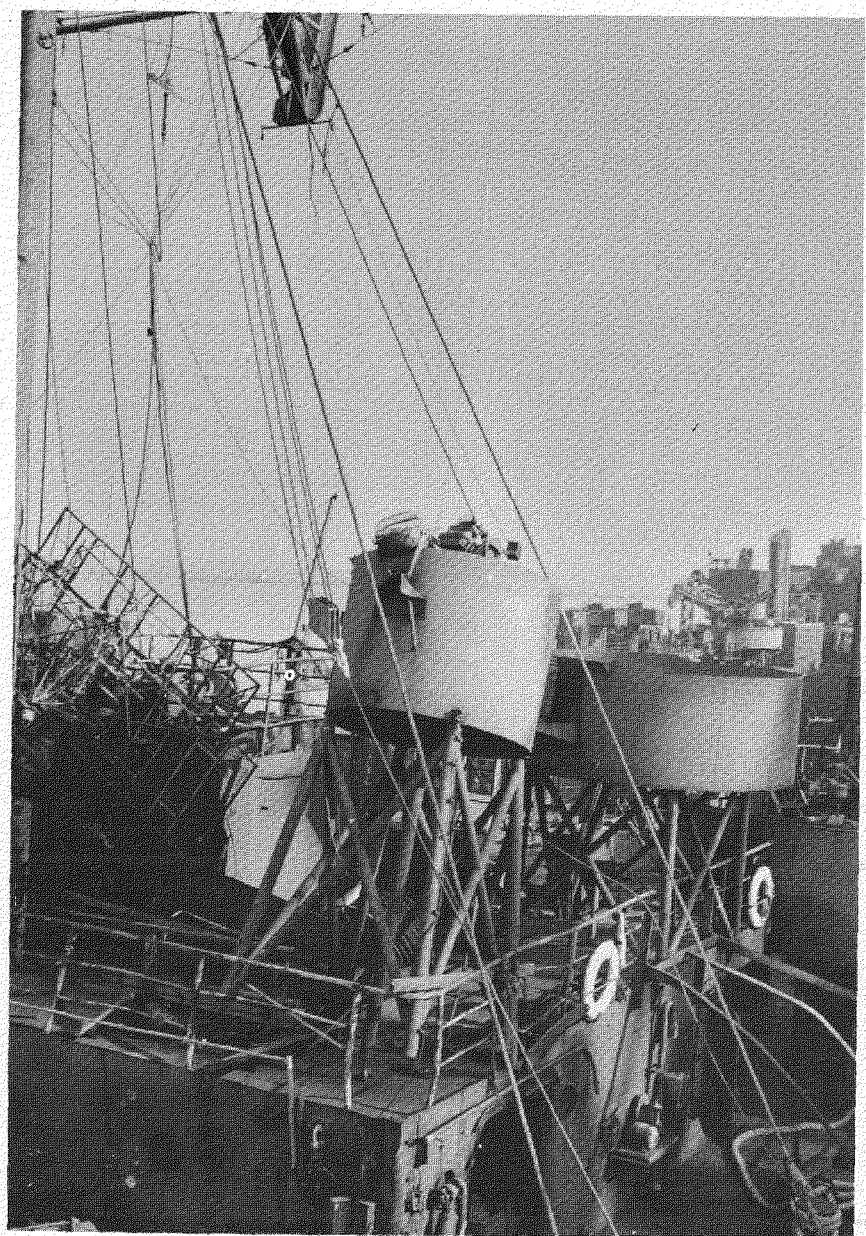

Figure 5.108b. Stern deck damage to U.S.S. Crittenden.

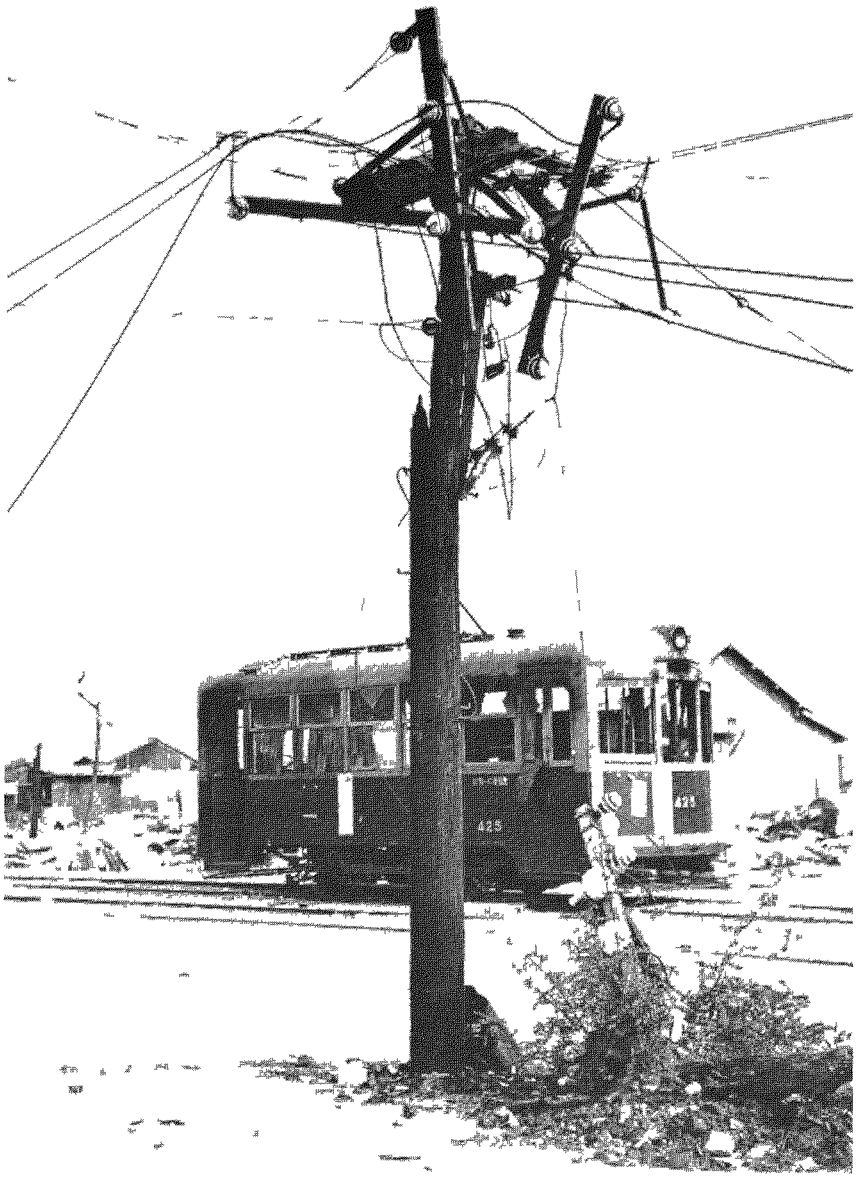

Figure 5.109. Damage to utility pole (0.80 mile from ground zero at Hiroshima).

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.

5.112 At an overpressure of 5 and a dynamic pressure of 0.6 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.

5.113 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. 5.113a). 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. 5.113b). In some parts of the United States, the suspension towers are of similar heavy construction. Structures of this type are sensitive to drag forces which are related to dynamic pressure, so that the overpressure is not the important criterion of damage.

5.114 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 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.

5.115 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. 5.115). Other damage was believed to be due to missiles.

5.116 Several distributor transformers had fallen from the poles, and secondary wires and service drops were down (Fig. 5.116). Nevertheless, the transformers, pot heads, arresters, cut-outs, pri-

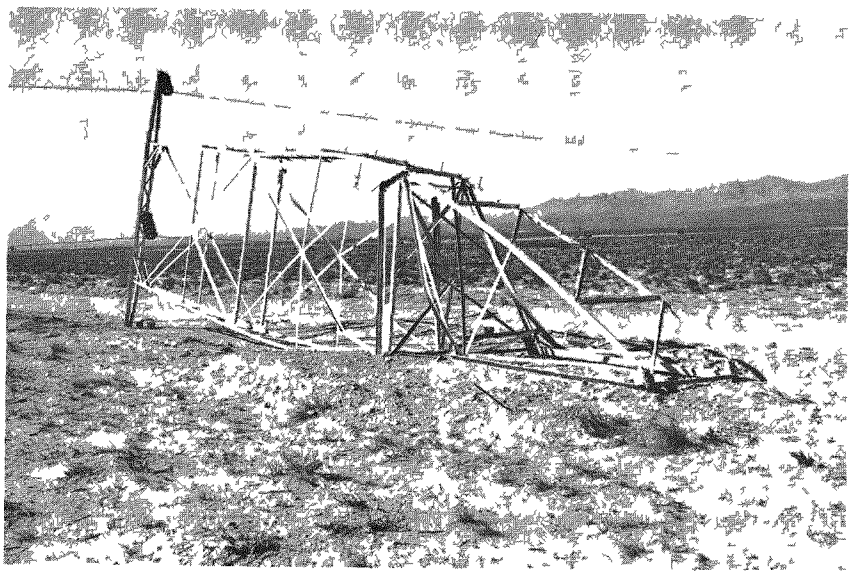

Figure 5.113a Collapsed suspension tower (5 psi overpressure, 0 6 psi dynamic pressure from 30-kiloton explosion), Nevada Test Site.

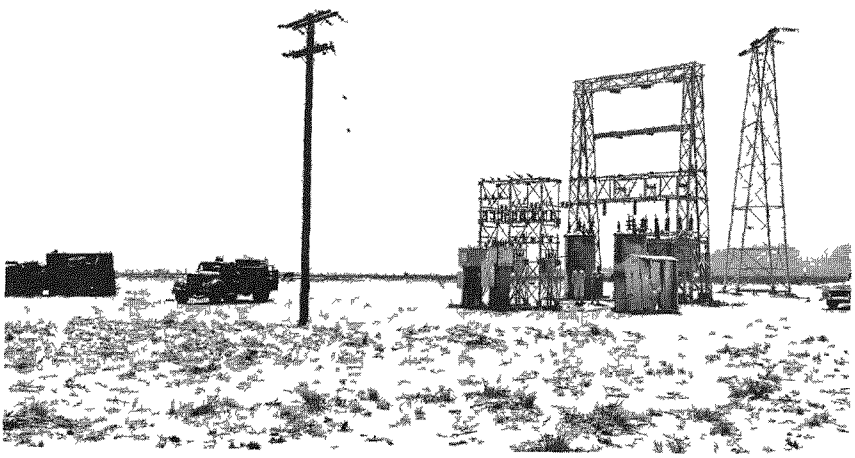

Figure 5 113b Dead-end tower, suspension tower, and transformers (5 psi overpressure, 0.6 psi dynamic pressure from 30-kiloton explosion), Nevada Test Site. The trucks at the left of the photograph are those in Figure 5.98.

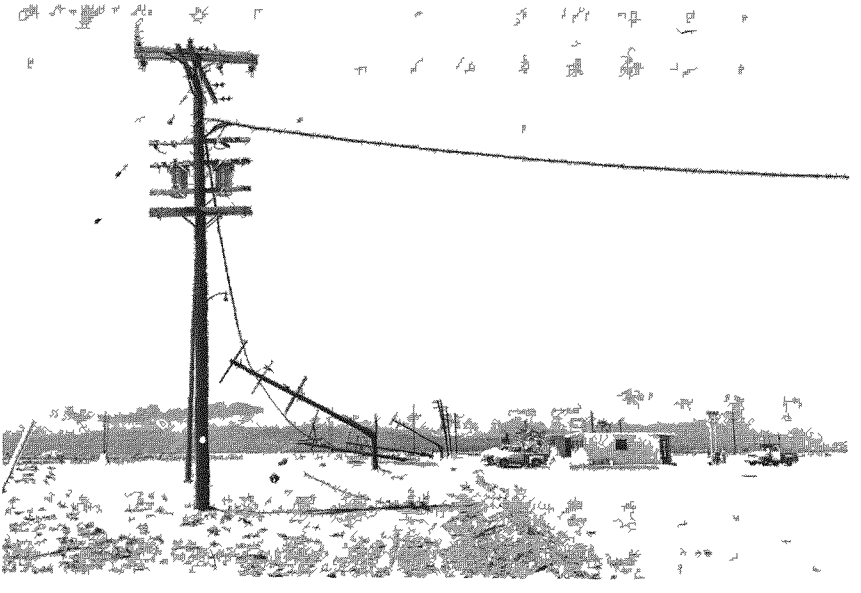

Figure 5 115 Collapse of utility poles on line (5 psi overpressure, 0 6 psi dynamic pressure from 30-kiloton explosion), Nevada Test Site

mary 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

5.117 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 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 5.117 a and b) The exceptional case was one in which the 12-inch cast iron water pipes were 3 feet below grade in a filled-in area. A number of depressions, up to 1 foot in depth, were produced in the fill, and these caused failure of the underground pipes, presumably due to unequal displacements.

5.118 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.

5.119 Gas holders suffered heavily from blast up to 6,000 feet (1.1 miles) from ground zero and the escaping gas was ignited, but

Figure 5.116. Transformer fallen from collapsed utility pole (5 psi overpressure, Nevada Test Site).

Figure 5.117a. Four-inch gate valve in water main broken by debris from brick wall (0 23 mile from ground zero at Hiroshima).

there was no explosion (Fig. 5.119). Underground gas mains appear to have been little affected by the blast.

Natural and Manufactured Gas Installations

5.120 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.

5.121 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.

5.122 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

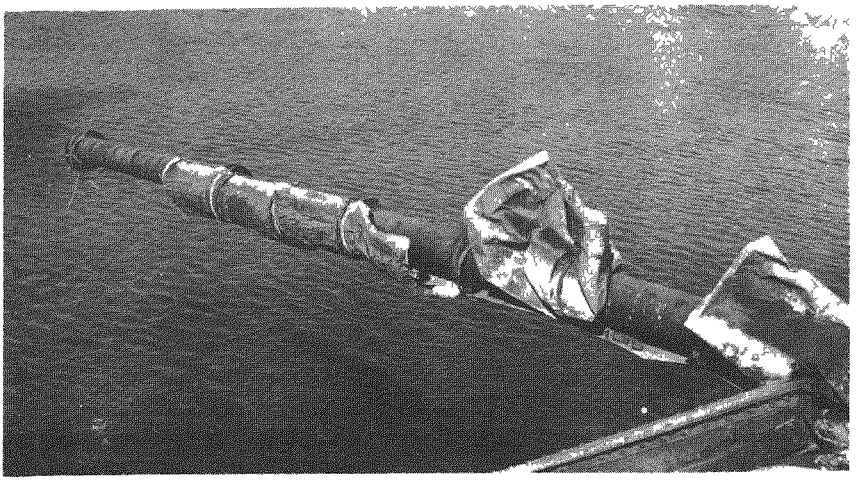

Figure 5 117b Broken portion of 16-inch water main carried on bridge (0 23 mile from ground zero at Hiroshima).

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 line 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

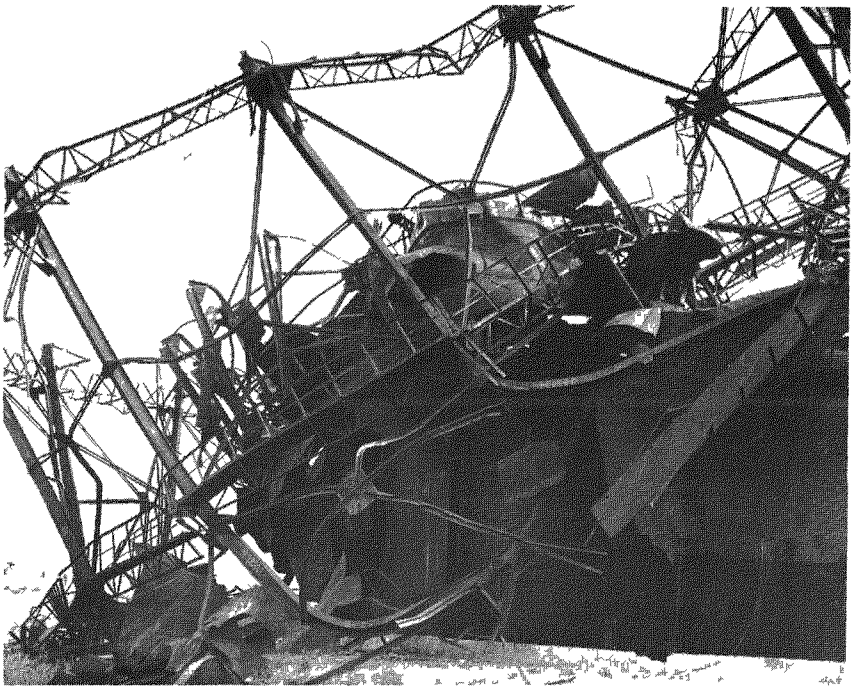

Figure 5.119. Gas holder destroyed by nuclear explosion (0.63 mile from ground zero at Nagasaki).

several houses. Duplicate installations were located at overpressures of 5 and 1.7 pounds per square inch, respectively.

5.123 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.

5.124 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

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.

5.130 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.

5.131 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. 5.38).

5.132 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. 5.132). 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, from 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.

(§ 5.30), the piping in the basement was displaced and bent as a result of 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.

5.125 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 refrigerator 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.

5.126 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

5.127 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.

5.128 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.

5.129 In addition to the foregoing, a complete bulk storage plant was erected at a point where the blast overpressure was 5 pounds per

Figure 5.132. Upper photo: LP-gas bulk storage and filling plant before a nuclear explosion. Lower photo: The plant after the explosion (5 psi overpressure).

5.133 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 used mainly for domestic purposes, it appears that the gas supply will not be affected under such conditions that the house remains habitable.

Communications Equipment

5.134 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 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 Fig. 458b.

5.135 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.

5.136 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. 5.136). This represented the only serious damage to any of the equipment tested.

5.137 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.

Figure 5 136 Unguyed lightweight 120-foot antenna tower (5 psi overpressure, 0 6 psi dynamic pressure from 30-kiloton explosion), Nevada Test Site

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

5 138 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 (§ 5.115), 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.

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* These documents may be obtained for a small charge from the Office of Technical Services, U. S. Department of Commerce, Washington 25, D.C.

CHAPTER VI

EFFECTS OF SURFACE AND SUB-SURFACE BURSTS

CHARACTERISTICS OF A SURFACE BURST

Air Blast

6.01 In this 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 (and blast) wave produced as a result of the rapid expansion of the intensely hot gases at extremely high pressures in the fireball formed by the explosion (see Chapter II).

6.02 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 slightly above the surface, so that the phenomena are substantially the same as for a true surface burst. 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. 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 contact surface burst the incident and reflected waves coincide immediately, forming a hemispherical shock front as shown in Fig. 3.30.

6.03 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.

Crater Formation

6.04 It was mentioned in Chapter II that in a surface burst a considerable quantity of material is vaporized because of the extremely

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high temperature. This material is sucked upward by the ascending air currents resulting from the rising fireball and eventually condenses in the radioactive 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 ground shock and by the rapid expansion of the hot gas bubble. In addition, the blast wave plays a part in determining the configuration of the excavated region. Soil material is removed by being pushed, thrown, and scoured out. Because of the outward motion of the gas, only a relatively small proportion of the earth falls back into the hole, although a considerable amount is deposited around the edges to form part of the lip.

6.05 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 (see Fig. 6.46). First, there is the "rupture zone" in which there are innumerable radial cracks of various sizes. These cracks, which represent rupture of the soil, arise from increased density and stresses in the soil material. Below the rupture zone is the "plastic zone" in which there is no visible rupture although the soil is permanently deformed and compressed to a higher density. Plastic deformation and shear of soil around the edges of the crater contribute to the production of the lip referred to above.

6.06 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.

6.07 Beyond the immediate crater region, the direct ground shock associated with surface bursts, i.e., the shock transmitted entirely through the earth, is usually small in comparison with that induced by the air blast wave passing over the surface. In general, it can be stated that, for buried structures outside the plastic zone, the damage will be caused by induced, rather than by direct, ground shock. The situation would be different, of course, for a deeply buried structure directly below ground zero which would receive only direct ground shock (§ 6.12 *et seq*).

6.08 It has been estimated that for a 1-kiloton nuclear burst near the surface, the diameter of the crater, i.e., of the hole, will be about 130 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 30 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 structural damage is related. The final depth, however, will be shallower because of "hydraulic fill," i.e., slumping back of wet material and the seepage of water carrying loose soil.

6.09 For the purpose of predicting crater dimensions, a surface burst will be defined as one in which the scaled burst depth (or height), i.e., the actual depth (or height) divided by $W^{0.3}$, where W is the explosion yield in kilotons, is 5 feet or less. For such a burst, the diameter (or radius) and depth of the crater increase roughly in proportion to the cube root of the energy of the explosion. Hence, for an explosion of W kilotons yield, on the surface, the diameter and depth of the crater will be $W^{1/3}$ times the values quoted above for a 1-kiloton burst. For example, for a 100-kiloton surface burst in dry soil, the diameter of the crater may be expected to be $130 \times (100)^{1/3} = 600$ feet, and the depth $30 \times (100)^{1/3} = 140$ feet. Curves showing variation with energy yield of the diameter and depth of the crater from a surface burst in dry soil, together with a correction factor for hard rock, are given toward the end of this chapter (see Fig. 6.48).

6.10 If the soil is saturated and the high water table is maintained after the detonation, the crater dimensions will change with time. Sloughing of the crater sides will continue until a stable condition exists for the material. It can be expected that the sides of very large craters will ultimately slump until their slopes decrease to 10 to 15 degrees. As a result, the craters will become shallower and broader. This will occur both in sands and clays. The time lag in the slumping of the walls will be a matter of hours in sands and years in clay soils. Examination of craters in coral at the Eniwetok Proving Grounds has shown that the inward rush of water carries material which would normally constitute the crater lip into the bottom of the crater. Post-shot measurements of these partially filled craters indicate depth of water-washed craters to be proportional to $W^{1/4}$.

6.11 The results quoted above apply to a burst at the surface. As the height of burst increases, the dimensions of the crater vary in a rather complicated manner, because of changes in the mechanism of crater formation. As a rough guide, it may be stated that the depth of the depression decreases rapidly with increasing height of burst and the ratio of crater radius to depth also increases. Long before a height of burst is reached at which the fireball just touches the ground, 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 maximum fireball radius.

Ground Shock

6.12 In a nuclear surface burst a small proportion of the explosion energy is expended in producing a shock (or pressure) wave in the ground; this is known to behave in a very complex manner. In general, the shock wave in the ground 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 rapidly so that it has a longer positive phase. Close to the explosion, rock is crushed and stresses are built up by the passage of the pressure wave. Since the cohesive forces in the soil are very weak (or nonexistent), radial cracks are produced by these stresses, as mentioned earlier. The strength of the pressure wave decreases with increasing distance from the explosion, and at large distances it becomes similar to an acoustic (or seismic) wave.

6.13 The effects of underground shock produced by a nuclear explosion have been described as being somewhat similar to those of an earthquake of moderate intensity. However, as pointed out in § 2.87, there may be significant differences between an underground burst and an earthquake (see Appendix C).

6.14 Following a nuclear explosion, a series of ground surface 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.

6.15 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 IV, 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 and containing action 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 the technical sections at the end of this chapter.

CHARACTERISTICS OF AN UNDERGROUND BURST

Air Blast

6.16 An underground burst is defined in general terms as one in which the center of the explosion is below the surface of the ground (§ 1.35). For explosions arising from weapons delivered from the air, practical considerations would suggest that an explosion occuring at a depth greater than 50 or 100 feet is rather improbable. Hence, the only underground nuclear explosions treated in this section are those in which the fireball 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.

6.17 The proportion of the explosion 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 (contact) surface burst. As the depth of burst increases, the amount of energy going into the air blast wave decreases. Consequently, the range for a given overpressure decreases, with the close-in higher pressures being suppressed more rapidly than lower pressures at longer ranges

Crater Formation and Ground Shock

6.18 The size of the crater produced by a shallow underground burst will be essentially the same as for a surface burst, as given above. If the weapon is located at a scaled depth (§ 6.09) greater than 5 feet, the explosion will be considered as an underground burst for the purpose of estimating the depth and radius of the crater. In these circumstances, the dimensions appear to be proportional to $W^{0.3}$, rather than to $W^{1/3}$ as in the case of a surface (or shallow underground) burst.

6.19 Most of the crater is formed by ejection. With increasing depth of burst, a decreasing fraction of the explosion energy appears as air blast, while an increasing fraction is spent producing ground shock and in crater formation. Hence, up to a point, diameter and depth of the crater increase with increasing depth of the explosion. Beyond this point crater dimensions decrease with increasing depth of explosion. As the crater dimensions decrease with increasing depth of burst, the mechanism of crater formation is also changing.

At a certain depth no ejection of material occurs, only collapse of overburden material into the spherical cavity formed by the explosion. Further information on this subject will be found in the technical section of this chapter (see Fig. 6.49).

DAMAGE CRITERIA

Ground Surface Bursts

6.20 For a nuclear burst at a moderate height above the ground the crater or depression formed will not be very deep, although it may cover a large area. Shallow buried and semi-buried structures, near ground zero will be damaged by this depression of the earth. For deep underground structures, ground shock may be the primary factor causing damage, but its effects are principally important to personnel and equipment within the structures. 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 IV). The area affected by air blast will greatly exceed that in which damage is caused by both direct and induced 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

6.21 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 true crater, which is larger than the apparent (or observable) crater (§ 6.46). Within this region there is practically complete destruction. The depth at which underground structures directly beneath the crater will remain undamaged cannot be clearly defined. This depth is dependent upon the attenuation of pressure and ground motion in the material.

6.22 The second region, which includes the rupture and plastic deformation zones, extends roughly out as far as the major displacement of the ground. In some materials the radius of this region may be about two and one-half times the radius of the (apparent) crater. Damage to underground structures is caused by a combina-

tion of direct ground shock and shock induced in the ground by air blast. Damage to doors, air intakes, and other exposed elements may be expected from direct air blast. 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 at the end of the chapter.

6.23 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, it appears that these structures, particularly when bored through solid rock and lined to minimize spalling, are very resistant to underground shock.

6.24 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, on the ground, 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

6.25 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 the blast wave 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.

6.26 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.

6.27 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.

6.28 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 negative pressure) wave. At a point below the surface the combination of the reflected wave with the direct wave produces a sharp decrease in the water shock pressure. This is referred to as the "surface cutoff."

6.29 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. 6.29. 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 negative 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.

6.30 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, signaling 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. 6.30, 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 may result in a decrease in the extent of damage sustained by the target.

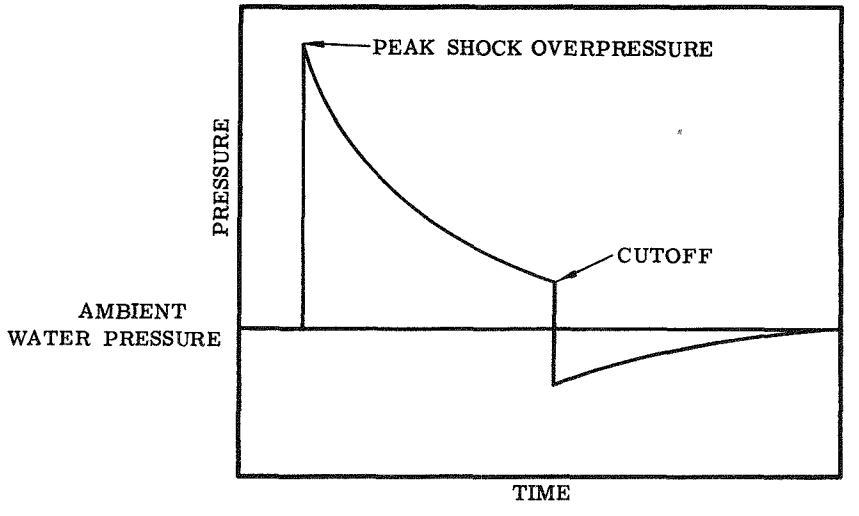

Figure 6.29. Variation of water pressure with time in an underwater explosion at a point near the air surface.

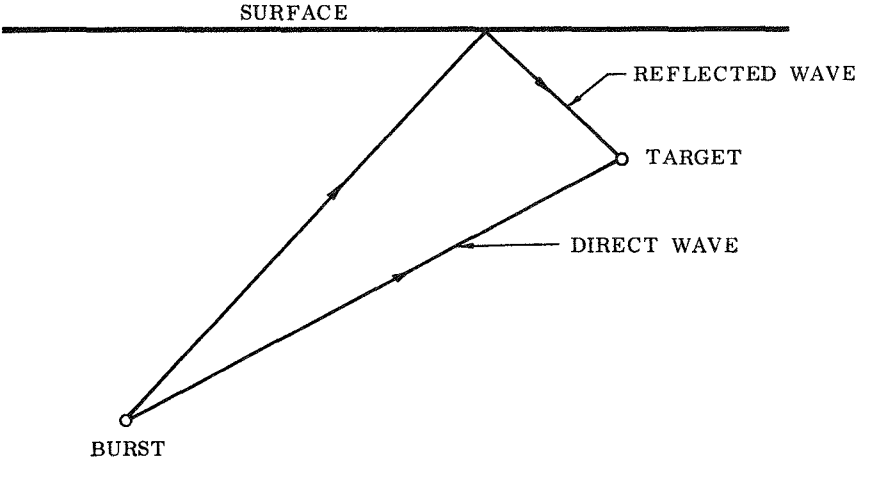

Figure 6.30. Direct and reflected waves reaching an underwater target.

Underwater Shock Damage: General Characteristics

6.31 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.

6.32 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 resulting from 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 leads to a rapid movement in both horizontal and vertical directions. This motion causes damage by shock to components and equipment within the ship.

6.33 Main feed lines, main steam lines, shafting, and boiler brickwork within the ship are especially sensitive to shock. Due to the effects 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. Electronic, fire control, and guided missile equipment is likely to be rendered inoperative, at least temporarily, by shock effects. However, equipment which has been properly designed to be shock resistant will suffer less seriously. In general, it appears that the damage to shipboard equipment is related to the peak velocity imparted to the particular article by the shock wave.

6.34 The damage to the hull of a ship is related to the energy per unit area of the shock wave, evaluated up to a time corresponding to the surface cutoff time at a characteristic depth. Damage to the gate structure of canal locks and drydock caissons is dependent mainly on the peak pressure of the underwater shock wave. 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, massive 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

6.35 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. 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, yield, depth of water, range, the ship type, whether it is operating or riding at anchor, and its orientation with respect to the position of the explosion.

6.36 With a shallow underwater burst, boilers and main propulsive machinery will suffer heavy damage due to motion caused by the water shock at close-in locations. As the range is increased, auxiliary machinery associated with propulsion of the ship will not suffer as severely, but light interior equipment, especially electronic equipment, will be affected to ranges considerably beyond the limit of hull damage. In vessels underway, machinery will probably suffer somewhat more damage than those at anchor.

6.37 Although the major portion of the shock energy from 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 (cf. §6.17). 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 explosion occurred not too far from shore. The damage criteria are then the same as for a surface burst over land, at the appropriate overpressures and dynamic pressures.

6.38 As the depth of burst increases, the proportion of the explosion energy going into air blast diminishes, in a manner similar to that in a burst beneath the earth's surface. Consequently, the range for a given overpressure decreases, with the close-in higher pressures being suppressed more rapidly than lower pressures at longer ranges.

Water Waves in Underwater Explosion

6.39 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 as a result of the impulse from 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. 6.39.

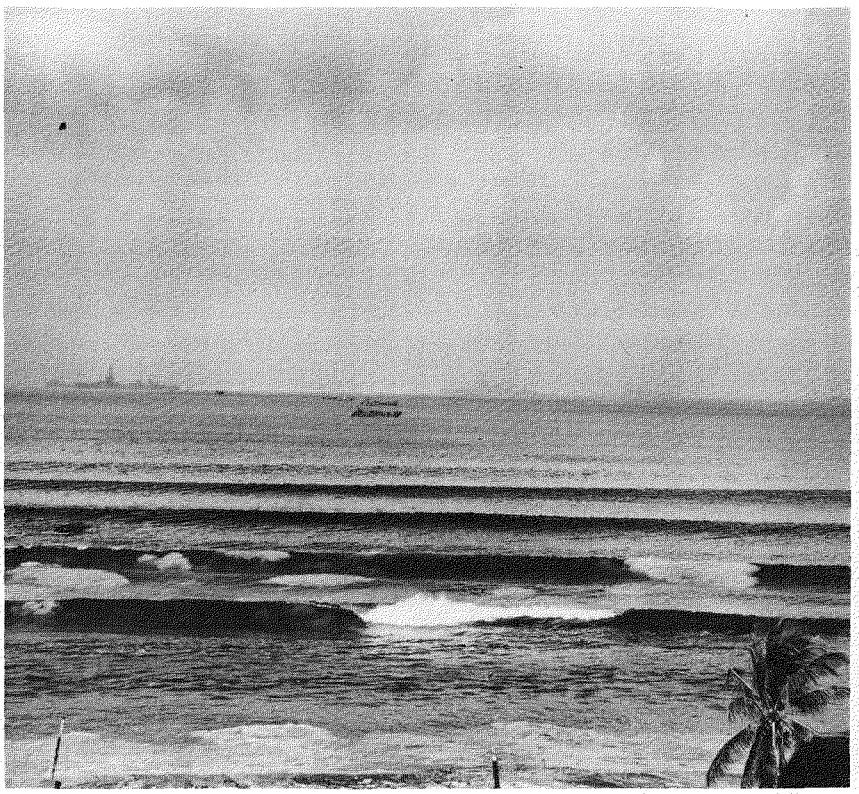

Figure 6.39. Waves from the BAKER underwater explosion reaching the beach at Bikini, 11 miles from surface zero.

6.40 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 sub-

sequent waves were probably formed by the venting of the gas bubble and refilling of the void created in the water. Later tests have shown that the initial, solitary wave is characteristic of explosions in shallow water. Detonations in deep water generate a train of waves in which the number of crests and troughs increases as the train propagates outward from the center of the explosion.

6.41 Near the BAKER 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. This recession of the maximum wave height has also been observed in explosions in deep water.

6.42 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 6.42. These results are based on observations made at the Bikini BAKER test. A more generalized treatment of wave heights, which can be adapted to underwater explosions of any specified energy, is given later in the chapter.

TABLE 6.42

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

6.43 For the conditions that existed in the BAKER test, water wave damage is possible to ships that are moderately near to ground zero. Fairly definite evidence was obtained of the destruction caused by waves to the carrier U.S.S. Saratoga, anchored in Bikini lagoon with its stern 400 yards from surface zero. After the dissipation of the base surge, the central part of the island structure was observed to be folded down on the deck of the carrier (Fig. 6.43). It appears highly probable that shortly after rising on the first wave crest, the Saratoga fell into the succeeding trough and was then struck by the second wave crest which caused the damage to the island structure.

6.44 Water waves generated by an underwater detonation cause damage in harbors or near the shore line, both by the force of the waves and by inundation. The waves will increase in height as they move into shallower water, and inundation, similar to that observed with

tidal waves, can occur to an extent depending on the beach slope and wave height and steepness (see §2.69).

Change in the Lagoon Bottom

6.45 The Bikini BAKER explosion resulted in 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

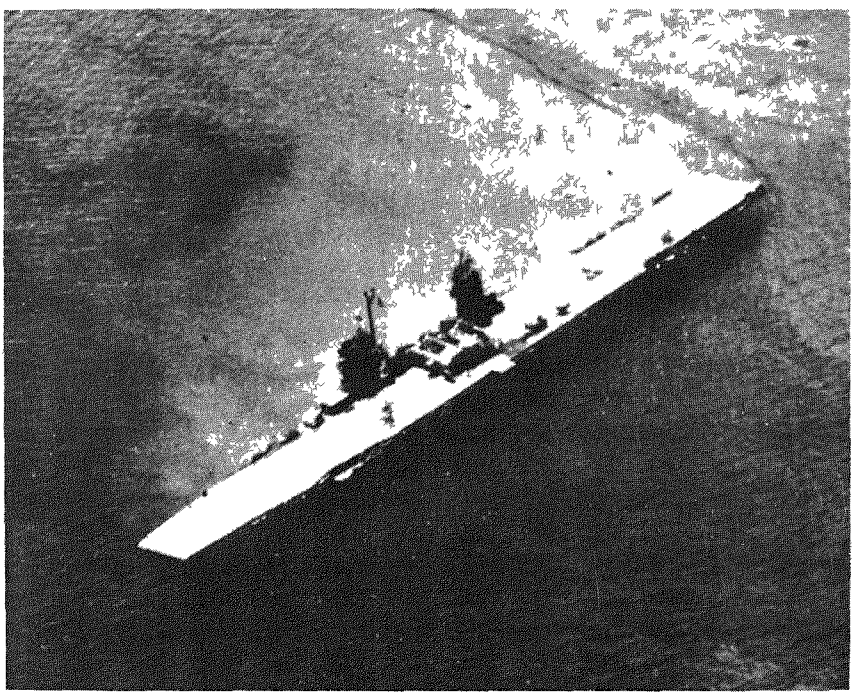

Figure 6.43 The aircraft carrier U.S.S. Saratoga after the BAKER explosion

this represented 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.

TECHNICAL ASPECTS OF SURFACE AND UNDERGROUND BURSTS [1]

Crater Dimensions in Surface Burst

6.46 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. 6.46, 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 of the (apparent) crater, assumed to be roughly paraboloid, is given approximately by

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

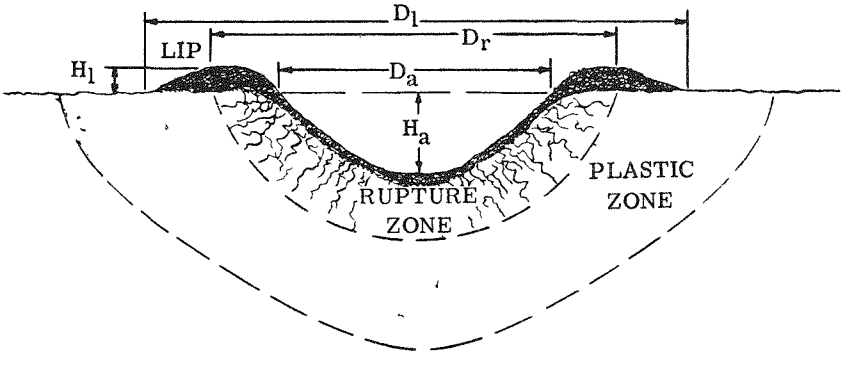

Figure 6.46 Characteristic dimensions of the crater in a surface burst

6.47 The diameter of the rupture zone, indicated by D_r in Fig. 6.46, is roughly one and one-half times the (apparent) crater diameter, i.e.,

$$D_r \approx 1.5\, D_a$$

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

$$D_l \approx 2D_a,$$

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

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

$$H_l \approx 0.25 H_a.$$

6.48 The depth and diameter of the (apparent) crater formed by a surface burst in dry soil of a weapon of energy yield W kilotons, ranging from 1 kiloton to 10,000 kilotons (10 megatons), can be obtained from Fig. 6.48. (The reason for including the curves for a burst depth of 150 $W^{0.3}$ feet is explained in §6.50.) The plots are based on the scaling law given in §6.09, namely, that the crater diameter and depth scale as $W^{1/3}$. Various soil characteristics, particularly, the moisture content, affect the dimensions of the crater. The crater dimensions in saturated soils are described qualitatively in §6.10. For craters in rock, a factor is used to modify the dimensions obtained for craters in dry soil. An example of the application of this factor to the prediction of crater size is given on the page facing Fig. 6.48.

Crater Dimensions in Underground Bursts

6.49 The dependence of crater radius and crater depth upon the depth of burst for a 1-kiloton explosion in dry soil is shown by the curves in Fig. 6.49, the data being uncertain for (scaled) burst depths greater than about 150 feet. It is seen that, with increasing depth of burst, the crater dimensions increase initially and subsequently decrease. The dashed lines in the figure indicate the range of variations that might reasonably be expected even under apparently similar conditions.

6.50 The best empirical fit to the existing crater data for dry soils indicates that both radius and depth vary as the 0.3 power of the explosion yield, i.e., as $W^{0.3}$. In order to determine the crater radius for an explosion of W kilotons yield at a specified burst depth, it is first necessary to determine the scaled burst depth by dividing the actual burst depth by $W^{0.3}$. The crater radius for this depth in the case of a 1-kiloton explosion is then read from Fig. 6.49. Upon multiplying the result by $W^{0.3}$ the required crater radius is obtained. Crater depth is found in a similar manner. In accordance with the statement made above, the results will not be very reliable for scaled burst depths greater than 150 feet, i.e., actual depths greater than 150 $W^{0.3}$ feet. Incidentally, this depth of burst is seen to correspond approximately to the maximum dimensions of the crater in an underground burst. It is for this reason that the curves for burst depths

of 150 $W^{0.3}$ feet were included in Fig. 6.48. The latter thus shows the range of crater dimensions possible from a surface burst to the approximate maximum for an underground burst, for any explosion energy yield from 1 kiloton to 10 megatons. The correction factor for hard rock is given in connection with the example facing Fig. 6.49.

6.51 In an attempt to explain the physical basis of the 0.3 scaling, it has been found that gravity scaling, i.e., the mass of material excavated is proportional to the explosion yield, taking account of overburden, fits the data better than cube root scaling but not as well as $W^{0.3}$ scaling. If gravity scaling using overburden is found to be correct, then crater dimensions will be smaller than those predicted by the estimates given above.

Deep Underground Explosions

6.52 A number of nuclear test explosions have been carried out at various depths underground. Some of the characteristics of such tests, including the proportion of the residual radioactivity on the surface, are given in Table 6.52. From these data it can be concluded, as a rough generalization, that containment, i.e., no radioactivity detectable at the earth's surface, will result if the scaled depth of burst in tuff is greater than about 500 feet. In other words the requirement for complete containment of the radioactive products of a nuclear explosion in tuff is that there should be a rock and dirt cover of roughly 500 $W^{0.3}$ feet or more, where W is the explosion energy yield in kilotons TNT equivalent.

Table 6.52

CHARACTERISTICS OF UNDERGROUND BURSTS

Test	Medium	Depth of cover	Scaled depth	Radioactivity on surface
		feet	$d/W^{0.3}$	*percent*
Jangle U	Alluvium	17	16	80
Teapot S	Alluvium	67	63	90
Neptune	Tuff	98.5	189	2
Blanca	Tuff	835	342	0.5
Logan	Tuff	830	512	0
Rainier	Tuff	790	680	0

6.53 Some of the data obtained in connection with the RAINIER test were described in Chapter II; others will be given here. The radius of the initial cavity formed by the explosion was equivalent to 47 $W^{0.3}$ feet and the initially melted rock, which was converted to

(Text continued on page 295.)

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The curves in Fig. 6.48 give the values of apparent crater diameter and depth in dry soil as a function of explosion yield for (*a*) a surface burst, i.e., actual depth 5 $W^{1/3}$ feet above or below the ground, and (*b*) a burst at an actual depth of 150 $W^{0.3}$ feet. These curves represent the range in crater dimensions from a surface burst to the (approximate) maximum value for an underground burst.

A factor of 0.8 is used as a multiplier for estimating crater dimensions in rock, e.g., granite or sandstone.

Example:

Given: A 20 KT surface burst over sandstone.

Find: The crater dimensions.

Solution: From Fig. 6.48, the crater radius and depth for a 20 KT surface burst in dry soil are 170 feet and 80 feet, respectively. By applying the factor for sandstone (0.8), the estimated (approximate) crater dimensions for a 20 KT surface burst are as follows:

Crater Diameter (D_a) $=340\times0.8=270$ feet.
Crater Depth (H_a) $=80\times0.8=64$ feet.
Diameter of Rupture Zone (D_r) $=1.5D_a=1.5\times270=405$ feet.
Height of Lip (H_l) $=0.25\ H_a=0.25\times64=16$ feet. *Answer.*

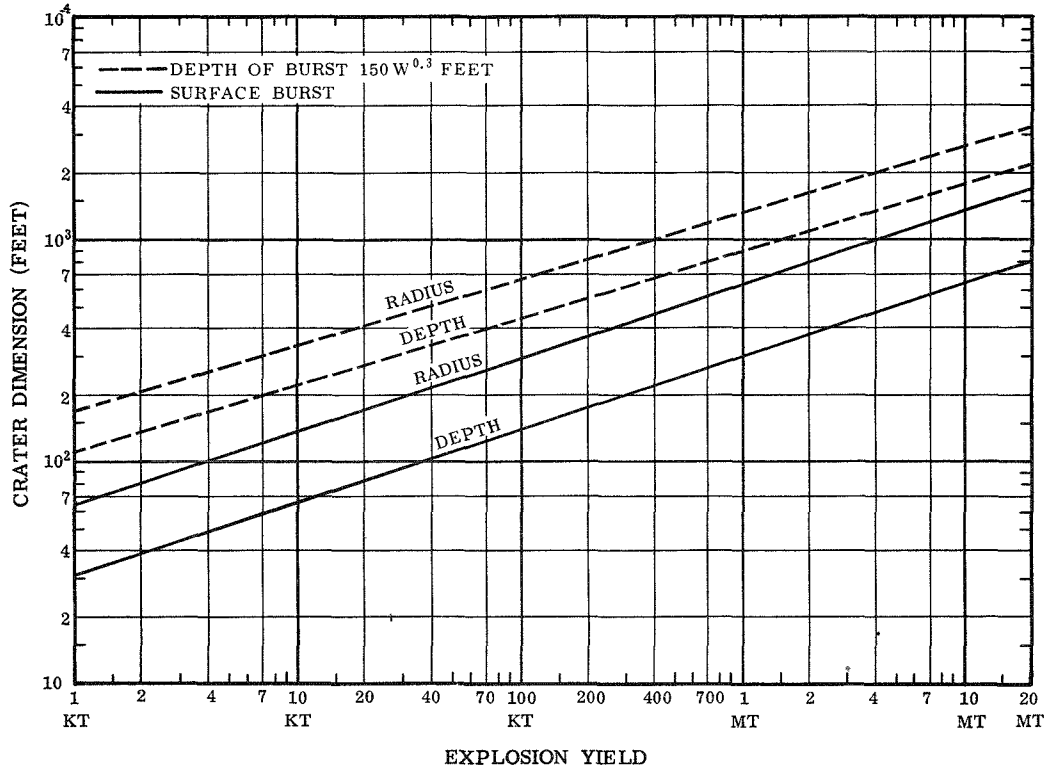

Figure 6.48. Apparent crater dimensions for bursts at the surface and at a depth of 150 $W^{0.3}$ feet in dry soil.

The solid curves in Fig. 6.49 give the estimated apparent crater radius and depth as a function of depth of burst for 1 KT explosions in dry soil. The dashed curves indicate the reasonable range of variations to be expected under apparently similar conditions. For rock, e.g., sandstone or granite, the multiplication factor of 0.8 should be used to obtain the crater dimensions.

The curves in Fig. 6.47 are uncertain at scaled depths of burst greater than 150 feet, i.e., for actual burst depths greater than 150 $W^{0.3}$ feet.

Scaling. To determine the crater radius and depth for a W KT yield, the actual burst depth is divided by $W^{0.3}$ to obtain the scaled depth. The radius and depth of crater for 1 KT at this depth of burst are obtained from Fig. 6.49. The dimensions are then multiplied by $W^{0.3}$. Values of $W^{0.3}$ can be obtained directly from the curves in Fig. 3.65.

Example

Given: A 20 KT burst at a depth of 50 feet in granite.

Find: Crater radius and depth.

Solution: The scaled burst depth is

$$d/W^{0.3}=50/20^{0.3}=50/2.46=20 \text{ feet.}$$

From Fig. 6.49 the crater radius for a 1 KT explosion at this depth is 117 feet. The corresponding depth of the crater is 55 feet. Hence, the crater radius and depth for a 20 KT burst at a depth of 50 feet in granite are:

Crater Radius $(R_a)=117\times20^{0.3}\times0.8=117\times2.46\times0.8=230$ feet.

Crater Depth $(H_a)=55\times2.46\times0.8=108$ feet. *Answer.*

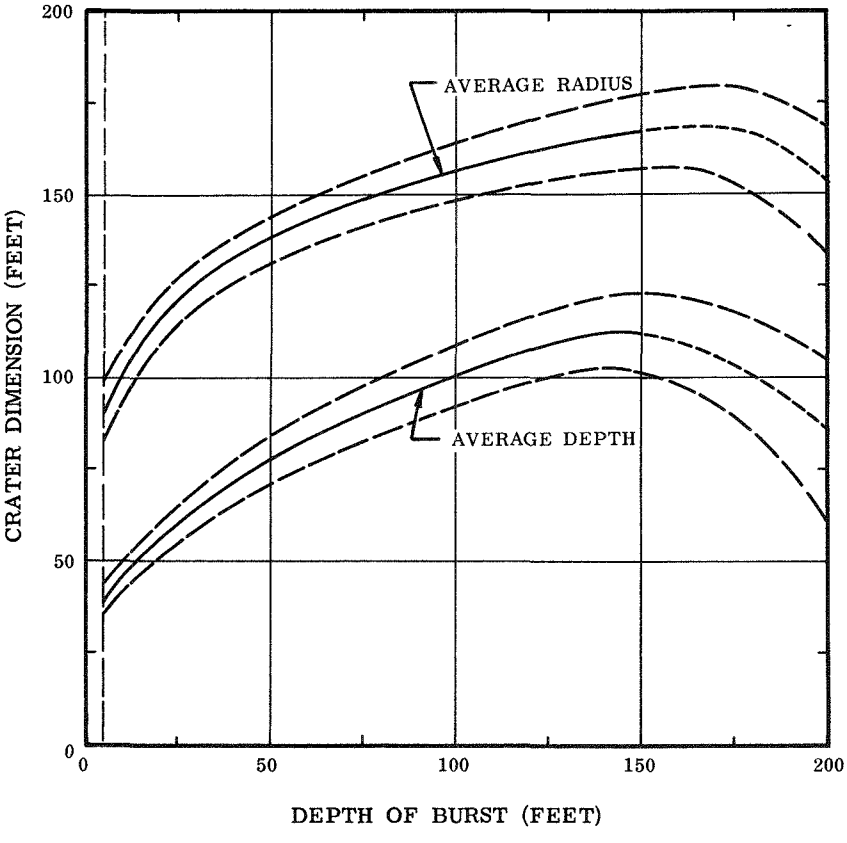

Figure 6.49. Apparent crater radius and depth as function of depth of burst for a 1-kiloton underground explosion in dry soil. (The data are uncertain for scaled depths of burst greater than 150 feet.)

(Text continued from page 291.)

glass upon cooling, amounted to 500 ± 150 tons per kiloton of energy yield. Collapse of the cavity produced a zone of broken permeable material of about 70,000 cubic yards (or 120,000 tons) per kiloton yield. The major portion (65 to 80 percent) of the fission product and induced radioactivity was retained as a dilute solution (0.1 part per million) in the glass formed from the molten rock. The remainder was distributed as a deposit on the surface of the broken material, throughout the collapsed zone of the chimney formed by the falling in of the cavity roof.

6.54 About 30 percent of the total energy release of the RAINIER explosion appeared initially as steam and heated rock at a tempera-

ture exceeding 1,200° C. However, because the rock contained a relatively large proportion (15 to 20 percent) of water, the temperature fell rapidly to that of boiling water at the Nevada altitude (about 93° C). A year after the explosion, nearly all of this energy was retained within a volume of radius somewhat less than 80 feet, i.e., slightly more than the radius of the initial cavity.

6.55 From seismographic observations, it has been found that the peak acceleration of the ground at a distance of R miles from an underground burst of W kilotons is roughly equal to $0.06\ gW^{0.75}/R^2$, where g is the normal acceleration of gravity. At the observation post 2.5 miles from the RAINIER explosion, the peak acceleration was about $0.02\ g$, although very few individuals detected the ground motion (§ 2.97).

LOADING ON BURIED STRUCTURES

Free-Field Pressure and Arching Effect

6.56. If the deformability of a buried structure is the same as that of the surrounding displaced soil, the loads produced on the structure by the air blast from a nuclear detonation will be determined by the free-field pressures, i.e., the pressures in the absence of the structure, induced in the soil by the blast wave. However, structures seldom, if ever, satisfy this postulated condition; consequently, the loads for which a buried structure must be designed can be determined only by considering the interaction of soil and structures. Although this is a difficult matter, certain general observations can be made which probably justify the procedures normally used.

6.57 Results of tests have indicated that there is no significant build-up of pressure due to reflection at the interface between the soil and a buried structure. It may be assumed, therefore, that the free-field pressure, regardless of its direction, can be taken as an upper limit of the pressure acting on the structure. If the structure is more deformable than the surrounding soil, the pressure on the buried structure will be considerably lower than the free-field pressure at the given depth. In this case, as the free-field pressure is exerted initially, the structure deflects away from the soil and a situation is created in which the "arching effect" within the soil serves to transmit part of the blast-induced pressure around the structure rather than through it.

6.58 It is generally accepted that the soil arching phenomenon, which has been observed under static conditions, also exists under

dynamic conditions, such as accompany a nuclear explosion. Unfortunately, the arching phenomenon is not well understood and no reliable method, either experimental or theoretical, is available to define its effects. Consequently, a conservative approach to the problem requires that it be neglected and that the free-field pressure be taken as the design pressure. The degree of conservatism involved is dependent upon the type of soil in which the structure is built, e.g., granular, cohesive, saturated, etc., and also upon the ratio of depth of cover to the span of the structure and perhaps the foundation conditions. If the foundations are such as to permit the structure to move away from the soil, the possibility of significant arch action would be increased.

Loading on Rectangular Structures

6.59 The treatment of the blast-induced loads on buried rectangular (or box-type) structures is simple in comparison with that for arched or domed structures. Neglecting initial nonuniformities of pressure and the arching action, the blast-induced pressures on the roof and equal sized base slabs of a rectangular structure can be taken as the free-field vertical pressures at the level of the roof, and the side wall pressures can be taken as the free-field lateral pressures (see § 4.43). If the proportions of the structure or the weapon yield warrant it, the side wall pressures may be decreased from top to bottom in the same manner as the free-field pressures attenuate.

Loading on Buried Arches and Domes

6.60 On arches and domes the actual loading is considerably more complex because of the constantly changing attitude of the surface of the structures with respect to a horizontal plane and also because, at very shallow depths, the initial nonuniformity of load cannot be neglected. As a blast wave passes over a buried arch or dome, the windward side is loaded earlier than the leeward side and, consequently, an unsymmetrical flexural mode of response is excited. Furthermore, after the structure is completely engulfed by the blast wave, the radial loading intensity will be very nearly symmetrical, although not uniform. The pressure at the crown, corresponding to the free-field vertical pressure closest to the ground surface, is therefore the maximum. Beyond the crown, the radial pressure decreases in intensity to a minimum at the springing line where, if the arch or dome has a 180° central angle, the pressure will correspond

to the free-field lateral pressure at the depth of the footings. This symmetrical nonuniform loading tends to excite a symmetrical flexural mode of response. In addition to these two flexural modes, the structures will also respond in a direct compression mode.

6.61 For the flexural modes to be significant, deformations corresponding to those modes must be possible. For such deformations to occur, the passive resistance of the surrounding soil must be overcome and a wedge of the soil must be displaced by the deforming structure. Thus, the passive resistance of the soil will tend to limit these deformations and prevent the flexural modes from being significant. Although the flexural modes may be important with shallow buried structures they decrease in importance very rapidly with depth since the passive resistance of the soil increases quite rapidly at the same time.

6.62 In the foregoing discussion it is assumed that the footings do not move with respect to the soil adjacent to them. If the footings do penetrate into the underlying material, the radial pressures on the arch or dome may be reduced slightly.

DAMAGE FROM GROUND SHOCK

Underground Structures

6.63 The damage to an underground structure itself, as distinct from the effects of ground shock on its contents, can be readily defined in terms of inelastic deformation or collapse. For fully buried arches and domes, severe damage corresponds to collapse either by elastic or, more frequently, inelastic buckling. If very near the ground surface, the deformations may be primarily flexural (bending). Light damage has little or no meaning unless it refers to partial impairment of operational capability of personnel and equipment. Moderate structural damage for concrete structures can be defined as deformations accompanied by significant spalling. Such deformation would correspond to stress levels in the concrete slightly above the yield point, i.e., a ductility factor of about 1.3. This presumes that failure is by inelastic deformation rather than by elastic buckling, as would be the case in a properly designed blast resistant structure. If failure is by elastic buckling, moderate damage cannot be realized.

6.64 For steel arches and domes, moderate structural damage can also be defined in terms of a reduced ductility factor although the nature of such damage for steel structures is not as clearly evident as in

the spalling of concrete. For underground, blast resistant, box-type structures, the several degrees of damage to arches and domes are also applicable, but the mechanism of deformation may be different. In a box structure, primary response may be in flexure of the walls, roof, or base slabs or in direct stress or buckling of the walls or columns. However, severe damage is still characterized by excessive deformation or collapse through any of these mechanisms; moderate damage corresponds to deformations of any of the elements associated with spalling of concrete and small permanent deflections; and light damage is virtually meaningless except in terms of shock effects on personnel and equipment.

6.65 For very low yield weapons, it is difficult to produce significant damage to a buried structure unless it is within the rupture zone around the crater (§ 6.05). With the exception of a number of special structural types, e.g., pipelines and small highly resistant reinforced concrete fortifications, soil pressures produced by air blast pressures on the ground surface constitute the primary source of damage to buried structures.

6.66 It should be emphasized that the term damage, as used here, refers to the inability of a particular structure to maintain its structural integrity. It is, of course, possible that a facility may survive an attack with little or no structural damage and yet be incapable of performing its function if inadequate provisions are made for the effects of shock, i.e., accelerations, velocities, and displacements, on sensitive equipment and personnel. Shock isolating materials should be used in mounting sensitive equipment in order to reduce the motion imparted to such equipment.

6.67 It is expected that underground structures whose span closely matches one-half the wave length of the shock 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.

6.68 As stated in § 6.21 *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 out to approximately two and one-half times the (apparent) crater radius; and (3) the zone in which transient earth movements occur without permanent measurable deformation, there generally being no serious ground shock damage in this region.

6.69 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 apparent crater radius. Some examples of this type of relationship are given in Table 6.69 for moderately deep underground structures, defined as structures located such that the ratio of the depth of cover at the crown to the span is greater than unity. There are certain minor variations in the distances due to the factors referred to in § 6.22, 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 damage from ground shock beyond the plastic zone, i.e., farther than about two and one-half (apparent) crater radii from surface zero.

TABLE 6.69

DAMAGE CRITERIA FOR MODERATELY DEEP UNDERGROUND STRUCTURES

Structural type	Damage type	Distance from surface zero	Nature of damage
Relatively small, heavy well-designed underground structures.	Severe	1¼ apparent crater radii	Collapse.
	Light	2½ apparent crater radii	Slight cracking, severance of brittle external connections.
Relatively long, flexible structures, e.g., buried pipelines, tanks, etc.	Severe	1½ apparent crater radii	Deformation and rupture.
	Moderate	2 apparent crater radii	Slight deformation and rupture.
	Light	2½ to 3 apparent crater radii	Failure of connections.

6.70 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.[2] Even in a soil medium, tunnels and subways could survive; flexible structures would resist damage by taking advantage of the tremendous passive earth pressure. However, construction in soil should be above the water table, if possible.

6.71 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

[2] 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 (§ 6.28).

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.

6.72 When structures are partly above and partly below ground, the damage to the underground portion will be very much as indicated in Table 6.69, 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 earlier. The overall damage is then determined by the air blast, and is in accordance with the discussion in Chapter IV.

TECHNICAL ASPECTS OF UNDERWATER EXPLOSIONS

Shock Wave Properties

6.73 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. 6.73. 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. 6.73 are independent of the cutoff effect. For an explosion and target near the surface, the impulse and energy would be greatly decreased.

6.74 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_1 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

$$D=D_1\times W^{1/3},$$

as in equation (3.56.2) 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 § 3.58. Thus,

$$I=I_1\times W^{1/3} \text{ at a distance } D=D_1\times W^{1/3},$$

$$E=E_1\times W^{1/3} \text{ at a distance } D=D_1\times W^{1/3},$$

where I and E are the impulse and energy, respectively, at a distance D from an explosion of W kilotons, and I_1 and E_1 are the values at a distance D_1 from a 1-kiloton explosion. These scaling laws are illustrated in connection with the example based on the use of Fig. 6.73.

(Text continued on p. 303.)

The curves in Fig. 6.73 show the peak water overpressure, the energy per unit area, the impulse per unit area, and the time constant (defined in § 6.75) as a function 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

$$D=D_1\times W^{1/3},$$

where D_1 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:

$$I=I_1\times W^{1/3} \text{ at } D=D_1\times W^{1/3},$$

$$E=E_1\times W^{1/3} \text{ at } D=D_1\times W^{1/3},$$

and

$$\theta=\theta_1\times W^{1/3} \text{ at } D=D_1\times W^{1/3},$$

where I_1, E_1, θ_1 are impulse, energy, and time constant for 1 KT at distance D_1, and I, E, and θ are impulse, energy, and time constant for W KT at distance D.

Example

Given: A 30 KT weapon 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_1 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 Fig. 6.73, 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 $1\times30^{1/3}=3.1$ 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. 6.73 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 = $6.5\times30^{1/3}=20.2$ lb-sec/in^2

Energy = $12.5\times30^{1/3}=39$ lb-ft/in^2

Time constant = $17.5\times30^{1/3}=54$ millisec. *Answer.*

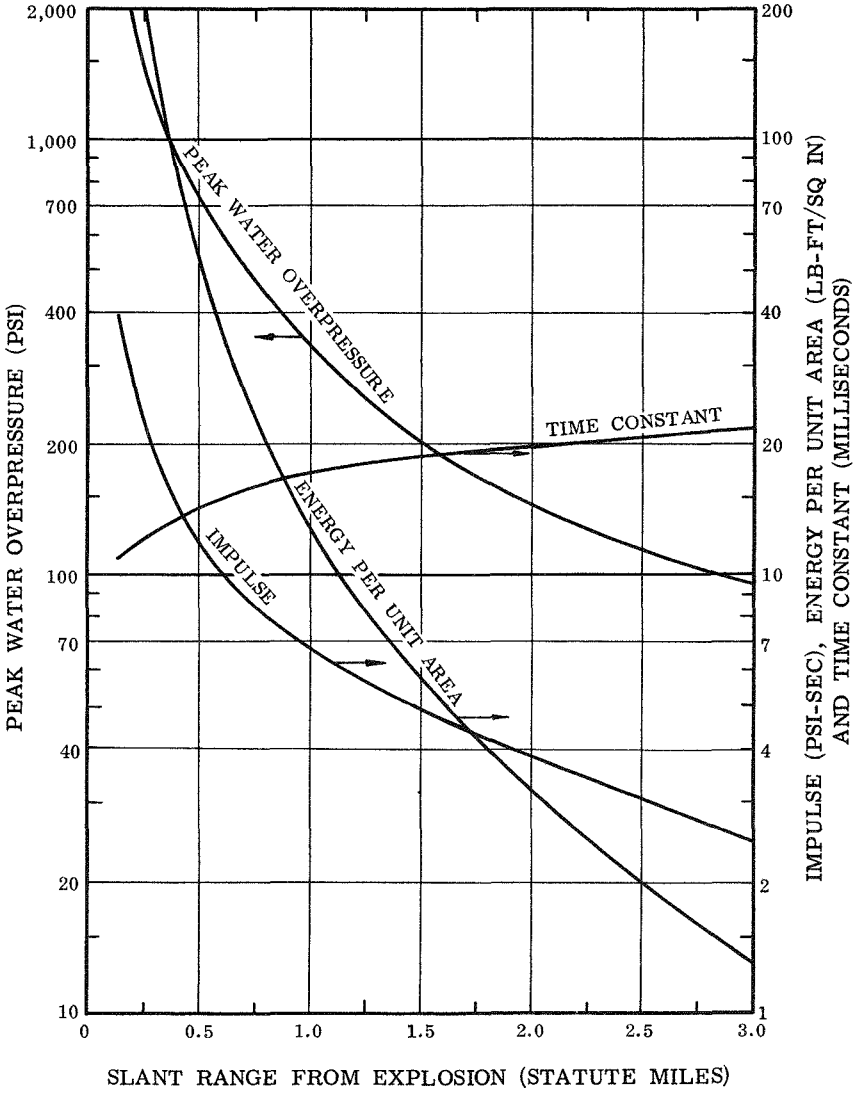

Figure 6 73. Water shock wave properties for a 1-kiloton explosion in deep water.

(Text continued from p. 301.)

6.75 The rate at which the shock pressure, at a fixed distance from the explosion, falls off with time can be represented by

$$p(t)=pe^{-t/\theta}, \tag{6.75.1}$$

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 θ is a parameter called the "time constant." Physically, θ 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. 6.73. The time constant for an explosion of W-kilotons energy may be obtained by the scaling method given above for energy and impulse.

6.76 It is apparent from equation (6.75.1) that θ 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 θ increases with increasing distance from the explosion, the duration of the shock wave increases correspondingly.

6.77 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 distances 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. 6.77. 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

6.78 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. 6.78 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

6.79 By empirical analysis and appropriate scaling of the wave heights observed at various tests, a curve (Fig. 6.79) has been con-

structed for estimating maximum wave heights (crest to trough) at various distances from a 1-kiloton underwater burst. The results apply to an explosion of W-kilotons energy yield in water having a scaled depth of 85 feet, defined in this case as the actual water depth in feet divided by $W^{1/4}$. 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. 6.79 by the scaling factor $W^{1/2}$. If the scaled depth of the water is less than 85 feet, the wave height is then directly proportional to the actual depth.

6.80 Experimental data from nuclear detonations in deep water are very limited. A curve based on theoretical considerations and the available measurements is included in Fig. 6.79; it gives a rough estimate of the maximum wave heights that could result from a 1-kiloton detonation in deep water, i.e., depth of water greater than 400 $W^{1/4}$ feet. Here also an approximate value of the wave height for a W-kiloton explosion can be obtained upon multiplying the result for 1-kiloton yield by the scaling factor $W^{1/2}$. It should be noted that the data in Fig. 6.79 are for a constant depth of water and, furthermore, they do not allow for peaking that may occur as the waves reach shallow water.

Underwater Crater Formation

6.81 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. 6.81. The values are for a burst less than 15 feet deep and for one on the bottom in water 50 feet deep with sand, sand and gravel, or soft-rock bottom. The correction factors for other bottom materials are given on the page facing Fig. 6.81. Caution should be used in applying the results since the water action will cause the various dimensions, particulatly the lip height, to change quite rapidly.

DAMAGE FROM UNDERWATER SHOCK

Damage to Ships

6.82 A description of the interaction of underwater shock with ships, based on experience at the Bikini BAKER test, was given in § 6.35 *et seq.* For most cases of underwater explosions, the water

(Text continued on page 314.)

The curve in Fig. 6.77 shows the dependence of the peak wate overpressure on the distance (slant range) from the explosion 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, i.e., actual depth divided by $W^{1/3}$, 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 weapon 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. 6.77 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 weapon, the peak overpressure of 300 psi occurs at

$$0.39\times30^{1/3}=0.39\times3.1=1.2 \text{ miles.} \quad \textit{Answer.}$$

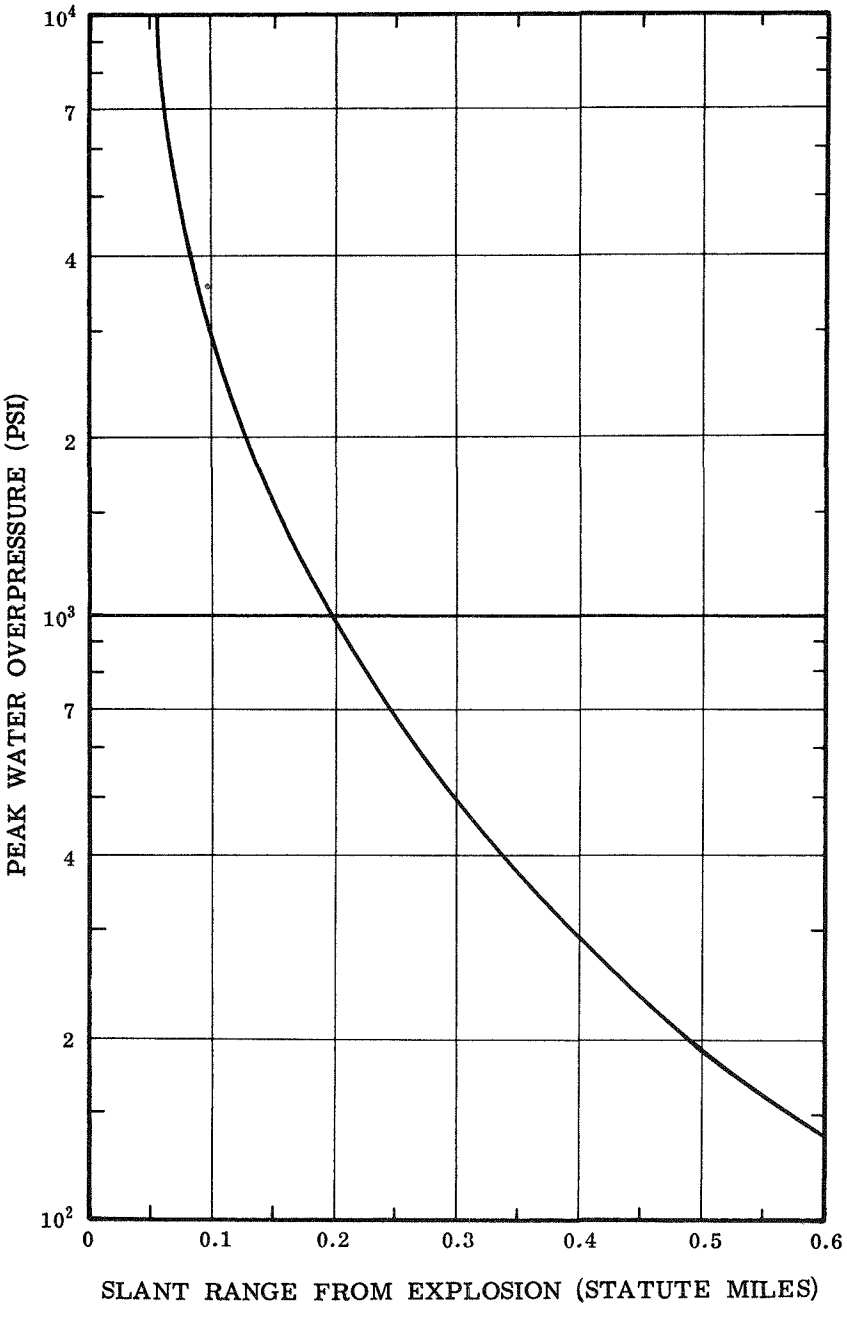

Figure 6.77. Peak water overpressure for a 1-kiloton explosion at mid-depth in water 66 feet deep.

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The curve in Fig. 6.78 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 weapon detonated in 100 feet of water.

Find: The distance at which the air overpressure at the surface is 5 psi.

Solution: From Fig. 6.78, 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

$$0.2 \times 30^{1/3} = 0.62 \text{ mile.} \quad \textit{Answer.}$$

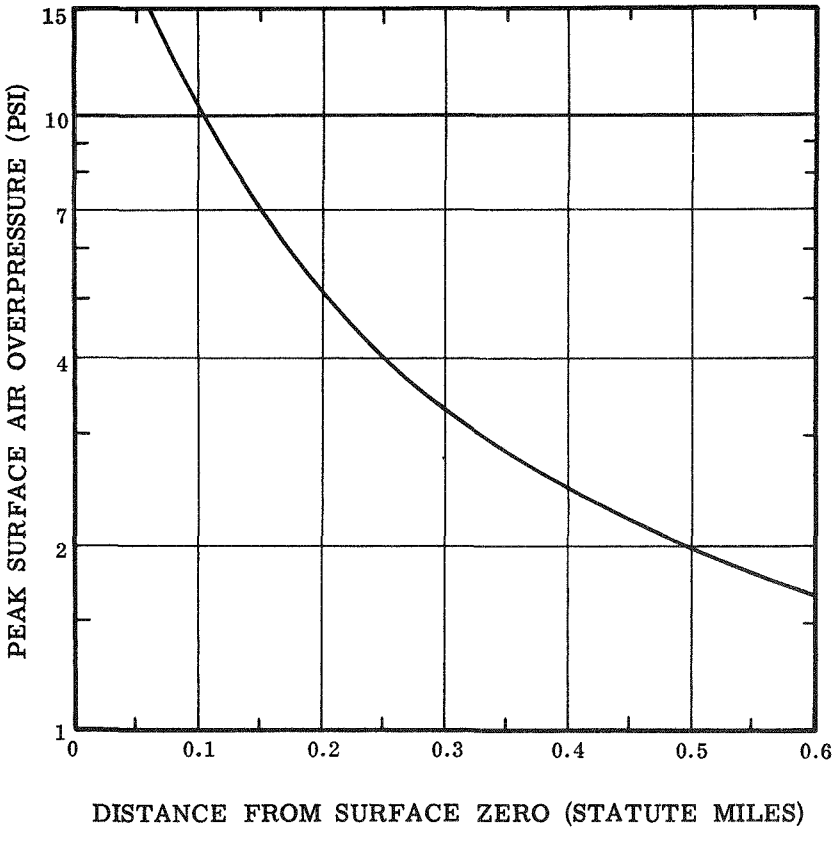

Figure 6.78. Peak air overpressure at surface for a 1-kiloton shallow underwater explosion.

The lower curve in Fig. 6.79 shows the approximate maximum crest-to-trough wave height versus horizontal surface distance for a 1 KT burst in water 85 feet deep. The upper curve is for a 1 KT burst in water more than 400 feet deep, so that the bottom does not affect the mechanism of wave formation.

Scaling. At a given distance from surface zero, the wave height for an explosion of W kilotons is $W^{1/2}$ times the wave height at this distance from a 1 KT burst in water of the same scaled depth, as obtained from Fig. 6.79. The scaled depth is $d/W^{1/4}$, where d is the actual depth in feet. For the lower curve in the figure the scaled depth is 85 feet and for the upper curve it is more than 400 feet.

For scaled water depths less than 85 feet, i.e., actual depths less than $85W^{1/4}$ feet, the estimated maximum wave height is proportional to the depth of water; thus,

$$h_d = h_{85}(d/W^{1/4}),$$

where h_d=wave height for any scaled water depth less than 85 feet, h_{85}=wave height for a scaled water depth of 85 feet obtained from Fig. 6.79, and d=depth of water in feet.

Example

Given: (*a*) A 30 KT weapon detonated in 200 feet of water.
(*b*) A 30 KT weapon detonated in 100 feet of water.
(*c*) A 30 KT weapon detonated in 1,000 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, the lower curve in Fig. 6.79 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 weapon 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 $85W^{1/4}$ when W is 30 KT, the wave height will now be proportional to the actual depth of the water. When the depth is $85W^{1/4}$, i.e., 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

$$5.5 \times \frac{100}{200} = 2.7 \text{ feet, crest to trough.} \quad \textit{Answer.}$$

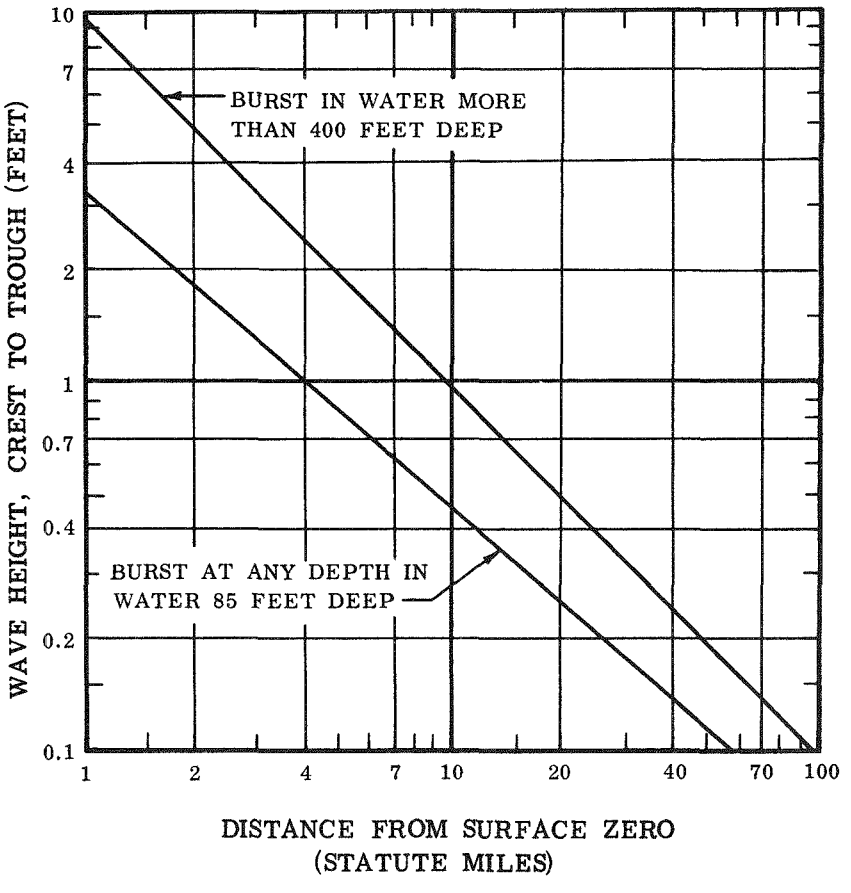

Figure 6.79. Maximum wave height in different types of 1-kiloton underwater bursts.

(*c*) The scaled depth of the water is

$$1{,}000/30^{1/4}=1{,}000/2.34=427 \text{ feet},$$

and since this is greater than 400 feet, the upper curve in Fig. 6.79 must be used. From the curve, the maximum wave height at 4 miles from a 1 KT explosion is 2.4 feet. Therefore, for a 30 KT weapon detonated (at the proper depth) in 1,000 feet of water, the maximum wave height at 4 miles is

$$2.4\times30^{1/2}=2.4\times5.5=13 \text{ feet, crest to trough.} \quad \textit{Answer.}$$

The curves in Fig. 6.81 give the depth, diameter, and lip height of the underwater crater as functions of yield. The results are for a burst less than 15 feet deep and for one on the bottom in 50 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. 6.81 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 weapon detonated in 50 feet of water; the bottom is predominantly clay.

Find: (*a*) The crater dimensions when the detonation is near the surface of the water.

(*b*) The crater dimensions when the detonation occurs on the bottom.

Solution: From Fig. 6.81, the crater dimensions for a 200 KT explosion are as follows:

	(*a*) *Feet*	(*b*) *Feet*
Diameter	1, 000	1, 900
Depth	44	120
Lip height	2. 4	14

For a clay bottom, the multiplication factors are 1.0 for the diameter, and 2.3 for both depth and lip height; hence, the required values are:

	(*a*) *Feet*	(*b*) *Feet*	
Diameter (factor 1.0)	1, 000	1, 900	
Depth (factor 2.3)	100	276	
Lip height (factor 2.3)	5. 5	32	*Answer.*

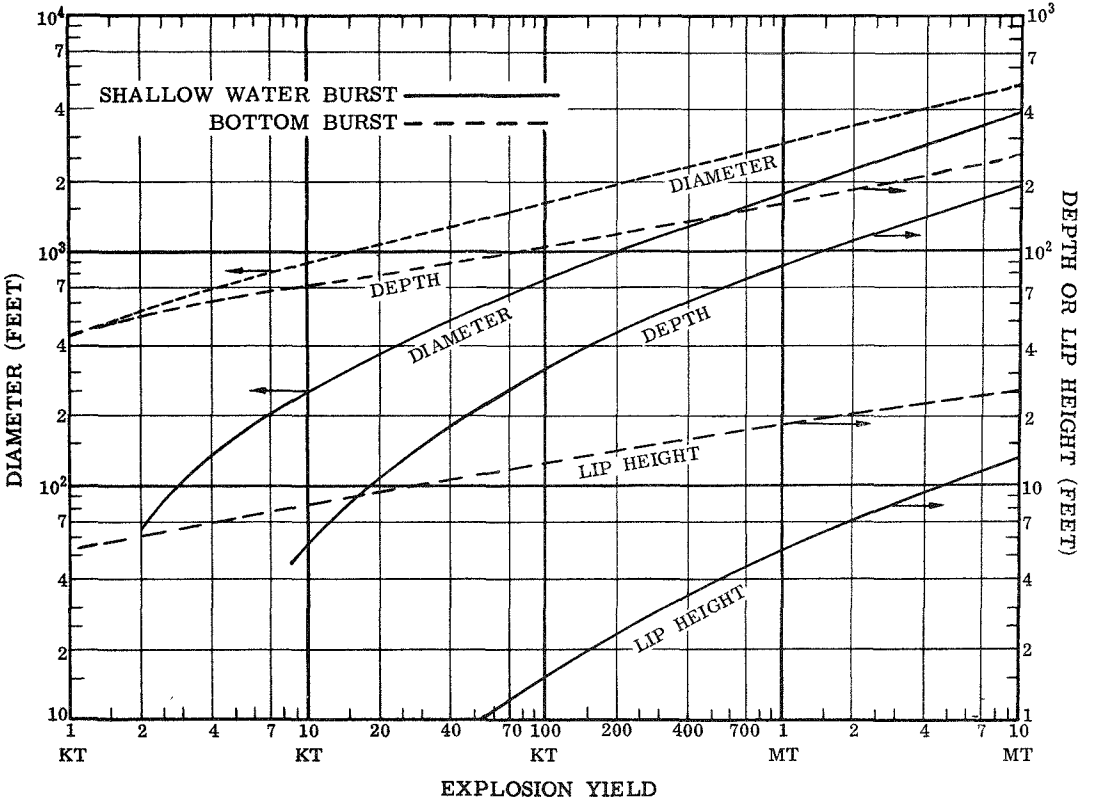

Figure 6.81. Dimensions of crater in underwater bursts as a function of explosion yield.

(Text continued from page 305.)

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.

6.83 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 4.53 are applicable, irrespective of whether water shock or air blast is the main cause of damage. The energy-distance relationships for various degrees of damage to merchant-type ships due to air blast are given in Fig. 4.58b.

Damage to Hydraulic Structures

6.84 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 (§ 6.75) 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 (§ 6.28) would be significant in certain cases.

6.85 If the time constant of the pressure wave and the cutoff time are 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.

6.86 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. 6.73). 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.

6.87 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. 6.73). If the structure is near the surface, the cutoff effect will decrease the amount of shock energy available for causing damage.

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*These documents may be obtained for a small charge from the Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C.

CHAPTER VII

THERMAL RADIATION AND ITS EFFECTS

RADIATION FROM THE FIREBALL

General Characteristics of Thermal Radiation

7.01 One of the important differences between a nuclear and a conventional high-explosive weapon 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 weapon, very high temperatures are attained. These are estimated to be several tens of million degrees, compared with a few thousand degrees in the case of a conventional explosion. As a consequence of these high temperatures, a considerable amount of energy is released in the form of electromagnetic radiations of short wave length. Initially, these are mainly in the soft X-ray region of the spectrum, but the X-rays are absorbed in the air, thereby, heating it to high temperatures. This heated air, which constitutes the fireball, in turn radiates in a spectral region roughly similar to that of sunlight received at the earth's surface. It is the radiation (ultraviolet, visible, and infrared) from the fireball, traveling with the velocity of light, which is received at distances from the explosion. The time elapsing, therefore, between the emission of thermal radiation from the fireball and its arrival at a target miles away, is quite insignificant.

7.02 It is desirable to state specifically what is meant by the term "thermal radiation" as it is used in the present chapter. Actually, all the energy released by a nuclear detonation, including that of the radioactive debris, ultimately is degraded to thermal energy, i.e., heat, but only part of it is regarded as constituting the thermal radiation which is emitted immediately by the hot fireball. Some of the thermal radiations, particularly in the ultraviolet region, are selectively absorbed by various atomic and molecular species in the heated air, which slowly re-emit this energy in a degraded, i.e., longer wavelength, form.

The delay in reaching the target, and the slower rate at which they are delivered, lowers the damaging effectiveness of these radiations. Consequently they are not considered as a part of the thermal radiation for present purposes. It is convenient, therefore, to define the effective (or prompt) thermal radiation as that emitted from the heated air of the fireball within the first minute (or less) following the explosion.

7.03 For an air burst at altitudes below 50,000 feet, the thermal radiation is emitted in two pulses, as described in Chapter II. The first, which is quite short, carries roughly 1 percent of the total radiant energy (§2.39); the second pulse is the more significant and is of longer duration. The total length of the effective thermal pulse increases with the energy yield of the explosion. Thus the, duration of the effective pulse from a 10-megaton air burst is about 30 seconds, whereas from a 1-kiloton explosion it is roughly 0.3 second. With increasing altitude the character of the thermal radiation pulse changes, as described in §2.119 *et seq.* At altitudes above about 100,000 feet, there is only a single thermal pulse and its effective duration, which depends on the height of burst and the energy yield of the explosion, is of the order of a second or less for weapons in the megaton range.

7.04 In an ordinary air burst, roughly 30 to 40 percent of the total energy yield is emitted from the fireball as thermal radiation. There is some evidence that the proportion of thermal energy decreases with increasing yield. In the present chapter, it will be assumed for simplicity that one-third of the total energy yield of an air burst is received as thermal energy. This means that for every kiloton of energy released, one-third of a kiloton, i.e., 3.3×10^{11} calories, is in the form of thermal radiation. This is equivalent to nearly 400,000 kilowatt-hours, and such a large amount of energy has important consequences.

7.05 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 and eye injuries in exposed individuals at such distances from the nuclear explosion that the consequences 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 radiations, but even then the latter would be an important cause of personnel injuries.

Attenuation of Thermal Radiation

7.06 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 within a short interval of time. 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.

7.07 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.

7.08 In order to estimate the amount of termal 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 portions of the thermal radiation. The absorption is most effective for the shorter wave length (or ultraviolet) rays. In this connection, oxygen molecules, as well as ozone, nitrogen dioxide, and nitrous acid formed by interaction of gamma radiation from the explosion with the gases in the atmosphere, play an important part.

7.09 Because of absorption, the thermal radiation, particularly that in the ultraviolet region, decreases markedly with increasing distance from the explosion. Some of the absorbed radiation is subsequently re-radiated, but the emission occurs with equal probability in all directions, so that the quantity proceeding in the direc-

tion of a given target is substantially reduced. Consequently, 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. However, the ultraviolet is more effective in causing biological injury than visible and infrared rays, so that even the small amount present could, under some conditions, be important.

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 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 daylight "visibility range" or, in brief, as the "visibility". This is defined as the horizontal distance at which a large dark object on the horizon has just enough contrast with the surrounding sky to be discernible in daylight. The international code for correlating the visibility with the condition of the atmosphere is given in Table 7.12.

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 certain limits, such is not the case. The attenuation increases continuously with increasing distance from the explosion, although not as rapidly as was previously supposed. Furthermore, at distances less than half the visibility range, the

degree of attenuation varies by no more than about 35 percent for atmospheric conditions between moderately and unusually clear, i.e., for visibilities from 10 to 50 miles. The observed variation is very much less than would be expected from the purely absorptive properties of the atmosphere.

Table 7.12

VISIBILITY AND CONDITION OF THE ATMOSPHERE

Atmospheric condition	*Visibility*	
	Kilometers	*Miles*
Exceptionally clear	280	170
Very clear	50	31
Clear	20	12
Light haze	10	6
Haze	4	2. 5
Thin fog	2	1. 2
Light to thick fog	1 or less	0. 6 or less

7.14 The reason for this 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 negligible amount of scattered radiation reaches the observation point. In this case, the radiation received is essentially only that which has been transmitted directly from the exploding weapon 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 object (or area) under consideration. Multiple scattering, i.e., subsequent scattering of already scattered radiation, which is very probable when the concentration of particles is high, will result in the arrival of radiation at the target from many directions. An appreciable amount of thermal radiation will thus reach the given area indirectly, in addition to that transmitted directly.

7.16 It is because of the partial compensation due to multiple scattering that the total amount of energy from a nuclear explosion falling upon unit area at a given distance may not be too 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 in-

dustrial haze. If these latter conditions should exist, another factor, namely absorption due to the increase in water vapor and carbon dioxide content of the air, will play a predominant role. The loss in the directly transmitted radiation, from scattering and absorption, cannot now be compensated by multiple scattering. There is consequently a 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 in § 7.13, that the thermal radiation attenuation is dependent on 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 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 smoke can behave like fog in attenuating thermal radiation. A smoke screen between the point of burst and a given target can reduce the thermal radiation to an extent dependent upon the density and thickness of the screen. Smoke screens, especially those which contain particles that absorb and do not merely scatter the radiation, thus appear to provide the possibility 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, there may be some cases in which 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, travels in straight lines from the fireball. Any solid, opaque material, e.g., a wall, a hill, or a tree, between a given object and the fireball will 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 fireball 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, in which the fireball actually touches the earth or water, the proportion of the explosion energy appearing at a distance as thermal radiation will be less than for an air burst. Some energy is utilized in melting or evaporating surface material, but this is relatively small (about 1 or 2 percent) and has a minor effect on the thermal radiation emitted. As far as the energy received at a distance from the explosion is concerned, other factors are more significant. First, there will be a certain amount of shielding due to terrain irregularities and, second, some absorption of the radiation will occur in the low layer of dust or water vapor produced near the burst point in the early stages of the explosion. In addition, 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 various particles is greater than at higher altitudes. Consequently, in the case of a surface burst, the amount of thermal energy reaching a target at a specified distance from the explosion may be from three-fourths to half that from an air burst of the same total energy yield. It is of interest to mention that when viewed from above, in an aircraft, surface explosions exhibit the same thermal characteristics as air bursts.

7.24 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 fireball. The thermal energy is then used up in heating and melting the soil or vaporizing the water, as the case may be. Normal thermal radiation effects, such as accompany an air burst, are thus absent.

7.25 When nuclear explosions occur at high altitudes, the thermal X-rays from the extremely hot weapon residues are absorbed in a large volume (and mass) of air because of the low density, as explained in §2.121. Consequently, the fireball temperatures are lower than for an air burst, and so it emits thermal radiation more slowly. Although something like 50 to 70 percent of the explosion energy may be absorbed by the air, only about half is emitted sufficiently rapidly to constitute the effective thermal radiation defined in §7.02. Hence, for heights of burst between about 100,000 and 350,000 feet, i.e., about 20 to 70 miles, the thermal radiation, emitted in a single pulse of fairly short duration (§7.03), constitutes some 25 to 35 percent of the total energy yield of the explosion.

THERMAL RADIATION EFFECTS

Absorption of Thermal Radiation

7.26 Because of the high temperatures attained in a nuclear explosion, the fireball resembles the sun in the respect that a large amount of energy is emitted as thermal radiation. With conventional high-explosive weapons 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 explosion. Consequently, the thermal radiation effects of a conventional weapon 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 phe-

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nomena associated with thermal radiation, particularly skin burns and incendiary effects on a large scale, are therefore novel as far as weapons 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 fireball 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, as already seen. Hence, at the target, both thermal pulses (§7.03) contain less ultraviolet radiation than might be expected from the temperature of the fireball.[1] As mentioned earlier, this is partly due to absorption by oxygen, ozone, and other substances formed by interaction of nuclear radiations from the explosion with the gases of the atmosphere. In addition, the ultraviolet rays are absorbed by the undisturbed atmosphere to a greater extent than is visible light. Nevertheless, since ultraviolet radiations have a greater capability for causing biological damage than visible or infrared rays, they may contribute to thermal injury in some circumstances.

7.28 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.

7.29 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

[1] 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 7,500° K (13,000° F), this maximum lies in the ultraviolet and X-ray regions of the spectrum (§ 7.83).

the other hand, if smoke is formed it will partially shield the underlying material from the subsequent radiation.

7.30 Essentially all of the thermal radiation absorbed serves to raise the temperature of the absorbing material and it is the high temperature attained which causes 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 is incident upon a particular surface, is very high. Because of this high intensity, the heat accompanying the absorption of of the thermal radiation is produced with great rapidity.

7.31 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, solid materials on the ground immediately below the burst were probably heated to about 3,000 to 4,000° C (5,400 to 7,200° F). It is true that the temperatures attained fell off rapidly with increasing distance from the explosion, but there is some evidence that they exceeded 1,600° C (2,900° F) even 4,000 feet away (§ 7.52).

7.32 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. 7.32). 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.

7.33 This behavior is illustrated in the photographs taken of one of the wood-frame houses exposed in the 1953 Nevada tests. As mentioned in § 5.12, 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. 7.33a. 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. 7.33b. Presumably, because the heat was partially conducted away from the surface, the temperature was not high enough, during the short effective period of the radiation pulse, for ignition of the wood to occur. It will be seen later (§ 7.44) that thin combustible material would probably have burst into flame at the same location.

Figure 7.32 Thermal radiation from a nuclear explosion ignited the upholstery and caused fire to spread in an automobile, Nevada Test Site

7.34 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.

7.35 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

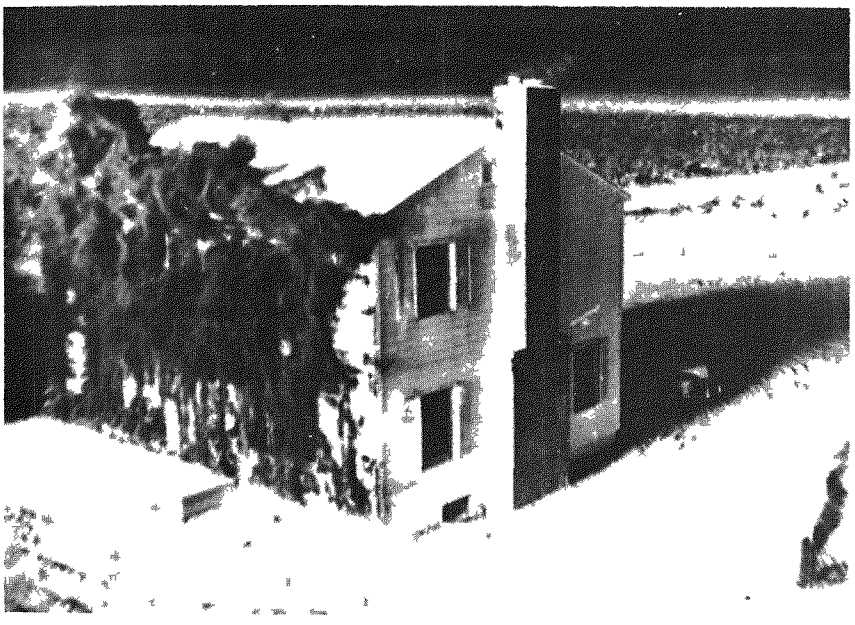

Figure 7.33a. Thermal effects on wood-frame house 1 second after explosion (about 25 cal/sq cm).

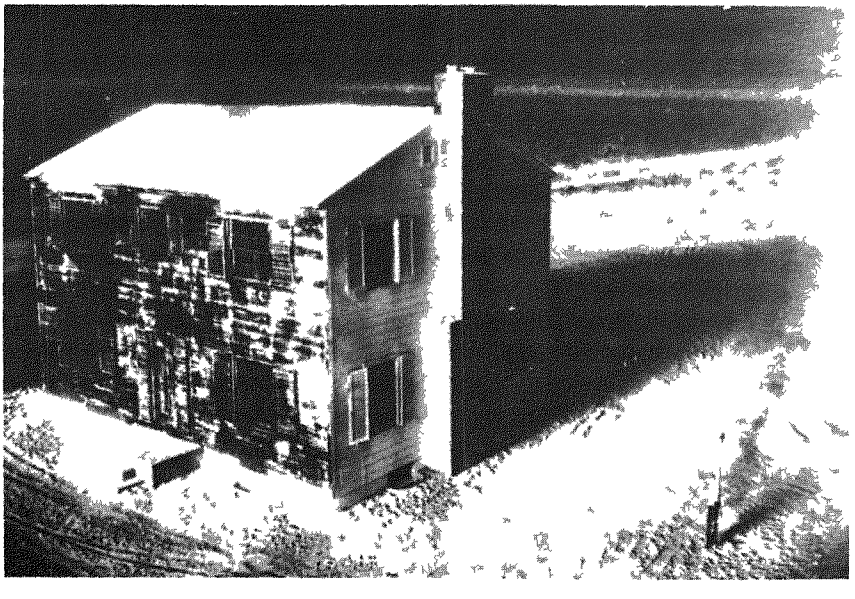

Figure 7.33b. Thermal effects on wood-frame house about ¾ second later.

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 a given amount of energy is delivered over a longer period of time, i.e., more slowly, in the former case.

7.36 There is evidence that for thermal radiation pulses of very short duration, such as might arise from air bursts of low-yield weapons or from explosions of large yield at high altitudes, this trend is reversed. In other words, a given amount of energy may be less effective if delivered in a very short pulse, e.g., a fraction of second, than in one of moderate duration, e.g., one or two seconds. In some experiments in which certain materials were exposed to short pulses of thermal radiation, it was observed that the surfaces were rapidly degraded and vaporized. It appeared as if the surface had been "exploded" off the material, leaving the remainder with very little sign of damage. The thermal energy incident upon the material was apparently dissipated in the kinetic energy of the "exploding" surface molecules before the radiation could penetrate into the depth of the material.

Thermal Radiation Effects on Skin and Eyes

7.37 One of the most serious consequences of the thermal radiation from a nuclear explosion is the production of "flash burns" resulting from the absorption of radiant energy by the skin of exposed individuals. In addition, because of the focusing action of the lens of the eye, thermal radiation can cause permanent damage to the eyes of persons who happen to be looking directly at the burst; however, such direct viewing will be fortuitous and rare. What is expected to be a more frequent occurrence, and therefore much more important to defensive action, is the temporary loss of visual acuity (flash blindness or dazzle) resulting from the extreme brightness, particularly at night when the eyes have been adapted to the dark. This may be experienced no matter what the direction in which the individual is facing. The various effects of thermal radiation on human beings will be considered more fully in Chapter XI, which is concerned with the possible hazards to personnel that can arise from a nuclear detonation.

Thermal Radiation Damage to Fabrics, Wood, and Plastics

7.38 Some mention has already been made of the damage caused to fabrics by the high surface temperatures accompanying the absorp-

tion 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 § 7.34. The following generalizations, however, appear to hold in most instances.

7.39 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. Fabric with a moderate moisture content behaves like dry fabric, but if the amount of moisture is fairly high, more thermal energy will be needed to produce damage.

7.40 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 7.40 to give an indication of the magnitude of the exposure required to ignite various fabric materials by the absorption of thermal radiation. The values are expressed in terms of gram-calories of thermal energy incident upon a 1 square centimeter area of material, i.e., cal/sq cm, generally referred to as the "radiant exposure." Results are presented for total explosion energies of 40 kilotons, 1 megaton, and 10 megatons, respectively. It will be noted that the values are highest in the latter case, for the reason given in § 7.35.

7.41 Wood is charred by exposure to thermal radiation, the depth of the char being closely proportional to the radiant exposure. For sufficiently large amounts of energy per unit area, 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.

TABLE 7.40

APPROXIMATE RADIANT EXPOSURES FOR IGNITION OF FABRICS*

Material	Weight	Ignition exposure** (cal/sq cm)		
	oz/sq yd	*40 kilotons*	*1 megaton*	*10 megatons*
Rayon gabardine (black)	6	9	20	26
Rayon-acetate drapery (wine)	5	9	22	28
Rayon gabardine (gold)#	7	(***)	24	28
Rayon twill lining (black)	3	7	17	25
Rayon twill lining (beige)	3	13	20	28
Acetate-shantung (black)#	3	10	22	35
Cotton chenille bedspread (light blue)#	----------	(***)	11	15
Cotton venetian blind tape, dirty (white)	----------	10	18	22
Cotton muslin oiled window shade (green)	8	7	13	19
Cotton corduroy (brown)	8	11	16	22
Cotton canvas (O.D.)	12	12	18	28
Cotton denim, new (blue)	10	12	27	44
Cotton venetian blind strap (white)#	----------	13	27	31
Cotton shirting (khaki)	3	14	21	28
Cotton heavy draperies (dark colors)	13	15	18	34

*Certain materials listed in previous editions and printings have been deleted.

**The values given are for near sea level detonations of weapons of the yields indicated. Ignition levels (except where marked #) are estimated to be valid within ± 25% under standard laboratory conditions. Under typical field conditions the values listed are estimated to be valid within ± 50% with a greater likelihood of higher rather than lower values. For materials marked #, ignition levels are estimated to be valid within ± 50% under laboratory conditions and within ± 100% under field conditions.

***Data not available or appropriate scaling not known.

7.42 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.[2]

7.43 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 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, Plexiglas, 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.

[2] The thermal radiation energy incident on the front of the house referred to in § 7.33 was about 25 calories per square centimeter.

Radiant Exposures for Ignition of Various Materials

7.44 In connection with the initiation of fires, the radiant exposures 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 per unit area that would be needed to cause a particular material to ignite. The data in Table 7.44 have been divided into two sections: one contains household materials and the other combustible substances which might start forest fires.

7.45 As far as the forest fuels are concerned, in particular, the radiant exposures required for ignition are greatly dependent upon the amount of moisture they contain. For the present purpose, it has been assumed that the leaves and grass are fairly dry, so that the radiant exposures given in Table 7.44 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

7.46 In order to utilize the data in Tables 7.40 and 7.44 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 a specific explosion yield, the variation of radiation exposure with distance from the point of burst depends upon a number of factors, including the height of burst and the condition (or clarity) of the atmosphere. As seen earlier, the proportion of the total yield that appears as thermal energy and the character and duration of the thermal pulse vary with the height of burst, especially if it is over about 100,000 feet (20 miles). Furthermore, the height of burst and the atmospheric visibility determine the fraction of the thermal energy that can penetrate the atmosphere without being absorbed.

7.47 The variation of radiant exposure with slant range from the explosion for a particular set of conditions can be conveniently

TABLE 7.44

APPROXIMATE RADIANT EXPOSURE FOR IGNITION OF HOUSEHOLD MATERIALS AND DRY FOREST FUELS*

Material	Weight	Ignition exposure** (cal/sq cm)		
	oz/sq yd	*40 kilotons*	*1 megaton*	*10 megatons*
Newspaper, shredded	2	4	6	11
Newspaper, dark picture area	2	5	7	12
Newspaper, printed text area	2	6	8	15
Paper, crepe (green)	1	6	9	16
Cotton string scrubbing mop, used (gray)#	----	10	15	21
Cotton string mop, weathered (cream)#	----	10	19	26
Matches, paper book, blue head exposed#	----	11	14	20
Excelsior, ponderosa pine (light yellow)#	2 lb/cu ft	(***)	23	23
Paper, Kraft, single sheet (tan)	3	10	13	20
Paper, bristol board, 3 ply (dark)	10	16	20	40
Paper, Kraft, carton, flat side, used (brown)	16	16	20	40
Paper, bond, typing, new (white)#	2	24	30	50
Dry rotted wood punk (fir)#	----	4	6	8
Deciduous leaves (beech)	----	4	6	8
Fine grass (cheat)	----	5	8	10
Coarse grass (sedge)	----	6	9	11
Pine needles, brown (ponderosa)	----	10	16	21

*Certain materials listed in previous editions and printings have been deleted.

**The values given are for near sea level detonations of weapons of the yields indicated. Ignition levels (except where marked #) are estimated to be valid within ±25% under standard laboratory conditions. Under typical field conditions the values listed are estimated to be valid within ±50% with a greater likelihood of higher rather than lower values. For materials marked #, ignition levels are estimated to be valid within ±50% under laboratory conditions and within ±100% under field conditions.

***Data not available or appropriate scaling not known.

represented in the form of Fig. 7.47. The curves in this figure apply to air bursts at moderate altitude, i.e., below about 20 miles, with the clarity of the atmosphere equivalent to a visibility of 50 miles, as defined in § 7.12. Suppose it is required to determine the range over which ignition may occur in newspaper as a result of exposure to a 1,000-kiloton (1-megaton) air burst under the given conditions. According to Table 7.44, the radiant exposure for ignition of the material in a 1-megaton explosion is about 8 calories per square centimeter. Entering Fig. 7.47 at the point on the vertical axis corresponding to 1 megaton, the horizontal line is followed until it intersects the curve for 8 calories per square centimeter of thermal radiation. The intersection is seen to correspond to a distance of about 9 miles from the explosion and this is the range over which

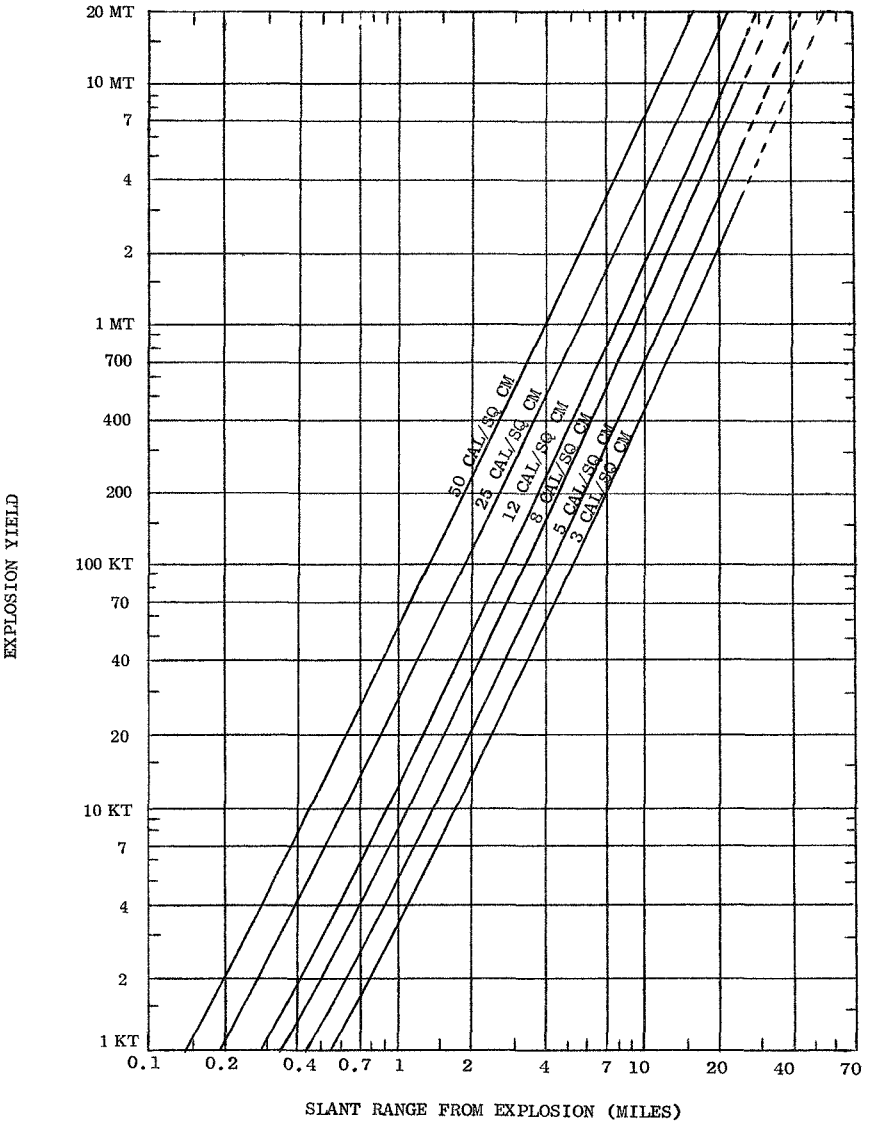

Figure 7.47. Slant ranges for specified radiant exposures as a function of energy yield of an explosion at moderate altitude (less than 20 miles) for 50-mile visibility.

ignitions may be started in newspaper as a direct result of the absorption of thermal radiation. Under hazy atmospheric conditions, or in the event of a surface burst, the distances obtained from Fig. 7.47 may be decreased. Similarly, in accordance with discussion in § 7.21 *et seq.*, a layer of dense cloud or smoke between the target and the point of burst will decrease the distance over which ignitions may occur.

Thermal Effects on Materials in Japan[3]

7.48 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 to the absorption of thermal radiation. Fabrics (Fig. 7.48a), utility poles (Fig. 7.48b), trees, and wooden posts, up to a radius of 11,000 feet (2.1 miles) from ground zero at Nagasaki, and 9,000 feet

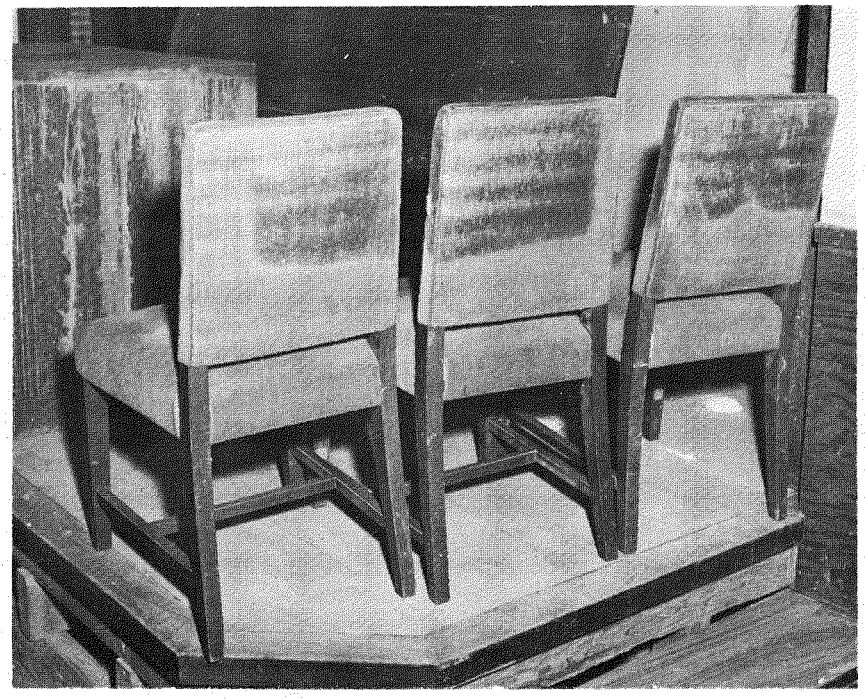

Figure 7.48a. Flash burns on upholstery of chairs exposed to bomb flash at window (1 mile from ground zero at Hiroshima).

[3] The effects of thermal radiations on human beings in Japan are described in Chapter XI.

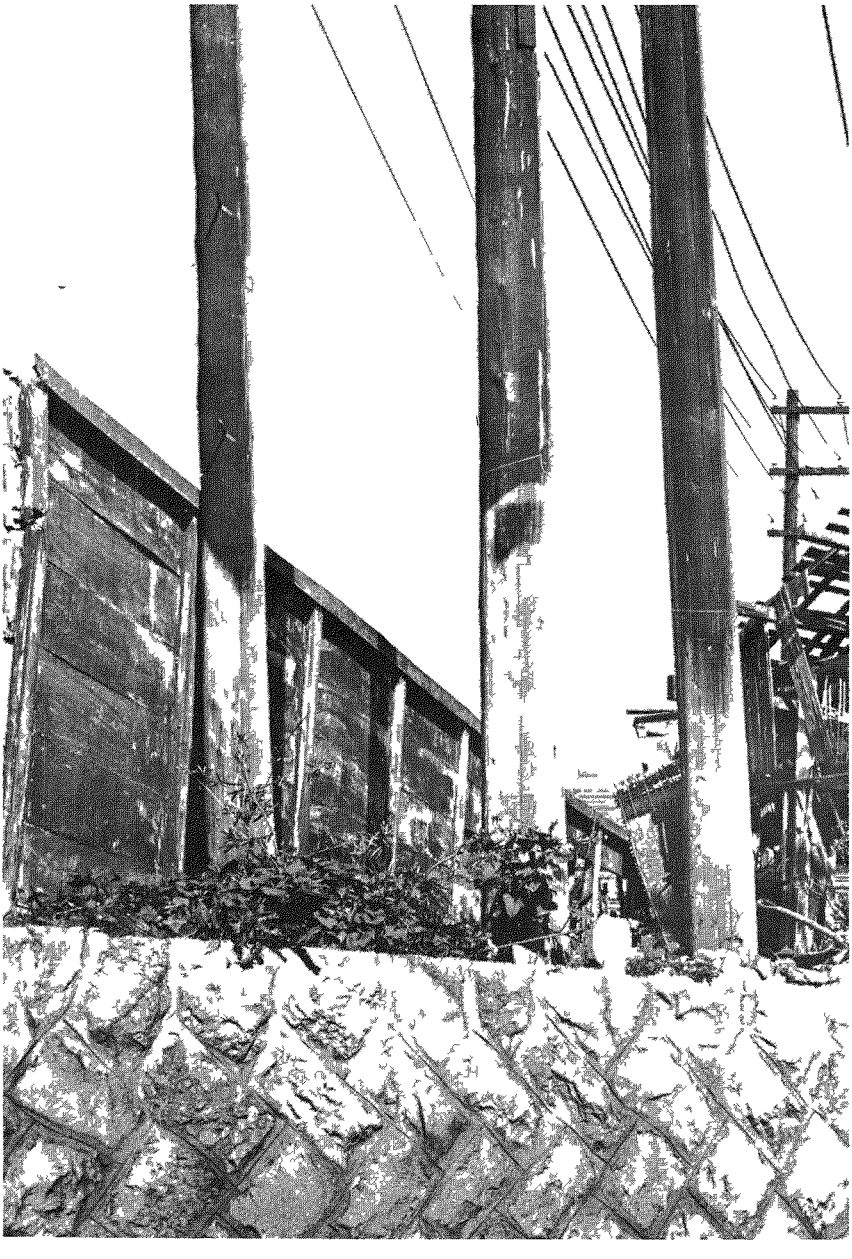

Figure 7 48b Flash burns on wooden poles (1 7 miles from ground zero at Nagasaki) The uncharred portions were protected from thermal radiation by a fence

(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.

7.49 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

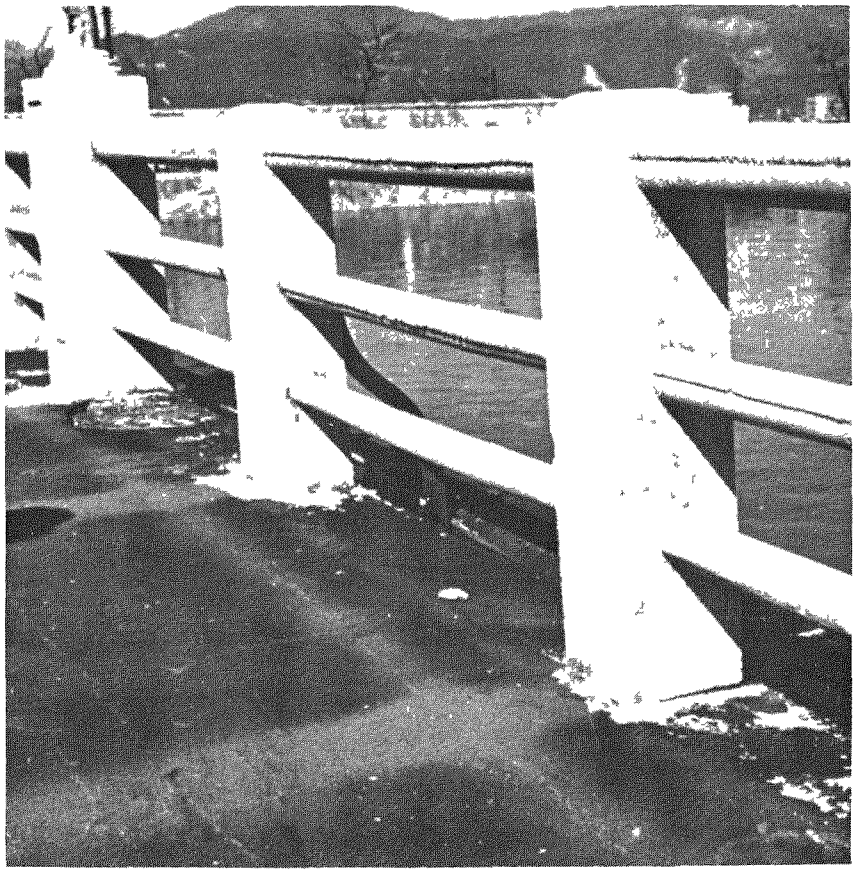

Figure 7.50a. Flash marks produced by thermal radiation on asphalt of bridge in Hiroshima. Where the railings served as a protection from the radiation, there were no marks; the length and direction of the "shadows" indicate the point of the bomb explosion.

by the blast wave which arrived after the thermal radiation. This radiation travels with the speed of light, whereas the blast wave advances much more slowly (§ 3.14).

7.50 From observations of the shadows left by intervening objects where they shielded otherwise exposed surfaces (Figs. 7.50 a and b), the direction of the center of the explosion was located with considerable accuracy. Furthermore, 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,

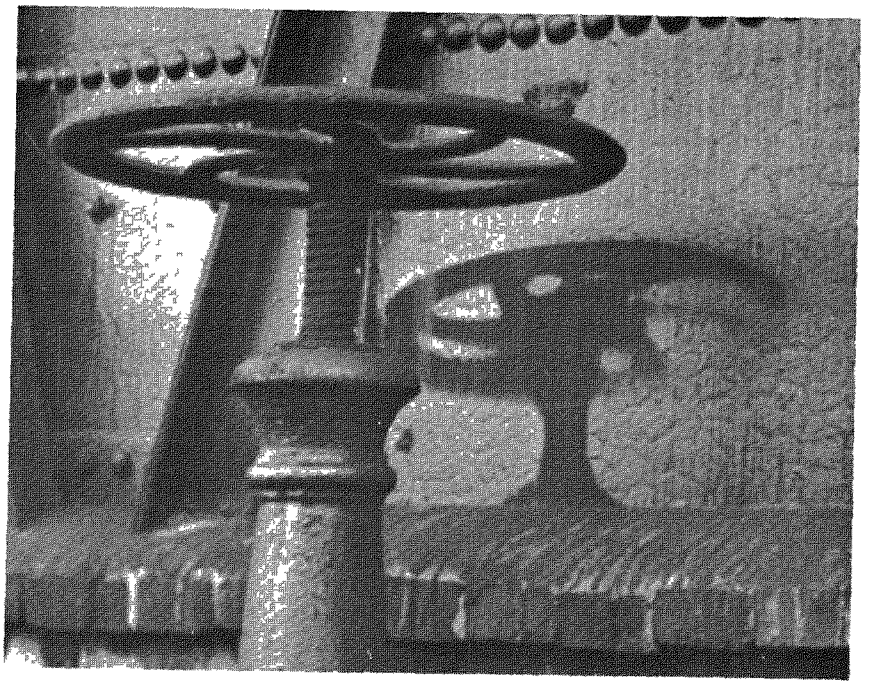

Figure 7.50b. Paint on gas holder scorched by the thermal radiation, except where protected by the valve (1.33 miles from ground zero at Hiroshima)

and from this it was possible to calculate the diameter of the fireball at the time the thermal radiation intensity was at a maximum.

7.51 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 mentioned in § 7.31, they were extremely high, especially near ground zero.

7.52 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. 7.52). The phenomenon was observed out to 3,900 feet (0.75 mile) from the explosion center, where the radiant exposure 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

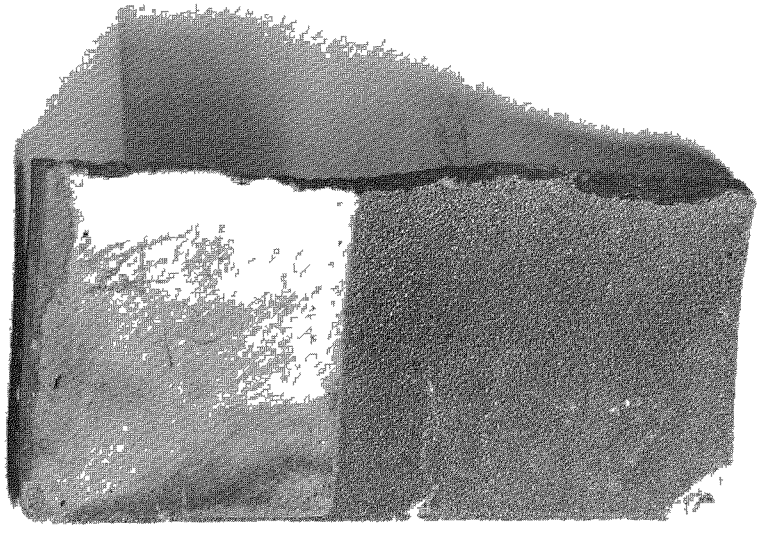

Figure 7.52. Blistered surface of roof tile; left portion of the tile was shielded by an overlapping one (0 37 mile from the explosion at Hiroshima)

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 the tile attained a

temperature of more than 1,800° C (3,270° F) for a period of less than 4 seconds.

7.53 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 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. 7.53). 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.

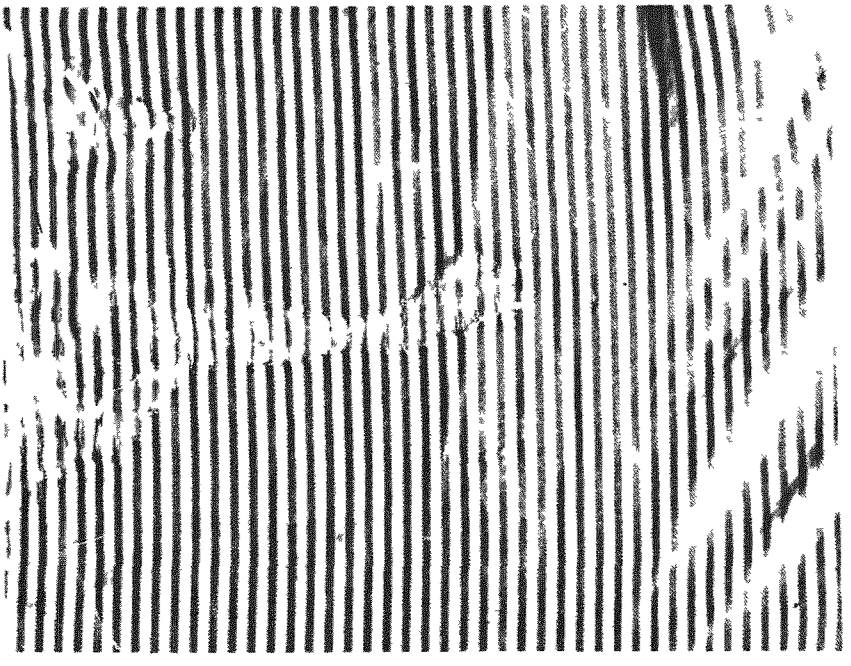

Figure 7.53. The light-colored portions of the material are intact, but some of the dark-colored stripes have been destroyed by the heat from the thermal radiation.

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INCENDIARY EFFECTS

Origin of Fires

7.54 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. The manner whereby fires in cities grow and spread from ignition points is a complex matter which will be discussed later. In the meantime, two aspects of the problem of the development of fires accompanying a nuclear explosion will be considered, namely, (1) the number of points at which fires originate, and (2) the character of the surrounding area.

7.55 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 are present which will produce a primary ignition and may result in a fire. In general, these materials may be expected to ignite when exposed to at least the appropriate radiant energy values given in Tables 7.40 and 7.44. The data in Fig. 7.55 are based on surveys made in a 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.[4] Paper was the commonest ignitable material found everywhere except in downtown retail areas where awnings represented the major source of fire.

7.56 The density of ignition points provides some indication of the chance of fires being started under ideal weather conditions. But the results in Fig. 7.55 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 moderate to severe blast damage occurs, almost all ignitable materials will constitute a fire hazard. On the other hand, at greater distances, only those most easily ignitable will catch fire. Further,

[4] The area types are in accordance with the classification used by the U.S. Bureau of Census.

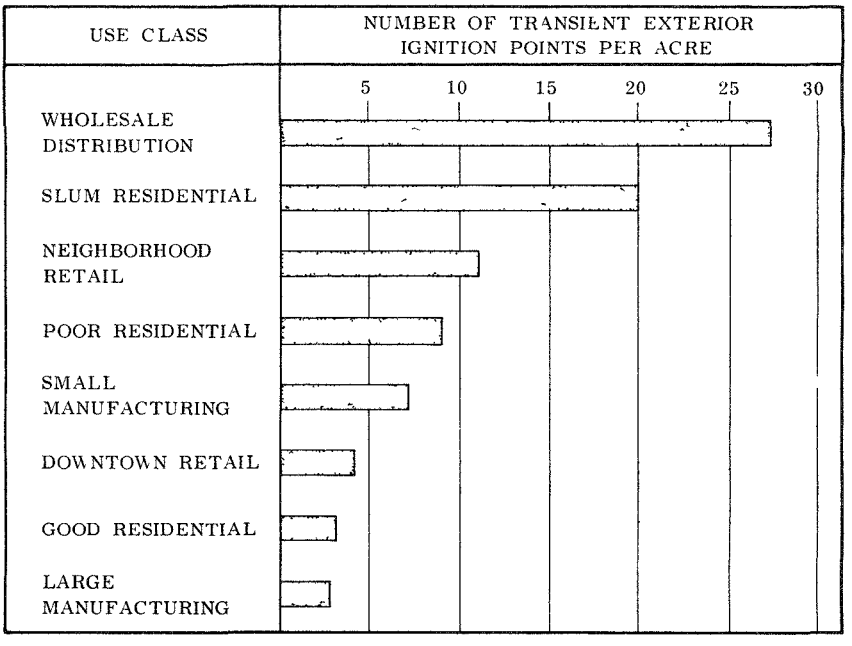

Figure 7.55 Frequency of exterior ignition points for various areas in a city

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.

7.57 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. 7.57, had weathered siding showing considerable decay, but the yard was free from trash. The next house also had a clean yard and in addition, 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.

7.58 The state of the three houses after the explosion is seen in Fig. 7.58. 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

Figure 7 57 Wooden test houses before exposure to a nuclear explosion, Nevada Test Site

Figure 7 58 Wooden test houses after exposure to a nuclear explosion

house exposed to about 25 calories per square centimeter was badly charred but did not ignite (see Fig. 7.33b).

7.59 The value of fire-resistive furnishing in decreasing the number of ignition points was also demonstrated in the 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 much ignition occurred, the recovery party, entering an hour after the explosion, was able to extinguish the fires.

7.60 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 (§ 7.67), 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 (§ 7.68).

Spread of Fires

7.61 The spread of fires in a city, including the development of a "fire storm" to which reference is made in § 7.75, depends upon a variety of conditions, e.g., weather, terrain, and closeness and combustibility of the buildings. Information concerning the growth and spread of fires from a large number of ignition points, such as might follow a nuclear explosion, and their coalescence into large fires (or conflagrations) is limited to the experience of World War II incendiary raids and the two atomic bomb attacks. There is consequently some uncertainty concerning the validity of extrapolating from these limited experiences to the behavior to be expected in other cities. It appears, however, that if other circumstances are more-or-less the same, an 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. Furthermore, the larger the spaces between buildings the greater the chances that the fire can be extinguished.

7.62 The curve in Fig. 7.62 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. It should be noted that Fig. 7.62 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.

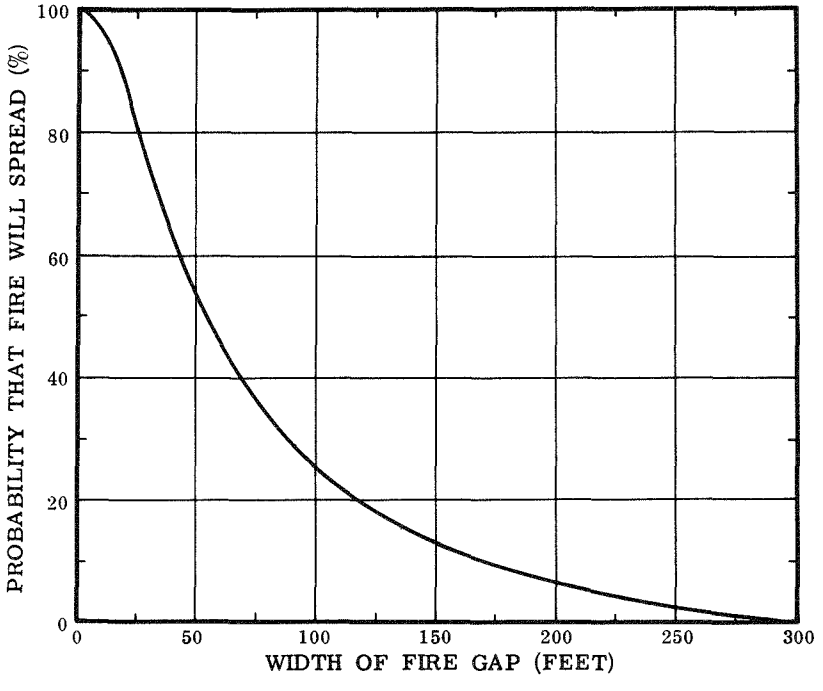

Figure 7.62. Width of gap and probability of fire spread.

7.63 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, 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

7.64 The incendiary effects of a nuclear explosion do not present any especially characteristic features. In principle, the same overall 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.

7.65 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 ranges of incendiary effects were 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

7.66 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 distance 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 re-

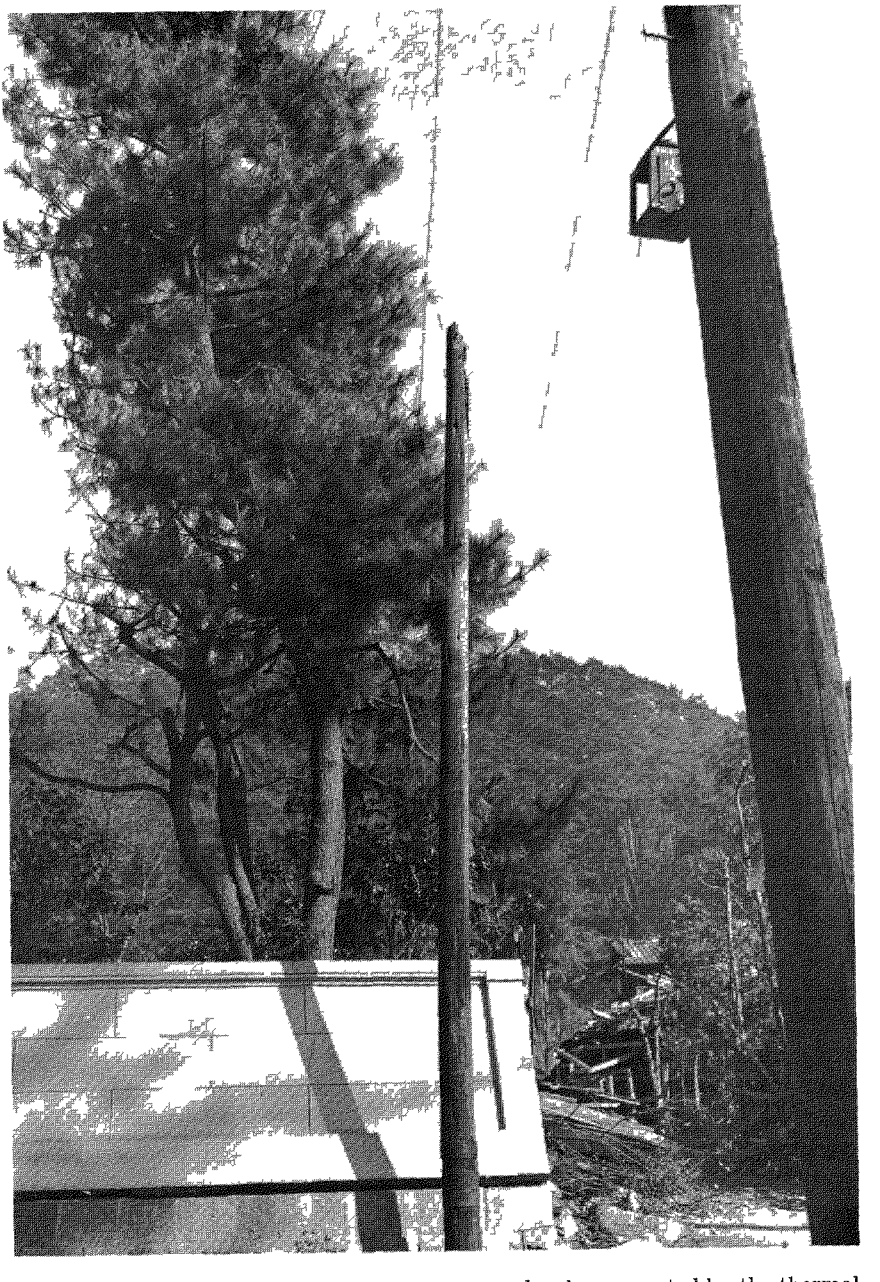

Figure 7 66 The top of a wood pole was reported as being ignited by the thermal radiation (1 25 miles from ground zero at Hiroshima) Note the unburned surroundings, the nearest burned building was 360 feet away

flection, scattering, and focusing effects, might have caused fires to originate at isolated points (Fig. 7.66).

7.67 Interesting evidence of the ignition of sound wood was found about a mile from ground zero at Nagasaki, where the radiant exposure 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.

7.68 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 (§ 7.33). Rotted and checked wood and excelsior, however, have been observed to burn completely, and the flame was not greatly affected by the blast wave.

7.69 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.

7.70 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 damaging fire shutters (Fig. 7.70), 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 (see Fig. 5.89d).

7.71 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. Moreover, 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.

Figure 7.70. 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).

7.72 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 burnout of some fire-resistive buildings.

7.73 One of the important aspects of the nuclear 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.

7.74 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 (§ 5.117).

Fire Storm in Hiroshima

7.75 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. Rain is often associated with a fire storm and is apparently due to the condensation of moisture on particles from the fire when they reach a cooler area. Because of the strong inward draft at ground level, the fire storm was a decisive factor in limiting the spread of 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.

7.76 It should be noted that the fire storm is by no means a special characteristic of nuclear weapons. 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. Because of limited experience, the conditions for the development of fire storms in cities are not well known. It appears, however, that some, although not necessarily all, of the essential requirements are the following: (1) thousands of nearly simultaneous ignitions over an area of at least a square mile, (2) heavy building density, e.g., more than 20 percent of the area is covered by buildings, and (3) little or no ground wind. Based on these criteria, only certain sections—usually the older and slum areas—of a very few cities in the United States would be susceptible to fire storm development.

7.77 It should be mentioned that no definite fire storm occurred at 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 [5]

Distribution and Absorption of Energy From the Fireball

7.78 Spectroscopic studies made in the course of weapons tests have shown that the fireball does not behave exactly like a black body, i.e., as a perfect radiator. Generally, the proportion of radiations of longer wave length (greater than 5,500 A) [6] corresponds to higher black body temperatures than does the shorter wave emission. The assumption of black body behavior for the fireball, however, serves as a reasonable approximation in interpreting the thermal

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

[6] The symbol "A" represents the "angstrom", i.e., 10^{-8} cm, the unit in which radiation wave lengths are commonly expressed.

radiation emission characteristics. For a black body, the distribution of radiant energy over the 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 λ to $\lambda+d\lambda$, then,

$$E_\lambda=\frac{8\pi hc}{\lambda^5}\cdot\frac{1}{e^{hc/\lambda kT}-1}, \tag{7.78.1}$$

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. It will be noted that hc/λ is the energy of the photon of wave length λ (§ 1.70).

7.79 From the Planck equation it is possible to calculate the rate of energy emission (or radiant power) of a black body for a given wave length, i.e., J_λ, as a function of wave length for any specified temperature, since

$$J_\lambda=\frac{c}{4}E_\lambda, \tag{7.79.1}$$

where J_λ is in units of energy (ergs) per unit area (cm^2) per unit time (sec) per unit wave length (A). The results of such calculations for temperatures ranging from 100 million (10^8) degrees to 2,000° K are shown in Fig. 7.79. It is seen that the total radiant power, which is given by the area under each curve, decreases greatly as the temperature is decreased.

7.80 An important aspect of Fig. 7.79 is the change in location of the curves with temperature; in other words, the spectrum of the radiant energy varies with the temperature. At high temperatures, radiations of short wave length predominate, but at low temperatures those of long wave length make the major contribution. For example, in the exploding weapon, before the formation of the fireball, the temperature is several tens of million degrees Kelvin. Most of the (primary) thermal radiation is then in the wave length range from about 0.1 to 100 A, i.e., 120 to 0.12 kev energy, corresponding roughly to the soft X-ray region. This is the basis of the statement made earlier that the primary thermal radiation from a nuclear explosion consists largely of X-rays. These radiations are absorbed by the surrounding air to form the fireball from which the effective thermal radiation of present interest is emitted. Since the surface temperature of the fireball is generally below 10,000° K, the radiation is mainly in the ultraviolet, visible, and infrared regions of the spectrum. The dimensions of the fireball in which the thermal X-rays are absorbed depends on the ambient air density, as will be seen shortly.

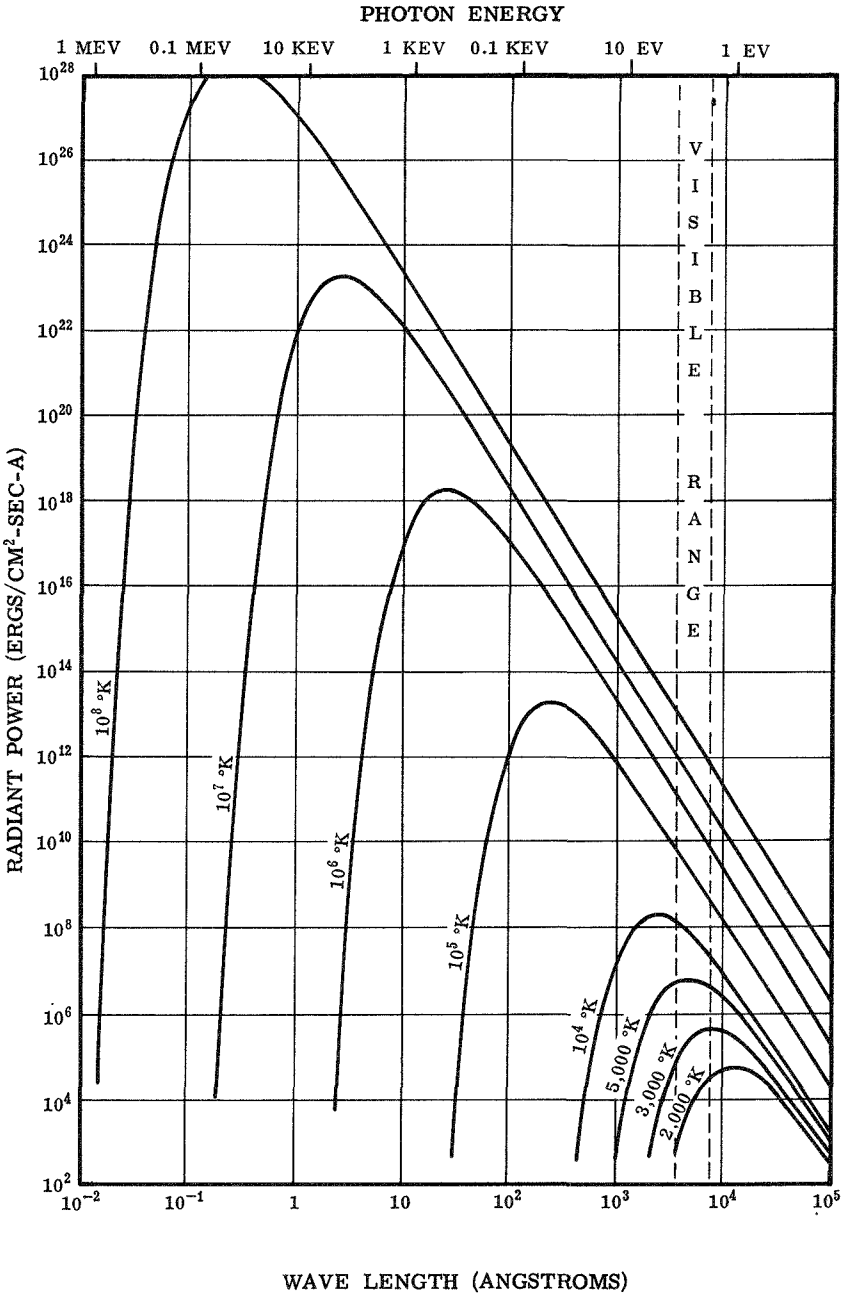

Figure 7.79. Radiant power of a black body as a function of wave length at various temperatures.

7.81 It will be recalled that the thermal radiation received at the earth's surface differs to some extent from that leaving the fireball. The reason is that the radiations of shorter wave length, i.e., in the ultraviolet, are more readily absorbed than the others by the atmosphere between the burst point and the earth's surface. The thermal radiation received at a distance from a nuclear explosion is fairly characteristic of a black body at a temperature of about 6,000 to 7,000° K, although somewhat depleted in the ultraviolet and other shorter wave lengths. Even if the detonation occurs at very high altitudes, the thermal radiation from the low-density fireball must pass through the denser atmosphere before reaching the ground. The effective thermal radiation received on the earth's surface is thus also composed of the longer wave lengths.

7.82 An expression for the wave length (λ_m) corresponding to the maximum in the radiant power as a function of the black body temperature can be obtained by differentiating equation (7.79.1) with respect to wave length and equating the result to zero. It is then found that

$$\lambda_m = \frac{C}{T}, \tag{7.82.1}$$

where C is a constant, equal to 2.90×10^7 angstroms-degrees K. This expression is known as Wien's displacement law.

7.83 The temperature at which the maximum in the radiant power distribution from a black body should just fall into the visible spectrum, i.e., wave length 3,850 A, is found from equation (7.82.1) to be about 7,500° K. This happens to be very close to the maximum surface temperature of the fireball after the minimum, i.e., during the second radiation pulse (Fig. 2.113). Since the apparent surface temperature generally does not exceed 8,000° K and the average is considerably less, it is evident that most of the thermal energy emitted in the second pulse should consist mainly of visible and infrared rays, with little in the ultraviolet region of the spectrum. This has been found to be the case in actual tests, even though the fireball deviates appreciably from black body behavior at this stage.

7.84 The mean free path (§ 2.104) in cold air, at sea-level density, of X-ray photons with energies from about 0.5 to 15 kev is given by the approximate relationship

$$\text{Mean free path} \approx \frac{E^3}{5} \text{ cm}, \tag{7.84.1}$$

where E is the photon energy in kilo-electron volts (kev). In order to make some order-of-magnitude calculations of the distances in

which thermal X-rays from a nuclear explosion are absorbed in air, a convenient round-number temperature of 10^7 degrees Kelvin will be used for simplicity. According to equation (7.82.1), the wave length at which the rate of emission of radiation from a black body at this temperature is a maximum is 2.9 A. According to equation (1.70.2) this corresponds to a photon energy of 4.3 kev, and from equation (7.84.1) the mean free path of these photons in normal air is about 15 cm. In traversing a distance of one mean free path the energy of the radiations decreased by a factor of e, i.e., approximately 2.7; hence 90 percent of the energy will be deposited within a radius of 2.3 mean free paths. It is seen, therefore, that 4.3-kev radiation will be largely absorbed in a distance of about 35 cm, i.e., a little over 1 foot, in a sea-level atmosphere.

7.85 The primary thermal radiations from a nuclear explosion cover a wide range of wave lengths, as is evident from Fig. 7.79. However, for the present purpose, which is to obtain a rough indication of the initial size of the fireball, the wave length (or energy) at which the radiant power from a black body is a maximum may be taken as typical. It follows, therefore, from the results given above that the thermal X-rays from a nuclear explosion will be almost completely absorbed by about a foot of air at normal density. Because the oxygen and nitrogen in the air in the vicinity of the explosion are considerably ionized, they do not absorb as effectively as do neutral molecules. Nevertheless, in a nuclear explosion in the atmosphere where the air density does not differ greatly from the sea-level value, most of the X-rays, which constitute the primary thermal radiation, will be absorbed within a few feet of the explosion. It is in this manner that the initial fireball is formed in an air burst.

7.86 With increasing altitude, the air density decreases roughly by a factor of ten for every 10 miles (see § 10.75), so that at 150,000 feet (approximately 30 miles) the density is about 10^{-3} of the sea-level value. The mean free path of the photon varies inversely as the density, so that for nuclear explosions at an altitude of about 30 miles, the region of the air heated by X-rays, which is equivalent to the fireball, extends over a radius of some thousands of feet. In spite of the lower density, the mass of heated air in this large volume is much greater than in the fireball associated with a nuclear explosion at lower altitudes, and so the temperature attained by the air is lower.

7.87 At altitudes of about 100,000 to 350,000 feet (20 to 70 miles) the manner in which the thermal radiation is emitted from a nuclear detonation is somewhat different from that at lower altitudes. At

the upper limit (350,000 feet), the heated (fireball) region can be about 0.5 to 6 miles in extent for yields of 1 kiloton to 1 megaton, respectively. The time required for a shock wave to form is of the order of 0.1 to 1 sec for these yields. For the reasons given in § 2.123, the thermal radiation is emitted from the fireball in a single pulse of relatively short duration. The limited data available indicate that the thermal radiation received on the ground from bursts at high altitudes is consistent with the statement (§ 7.25) that roughly 25 to 35 percent of the total yield of the weapon is converted into effective thermal radiation.

7.88 For altitudes in excess of 350,000 feet (above 70 miles) the air density is less than 10^{-7} of that at sea level. The mean free path of the dominant thermal X-rays produced in a nuclear explosion is then several hundred miles. In spite of the low density, the mass of air in which the thermal energy is deposited is many million tons, and so the temperature will not increase appreciably. At the low air temperatures, the thermal radiation emitted from an explosion in the megaton range is incapable of causing damage at the earth's surface.

Total Radiant Power From Fireball

7.89 According to the Stefan-Boltzmann law, the total amount of energy (of all wave lengths), J, radiated per square centimeter per second by a black body in all directions in one hemisphere is related to the absolute temperature, T, by the equation

$$J=\sigma T^4, \tag{7.89.1}$$

where σ is the Stefan-Boltzmann constant. The value of J can also be obtained by integration of equation (7.79.1) over all wave lengths from zero to infinity. It is then found that

$$\begin{aligned}\sigma&=2\pi^5k^4/15h^3c^2\\&=5.67\times10^{-5}\ \text{erg/(cm}^2\text{) (sec) (deg}^4\text{)}\\&=1.38\times10^{-12}\ \text{cal/(cm}^2\text{) (sec) (deg}^4\text{).}\end{aligned}$$

With σ known, the total radiant energy intensity from the fireball behaving as a black body can be readily calculated for any required temperature.

7.90 In accordance with the definition of J, given above, it follows that the total rate of emission of radiant energy from the fireball can be obtained upon multiplying the expression in equation

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(7.89.1) by the area. If R is the radius of the fireball, its area is $4\pi R^2$, so that the total rate of thermal energy emission (or total radiant power) is $\sigma T^4 \times 4\pi R^2$. Representing this quantity by the symbol P, it follows that

$$P = 4\pi\sigma T^4 R^2$$
$$= 1.71 \times 10^{-11}\ T^4 R^2 \text{ calories per second,}$$

where T is in degrees Kelvin and R is in centimeters. Alternatively, if the radius, R, is expressed in feet, then,

$$P = 1.59 \times 10^{-8}\ T^4 R^2 \text{ calories per second.} \qquad (7.90.1)$$

7.91 The power, P, is measured directly as a function of time, t, for each explosion, but 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. 7.91 is then of general applicability, irrespective of the yield of the explosion. The zero of the scaled time axis is taken as the time of the first minimum; as seen in §2.116, this is approximately equal to $0.0025W^{1/2}$ second, where W is the total explosion yield in kilotons. The first pulse is so short that the amount of thermal radiation energy received prior to the first minimum is only about 1 percent of the total.

7.92 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 approximately to the yield, W kilotons, in the following manner for air bursts:

$$P_{max} \approx 4W^{1/2} \text{ kilotons per second,}$$

and

$$t_{max} \approx 0.032\ W^{1/2} \text{ seconds.}$$

For air bursts in the megaton range, the value of t_{max} may be somewhat less than given by this expression. For a contact surface burst the fireball develops in a manner approaching that for an air burst of twice the yield, because the blast wave energy is reflected back from the surface into the fireball (§§ 2.117, 3.30). Hence, t_{max} may be expected to be larger than for an air burst of the same actual yield.

7.93 The amount of thermal energy, E, emitted by the fireball in an air burst 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_{tot} versus t/t_{max}, is shown by the second curve (right scale) in Fig. 7.91. The quantity E_{tot} is the total thermal energy emitted in the second pulse by the fireball; this may range from 30 to 40 percent of the energy yield of the explosion, but for the present purpose it will be assumed, for the reason given in § 7.04, that

$$E_{tot} \text{ (kilotons)} \approx {}^1/_3 W. \tag{7.93.1}$$

This equation gives the thermal energy in terms of kilotons of TNT equivalent, but if it is required in calories the result is multiplied by 10^{12}.

7.94 The curves in Fig. 7.91 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_{max} curve, followed by a somewhat less sharp drop which tapers off as the fireball approaches its final stages.

7.95 From the standpoint of protection against skin burns (and possibly eye injury) by taking evasive action, the important quantity is t_{max}, since the rate of emission of thermal radiation from the fireball is then a maximum. It is seen from the relationship in § 7.92 that this time increases in proportion to the square root of the energy yield of the explosion. Thus, t_{max} is about 0.1 second for a 10-kiloton explosion, but it is some 3 seconds for a weapon 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 air bursts of high energy yield. The dependence of t_{max} on the explosion yield is indicated in another way in Fig. 7.95 which shows the percentage of the total thermal energy emitted at various times after the first minimum for 10- and 100-kiloton and 1- and 10-megaton air bursts. Close to 20 percent of the thermal energy will have been emitted at t_{max} in each case. At $10t_{max}$, which is taken as the effective duration of the second thermal pulse (§ 7.03), over 80 percent of the thermal radiation has been released.

7.96 The results described above are applicable to detonations at altitudes below about 100,000 feet (20 miles) where the density of the air is still appreciable. With increasing altitude, the fireball phenomena change, as described in Chapter II, and above 100,000 feet essentially all of the thermal energy is emitted in a single pulse of short

The curves in Fig. 7.91 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_{tot} (right ordinate), in the second thermal pulse of an air burst.

Scaling. In order to apply the data in Fig. 7.91 to an explosion of any energy, W kilotons, the following expressions are used:

$$P_{max} \approx 4W^{1/2} \text{ kilotons per second}$$

$$t_{max} \approx 0.032W^{1/2} \text{ seconds}$$

$$E_{tot} \approx \tfrac{1}{3}W \text{ kilotons,}$$

where t_{max} is the time after explosion for temperature maximum in second thermal pulse, P_{max} is the maximum rate (at t_{max}) of emission of thermal energy from fireball, and E_{tot} is the total thermal energy emitted by fireball in the second pulse.

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 $t_{max}=0.032\times22.4=0.72$ second, and the scaled time at 2 seconds after the explosion is

$$t/t_{max}=2.0/0.72=2.8.$$

(*a*) From Fig. 7.91, the value of P/P_{max} at this scaled time is 0.26, and since $P_{max}=4\times22.4=90$ kilotons per second, it follows that,

$$\dot{P}=0.26\times90=23 \text{ kilotons per second}$$

$$=23\times10^{12} \text{ calories per second.} \quad \textit{Answer.}$$

(*b*) At the scaled time of 2.8, the value of E/E_{tot} from Fig. 7.91 is 58 percent, i.e., 0.58, and

$$E_{tot}=\tfrac{1}{3}\times500=167 \text{ kilotons.}$$

Hence,

$$E=0.58\times167=97 \text{ kilotons}$$

$$=97\times10^{12} \text{ calories.} \quad \textit{Answer.}$$

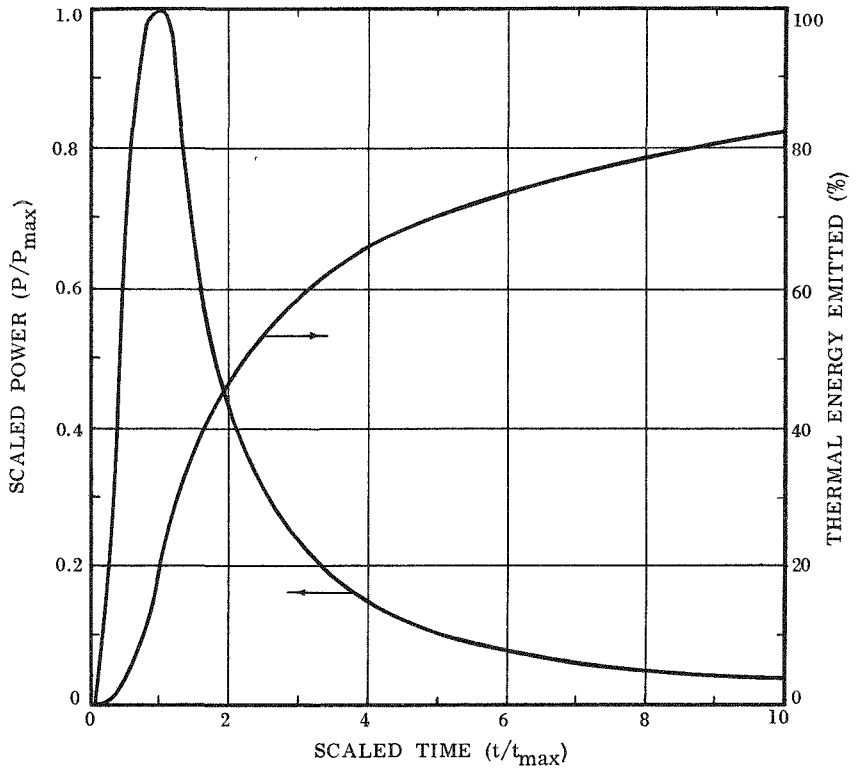

Figure 7.91. Scaled fireball power and fraction of thermal energy versus scaled time in second thermal pulse of an air burst.

duration, e.g., in less than a second for a megaton-range explosion at 250,000 feet altitude (§ 2.121). Scaling of the pulse length with respect to the explosion yield is very complex and depends upon a variety of factors. However, the duration of the pulse will probably not be strongly dependent on the total yield. At higher altitudes, the thermal pulse length may be expected to be longer because of the larger mass and lower temperature of the radiating fireball.

7.97 It appears that under such conditions that sufficient thermal radiation is received on the ground to cause skin burns, the emission time is too short to permit evasive action. For detonations in the megaton range occurring near the lower limit of the high-altitude region, i.e., around 20 miles, skin burns are possible on the earth's surface. But at higher altitudes, the distance of the explosion makes the probability very small that exposed persons on the ground will suffer such burns. On the other hand, altitude can increase the

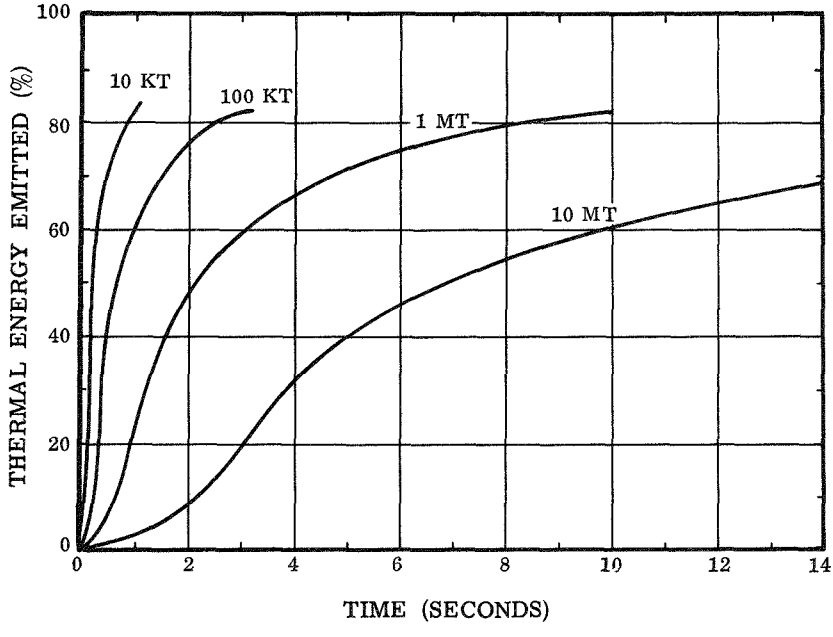

Figure 7.95. Percentage of thermal energy emitted as a function of time for air bursts of various yields.

possibility of eye injuries, especially of flash blindness (§7.37). During the period of the blink reflex (0.15 second), a significant portion of the thermal radiation from a high-altitude detonation will have been received on the ground. Furthermore, the light from the fireball will be visible over a considerable area. In fact, it is possible that a high-altitude nuclear explosion in the megaton range could produce effects on the eye at all distances up to the line of sight permitted by the earth's curvature.

Thermal Energy-Distance Relationship

7.98 The next matter to consider is the variation with distance from the explosion of the total thermal energy (in calories) received per square centimeter, i.e., thermal (or radiant) exposure, of a target material. As seen earlier in this chapter, such information, combined with the data in Fig. 7.46 (see also Fig. 7.105) and in Tables 7.40 and 7.44, permits estimates to be made of the probable ranges for various thermal radiation effects.

7.99 If there is no atmospheric attenuation, the thermal energy, E_{tot}, at a distance D from the explosion, may be regarded as being spread uniformly over the surface of a sphere of area $4\pi D^2$. The energy received per unit area of the sphere would thus be $E_{tot}/4\pi D^2$. If attenuation were due only to absorption in a uniform atmosphere, e.g., for an air burst, this quantity would be multiplied by the factor $e^{-\kappa D}$, where κ is an absorption coefficient averaged over the whole spectrum of wave lengths. Hence, in these circumstances, using the symbol Q to represent the radiant exposure, i.e., the energy received per unit area normal to the direction of propagation, at a distance D from the explosion, it follows that

$$Q=\frac{E_{tot}}{4\pi D^2}e^{-\kappa D}. \tag{7.99.1}$$

7.100 When scattering of the radiation occurs, in addition to absorption, the coefficient κ 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

$$Q=\frac{E_{tot}T}{4\pi D^2}, \tag{7.100.1}$$

where the transmittance, T, i.e., the fraction of the radiation (direct and scattered) which is transmitted, is a complex function of the visibility (scattering), absorption, and distance.[7]

7.101 The amount of thermal radiation energy, E_{tot}, emitted from a nuclear detonation can be related to the weapon yield W by the general expression

$$E_{tot}=fW, \tag{7.101.1}$$

where f is the fraction of the total yield in the form of thermal radiation energy. Hence, the radiant exposure can be expressed as

$$Q=\frac{fTW}{4\pi D^2} \tag{7.101.2}$$

by substituting fW for E_{tot} in equation (7.100.1).

[7] Scattered radiation does not cause permanent damage to the retina of the eye. Hence, to determine the effective radiant exposure in this connection equation (7.99.1) should be used; κ is about 0.03 km^{-1} for a visibility of 80 km (50 miles), 0.1 km^{-1} for 40 km (25 miles), and 0.2 km^{-1} for 20 km (12.4 miles). Scattered radiation can, however, contribute to flash blindness, resulting from the dazzling effect of bright light.

7.102 In a weapons test, it is possible to measure Q and W, and since the distance D from the explosion is known the magnitude of the product fT can be determined from equation (7.101.2). To obtain f, the value of T for the atmosphere between the explosion and the observation point must be known. However, the atmospheric transmittance over a long distance varies with both time and direction, so that the value at the instant when Q is measured cannot be obtained with a precision better than about ± 20 percent. Consequently, average values of T, such as those given in Fig. 7.104 below, are employed. Using these data and analyzing values of the product fT from a large number of weapons tests, f is found to range from about 0.3 to 0.4, with a mean of about one-third, for air bursts.

7.103 By utilizing the fact that 1 kiloton of TNT is equivalent to 10^{12} calories and taking f as $\frac{1}{3}$, equation (7.101.2) for an air burst becomes

$$Q(\text{cal/sq cm}) = \frac{10^{12} WT}{12\pi D^2}, \tag{7.103.1}$$

where D is in centimeters. If the distance (or slant range) is expressed in miles, equation (7.103.1) reduces approximately to

$$Q(\text{cal/sq cm}) \approx \frac{1.04 WT}{D^2}, \tag{7.103.2}$$

where D is now in miles.

7.104 The value of T, for any given atmospheric condition, depends on the solid angle over which scattered radiation can reach a particular exposed object. For the present purpose it will be assumed that the target is such, e.g., an appreciable flat area, that scattered radiation is received from all directions above, in addition to the direct thermal radiation from the source. The variation of the transmittance with distance from the explosion for the two different visibility ranges is shown in Fig. 7.104; one curve is for a visibility of 50 miles and 5 grams of water vapor per cubic meter of air and the other is for a visibility of 10 miles and 10 grams of water vapor per cubic meter. The data may be considered to be reliable up to distances of half the visibility in each case.

7.105 In order to simplify the use of equation (7.103.2), in conjunction with Fig. 7.104, the values of the thermal radiation exposure, Q, in calories per square centimeter, for various distances (slant ranges), D, from an air burst are plotted for $W = 1$ kiloton in Fig. 7.105. The results are applicable provided D is less than half the appropriate visibility, between 10 and 50 miles. The thermal energy

received from an explosion of W kilotons is then obtained upon multiplying the radiant exposure for the same distance in Fig. 7.105 by W. If the distances of interest are greater than half the visibility range, the thermal radiation exposures derived from Fig. 7.105 will be less reliable but in the majority of cases they will be conservative.

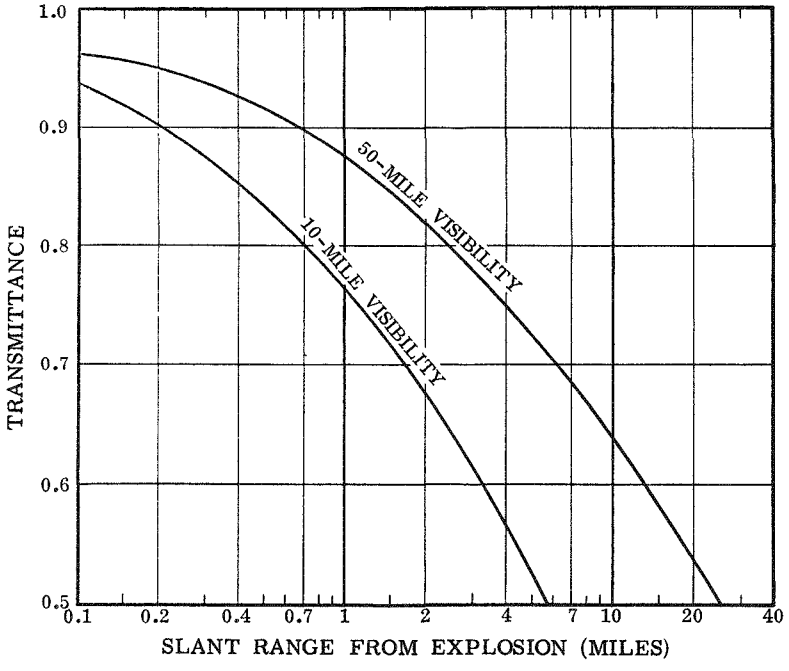

Figure 7.104. Atmospheric transmittance as a function of distance for visibilities of 10 miles and 50 miles.

7.106 For a surface burst, the radiant exposures along the earth's surface will be less than for equal distances from an air burst of the same total yield. This difference is partly due, as indicated in § 7.23, to the decreased transmittance of the intervening low air layer due to dust and water vapor produced by the explosion. Furthermore, the normal atmosphere close to the earth's surface transmits less than at higher altitudes. The thermal exposure from a surface burst thus ranges from about three-quarters at short distances to one-half at longer distances of the corresponding value for an air burst derived from equation (7.103.2) or from Fig. 7.105. In other words the f

The plot in Fig. 7.105, which is in two parts for convenience of representation, shows the amount of thermal energy (or radiant exposure) in calories per square centimeter received at various distances from a 1 KT air burst for atmospheric visibility between 10 and 50 miles.

Scaling. The radiant exposure 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 between 10 and 50 miles.

Find: The radiant exposure received at a distance of 3 miles from the explosion.

Solution: From Fig. 7.104 the amount of thermal energy received at 3 miles from a 1 KT air burst is between 0.07 and 0.10 calorie per square centimeter. Consequently, the radiant exposure received at 3 miles from a 100 KT air burst is between

$$100 \times 0.07 = 7 \text{ calories per square centimeter.}$$

and

$$100 \times 0.10 = 10 \text{ calories per square centimeter.} \quad \textit{Answer.}$$

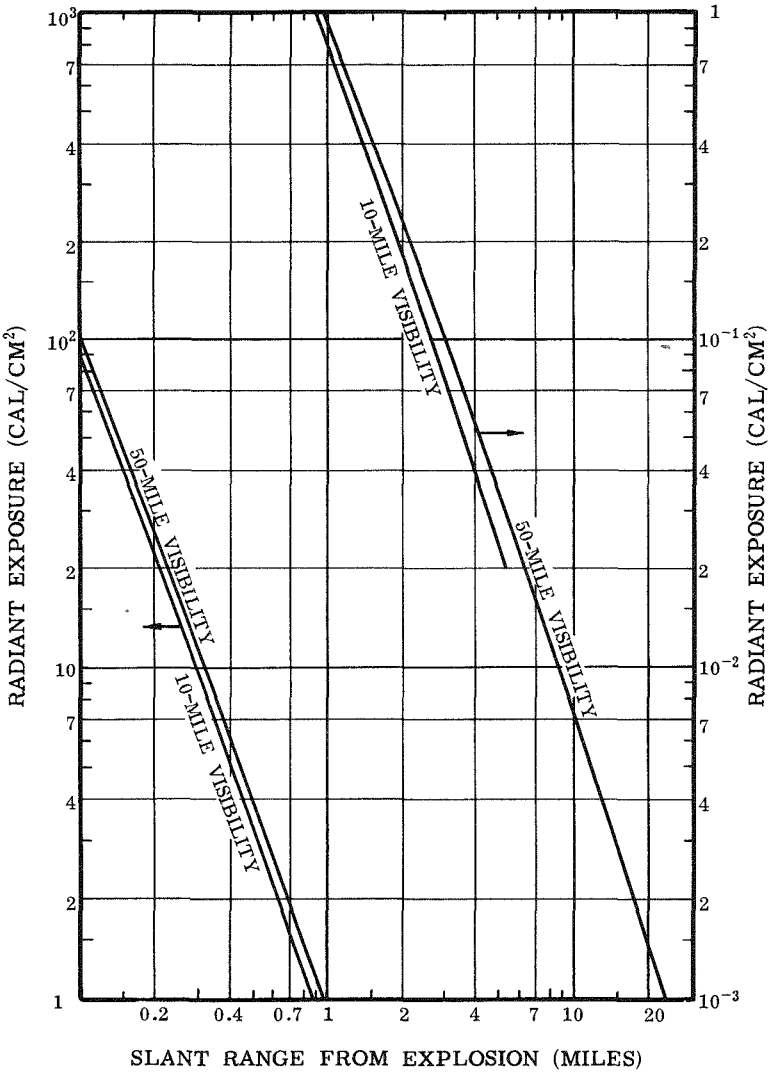

Figure 7.105. Radiant exposure as a function of slant range from a 1-kiloton air burst for visibilities of 10 miles and 50 miles.

factor of equation (7.101.2) has values which lie approximately between ¼ and ⅐. Thus, for a surface burst,

$$Q(\text{cal/sq cm}) \approx 0.8 \text{ to } 0.5\,\frac{WT}{D^2}, \tag{7.106.1}$$

where D is the slant range in miles. It appears that as the yield increases the radiant exposure tends towards the larger limit of the values given by equation (7.106.1).

7.107 In the calculation of the thermal radiation exposure at some distance from a high-altitude nuclear explosion, e.g., at the earth's surface, equation (7.101.2), must be modified in two respects. First, the thermal energy capable of causing damage is approximately 25 to 35 percent of the total yield (§7.25), for detonations of altitudes from about 100,000 to 350,000 feet (20 to 70 miles). Correction for this difference can be made by taking E_{tot} to be roughly 0.25 W kilotons.

7.108 Second, in their passage from the burst point to the earth, the radiations pass through regions where the atmospheric density varies continuously and is considerably less than at sea level. The attenuation can be calculated in an approximate manner by utilizing the concept of the "reduced height of the atmosphere." This is equal to the total mass of air contained in a vertical column of unit cross section above the observer divided by the sea-level density of air. On the ground at sea level, the reduced height of the atmosphere is about 25,000 feet or roughly 5 miles. If an explosion occurs at an altitude of H miles, for example, it is assumed, for purposes of estimating the thermal attenuation, that, in arriving at a target on the ground vertically below the burst point, the radiation traverses $H-5$ miles of vacuum, in which there is no absorption or scattering, and 5 miles of sea-level atmosphere. If the explosion center is not immediately above the target, but makes an angle of elevation ϕ with the horizon, then the respective distances are $(H-5)/\sin\phi$ and $5/\sin\phi$, respectively.

7.109 On the basis of the foregoing argument, it can be shown that for a high-altitude explosion equation (7.103.2) can be written in the approximate general form

$$Q(\text{cal/sq cm}) \approx \frac{0.76WT}{H^2}\sin^2\phi \tag{7.109.1}$$

where T is the appropriate transmittance for the angle ϕ. If the shot is directly overhead, ϕ is 90° and $\sin^2\phi$ is unity. Values for the transmittance as a function of angle of elevation, for detonations at high altitude, are given in Fig. 7.109; with these data equation

(7.109.1) can be used to give results which are reliable within a factor of two or so. Observations of radiant exposure made on Johnston Island in connection with the TEAK shot, described in Chapter II, are in general agreement with equation (7.109.1).

7.110 For detonations at altitudes above about 70 miles, equation (7.109.1) is no longer applicable. As explained in §7.88, the volume of air heated by the thermal X-rays is so large that the temperatures attained are relatively low. Thermal radiation is then emitted at such a slow rate that, at distances of interest, the radiant energy capable of causing any kind of damage is less than for bursts of the same yield at lower altitudes.

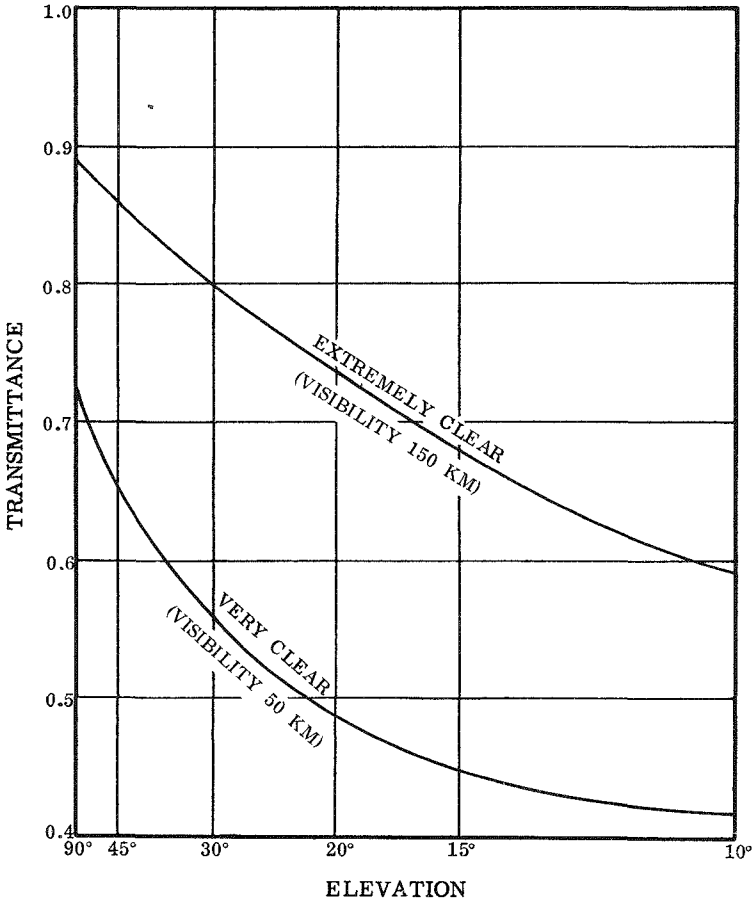

Figure 7.109. Atmospheric transmittance as a function of elevation for use in calculating radiant exposures from high-altitude explosions.

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*These documents may be obtained for a small charge from the Office of Technical Services, U.S. Department of Commerce, Washington 25, D.C.

**These documents may be obtained from the Library of Congress, Washington 25, D.C.

CHAPTER VIII

INITIAL NUCLEAR RADIATION

NATURE OF NUCLEAR RADIATIONS

Neutrons and Gamma Rays

8.01 It was stated in Chapter I that one of the special features of a nuclear explosion is the fact that it is accompanied by the emission of nuclear radiations. 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 part of the gamma rays are emitted in the actual fission process, that is to say, simultaneously with the explosion. The remainder of the gamma rays are produced in various secondary nuclear processes, including decay of the fission products. The beta particles are also emitted as the fission products decay. Some of the alpha particles result from the normal radioactive decay of the uranium or plutonium which has escaped fission in the weapon, and others (helium nuclei) are formed in hydrogen fusion reactions (§1.65).

8.02 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 (§ 1.02). The line of demarcation is somewhat arbitrary, but it may be taken as about 1 minute after the explosion, for the reasons given in § 2.43. 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 (§§ 2.79, 2.92), although the distinction may be made if desired.

8.03 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 fireball 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 travel 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. Although the energy of the initial gamma rays and neutrons is only about 3 percent of the total explosion energy, compared with some 35 percent appearing as thermal radiation in an air burst, the nuclear radiations can cause a considerable proportion of the casualties.

8.04 Most of the gamma rays accompanying the actual fission process are absorbed by the weapon 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 weapon, 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 weapon residues or by the air through which they travel. Nevertheless, a sufficient number of fast (fission) neutrons escape from the explosion region to represent a significant hazard at considerable distances away.

Comparison of Nuclear Weapon Radiations

8.05 Although shielding from thermal radiation at distances not too close to the point of the explosion of a nuclear weapon is a fairly simple matter, this is not true for gamma rays and neutrons. For example, at a distance of 1 mile from a 1-megaton explosion, the initial nuclear radiation would probably prove fatal to a large proportion of exposed human beings even if surrounded 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.

8.06 The effective injury ranges of these two kinds of nuclear weapon 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 air burst, 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.

8.07 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 the chapter.

GAMMA RAYS

Sources of Gamma Rays

8.08 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, others escape, and a large number 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."

8.09 Neutrons produced in fission can undergo radiative capture reactions with the nuclei of various materials present in the weapon, 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 certain atomic nuclei, particularly heavy nuclei, provides another source of gamma rays. When a "fast neutron," i.e., one having a large amount of kinetic energy, collides with such a nucleus, the neutron may transfer some of its energy to the nucleus, leaving the latter in an excited (high-energy) state. The excited nucleus can then return to its normal

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energy (or ground) state by the emission of the excess energy as gamma rays. This type of interaction of a fast neutron with a nucleus is called "inelastic scattering" and the accompanying radiations are referred to as "inelastic scattering gamma rays." [1]

8.11 The gamma rays produced in fission and as a result of other neutron reactions and nuclear excitation of the weapon 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 fraction of a second 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 weapon. The instantaneous gamma rays are produced almost entirely before the weapon has completely blown apart. They are, therefore, strongly absorbed by the dense weapon 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 weapon 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 more than 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.

[1] The term "scattering" is used because, after interacting with the nucleus, the neutron of lower energy generally moves off in a direction different from that in which the original neutron was traveling before the collision.

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 (or water). This may be accompanied by the emission of gamma rays which will commence at the time of the explosion and will continue thereafter. However, except near ground zero, where the intensity of gamma rays from other sources is very high in any event, the contribution of induced radioactivity to the initial gamma radiation is small. Consequently, the radioactivity induced in the earth's surface by neutrons will be treated in the next chapter as an aspect of the residual nuclear radiation.

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 electronically 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 electrical devices. With glass containing silver phosphate, the excitation energy resulting from the absorption of gamma rays makes the material sensitive to ultraviolet light. When exposed to such light the glass then produces a phosphorescent glow which can be measured by means of a photoelectric instrument.

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 under 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.

The Roentgen[2]

8.21 In order to express the exposure to gamma radiation (or X-rays) at any particular point, it is necessary to have a suitable unit of measurement. The unit which is specifically used in this connection is called the "roentgen." As mentioned above, the interaction of gamma radiation with matter may result in ionization, that is, the

[2] For a discussion of other radiation units, see § 11.80 *et seq.*

production of ion pairs. The actual extent of ion pair formation serves as the basis for the quantitative measurement of the amount of impinging gamma radiation. Thus, in simple terms, a roentgen may be defined as the quantity of gamma radiation (or X-rays) which will give rise to the formation of 2.08×10^9 ion pairs per cubic centimeter of dry air, at S.T.P., i.e., at standard temperature (0° C) and pressure (1 atmosphere). This is equivalent to the release of about 88 ergs of energy when 1 gram of dry air under S.T.P. conditions is exposed to 1 roentgen of gamma radiation.

8.22 In actual practice, measuring instruments do not directly determine the number of roentgens. Instead one or other of several observable effects of the radiations, such as electric pulses, scintillations, or fogging of photographic films, serves as the basis for the actual determination. The instruments designed to measure any particular effect can then be used to indicate the radiation exposure in roentgens after being calibrated with a standard gamma-ray source. For the latter purpose, a known quantity of radium or radioactive cobalt is generally employed.

8.23 Two fundamental types of measurements, both of which are important, are made with radiation instruments. The first kind involves the determination of the total radiation dose (or amount) in roentgens received during a given period of exposure. Pocket ion chambers, photographic film badges, and silver phosphate activated glass devices are examples of personnel dosimeters employed in determining total radiation dose. The second type of measurement is that of the dose rate which can be expressed in roentgens per hour or, for smaller dose rate, as milliroentgens per hour, where 1 milliroentgen is one thousandth of a roentgen. For determining dose rate, survey meters are employed, e.g., ion chambers, Geiger-Mueller tubes, or scintillation detectors, together with associated electronic counting circuitry. In general, these survey meters are portable and battery powered. The dose rate measurement may be converted into the total radiation dose by multiplying the properly averaged dose rate by the total time of exposure.

8.24 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. However, the ability to measure both dose rate and total dose is important for the initial nuclear radiation as well as for the delayed radiation to be discussed in Chapter IX.

8.25 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 [3] of less than 25 roentgens will produce no detectable clinical effects. Larger doses have increasingly more serious consequences and whole-body exposure of 1,000 roentgens would probably prove fatal in nearly all cases, although death would not occur until a few days later.

Gamma-Ray Dose-Distance Relationship

8.26 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 explosion. As with thermal radiation (§7.07), the dose received is inversely proportional to the square of the distance from the explosion, so that it is said to be governed by the "inverse square" law. Second, there is an attenuation factor to allow for the decrease in intensity due to absorption and scattering of gamma rays by the intervening atmosphere.

8.27 The gamma-radiation exposure doses at known distances from explosions of different energy yields have been measured at a number of nuclear test explosions. The results obtained for air bursts are summarized in the form of two graphs: the first (Fig. 8.27a) shows the dependence of the initial gamma-ray dose on the actual distance (or slant range) from a 1-kiloton explosion; the second (Fig. 8.27b) 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. The data are based on the assumption that the average density of the air in the transmission path, between the burst point and the target, is 0.9 of the normal sea-level density.[4] Because of variations in weapons design and the different characteristics of the gamma rays associated with fission and fusion, as well as for other reasons (§ 8.85), the gamma-ray doses calculated from Figs. 8.27a and b cannot be exact. For yields from about 1 to 100 kilotons TNT equivalent they are reliable within a factor of two or so; from 100 kilotons to 1 megaton, within a factor of 5; and above 1 megaton, within a factor of about 10.

[3] The "exposure dose" of gamma (or X-) rays is a measure of the radiation that is based upon its ability to produce ionization. The "absorbed dose" of *any* ionizing radiation is the energy imparted to matter by ionizing particles per unit mass of irradiated materials; absorbed dose units are treated in Chapter XI.

[4] The density referred to here (and subsequently) is that of the air before it is disturbed by the explosion (cf. § 8.30).

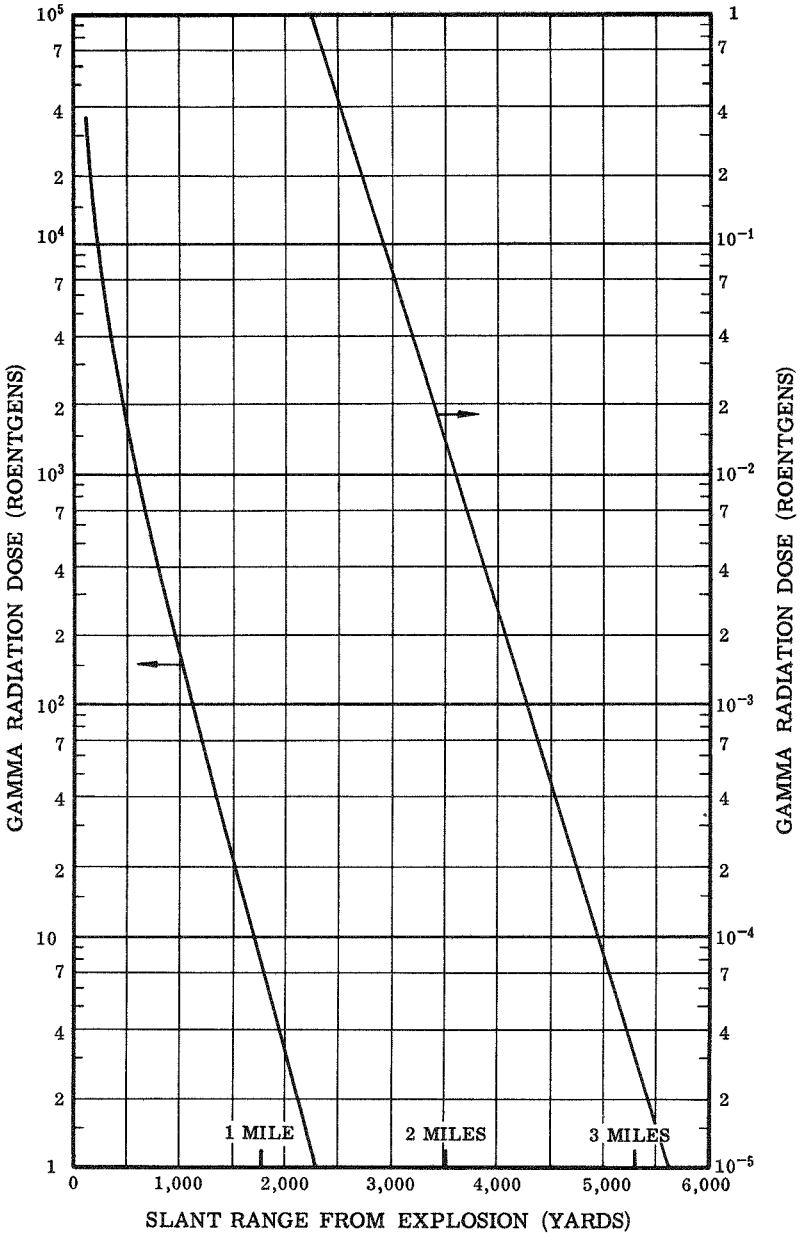


Figure 8.27a. Initial gamma-radiation dose as function of slant range from explosion for 1-kiloton air burst, based on 0.9 sea-level air density.

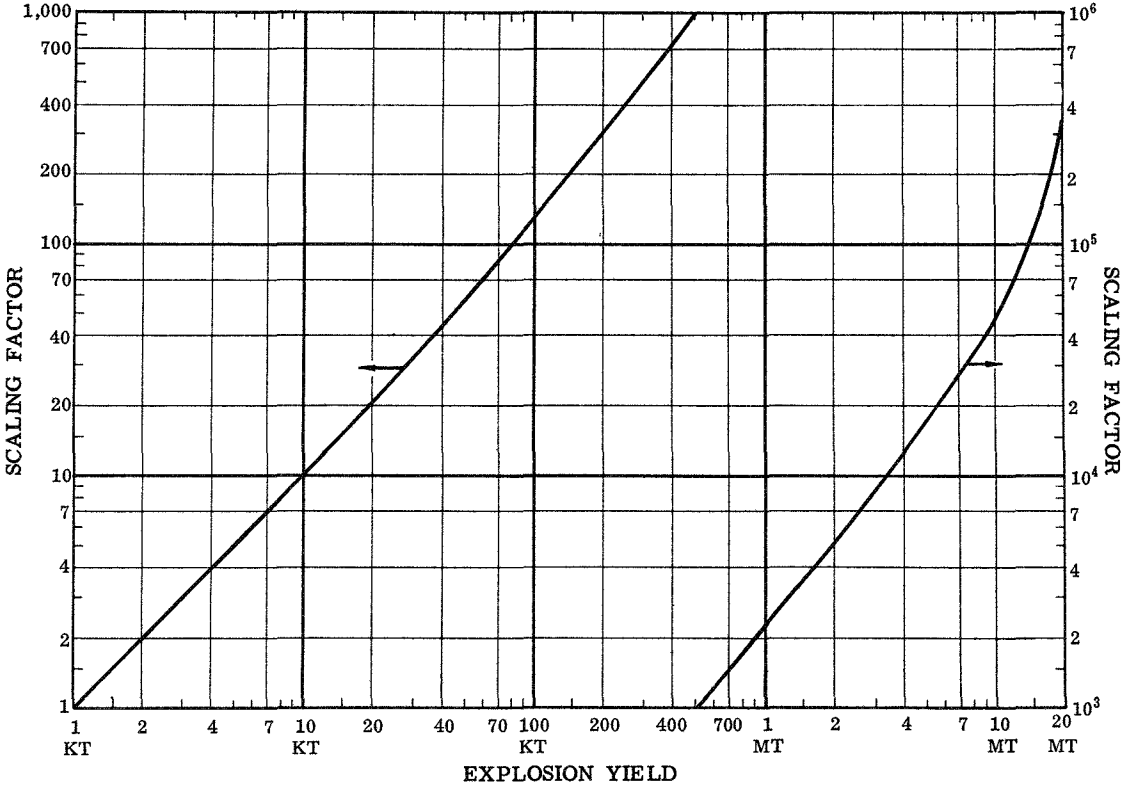


Figure 8.27b. Scaling factor for initial gamma-radiation dose.

8.28 The method of using the curves in Figs. 8.27a and 8.27b may be illustrated by determining from them the initial gamma-radiation dose received at a distance of 1,700 yards from a 100-kiloton air burst. From Fig. 8.27a, the exposure dose at this distance from a 1-kiloton air burst is 10 roentgens. The scaling factor for 100 kilotons is found from Fig. 8.27b to be 120. Hence, the gamma-ray dose in the case specified is $10 \times 120 = 1{,}200$ roentgens.

8.29 The values in Fig. 8.27a 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 an average air density in the transmission path of 0.9 of the sea-level value. If the actual density is higher or lower, the gamma-ray dose will be decreased or increased, respectively.

8.30 It will be noted from Fig. 8.27b 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 about 120, and for a 1,000-kiloton (1-megaton) yield it is roughly 2,100. The reason for this increase is the sustained low air density, following the passage of the positive phase of the shock wave (§3.04), especially for explosions of high energy yield. As a result, there is less attenuation of the (delayed) gamma rays from the fission products.

8.31 The gamma-ray doses to be expected from explosions of various energies can be expressed in another form, as in Fig. 8.31. The slant ranges from 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 10 megatons, can be read off directly. For intermediate doses, the corresponding slant distances can be estimated by interpolation.

8.32 Strictly speaking, the foregoing data and conclusions are applicable only to air bursts. In a surface burst, the presence of dust and debris produced by the explosion will cause a reduction in the exposure dose at any given distance (slant range) from the point of burst. Consequently, the dose-distance relationships may be expected to vary with the height of burst, especially if the detonation occurs not too far above the earth's surface. It is generally suggested that the initial gamma-radiation dose from a surface burst be taken as two-thirds that from an air burst at the same slant

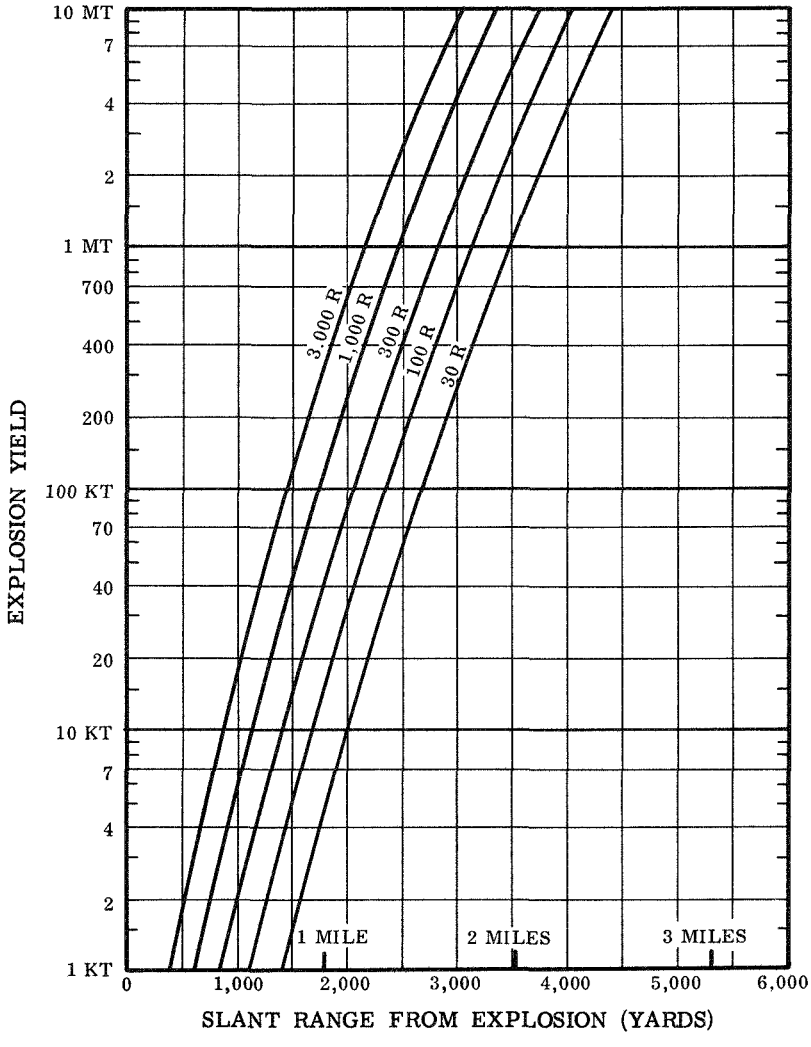


Figure 8.31. Slant ranges for specified initial gamma-ray doses as function of energy yield of the explosion.

distance. However, the errors inherent in the available data, as mentioned in §8.27, are such that the variations arising from the proximity of the burst to the surface are usually not significant.

Shielding Against Gamma Rays

8.33 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 weapon, and an individual, the exposure dose can be reduced to negligible proportions.

8.34 The approximate effectiveness of a given substance in decreasing the intensity of impinging radiation is sometimes expressed by means of a quantity called the "tenth-value thickness." This is defined as the thickness of the specified material which reduces the radiation dose (or dose rate) to one tenth of that falling upon it; in other words, one tenth-value thickness of the material decreases the radiation by a factor of ten. Thus, if a person were in a location where the exposure dose is 500 roentgens, e.g., of initial gamma radiation, with no shielding, the introduction of the appropriate tenth-value thickness of any substance would decrease the dose to (approximately) 50 roentgens. The addition of a second tenth-value thickness would result in another decrease by a factor of ten, so that the dose received would be (approximately) 5 roentgens. Each succeeding tenth-value thickness would bring about a further reduction by a factor of ten. Thus, one tenth-value thickness decreases the radiation exposure dose by a factor of (approximately) 10; two tenth-value thicknesses by a factor of 10×10, i.e., 100; three tenth-value thicknesses by a factor of $10 \times 10 \times 10$, i.e., 1,000; and so on.[5]

8.35 To be precise, the tenth-value thickness concept should be employed only when monoenergetic radiation, i.e., radiation having a single energy, is involved. Even then, it is necessary either that the radiation be in the form of a narrow beam or that the shielding material be 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.

[5] The "half-value thickness" is sometimes used; it is defined as the thickness of a given material which reduces the dose of impinging radiation to (approximately) one half. Two such thicknesses decrease the dose to one fourth; three thicknesses to one eighth, etc.

Consequently, the determination of the effectiveness of a given shield is a complex problem involving many factors which vary in different situations. Nevertheless, approximate tenth-value thicknesses, which have been adjusted to allow, to some extent, for the variable factors, can serve a useful practical purpose in providing a rough indication of the degree of attenuation of the initial gamma radiation that can be achieved by a given amount of shielding.

8.36 The adjusted values of the tenth-value thicknesses of some materials of interest in radiation shielding are given in Table 8.36,[6] for the gamma rays emitted by the fission products in the first 10 seconds after the detonation and for those accompanying the capture of neutrons by nitrogen in the air (§ 8.09). These particular radiations were chosen because they are representative of the main constituents of the initial gamma rays. It will be noted that the thickness of any material required to decrease the nitrogen capture gamma rays to one tenth is nearly 50 percent greater than for the fission product gamma rays; this is because the former have a considerably higher energy.

TABLE 8.36

APPROXIMATE TENTH-VALUE THICKNESSES FOR FISSION PRODUCT AND NITROGEN CAPTURE GAMMA RAYS

Material	Density (lb/cu ft)	10-sec fission product		Nitrogen capture	
		Tenth-value thickness (inches)	$D \times T$ (lb/sq ft)	Tenth-value thickness (inches)	$D \times T$ (lb/sq ft)
Steel	490	3.7	150	5.3	215
Concrete	144	12	145	18	215
Earth	100	18	150	26	215
Water	62.4	26	135	37	190
Wood	34	50	140	70	200

8.37 The second column for each type of gamma radiation, designated $D \times T$ (lb/sq ft), gives the product of the density, D, of the material (in lb/cu ft) and the tenth-value thickness, T (in feet). It will be noted that this is approximately constant for a given gamma radiation. Consequently, if the tenth-value thickness for a particular material is not known, but the density is, a fair estimate can be made by assuming $D \times T$ to be 150 lb/sq ft for fission product gamma

[6] The tenth-value thicknesses are for gamma rays that are incident perpendicularly on the slab of material. If the rays make an angle θ with the perpendicular, the tenth-value thickness is obtained approximately by multiplying the values in the table by cosine θ, provided θ is less than 45°.

rays and 215 lb/sq ft for nitrogen capture gamma rays. If the tenth-value thickness is to be used to estimate the effectiveness of a given shield as a protection against the initial radiation from a nuclear explosion, it is recommended that the higher value in Table 8.36 always be employed. The result will indicate a smaller degree of shielding than can actually be obtained, but it is better to be conservative in this respect than to overestimate the effectiveness of the shield.

8.38 A more accurate estimate of the protection that can be provided by a particular shield inserted between the source of the radiation and the target, e.g., a person, can be made by taking a number of factors into consideration. These include the energy distribution of the gamma radiation falling on the shield, the angle of incidence of the radiation, and the geometry (or form) of the shielding material. By making appropriate allowance for the various parameters, a series of useful curves have been developed, as shown in Fig. 8.38. These give the "dose transmission factor," i.e., the fraction of the initial gamma radiation dose falling on the shield that actually reaches the target, for a range of thicknesses of various materials.

8.39 The use of Fig. 8.38 may be illustrated by means of two examples. Suppose that at a certain location the initial gamma-ray exposure dose without shielding would be 500 roentgens; what would be the dose received behind an earth shield 5 feet, i.e., 60 inches, thick? From Fig. 8.38, the dose transmission factor for 60 inches of earth is found to be about 4.0×10^{-3}, so that the actual exposure dose received would be $500\times4.0\times10^{-3} = 2.0$ roentgens. Alternatively, suppose it is required to determine the thickness of concrete needed to reduce an exposure dose of 500 roentgens to 1 roentgen; the necessary transmission factor is 1/500, i.e., 2×10^{-3}. From the curve for concrete, this is seen to correspond to a thickness or 45 inches, i.e., 3 feet 9 inches.

8.40 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, expecially by the oxygen and nitrogen in the air. Consequently, gamma rays will reach a particular target on the ground from many directions. Most of the dose received will come from the direction of the explosion, but a considerable amount of radiation will arrive from other directions. The gamma radiation reaching a target as a result of scattering in the air is called "skyshine."

8.41 The fact that gamma rays can reach a target from directions other than that of the burst point has an important bearing on the problem of shielding. A person taking shelter behind a single wall,

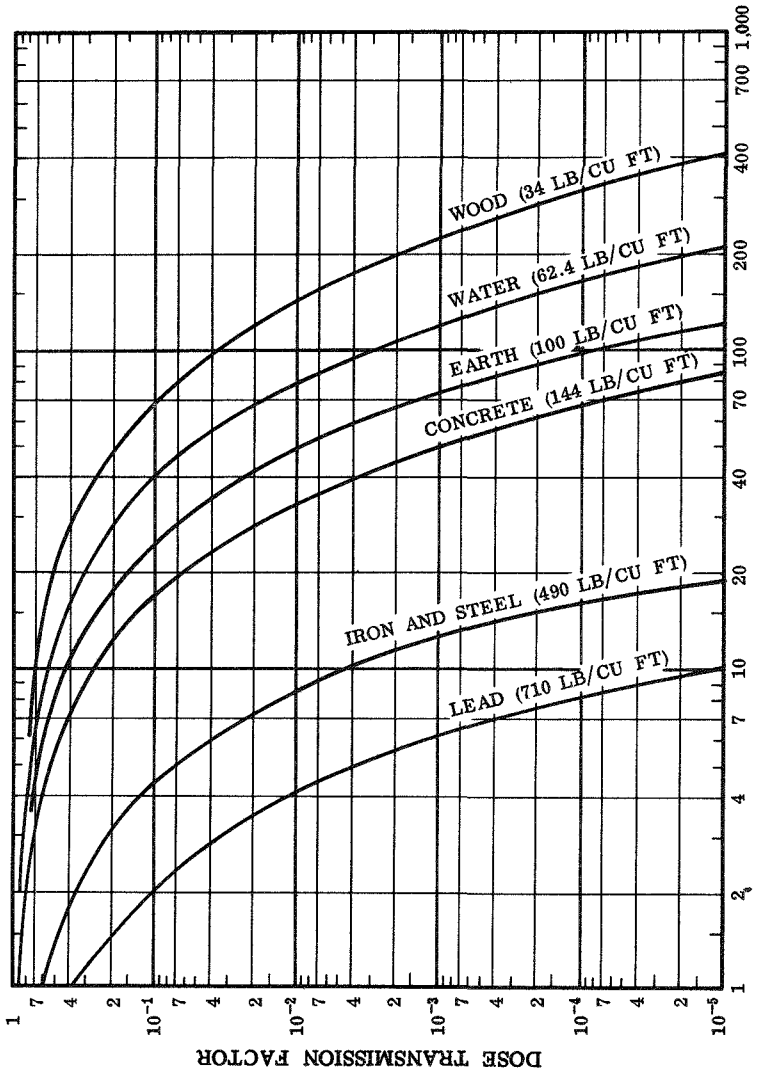
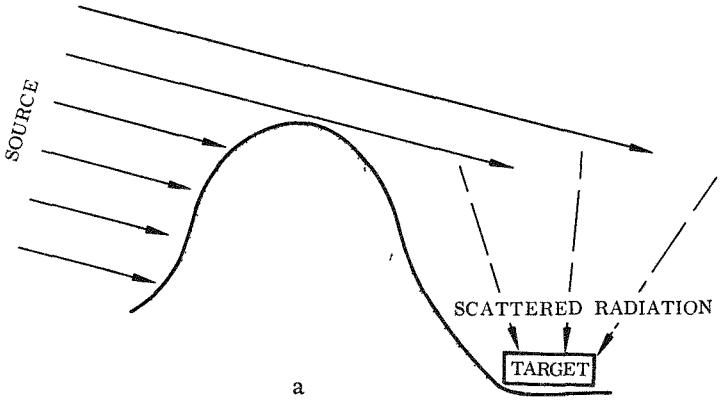


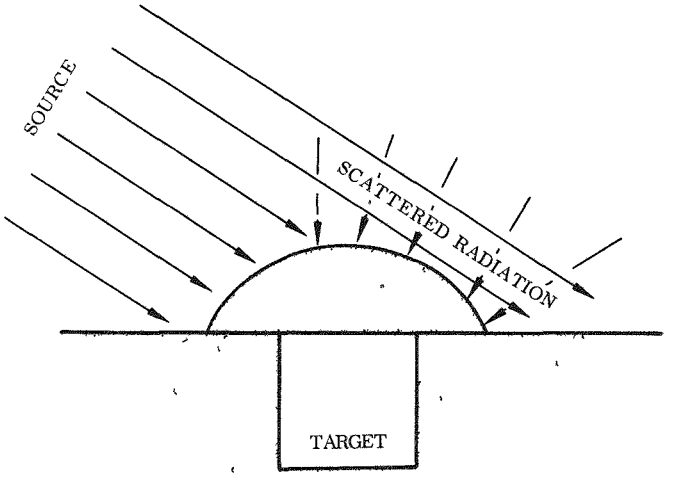
Figure 8.38. Dose transmission factors for initial gamma radiations of various materials as function of thickness.

an embankment, or a hill will be shielded, to some extent, from the direct gamma rays, but will still be exposed to the scattered radiation (or skyshine), as shown by the broken lines in Fig. 8.41a. Adequate protection from gamma rays can be secured only if the shelter is one which surrounds the individual, so that he can be shielded from all directions (Fig. 8.41b). In this case, both direct and scattered radia-



a

Figure 8.41a. Target exposed to scattered gamma radiation.



b

Figure 8.41b. Target shielded from scattered gamma radiation.

tions can be attenuated. The variation in the amounts of radiation received at a target from different directions is called the "angular distribution." It has been found that the angular distribution of the initial gamma radiation is relatively insensitive to the type of weapon and to the distance of the target from ground zero.

Rate of Delivery of Initial Gamma Rays

8.42 Radiation dose calculations based on Figs. 8.27 a and b 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 weapon. If this information is available, it is possible to obtain some 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.

8.43 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 is shown in Fig. 8.43. One

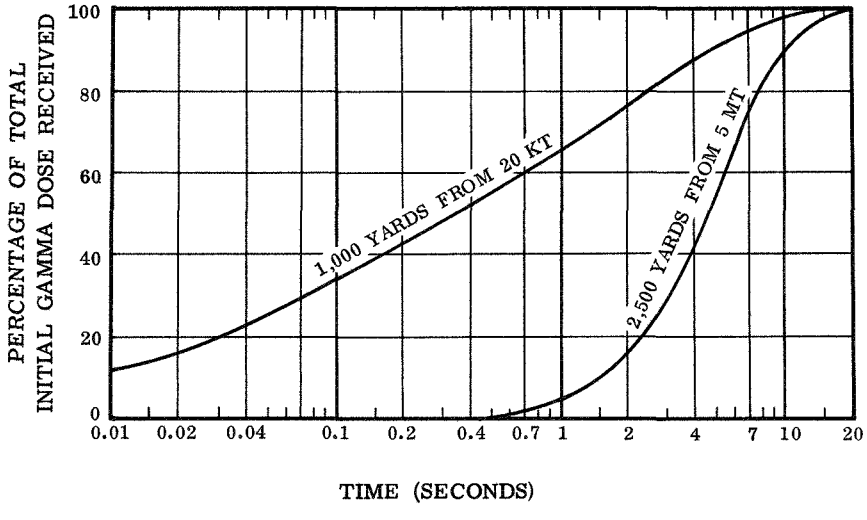


Figure 8.43. Percentage of initial gamma-radiation dose received as function of time for 20-kiloton and 5-megaton air bursts.

curve represents the rate of delivery at a distance of 1,000 yards from a 20-kiloton air burst and the other at 2,500 yards from a 5-megaton explosion. It is seen that in the former case about 65 percent and in the latter case about 5 percent of the total initial gamma radiation dose is received during the first second after the detonation.

8.44 If some shelter could be obtained, e.g., by falling prone behind a substantial object, within a second of seeing the explosion flash, in certain circumstances it might make the difference between life and death. The curves in Fig. 8.43 show that for a weapon 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

8.45 Although neutrons are nuclear particles of appreciable mass, whereas gamma rays are electromagnetic waves, analogous to X-rays (§ 1.69), 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 to 1 percent) of the explosion energy which they carry.

8.46 Essentially all the neutrons accompanying a nuclear explosion are released either in the fission or fusion process (§§ 1.38, 1.63). 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.

8.47 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 released within the first minute, however, they constitute part of the initial nuclear radiation. Some neutrons are also produced by the action of gamma rays of high energy on the weapon materials. But these make a very minor contribution and so can be ignored.

8.48 Despite their almost instantaneous release, the prompt fission neutrons are slightly delayed in escaping from the environment

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of the exploding weapon. This delay arises from the numerous scattering collisions suffered by the neutrons with the nuclei present in the weapon residues. As a result, the neutrons traverse a complex zigzag path before they finally emerge. However, they move so fast that the delay in the escape of the prompt neutrons is much less than a one-hundredth part of a second.

8.49 It is true that neutrons travel with speeds less than that of light. Nevertheless, at distances from the explosion where they represent a hazard, nearly all of the neutrons are received within a second of the explosion. The evasive action described in § 8.44 thus has little effect on the neutron dose received.

8.50 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 the fast neutrons referred to in § 8.10, 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 energy between the neutrons and nuclei. Within the weapon itself, where heavy nuclei, e.g., of uranium, are present, some of the neutrons lose energy as a result of inelastic scattering, the energy removed being emitted in the form of gamma radiation (§ 8.10). In other collisions, there is a simple transfer of kinetic energy from the fast neutron to the struck nucleus; these are called "elastic collisions" and are not accompanied by gamma radiation. Because of the variety of collisions which occur with different nuclei, the neutrons leaving the region of the explosion 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.

8.51 After the neutrons leave the environment of the weapon, 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 weapon, 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.

8.52 Furthermore, in some collisions, particularly with nitrogen nuclei, the neutrons can be captured, as described in § 8.08, 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 weapon 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.

8.53 It is important in connection with the measurement of nuclear weapon 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 weapons 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."

8.54 The occurrence of an equilibrium spectrum is related to a combination of circumstances which arise during passage of the neutrons through the air: the loss of the slower neutrons by capture, e.g., by nitrogen nuclei, is just compensated by the slowing down of fast neutrons. Consequently, the proportion (or fraction) of neutrons present in any particular energy range appears to be essentially constant at all distances of interest. The total number of neutrons, however, 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 (cf. §8.26), some of the neutrons are removed by capture.

Measurement of Neutron Flux

8.55 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. 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. Fast

neutrons are also captured by nitrogen nuclei and protons capable of producing ionization are emitted.[7]

8.56 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.

8.57 All of the foregoing indirect ionization processes can be used to detect and measure neutron intensities. The quantity determined, either directly or indirectly, is called the "neutron flux;" it is the product of the neutron density, i.e., the number per unit volume, and the average velocity. The instruments employed for the measurement of neutron flux, such as boron counters and fission chambers, are somewhat similar, in general principle, to the dose rate (survey) meters commonly used for gamma radiations (§ 8.23). "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.

8.58 In addition to the procedures described above, "foil activation" methods have been extensively used in the detection and measurement of neutrons in various energy ranges. These methods are based upon the fact that certain elements become radioactive as a result of the capture of neutrons. Under appropriate conditions, the extent of the radioactivity, as measured by the rate of emission of radiation (beta or gamma or both), is related to the "integrated flux" of incident neutrons, i.e., the product of the flux and time, expressed as neutrons per square centimeter.[8] Hence, by the use of appropriate conversion factors, the integrated neutron flux can be calculated. In practice the elements are used in the form of thin sheet or foil, so that they produce a minimum disturbance of the neutron field. The technique is referred to as "activation detection" and the elements employed are known as "activation detectors." An activation detector having an appreciable probability of reaction only when the energy of the neutron exceeds a particular (threshold) value is called a "threshold detector." The procedure is then described as the "thresh-

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[7] The ionization resulting from the interaction of fast neutrons with hydrogen and nitrogen in tissue is the main cause of biological injury by neutrons.

[8] For the conversion of integrated neutron flux into absorbed dose, see § 11.90.

old detector technique" and is used to determine the number of neutrons with energies in excess of the threshold value.

8.59 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 integrated neutron flux to which the fissionable material was exposed can be determined.

Integrated Neutron Flux-Distance Relationship

8.60 A basic difficulty in expressing the dependence of the integrated neutron flux on the distance from the nuclear explosion is the fact that the results may vary with changes in the characteristics of the weapon. The 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 §1.68, 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.

8.61 In view of these considerations, it is evident that the actual number of neutrons emitted per kiloton of explosion energy yield, as well as their energy distribution, may vary not only between weapons of different types, i.e., fission and fusion, but also between weapons of the same kind. Hence, any curve which purports to indicate the variation of the integrated neutron flux with distance must represent a compromise; it obviously cannot be correct for all situations which may arise. It is with this limitation in mind that the curve in Fig. 8.61 for an air burst of 1-kiloton TNT equivalent energy yield is presented. It shows the variation of the integrated neutron flux with distance from the explosion, assuming the density of the air in the transmission path to be 0.9 that of the normal sea-level value. In order to determine the approximate integrated flux received from an air burst of W kilotons energy yield, the value for the given distance as obtained from Fig. 8.61 is multiplied by W. This scaling procedure is by no means exact, but it is probably adequate in the circumstances. It will be observed that, as with other types of radiation, the integrated flux decreases with increasing distance from the

explosion center, partly because the neutrons are spread over a larger area (inverse square law) and partly as a result of absorption and scattering.

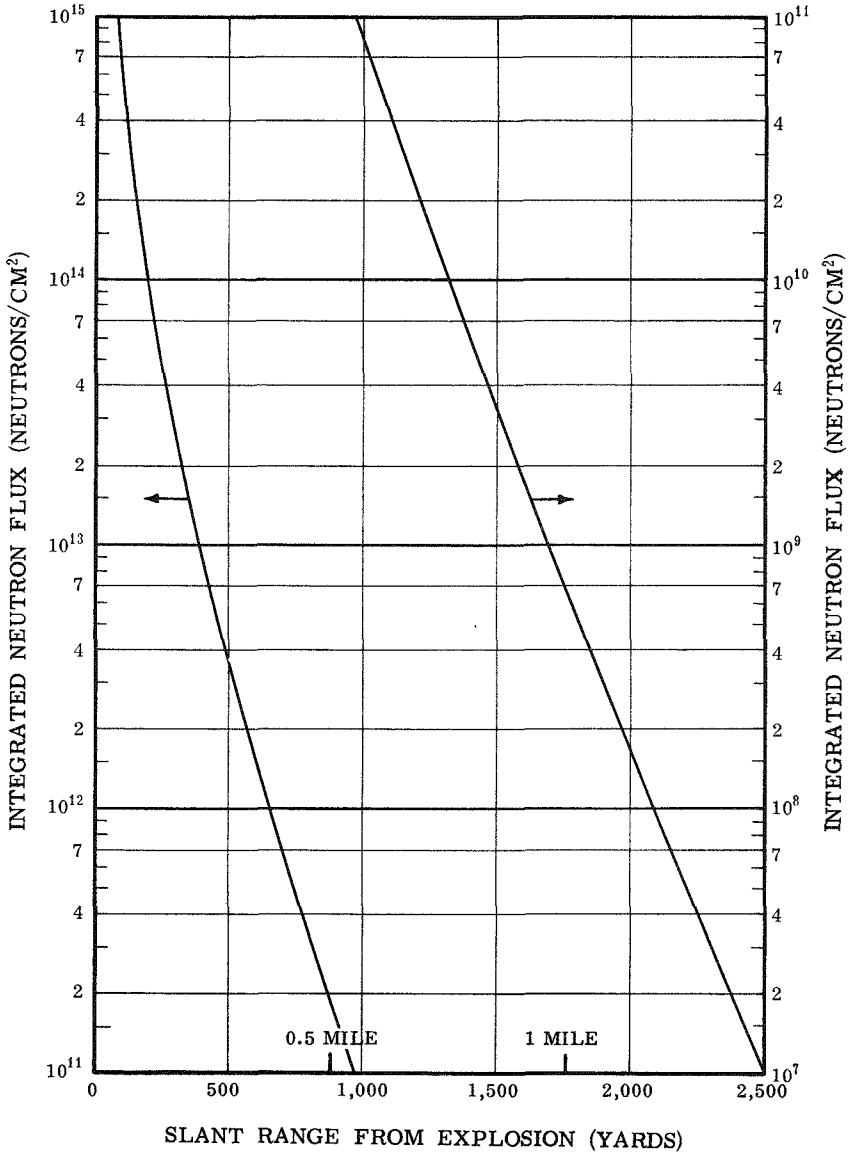

Figure 8.61. Integrated neutron flux as a function of the slant range in air of 0.9 sea-level density for a 1-kiloton explosion.

Shielding Against Neutrons

8.62 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, make good gamma-ray shields because of their high density. These elements alone, however, are not quite as satisfactory for neutron shielding. An iron shield will attenuate weapon neutrons to some extent, but it is less effective than some of the types described below.

8.63 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 (by elastic scattering) 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 (§ 8.08). Consequently, sufficient gamma-attenuating material must be included to minimize the escape of the capture gamma rays from the shield.

8.64 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 integrated neutron flux 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, although about 50 percent greater thickness would be required.

8.65 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. Alternatively, the mineral barytes, which is a compound of barium, may be included in the concrete. 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 integrated neutron flux by a factor of 10 requires about 7 inches of this heavy concrete.

8.66 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 (§ 8.56), 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.

8.67 It was pointed out in § 8.41 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. 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.

TECHNICAL ASPECTS OF INITIAL NUCLEAR RADIATION [9]

Interaction of Gamma Rays with Matter

8.68 There are three important types of interaction of gamma rays with matter, as a result of which the photons (§1.70) are scattered or absorbed. The first of these is called the "Compton effect." In this interaction, the gamma-ray (primary) photon collides with an electron and some of the energy of the photon is transferred to the electron. Another (secondary) photon, with less energy, then moves off in a new direction at an angle to the direction of motion of the primary photon. Consequently, Compton interaction results in a change of direction

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

(or scattering) of the gamma-ray photon and a degradation in its energy. The electron which, after colliding with the primary photon, recoils in such a manner as to conserve energy and momentum is called a Compton (recoil) electron.

8.69 The total extent of Compton scattering per atom of the material with which the radiation interacts is proportional to the number of electrons in the atom, i.e., to the atomic number (§1.09). 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.

8.70 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 a 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.

8.71 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 pohtoelectric 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 lower 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.

8.72 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.

8.73 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

8.74 If a narrow (or collimated) beam of gamma rays of a specific energy, having an intensity of I_0,[10] falls upon a thickness x of a given material, the intensity, I, of the rays which emerge can be represented by the equation

$$I = I_0 e^{-\mu x}, \tag{8.74.1}$$

where μ is called the "linear absorption coefficient." The distance x is usually expressed in centimeters, so that the corresponding units for μ are reciprocal centimeters (cm^{-1}). The value of μ, 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 (8.74.1) 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 μ. 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.

8.75 The value of μ, under any given conditions, can be obtained with the aid of equation (8.74.1) by determining the gamma-ray intensity (or dose) before (I_0) and after (I) passage through a known

[10] 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 (8.74.1) 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.

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 8.75. 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.

TABLE 8.75

LINEAR ABSORPTION COEFFICIENTS FOR GAMMA RAYS

Gamma-ray energy (Mev)	Linear absorption coefficient (μ) in cm^{-1}				
	Air	Water	Concrete	Iron	Lead
0.5	1.11×10^{-4}	0.097	0.22	0.66	1.7
1.0	0.81×10^{-4}	0.071	0.15	0.47	0.80
2.0	0.57×10^{-4}	0.049	0.11	0.33	0.52
3.0	0.46×10^{-4}	0.040	0.088	0.28	0.47
4.0	0.41×10^{-4}	0.034	0.078	0.26	0.47
5.0	0.35×10^{-4}	0.030	0.071	0.25	0.50
10	0.26×10^{-4}	0.022	0.060	0.23	0.61

8.76 By suitable measurements and theoretical calculations, it is possible to determine the separate contributions of the Compton effect (μ_c), of the photoelectric effect (μ_{pe}), and of pair production (μ_{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. 8.76a and those for air, a mixture of light elements (low atomic weight) with a small absorption coefficient, in Fig. 8.76b. 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. 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. 8.76a, as well as in the last column of Table 8.75, 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.

8.77 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

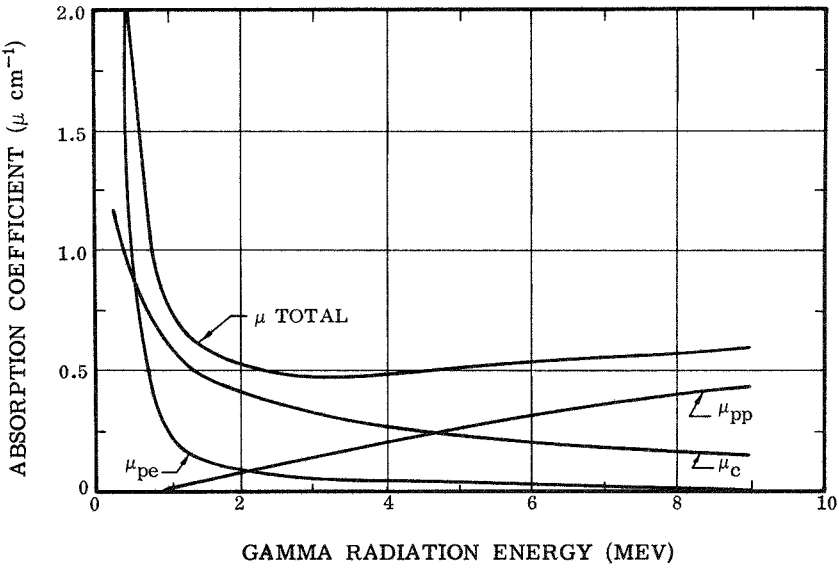

Figure 8.76a. Linear absorption coefficient of lead as function of gamma-ray energy.

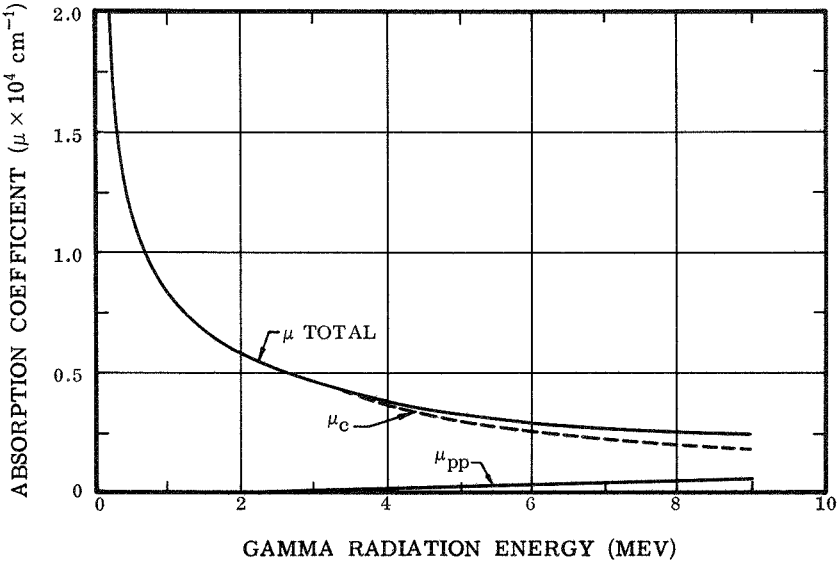

Figure 8.76b. Linear absorption coefficient of air as function of gamma-ray energy.

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.

8.78 An examination of Table 8.75 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 § 8.33, 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

8.79 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. 8.76b). For the initial gamma rays, the effective mass absorption coefficient has a value close to 0.023 for water, concrete, earth, and iron, the densities being expressed in grams per cubic centimeter.[11]

8.80 If the symbol ρ is used for the density of the shield material, then the equation (8.74.1) can be rewritten in the form

$$I/I_0 = e^{-\mu x} = e^{-(\mu/\rho)(\rho x)}, \qquad (8.80.1)$$

where I/I_0 is the dose transmission factor, as defined in § 8.38, of the shield of thickness x cm, and μ/ρ is, by definition, the mass absorption coefficient. Taking μ/ρ to be 0.023 for initial gamma rays, it follows from equation (8.80.1) that

$$\text{Transmission factor} \approx e^{-0.023\rho x} \approx 10^{-0.01\rho x}. \qquad (8.80.2)$$

In the absence of better information, this expression may be used to provide a rough idea of the dose transmission factor of a thickness

[11] In taking the effective mass absorption coefficient as 0.023, an attempt is made to allow for the conditions applying to thick shields or broad radiation beams (see § 8.82 *et seq.*)

x centimeters of any material (of known density) of low or moderate atomic weight.

8.81 The concept of the tenth-value thickness is based on equation (8.74.1). For such a thickness the transmission factor is 0.1 and if the thickness is represented by $x_{0.1}$, it follows that

$$0.1 = e^{-\mu x_{0.1}}$$

or

$$x_{0.1} = \frac{2.30}{\mu} \text{ cm.} \tag{8.81.1}$$

If μ/ρ is taken to be 0.023 for the initial gamma radiation then, as a "rule-of-thumb" approximation,

$$x_{0.1} \approx \frac{100}{\rho} \text{ cm} \approx \frac{39}{\rho} \text{ inches,}$$

where ρ is the density of the material in grams per cubic centimeter. The tenth-value thicknesses obtained from this approximate expression are in agreement with those in Table 8.36 for nitrogen capture gamma rays.

Thick Shields: Build-Up Factor

8.82 Equation (8.74.1) 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 (8.74.1). 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, the nature of the material, and the energy of the impinging radiation; thus, equation (8.74.1) is now written as

$$I = I_0 B(x) e^{-\mu x}.$$

Values of the build-up factor for a variety of conditions have been calculated for a number of elements from a theoretical consideration of the scattering of photons by electrons. The fact that these values are frequently in the range from 10 to 100 shows that serious errors

could arise if equation (8.74.1) is used to determine the attenuation of gamma rays by thick shields.

8.83 It will be apparent, therefore, that equation (8.74.1) and others derived from it, such as equations (8.80.2) and (8.81.1), as well as the tenth-value thickness concept, 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 0.023, as given in § 8.79, 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 derived in § 8.80 and § 8.81 hold moderately well for the attenuation of the initial gamma radiations by thick shields. It may be noted, too, that the transmission factors in Fig. 8.38 include allowances for multiple scattering in thick shields.

The Initial Gamma-Ray Spectrum

8.84 As seen earlier, the initial gamma radiation arises from three main sources, namely (1) neutron capture and inelastic scattering by the weapon materials, (2) neutron capture by nitrogen in the air, and (3) the fission products during the first minute after the burst. However, the major portion of the initial gamma radiation is derived from the two latter sources (§ 8.08 *et seq.*). The effective energy of the nitrogen capture gamma rays is approximately 6.5 Mev, whereas that from the fission products within the first minute of the explosion is about 2 Mev. After passage through an appreciable distance in air, some of the photons will have been degraded in energy, as a result of Compton scattering, and these and others, especially of low energy, will have been absorbed. There will consequently be an increase in the proportion of rays of higher energy.

8.85 Information concerning the energy distribution (or spectrum) of the initial gamma radiation is important because the susceptibility of living organisms, the attenuation properties of air and shielding materials, and the response of radiation instruments are all strongly dependent on this distribution. However, the energy spectrum observed at a particular distance from the explosion will be different from that at almost any other distance because the various components are degraded in energy and absorbed differently in their passage through air or other attenuating medium. Nevertheless, a knowledge of the initial gamma radiation spectrum at the source, i.e., the exploding weapon, combined with existing data on scattering

and absorption of photons of different energies in the intervening medium, can be employed to provide an approximate indication of the spectrum at a given distance from the explosion. An example is given in Fig. 8.85, which shows the spectrum of the initial gamma radiation received at a distance of 2,000 yards from the explosion of a fission weapon of about 20-kilotons energy. It is seen that, at this point, where the radiation dose (in roentgens) has been attenuated several thousandfold, some 70 percent of the gamma-ray photons have energies less than 0.75 Mev. It is important to remember, in designing a shield, that it is the photons of high energy which are generally the most difficult to absorb and so must be given prime consideration.

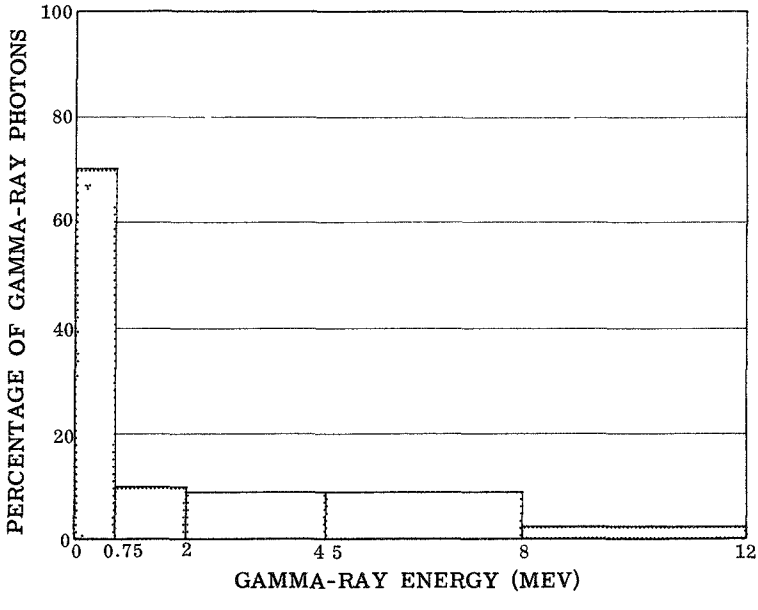

Figure 8.85. Spectrum of initial gamma radiation 2,000 yards from a 20-kiloton explosion

Interactions of Neutrons With Matter

8.86 The modes of interaction of neutrons with matter are quite different from those experienced by gamma-ray photons. Unlike photons, neutrons are little affected by electrons but they do interact in various ways with the nuclei of atoms present in all forms of matter. These neutron-nucleus interactions are of two main types,

namely, scattering and absorption. As already seen, scattering reactions can be either inelastic (§ 8.10) or elastic (§ 8.50). In inelastic scattering part of the kinetic energy of the neutron is converted into internal (or excitation) energy of the struck nucleus; this energy is then emitted as gamma radiation. For inelastic scattering to occur, the neutron must initially have sufficient energy to raise the nucleus to an excited state. The magnitude of this energy depends on the nature of the nucleus and varies greatly from one element to another. However, a rough general rule is that for many, but not all, heavy or moderately heavy nuclei, e.g., iron, barium, and uranium, the neutron energy must be at least about 0.5 Mev for inelastic scattering to occur. For lighter nuclei, inelastic scattering is possible only when the neutrons have much higher energies, e.g., 6 Mev for oxygen. Neutrons with energies below the appropriate threshold values for the nuclei present in the medium cannot undergo inelastic scattering.

8.87 When elastic scattering occurs, the interaction of the neutron with a nucleus is equivalent to a collision between two billiard balls; kinetic energy is conserved and is merely transferred from one particle to the other. None of the neutron energy is transformed into excitation energy of the nucleus and there is no accompanying gamma radiation. In contrast with inelastic scattering, elastic scattering can occur with neutrons of all energies and any nucleus. For a given angle of impact, the fraction of the kinetic energy of the neutron that is transferred to the nucleus in a collision is dependent only on the mass of the latter. The smaller the mass of the nucleus the greater is the fraction of the neutron energy it can remove. Theoretically, the whole of the kinetic energy of a neutron could be transferred to a hydrogen nucleus (proton) in a single head-on collision. In fact, hydrogen, the lightest element, offers the best means for rapidly degrading fast neutrons with energies less than about 0.5 Mev. It is for this reason that hydrogen, e.g., as water, is an important constituent of neutron shields (§ 8.63). For neutrons of higher energy than 0.5 Mev, it is better to take advantage of inelastic scattering to slow down the neutrons. The heavy element in the special concretes described in § 8.65 serves this purpose.

8.88 The second fundamental type of interaction of neutrons with matter involves complete removal of the neutron by capture. Radiative capture, which was described in § 8.08, is the most common kind of capture reaction; it occurs to some extent, at least, with nearly all nuclei. The probability of capture is greater for slow neutrons than for those of high energy. Most light nuclei, e.g., carbon and oxygen, show little tendency to undergo the radiative capture reaction with

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neutrons, but with others, especially some of medium or high mass, e.g., cadmium, this type of reaction occurs very readily. In certain cases, the product of the radiative capture reaction is radioactive; this is of importance in some aspects of weapons effects, as will be seen in the next chapter (cf. § 9.31 *et seq.*).

8.89 Another type of capture reaction is that in which the incident neutron enters the target nucleus and the compound nucleus so formed has enough excitation energy to permit of the expulsion of another (charged) particle, e.g., a proton, deuteron, or alpha particle. The residual nucleus is often in an excited state and emits the excess energy as a gamma-ray photon. This type of reaction usually occurs with light nuclei and fast neutrons, although there are a few instances, e.g., lithium-7 and boron-10, where it takes place with slow neutrons. The reaction of nitrogen with fast neutrons, which is accompanied by the emission of a proton and the formation of radioactive carbon-14, is of special interest (§ 9.34).

8.90 Fission, is of course, also a form of interaction between neutrons and matter. But since it is restricted to a small number of nuclear species and has been considered in detail in Chapter I, it will not be discussed further here.

8.91 The rate of interaction of neutrons with nuclei can be described quantitatively in terms of the concept of nuclear "cross sections." The cross section may be regarded as the effective area of a particular type of nucleus for a given reaction and is a measure of the probability that the interaction will occur between a neutron, of specified energy, and that nucleus. For a given nuclear species, there is a scattering cross section, capture cross section, etc.; the total cross section is the sum of the specific cross sections for the individual interactions. Both specific and total cross sections vary with the energy of the neutron, often in a very complex manner.

8.92 The nuclear cross sections for neutron-nucleus interactions are physically equivalent to the linear absorption coefficient (for gamma rays) divided by the number of nuclei in unit volume of the medium. In fact, an expression similar to equation (8.74.1) can be employed to describe the attenuation of a narrow beam of monoenergetic neutrons in their passage through matter. However, because the neutrons in the initial nuclear radiation are far from monoenergetic and the cross sections are so highly dependent on the neutron energy, the equivalent of equation (8.74.1) must not be used to calculate neutron attenuation for shielding purposes. Shielding calculations can be made by utilizing cross sections, the neutron energy distribution in space and direction, and other data, but they are too complicated to be described here.

The Neutron Energy Spectrum

8.93 The energies of the neutrons received at some distance from a nuclear explosion cover a very wide range, from several millions 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 flux within a few specified ranges, from the results of which a general idea of the spectrum can be obtained.

8.94 Measurements of this kind are made by the use of "threshold" detectors of the activated foil or fission foil type (§§ 8.58, 8.59). For example, the element sulfur acquires induced radioactivity as the result of the capture of neutrons having energies greater than 3.0 Mev but not if the neutrons have lower energies. Hence, the extent of activation of a sulfur foil is a measure of the neutron flux for energies in excess of 3.0 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 flux of neutrons having energies above 1.5 Mev. The difference between the two results obtained as just described gives the neutron flux in the energy range from 1.5 to 3.0 Mev. Other foil materials, which are used in the same manner, are neptunium-237, fission threshold 0.75 Mev; plutonium-239 (shielded with boron), fission threshold 200 ev; and gold, which is activated by slow neutrons.

8.95 The results of a series of measurements, made at various distances from a nuclear test explosion, are shown in Fig. 8.95, in which $N \times D^2$ 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, i.e., the integrated neutron flux (§ 8.58), which produces fission or activation of foils of the indicated materials at a distance D yards from the explosion.

8.96 It will be observed from Fig. 8.95 that, as is to be expected, the various lines slope downward to the right, indicating a steady decrease in the integrated neutron flux at all energies with increasing distance from the explosion. However, the really significant fact is that the lines are almost 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

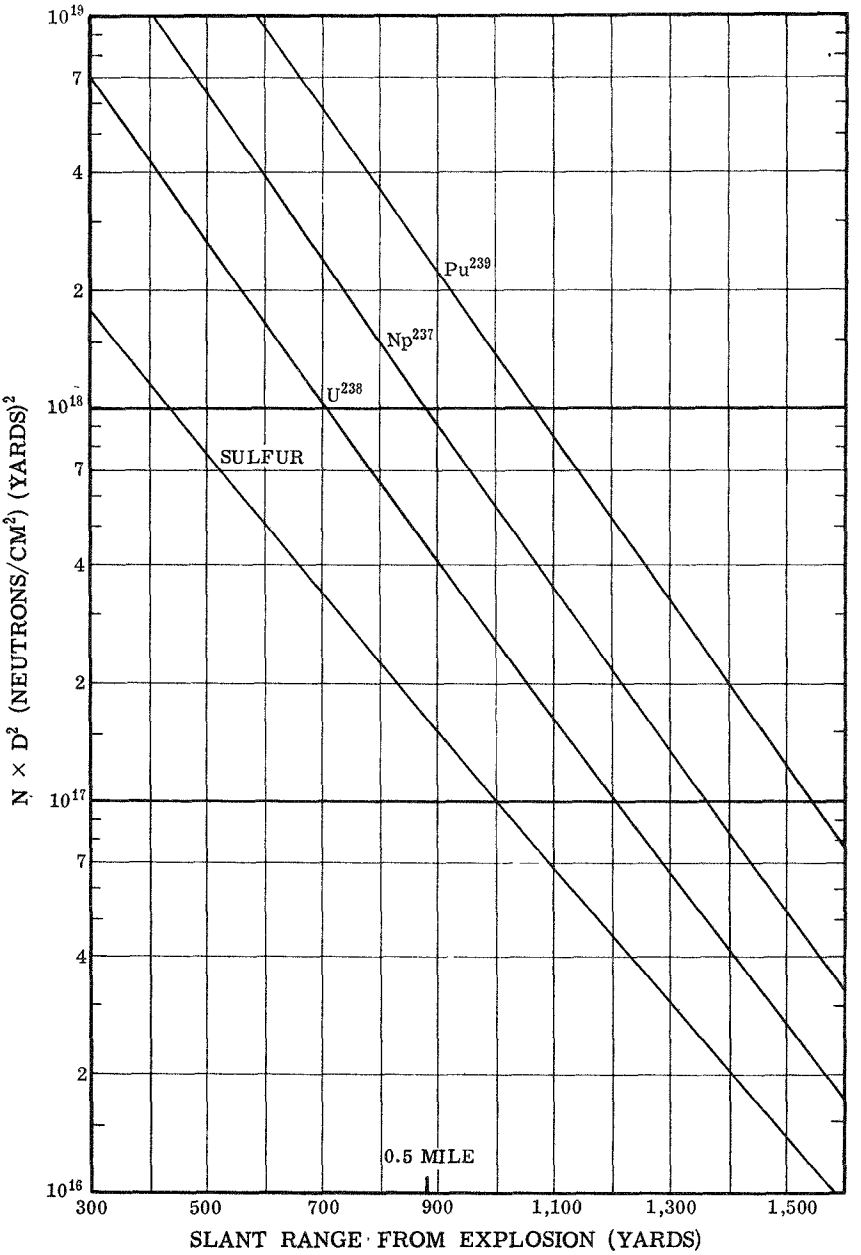

Figure 8.95. Threshold detector data as function of slant range from explosion.

independent of distance from the explosion. A typical equilibrium spectrum in the energy range above 200 ev, from a fission weapon, is given in Fig. 8.96.

8.97 One consequence of this conclusion is that, if the results are of general applicability, it should be possible, to treat the neutrons as a single group, with a definite energy distribution beyond a certain distance. Thus, assuming an equilibrium spectrum, one foil measure-

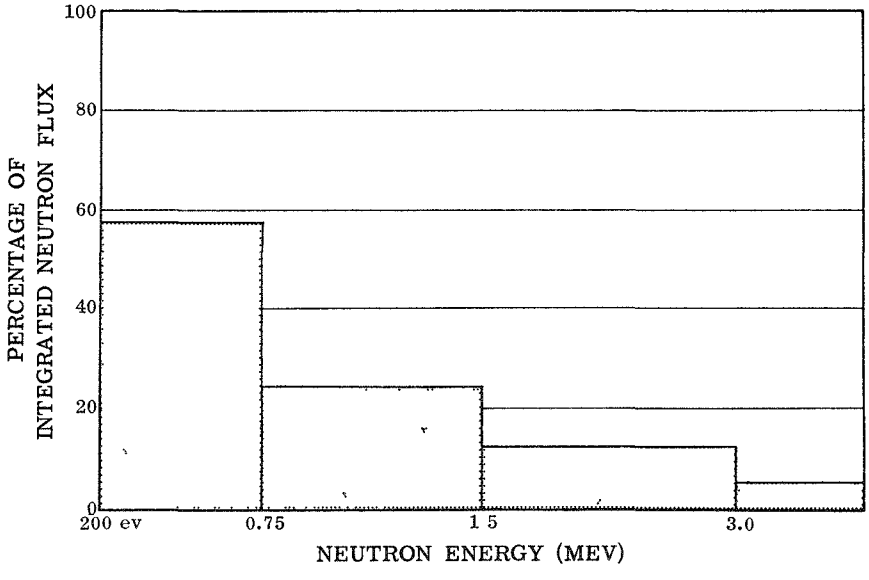

Figure 8.96. Typical neutron energy spectrum.

ment would be sufficient to indicate the integrated neutron flux at any given location. Furthermore, the analytical expression of the variation of the integrated flux with distance would be simplified, as will be seen in § 8.102.

Transmission of Gamma Rays from Source

8.98 As an alternative to Fig. 8.27a, which gives the dependence of the initial gamma-ray exposure dose as a function of distance from a nuclear explosion, it is possible to derive a simple, semi-empirical analytical expression. Because distances of interest are large in comparison with the size of the exploding weapon, the latter may be treated as a point source emitting a total R_γ of initial radiation, in

appropriate units. At a distance D from the explosion, this radiation will spread over the surface of a sphere of radius D and, hence, of area $4\pi D^2$. If the radiation distribution is isotropic, i.e., it is uniformly distributed in all directions, the amount recieved per unit area normal to the direction of propagation will be $R_\gamma/4\pi D^2$, apart from loss due to attenuation by the intervening air. Allowance for this attenuation may be made by means of equation (8.74.1), with the absorption coefficient derived from actual measurements on the initial gamma radiation, so that it is (partially) adjusted for the deviations to be otherwise expected. It follows, therefore, that the radiation dose I_0 that would be received at a distance D from the explosion can be represented approximately by

$$I_0 \approx \frac{R_\gamma}{4\pi D^2} e^{-\mu D}, \tag{8.98.1}$$

where μ 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, as determined from actual observations.

8.99 For various reasons, it is convenient to replace μ by $1/\lambda$, where λ 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.[12] Thus, equation (8.98.1) is generally written as

$$I_0 \approx \frac{R_\gamma}{4\pi D^2} e^{-D/\lambda}, \tag{8.99.1}$$

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. 8.27a.

8.100 By rearranging equation (8.99.1), so that the left side becomes $I_0 D^2$, and taking logarithms, it is found that

$$\log I_0 D^2 \approx \text{Constant} - 0.4343 \frac{D}{\lambda}.$$

This means that if $I_0 D^2$ is plotted on a logarithmic scale against D on a linear scale, the result should be a straight line. An example of such a plot, based on the data in Fig. 8.27a for an explosion of 1-kiloton yield, is shown in Fig. 8.100. However, it is seen that the plot is linear only for distances in excess of about 1,200 yards. The reason

[12] The tenth-value thickness is equal to 2.30λ, as is apparent from equation (8.81.1).

for this is that equation (8.99.1) oversimplifies the conditions existing at points close to the explosion center. From the slope of the straight line, at distances greater than 1,200 yards, the relaxation length λ of the gamma rays, which is equal to $-0.4343/\text{slope}$, can be calculated. The value of λ in air at 0.9 sea-level density found in this way from Fig. 8.100 is 360 yards,[13] and from the intercept $R_\gamma/4\pi$ is 3.2×10^9 in (roentgens) (yards)^2 units. The expression, of the form of equation (8.99.1), representing the variation of the dose in roentgens with distance, D, in yards then becomes

$$I_0=\frac{3.2\times10^9}{D^2}\,e^{-D/360}\ \text{roentgens}$$

for a 1-kiloton explosion.

8.101 If the total initial gamma radiation were 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 § 8.30, the value of λ, for yields higher than about 20 kilotons, is actually greater than 360 yards and varies with the energy yield. Instead of adjusting this, however, it is simpler to use a scaling factor, W', obtained from Fig. 8.27b, 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

$$I_0\approx\frac{3.2\times10^9\,W'}{D^2}\,e^{-D/360}\ \text{roentgens.}$$

It should be recalled that this result is applicable at ranges over 1,200 yards and for air of 0.9 normal density.

Transmission of Neutrons from Source

8.102 The transmission of neutrons through the air from the exploding weapon, treated as a point source, to a location an appreciable distance away, can be represented in a manner quite similar to that described above for gamma rays. If N_0 represents the integrated neutron flux received at a distance D from the point of burst, then, by analogy with equation (8.99.1),

$$N_0\approx\frac{R_n}{4\pi D^2}\,e^{-D/\lambda_n}, \qquad (8.102.1)$$

[13] For air of normal density, the relaxation length would be about 360×0.9, i.e., 325 yards.

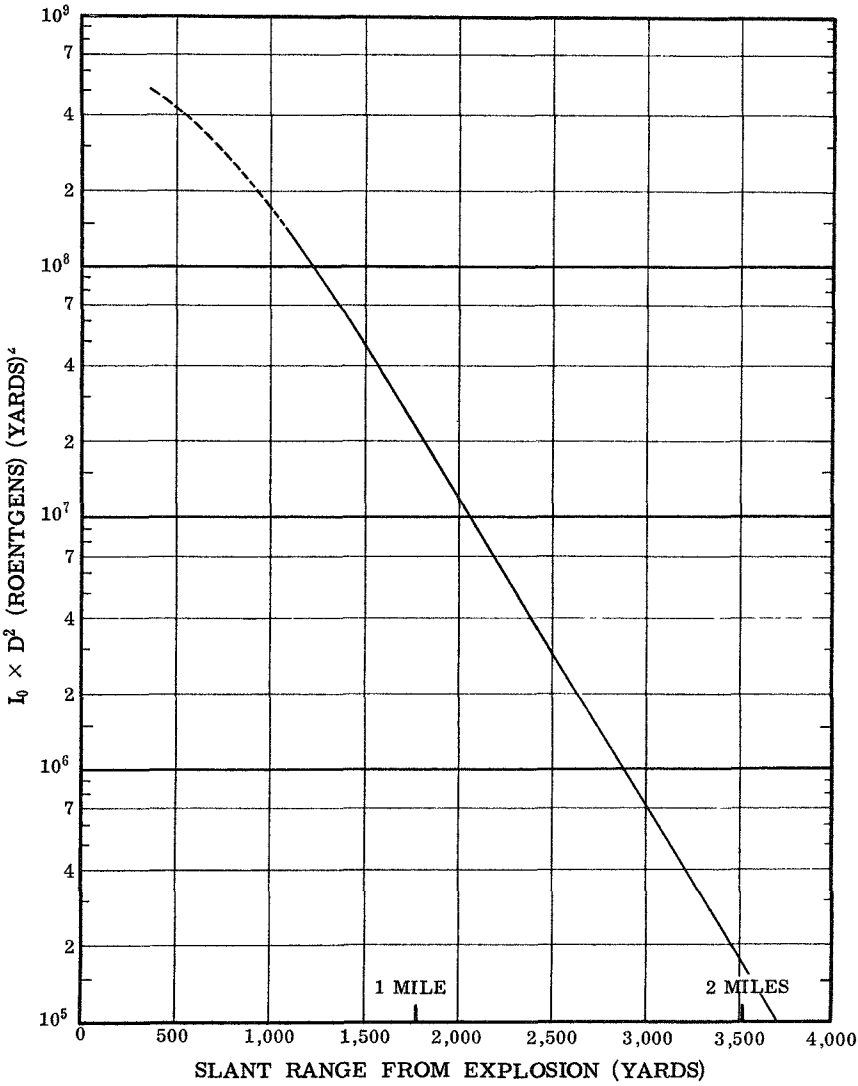

Figure 8.100. Initial gamma-radiation dose times distance squared as a function of the slant range.

where R_n is a neutron source term related to the explosion yield and λ_n is here the relaxation length for neutrons in air. Since the weapon neutron spectrum is essentially independent of distance, λ_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 integrated neutron flux.

8.103 Upon rearranging equation (8.102.1) and taking logarithms, as in §8.100, the result is

$$\log N_0 D^2 \approx \text{Constant} - 0.4343 \frac{D}{\lambda_n},$$

so that a semilogarithmic plot of $N_0 D^2$ versus D should be a straight line. The data in Fig. 8.61, which gives the integrated flux N_0, in neutrons per square centimeter, as a function of D in yards for a 1-kiloton explosion, have been used to obtain Fig. 8.103.

8.104 From the slope of the straight line, λ_n is calculated as 210 yards for air of 0.9 sea-level density,[14] and from the intercept the value of $R_n/4\pi$ for the 1-kiloton explosion is found to be 8.6×10^{18} (neutrons/cm^2) (yards)^2. Consequently, assuming that the integrated neutron flux is directly proportional to the energy yield of the explosion, although this is not a good approximation (see §8.61), it follows that

$$N_0 \approx \frac{8.6\times10^{18} W}{D^2} e^{-D/210} \text{ neutrons/cm}^2,$$

where W kilotons is the explosion yield; the distance D from the explosion is in yards. This expression is applicable only for ranges in excess of about 500 yards.

8.105 Since the relaxation length for the initial gamma radiation is 360 yards, whereas that for the neutrons is 210 yards, it is evident that weapon 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. A consequence of this fact is that the neutron dose decreases more rapidly than the gamma-ray dose with increasing distance from the explosion (see §11.92).

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[14] For air of normal density, the relaxation length would be approximately 210×0.9, i e., 190 yards.

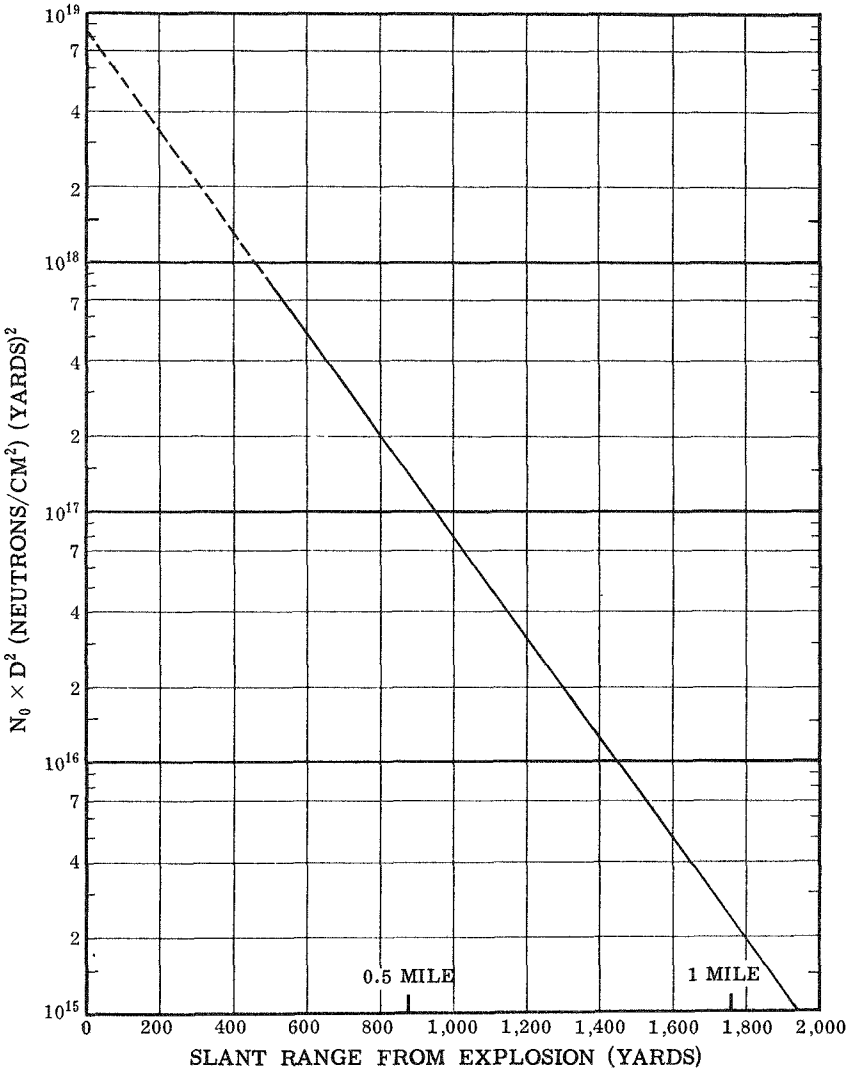

Figure 8.103. Integrated neutron flux times distance squared as a function of the slant range.

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CHAPTER IX

RESIDUAL NUCLEAR RADIATION AND FALLOUT

SOURCES OF RESIDUAL RADIATION

Introduction

9.01 The residual nuclear radiation is defined as that which is emitted later than 1 minute from the instant of the explosion (§ 8.02). The sources and characteristics of this radiation will vary in accordance with the relative extents to which fission and fusion reactions contribute to the energy of the weapon. The radiation from a fission weapon arises mainly from the weapon 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 by neutron reactions, other than fission, in the weapon materials. Another source of residual radiation is the activity induced by the interaction of neutrons with various elements present in the earth, sea, air, or other substances in the explosion environment. The residues from a predominantly fusion weapon, on the other hand, will not contain the quantities of fission products associated with a fission weapon of the same energy yield. However, large numbers of high-energy neutrons are produced (§ 1.68), so that the residual radiation from fusion weapons will arise primarily from neutron reactions in the weapon and its surroundings, if the fission yield is sufficiently low.

9.02 The primary hazard of the residual radiation results from the creation of fallout particles (§ 2.23) which incorporate the radioactive weapon residues and the induced activity in the soil, water, and other materials in the vicinity of the explosion. These particles are dispersed over large areas by the wind. A secondary hazard may arise from neutron induced activity on the earth's surface in the immediate neighborhood of the burst point. Both the absolute

and relative contributions of the fission product and induced radioactivity will depend on the total and fission yields of the weapon, the height of burst, the nature of the surface at the burst point, and the time after the explosion.

9.03 As mentioned in §2.28, it is convenient to consider the fallout in two parts, namely, early and delayed. Early fallout is defined as that which reaches the ground during the first 24 hours following a nuclear explosion. It is the early fallout from surface, subsurface, or low air bursts that is capable of producing radioactive contamination over large areas with an intensity great enough to represent an immediate biological hazard. Delayed fallout, which is that arriving after the first day, consists of very fine, invisible particles which settle in low concentrations over a considerable portion of the earth's surface. The radiation from the fission products and and other substances is greatly reduced in intensity as a result of radioactive decay (§ 9.12 *et seq.*) during the relatively long time the delayed fallout remains suspended in the atmosphere. Because of these characteristics, the radiations from the delayed fallout generally pose no immediate danger to health, although there may be a long-term hazard (§ 11.174 *et seq.*).

9.04 In the case of an air burst, particularly when the fireball 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 weapon 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.

9.05 With surface and, especially, subsurface explosions, the demarcation between initial and residual nuclear radiations is not as definite. Some of the radiations from the weapon 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 since they are absorbed by the surrounding medium. The residual radiations, from fission products and from radioactive species produced by neutron interaction, are then the only kind of nuclear radiations that need be considered. In a surface burst, however, both initial and residual nuclear radiations must be taken into account.

Early Fallout

9.06 The radiological characteristics of the early fallout from a nuclear weapon are those of the fission products and any induced activity produced. The relative importance of these two sources of residual radiation depends upon the percentage of the total yield that is due to fission, and other factors mentioned in § 9.02. There are, however, two additional factors, namely, "fractionation" and "salting" which may affect the activity of the early fallout; these will be described below.

9.07 As the fireball cools, the fission products and other vapors are gradually condensed on such soil and other particles as are sucked up from below while the fireball rises in the air. For detonations over land, where the particles consist mainly of soil minerals, the fission product vapors condense onto both solid and molten soil particles and also onto other particles that may be present. In addition, the vapors of the fission products may condense with vapors of other substances to form mixed solid particles of small size. In these condensation processes the composition of the fission product mixture may be changed by the phenomenon known as "fractionation." The occurrence of fractionation is shown, for example, by the fact that in a land surface burst the larger particles, which fall out of the fireball at early times and are found near ground zero, have different radiological properties from the smaller particles that leave the radioactive cloud at later times and reach the ground some distance downwind.

9.08 The details of the fractionation process are not well understood, but the effect is related, in part at least, to the presence in the early stages of certain fission products which are inherently gaseous, e.g., krypton and xenon. Subsequently, these radioactive gases decay to form rubidium and cesium, respectively, which can condense onto solid particles. Consequently, the first solid particles to fall out, near ground zero, will be depleted not only in krypton and xenon, but also in their various decay (or daughter) products. On the other hand, small particles which have remained in the cloud for some time will have rubidium and cesium, and their daughters, strontium and barium, condensed upon them. Hence, the more distant fallout will be relatively richer in those elements in which the close fallout is depleted.

9.09 An additional phenomenon which contributes to the fractionation of fission product isotopes is the separation of the elements in the ascending fireball as they condense at different times, corresponding to their different boiling points. Thus the refractory elements can

condense at early times in the fireball history, when its temperature is quite high, onto the relatively larger particles which are more abundant at these times. Conversely, volatile elements, with low boiling points, cannot condense until later, when the fireball has cooled and when the larger particle sizes will be depleted. Refractory elements are expected to be relatively more abundant in the close-in early fallout, representing the larger particles, and to be relatively depleted in the more distant portion of the early fallout deposited by smaller particles. The reverse will be true for the more volatile elements. Elements with intermediate boiling points will exhibit behavior between these two extremes.

9.10 For detonations of large energy yield at or near the surface of the sea, where the condensed particles consist of sea-water salts and water, fractionation of the fallout is usually very small. The reason is that the fireball must cool to 100° C (212° F) or less before the evaporated water condenses. The long cooling time and the presence of very small water droplets permit removal from the radioactive cloud of the daughters of the gaseous krypton and xenon along with the other fission products. In this event, there is little or no variation in composition of the radioactive fallout (or rainout) with distance from the explosion.

9.11 The composition of the fallout can also be changed by "salting" the weapon to be detonated. This consists in the inclusion of significant quantities of certain elements, possibly enriched in specific isotopes, for the purpose of producing induced radioactivity. There are several reasons why a weapon might be salted. For example, salting has been used in some weapons tests to provide radioactive tracers for various purposes, such as the study of the paths and relative compositions of the early and delayed stages of fallout. By the choice of elements, to give radioactive products of suitable half lives and radioactivity, the characteristics of the early fallout from a nuclear weapon could be modified for application in radiological warfare (§ 9.110).

Activity and Decay of Early Fallout

9.12 As stated in Chapter I, the fission products constitute a very complex mixture of over 200 different forms (isotopes) of 36 elements. Most of these isotopes are radioactive, decaying by the emission of beta particles, frequently accompanied by gamma radiation. About 2 ounces of fission products are formed for each kiloton (or 125 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 radioactive decay (§§ 1.23, 1.57).

9.13 At 1 minute after a nuclear explosion, when the residual nuclear radiation has been postulated as beginning, the gamma-ray activity of the 2 ounces of fission products from a 1-kiloton fission yield explosion is comparable with that of about 30,000 tons of radium in equilibrium with its decay products. 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 3,000 by the end of the day, the radiation intensity will still be large.

9.14 It has been calculated that if all the fission products from an explosion with a 1-megaton fission yield could be spread uniformly over a smooth area of 10,000 square miles, the radiation dose rate after 24 hours would be 6 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 the explosion center, whereas at much greater distances it will usually be less.

9.15 As stated in § 9.01, the early fallout consists mainly, but not entirely, of fission products. An indication of the manner in which the dose rate of the actual mixture decreases with time may be obtained from the following approximate rule: for every seven-fold increase in time after the explosion, the dose rate decreases by a factor of ten. For example, if the radiation dose rate at 1 hour after the explosion is taken as a reference point, then at 7 hours after the explosion the dose rate will have decreased to one-tenth; at $7\times7=49$ hours (or roughly 2 days) it will be one-hundreth; and at $7\times7\times7=343$ hours (or roughly 2 weeks) the dose rate 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 dose rate will be one-tenth of the value after 1 day. This rule is accurate to within about 25 percent up to 2 weeks or so and is applicable to within a factor of two up to roughly 6 months after the nuclear detonation. Subsequently, the dose rate decreases at a much more rapid rate than predicted by this rule.

9.16 Information concerning the decrease of dose rate in the early fallout can be obtained from the continuous curve in Figs. 9.16a and b, in which the ratio of the approximate exposure dose rate (in r/hr,

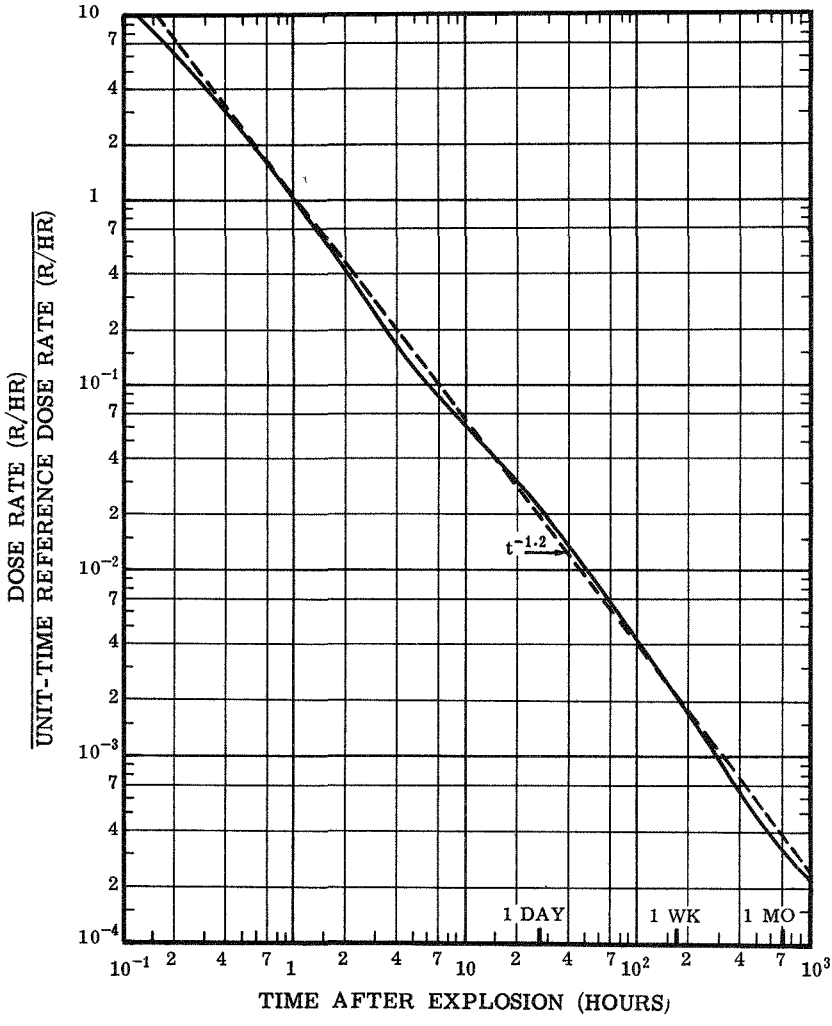

Figure 9.16a. Dependence of dose rate from early fallout upon time after explosion.

i.e., in roentgens per hour) at any time after the explosion to a convenient reference value, called the "unit-time reference dose rate," is plotted against time in hours.[1] The use of the reference dose rate simplifies the representation of the results and the calculations based on them, as will now be shown.

[1] The significance of the dashed lines, marked "$t^{-1.2}$," will be described in § 9.170 *et seq.*, where the physical meaning of the unit-time reference dose rate will be explained. For the present, the dashed lines may be ignored.

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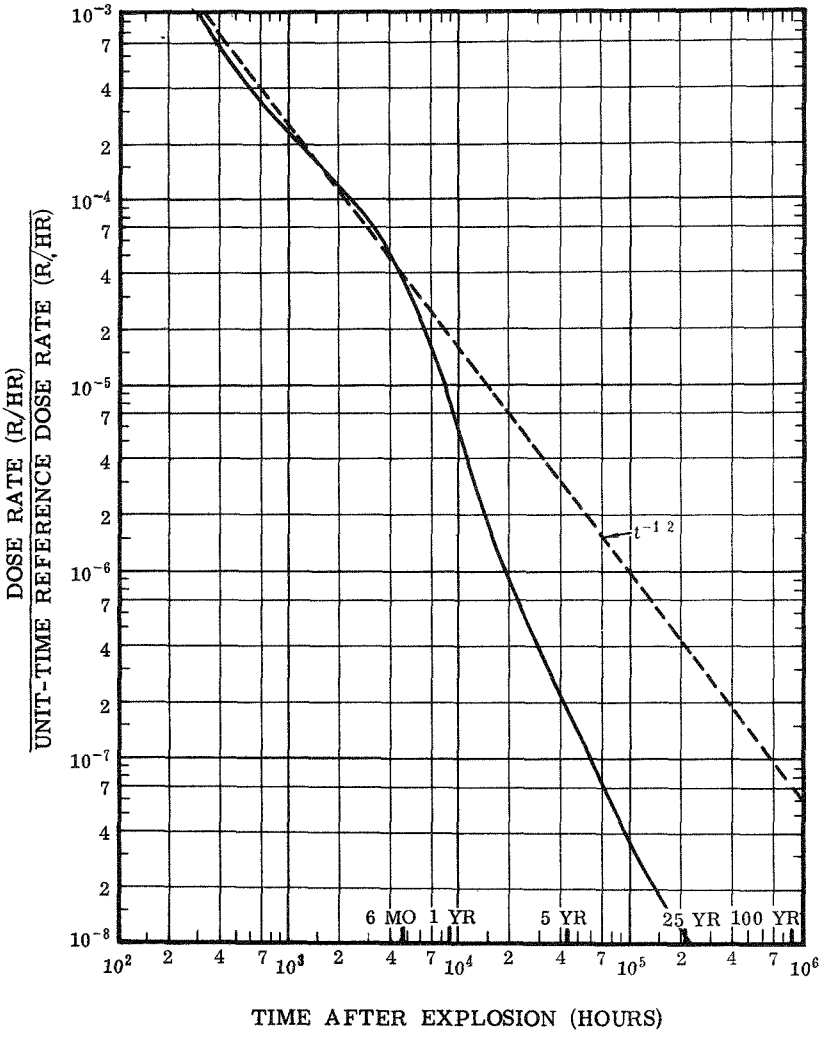

Figure 9.16b. Dependence of dose rate from early fallout upon time after explosion.

9.17 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 4.0 roentgens per hour. From the curve in Fig. 9.16a (or the data in Table 9.19), it is seen that at 15 hours after the explosion, the ratio of the actual dose rate to the reference value is 0.040; hence, the reference dose rate must be $4.0/0.040 = 100$ roentgens per hour. By means

of this reference value and the decay curves in Figs. 9.16a and b, it is possible to estimate 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. 9.16a is entered at the point representing 24 hours on the horizontal axis. Moving upward vertically until the plotted (continuous) line is reached, it is seen that the required dose rate is 0.023 multiplied by the unit-time reference dose rate, i.e., $0.023 \times 100 = 2.3$ roentgens per hour.

9.18 If the dose rate at any time is known, by actual measurement, the value at any other time can be estimated. All that is necessary is to compare the ratios (to the unit-time reference dose rate) for the two given times as obtained from Fig. 9.16a or Fig. 9.16b. 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 curve in Fig. 9.16a, are 0.23 and 0.033, with respect to the unit-time reference dose rate. Hence, the dose rate at 18 hours after the explosion is $50 \times 0.033/0.23 = 7.2$ roentgens per hour.

9.19 The results in Figs. 9.16a and b may be represented in an alternative form, as in Table 9.19, which is more convenient, although somewhat less complete. The dose rate, in any suitable units, is taken as 1,000 at 1 hour after a nuclear explosion; the expected dose rate in the same units at a number of subsequent times, for the same quantity of early fallout, are then as 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.[2]

TABLE 9.19

RELATIVE THEORETICAL DOSE RATES FROM EARLY FALLOUT AT VARIOUS TIMES AFTER A NUCLEAR EXPLOSION

Time (hours)	*Relative dose rate*	*Time (hours)*	*Relative dose rate*
1	1,000	36	15
1½	610	48	10
2	440	72	6.2
3	230	100	4.0
5	130	200	1.7
6	100	400	0.70
10	63	600	0.42
15	40	800	0.31
24	23	1,000	0.24

[2] Several devices, similar to a slide rule, are available for making rapid calculations of the decay of fallout dose rates and related matters.

9.20 It should be noted that Figs. 9.16a and b and Table 9.19 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 (§ 8.23). However, since the dose rate is steadily decreasing during the exposure, appropriate allowance for this must be made. The results of the calculations based on Fig. 9.16a are expressed by the curve in Fig. 9.20. It gives the total dose received from early fallout, between 1 minute and any other specified time after the explosion, in terms of the unit-time reference dose rate.

9.21 To illustrate the application of Fig. 9.20, suppose that an individual becomes exposed to a certain quantity of gamma radiation from early fallout 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 the explosion? The first step is to determine the unit-time reference dose rate. From Fig. 9.16a it is seen that

$$\frac{\text{Dose rate at 2 hours after explosion}}{\text{Unit-time reference dose rate}} = 0.40$$

and, since the dose rate at 2 hours is known to be 1.5 roentgens per hour, the reference value is $1.5/0.40 = 3.8$ roentgens per hour. Next, from Fig. 9.20, it is found that for 2 hours and 14 hours, respectively, after the explosion,

$$\frac{\text{Total dose at 2 hours after explosion}}{\text{Unit-time reference dose rate}} = 5.8$$

and

$$\frac{\text{Total dose at 14 hours after explosion}}{\text{Unit-time reference dose rate}} = 7.1.$$

Hence, by subtraction

$$\frac{\text{Dose received between 2 and 14 hours after explosion}}{\text{Unit-time reference dose rate}} = 1.3.$$

The unit-time reference dose rate is 3.8 roentgens per hour, and so the total dose received in the 12 hours, between 2 and 14 hours after the explosion, is $3.8 \times 1.3 = 4.9$ roentgens.

9.22 The percentage of the "infinity (residual radiation) dose" that would be received from a given quantity of early fallout, computed from 1 minute to various times after a nuclear explosion, is

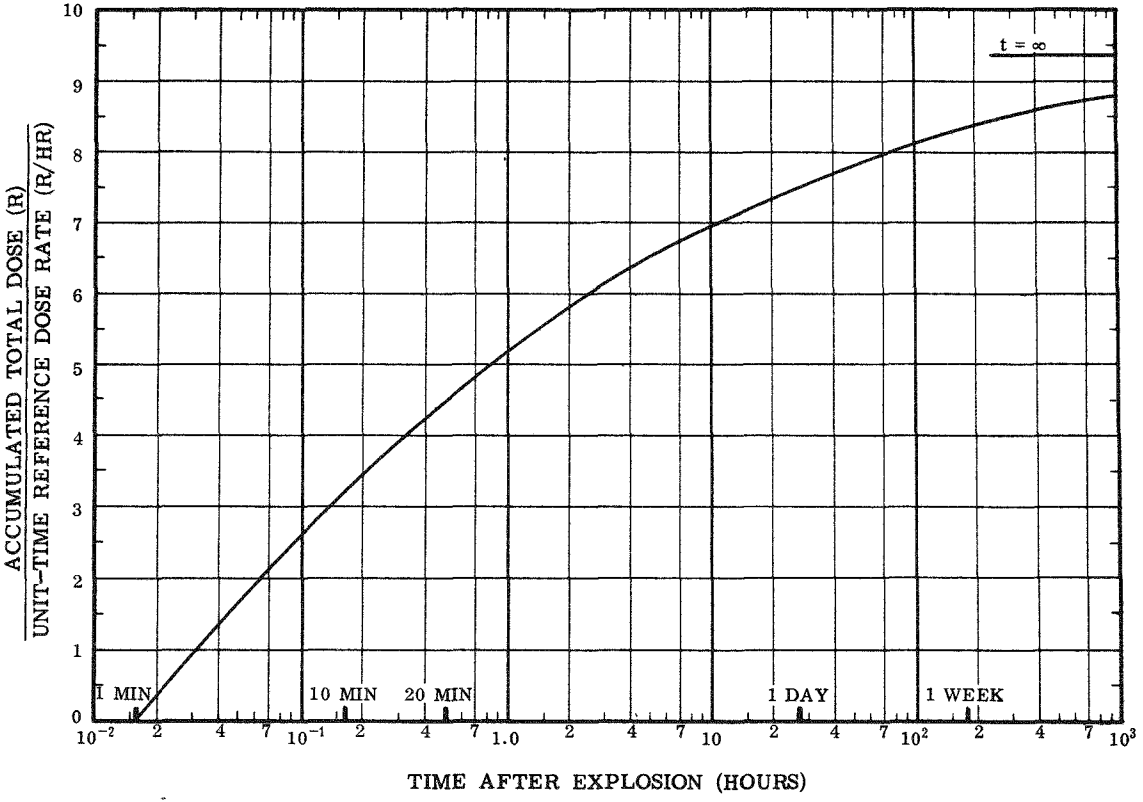

Figure 9.20. Curve for determining total dose from early fallout at various times after explosion.

shown in Table 9.22. The infinity dose is essentially that which would be received as a result of continued exposure to a certain quantity of early fallout 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 early fallout from a nuclear explosion.

TABLE 9.22

PERCENTAGES OF INFINITY RESIDUAL RADIATION DOSE RECEIVED FROM 1 MINUTE UP TO VARIOUS TIMES AFTER EXPLOSION

Time (hours)	*Percent of infinity dose*	*Time (hours)*	*Percent of infinity dose*
1	55	72	86
2	62	100	88
4	68	200	90
6	71	500	93
12	75	1,000	95
24	80	2,000	97
48	83	10,000	99

9.23 For example, if an individual is exposed to a certain amount of early 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 (or estimated from) Table 9.22, i.e., 76 (for 14 hours) minus 62 (for 2 hours), giving 14 percent, i.e., 0.14, of the infinity dose. The actual value of the infinity dose computed from 1 minute after detonation, is 9.3 times the unit-time reference dose rate (in roentgens per hour), as shown in Fig. 9.20. Hence, if the reference value is 3.8 roentgens per hour as in the above example, the dose received between 2 hours and 14 hours after the burst is $0.14 \times 9.3 \times 3.8 = 4.9$ roentgens, as before.

9.24 With the aid of Figs. 9.16 a and b and Fig. 9.20 (or the equivalent Tables 9.19 and 9.22) many different types of calculations relating to radiation dose rates and total doses received from early fallout can be made. The procedures can be simplified, however, by means of special charts, as will be shown below. The results, like those given above, are applicable to a particular quantity of fallout. If there is any change in the situation, either by further contamination or by decontamination, the conclusions will not be valid.

9.25 If the radiation dose rate from early fallout is known at a given location, Fig. 9.25 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 nomo-

graph can be utilized, alternatively, to determine the time after the explosion at which the dose rate will have attained a specified value. It should be mentioned that the nomograph is based on the straight line marked "$t^{-1.2}$" in Figs. 9.16 a and b which is seen to deviate slightly from the theoretical decay curve. Nevertheless, it is possible to obtain from Fig. 9.25 approximate dose rates, which are within 25 percent of the theoretical decay values of Figs. 9.16 a and b for the first 200 days after the nuclear detonation.

9.26 To determine the total radiation dose received during a specified time of stay in an area contaminated with early fallout, if the dose rate in that area at any given time is known, use is made of Fig. 9.26 in conjunction with Fig. 9.25. The chart may also be employed to evaluate the time when a particular operation may be commenced in a contaminated area in order not to exceed a certain total radiation dose.

9.27 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. 9.26, which also requires the use of Fig. 9.25, 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. 9.27 which avoids the necessity for evaluating the unit-time reference dose rate, provided the dose rate at the time of entry into the contaminated area is known.

9.28 If the whole of the early fallout reached a given area within a short time, Fig. 9.27 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 early 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 $9R$ roentgens in 1 day, $12R$ roentgens in 2 days, and $16R$ roentgens in 5 days.

9.29 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 the early fallout is concerned. Although the particular values given above apply to the case specified, i.e., complete early 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.

(Text continued on p. 432)

The nomograph in Fig. 9.25 gives an approximate relationship between the dose rate at any time after the explosion and the unit-time reference value. If the dose rate at any time is known, that at any other time can be derived from the figure. Alternatively, the time after the explosion at which a specific dose rate is attained can be determined approximately.

For the conditions of applicability of Fig. 9.25, see §9.30.

Example

Given: The radiation dose rate due to fallout at a certain location is 8 roentgens per hour at 6 hours after a nuclear explosion.

Find: (*a*) The dose rate at 24 hours after the burst.

(*b*) The time after the explosion at which the dose rate is 1 roentgen per hour.

Solution: By means of a ruler (or straight edge) join the point representing 8 roentgens per hour on the left scale to the time 6 hours on the right scale. The straight line intersects the middle scale at 70 roentgens per hour; this is the unit-time reference value of the dose rate.

(*a*) Using the straight edge, connect this reference point (70 r/hr) with that representing 24 hours after the explosion on the right scale, and extend the line to read the corresponding dose rate on the left scale, i.e., 1.5 roentgens per hour. *Answer*

(*b*) Extend the straight line joining the dose rate of 1 roentgen per hour on the left scale to the reference value of 70 roentgens per hour on the middle scale out to the right scale. This is intersected at 34 hours after the explosion. *Answer*

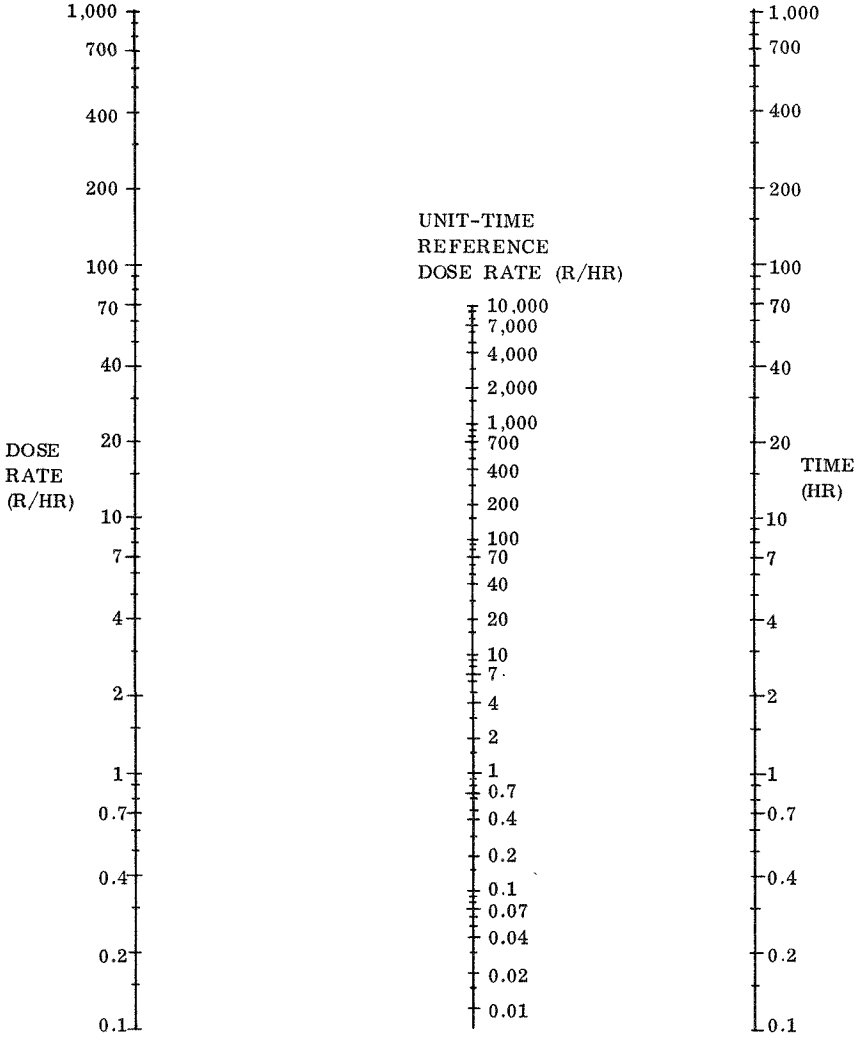

Figure 9.25. Nomograph for calculation of approximate dose rates from early fallout.

From Fig. 9.26 the total radiation dose received from early fallout during any specified stay in a contaminated area can be estimated 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.

For conditions of applicability of Fig. 9.26, see § 9.30.

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 unit-time reference dose rate (R_1). From Fig. 9.25, 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. 9.26 at 6 hours after the explosion (horizontal scale) and move up to the curve representing a time of stay of 2 hours. The corresponding reading on the vertical 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

$$0.19 \times 32 = 6.1 \text{ roentgens.} \quad \textit{Answer}$$

(*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. 9.26 at this point on the vertical scale and moving across until the (interpolated) curve for 5 hours stay is reached, the corresponding reading on the horizontal scale, giving the time after the explosion, is seen to be 21 hours. *Answer*

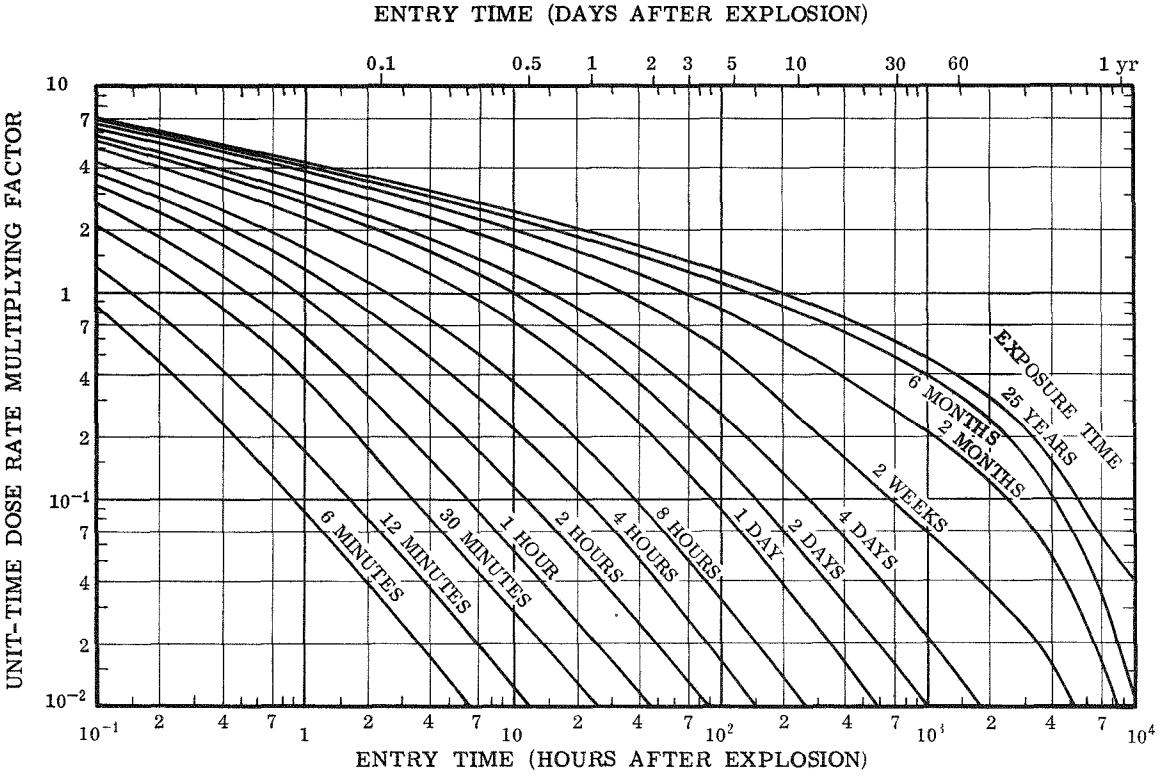

Figure 9.26. Total radiation dose from early fallout based on unit-time reference dose rate.

From the chart in Fig. 9.27, the total radiation dose received from early fallout during any specified stay in a contaminated area can be estimated 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.

For conditions of applicability of Fig. 9.27, see §9.30.

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 20 roentgens.

Solution: (*a*) Start at the point on Fig. 9.27 representing 12 hours after the explosion on the horizontal scale and move up 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 vertical scale, is seen to be 1.9. Hence, the total dose received is

$$1.9 \times 5 = 9.5 \text{ roentgens.} \quad \textit{Answer.}$$

(*b*) The total dose is 20 roentgens and the dose rate at the time of entry is 5 roentgens per hour; hence, the multiplying factor is $20/5 = 4.0$. Enter Fig. 9.27 at the point corresponding to 4.0 on the vertical scale and move horizontally to meet a vertical line which starts from the point representing 12 hours after the explosion on the horizontal scale. The two lines are found to intersect at a point indicating a time of stay of about 4½ hours. *Answer.*

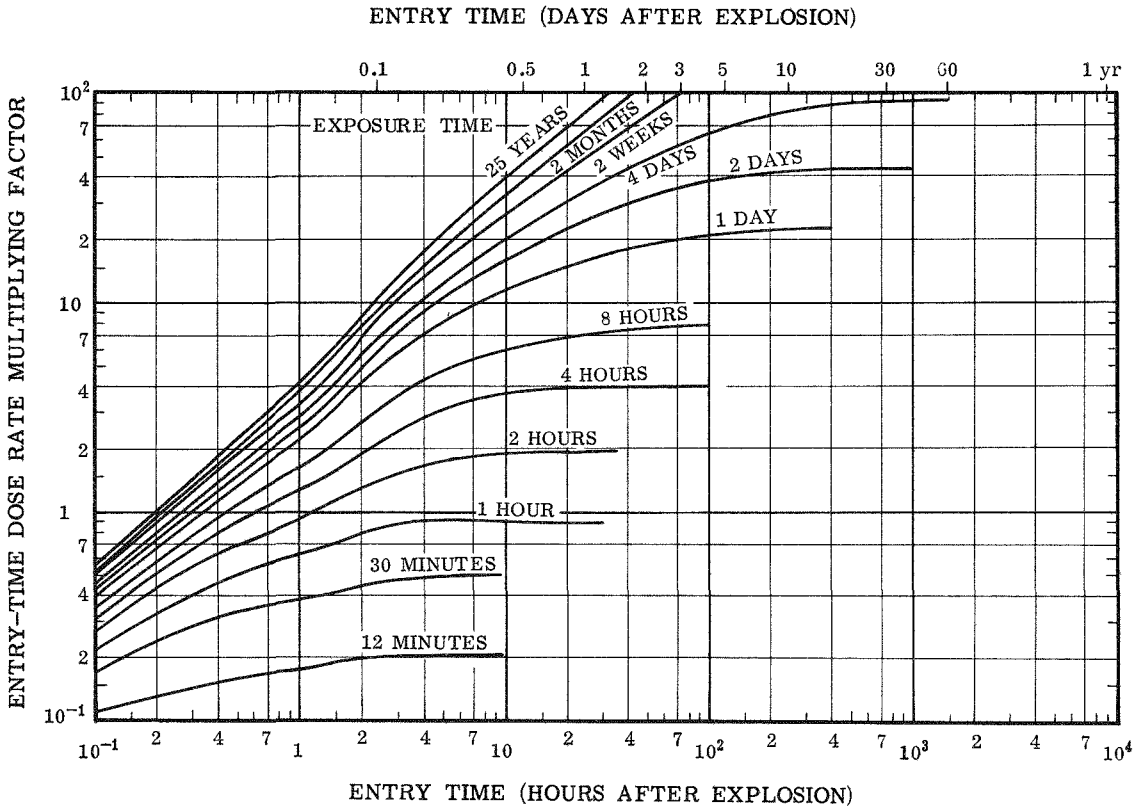

Figure 9.27. Total radiation dose from early fallout based on dose rate at time of entry.

(Text continued from p. 425.)

9.30 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 early fallout and remains exposed continuously (without protection) to this same quantity for a period of time. In an actual fallout situation, however, these conditions probably would not exist. For one thing, any shelter which attenuates the radiation will reduce the exposure dose rate (and dose) as given by the calculations. Furthermore, the action of wind and weather will generally tend to disperse the fallout particles in some areas and concentrate them in others. As a result, there may be a change in the quantity of early fallout at a given location during the time of exposure; the radiation dose rate (and dose) would then change correspondingly. The same would be true, of course, if there were additional fallout from another nuclear explosion.

Neutron-Induced Activity

9.31 The neutrons liberated in the fission process, but which are not involved in the propagation of the fission chain, are ultimately captured by the weapon 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.

9.32 The activity induced in the weapon 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 residues will remain associated with the fission products. The curves and tables given above have been adjusted to include the contribution of such isotopes, e.g., uranium-237 and -239 and neptunium-239 and -240. In the period from 20 hours to 2 weeks after the burst, depending to some extent upon the weapon materials, these isotopes can contribute up to 40 percent of the total activity of the weapon residues. At other times, their activity is negligible in comparison with that of the fission products.

9.33 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 early residual radiation is concerned. Oxy-

gen, 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.

9.34 The radioactive product of neutron capture by nitrogen is carbon-14 (§ 8.89) which emits beta particles of relatively low energy but no gamma rays. Although carbon-14 has a long half-life (5,760 years) and is not highly active, in the form of carbon dioxide it is readily incorporated by all forms of plant life and thus finds its way into the human body. The carbon in all living organisms contains a certain proportion of carbon-14 resulting from the capture by atmospheric nitrogen of neutrons from naturally occurring cosmic rays. The total reservoir of carbon-14 in nature, including oceans, atmosphere, and biosphere (living organisms), is known to be from 50 to 80 tons; of this amount, about 1 ton is in the atmosphere and 0.2 ton in the biosphere. It is estimated that before September 1961, weapons testing had produced 0.65 ton of carbon-14 and about half had dissolved in the oceans. Consequently, the carbon-14 content of the atmosphere had been increased by about 30 percent over the normal (1950) value. In the course of time, more and more of the carbon-14 will enter the oceans and, provided there is no great addition as a result of weapons tests, the level in the atmosphere will fall to less than 1 percent above normal in 50 to 100 years.

9.35 An important contribution to the residual nuclear radiation can arise from the activity induced by neutron capture in certain elements in the earth and in sea water. The extent of this radioactivity is highly variable. The element which probably deserves most attention, as far as environmental neutron-induced activity is concerned, 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 15 hours and emits both beta particles, and more important, gamma rays of relatively high energy.[3]

9.36 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

[3] 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 at 1 hour after formation is about 1 Mev.

first few hours after an explosion, the manganese may constitute a serious hazard, greater than that of sodium.

9.37 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 aulminum-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.

9.38 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 in § 9.33, 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.

9.39 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 decrease the induced activity.

Uranium and Plutonium

9.40 The uranium and plutonium which may have escaped fission in the nuclear weapon 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.

9.41 It will be seen later (§ 9.130) 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.

9.42 Although there is negligible danger from uranium and plutonium outside the body, it is possible for dangerous amounts of these elements to enter 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 can cause serious harm.

9.43 At one time it was suggested that the explosion of a sufficiently large number of nuclear weapons might result in such an extensive distribution of the plutonium as to represent a worldwide hazard. 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 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.

Clean and Dirty Weapons

9.44 The terms "clean" and "dirty" are often used to describe the amount of radioactivity produced by a fusion weapon (or hydrogen bomb) relative to that from what might be described as a "normal" weapon. The latter may be defined as one in which no special effort has been made either to increase or to decrease the amount of radioactivity produced for the given explosion yield. A "clean" weapon would then be one which is designed to yield significantly less radioactivity than an equivalent normal weapon. It should be noted, however, that a clean fusion weapon would inevitably produce some radioactive species. Even if a pure fusion weapon, with no fission, should be developed, its explosion in air would still result in the formation of carbon-14 and possibly other neutron-induced

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activities. If special steps were taken in the design of a fusion device, e.g., by salting (§ 9.11), so that upon detonation it generated more radioactivity than a similar normal weapon, it would be described as "dirty." By its very nature, a fission weapon must be regarded as being dirty.

DISTRIBUTION OF EARLY FALLOUT

Modes of Contamination

9.45 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 descent of radioactive particles from the column and cloud formed in the explosion (§ 2.18). The amount of contamination and its distribution over the earth's surface are principally dependent upon the energy yield of the explosion, the relative contributions of fission and fusion to the total yield, the height of burst, the nature of the surface over (or on) which the detonation occurs, and, finally, the meteorological conditions.

9.46 An air burst, by definition, is one taking place at such a height above the earth that no appreciable quantities of surface materials are taken up into the fireball. The radioactive residues of the weapon then condense into extremely small particles which remain suspended in the atmosphere for a long time. Hence, except possibly under special meteorological conditions, there will be no early (or local) fallout. However, depending on the characteristics of the weapon, the height of burst, and the nature of the surface there will be more or less contamination, in the general vicinity of ground zero, as a result of radioactivity induced by neutron capture. The contamination which might arise in this manner is highly variable, but it is probable that, apart from strong underground structures, the area affected would be completely devastated by blast and fire.

9.47 As the height of burst decreases, and earth, dust, and other debris from the earth's surface are taken up into the fireball, an increasing proportion of the fission (and other radioactive) products of the nuclear explosion condense onto particles of appreciable size. These contaminated particles range in diameter from less than 1 micron (see § 2.27, footnote) to several millimeters; the larger ones begin to fall back to earth even before the radioactive cloud has at-

tained its maximum height, whereas the very smallest ones may remain suspended in the atmosphere for long periods. In these circumstances there will be an early fallout, with the larger particles reaching the ground within 24 hours.

9.48 The proportion of the total radioactivity of the weapon residues that is present in the early fallout, sometimes called the "early fallout fraction," appears to vary from one test explosion to another. For land surface bursts the early fallout fraction has been estimated to range from 50 to 70 percent. Values somewhat higher than this are expected from shallow underground bursts, whereas for water surface bursts the value is lower, in the neighborhood of 30 percent. Some variability is expected in the fallout fraction for a given type of burst due to variation in environmental and meteorological conditions. Nevertheless, it will be assumed here that 60 percent of the total radioactivity from a land surface burst weapon will be in the early fallout (§ 9.184). The remaining 40 percent will eventually reach the earth in the delayed fallout, most of it many hundreds or thousands of miles away (§ 9.141 *et seq.*).

Distribution of Contamination

9.49 The distribution on the ground of the activity from the early fallout, even for similar nuclear yields, also shows great variability. In addition to the effect of wind, such factors as the dimensions of the radioactive cloud, the distribution of radioactivity within the mushroom head, and the range of particle sizes contribute to the uncertainty in attempts to predict the fallout pattern.

9.50 The spatial distribution of radioactivity within the cloud is not known accurately, but some of the gross features have been derived from observations and theoretical considerations. It is generally accepted that the mushroom head from a land surface burst contains about 90 percent of the total activity with the remainder residing in the stem. The proportion of activity in the stem may be even less for a water surface burst and almost zero for an air burst. However, it appears that some radioactive particles from the mushroom head fall or are transported by subsiding air currents to lower altitudes even before the cloud reaches its maximum height. There is some evidence that, for explosions in the megaton range, the highest concentration of radioactivity initially lies in the lower third of the head of the mushroom cloud. It is probable, too, that in detonations of lower yield, a layer of relatively high activity exists somewhere in the cloud. However, the location of the peak concentration appears

to vary with different detonations, perhaps as a function of atmospheric conditions.

9.51 Because particles of different sizes descend at different rates and carry different amounts of radioactive contamination, the fallout pattern will depend markedly on the size distribution of the particles in the cloud after condensation has occurred. In general, larger particles fall more rapidly and carry more activity, so that a high proportion of such particles will lead to greater contamination near ground zero, and less at greater distances, than would be the case if small particles predominated.

9.52 The particle size distribution in the radioactive cloud may well depend on the nature of the material which becomes engulfed by the fireball. A surface burst in a city for example, could result in a particle size distribution, and consequent fallout pattern, which would differ from those produced under test conditions in Nevada and the Pacific. However, in the absence of any definite evidence to the contrary it is generally assumed that the fallout pattern for a surface burst in a large city will not differ greatly from those associated with surface and tower shots in the Nevada desert.

Area of Contamination

9.53 The largest particles fall to the ground from the radioactive cloud and stem shortly after the explosion and hence are found within a short distance of surface zero. Smaller particles, on the other hand, will require many hours to fall to earth. During this period they may be carried hundreds of miles from the burst point by the prevailing winds. The very smallest particles have no appreciable rate of fall and so they may circle the earth many times before reaching the ground, generally in precipitation with rain or snow.

9.54 The fact that small particles from the radioactive cloud may reach the ground at considerable distances from the explosion means that fallout from a surface burst can produce serious contamination far beyond the range of other effects, such as blast, shock, thermal radiation, and initial nuclear radiation. 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. However, the total quantity of contaminated material produced by the surface burst of a megaton weapon with a high fission yield is so large that fallout may continue to arrive in hazardous concentrations up to perhaps 24 hours after the burst. Radioactive contamination from a single deto-

nation may thus affect vast areas and so fallout must be regarded as one of the major effects of nuclear weapons.

9.55 An important factor determining the area covered by appreciable fallout, as well as its distribution within that area, is the wind pattern from the ground up to the top of the radioactive cloud. The direction and speed of the wind at the cloud level will influence the motion and extent of the cloud itself. In addition, the winds at lower altitudes, which may change both in time and space, will cause the fallout particles to drift one way or another while they descend to earth. The situation may be further complicated by the effect of rain and of irregularities in the terrain. These, as well as irregular distribution of activity in the cloud and fluctuations in the wind speed and direction, will contribute to the development of "hot spots" of much higher activity than in the immediate surroundings.

Fallout Patterns

9.56 Information concerning fallout distribution has been obtained from observations made during nuclear weapons tests at the Nevada Test Site and the Eniwetok Proving Grounds. However, there are many difficulties in the analysis and interpretation of the results, and their use to predict the situation that might arise from a land surface burst over a large city. This is particularly the case for the megaton-range detonations at the Eniwetok Proving Grounds. Since the fallout descends over vast areas of the Pacific Ocean, the contamination pattern of a large area must be inferred from a relatively few radiation dose measurements (§ 9.101). Furthermore, the presence of sea water affects the results, as will be seen below.

9.57 Nuclear tests in Nevada have been confined to weapons having yields below 100 kilotons and most of the detonations were at the tops of steel towers 100 to 700 feet high or from balloons at levels of 400 to 1,500 feet. None of these could be described as a true surface burst and, in any event, in the tower shots there is evidence that the fallout was affected by the tower. There have been a few surface bursts, but the energy yields were about 1 kiloton or less, so that they provided relatively little useful information concerning the effects to be expected from weapons of higher energy. Tests of fusion weapons with yields up to 15 megatons TNT equivalent have been made at the Eniwetok Proving Grounds. A very few were detonated on atoll islands, but most of the shots were fired on barges in the lagoons or on coral reefs. In all cases, however, considerable quantities of sea water were drawn into the radioactive

cloud, so that the fallout was probably quite different from what would have been associated with a true land surface burst.

9.58 The irregular nature of the fallout distribution is shown by the patterns in Figs. 9.58 a and b; the lines are drawn through points having the indicated dose rates at 12 hours after the detonation time. Figure 9.58a refers to the BOLTZMANN shot (12 kilotons, 500-foot tower) of May 28, 1957 and Fig. 9.58b to the TURK shot (43 kilotons, 500-foot tower) of March 7, 1955. Because of the difference in wind conditions, the patterns are quite different. Furthermore, attention should be drawn to the hot spot, some 60 miles NNW of the northern boundary of the Nevada Test Site, that was observed in connection with the BOLTZMANN test. This area was found to be seven times more radioactive than its immediate surroundings. The location was immediately downwind of a mountain range and rain was reported in the general vicinity at the time the fallout occurred. Either or both of these factors may have been responsible for the increased radioactivity.

9.59 Measurement of fallout activity from megaton-yield weapons in the Pacific Ocean area has indicated the presence of marked irregularities in the overall pattern. Some of these may have been due to the difficulties involved in collecting and processing the limited data. Nevertheless, there is evidence to indicate that a hot spot some distance (50 to 75 miles) downwind of the burst point may be typical of the detonations at the Eniwetok Proving Grounds and, in fact, some fallout prediction methods have been designed to reproduce this feature. Whether a similar hot spot would appear following a land surface burst is quite uncertain.

Prediction of Fallout Patterns

9.60 Several methods, of varying degree of complexity, have been developed for predicting dose rates and integrated (total) doses resulting from fallout. These methods fall into four general categories; they are, in decreasing order of complexity, and hence detail, the mathematical fallout model, the idealized fallout pattern, the danger sector forecast, and the analog method. Each of these techniques requires, of course, a knowledge of the total and fission yields of the explosion, the burst height, and the wind structure to the top of the radioactive cloud in the vicinity of the burst.

9.61 In the fallout model method, an attempt is made to describe fallout mathematically and, with various inherent assumptions, to predict the dose-rate contours resulting from a particular situation.

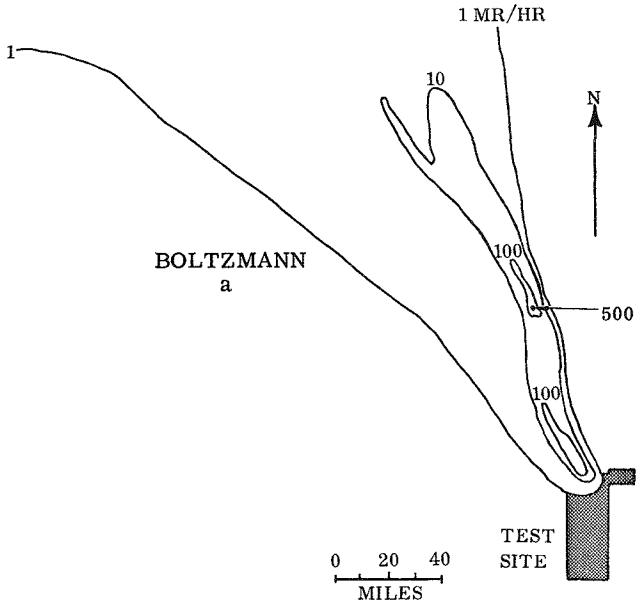

Figure 9.58a. Early fallout dose-rate contours from the BOLTZMANN shot at the Nevada Test Site.

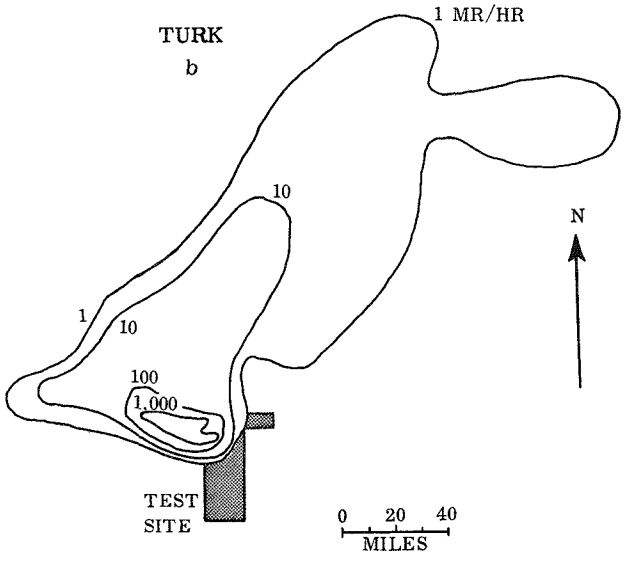

Figure 9.58b. Early fallout dose-rate contours from the TURK shot at the Nevada Test Site.

Most of the procedures are so complex as to require the use of a digital computer in their application to a variety of circumstances. They are, consequently, employed primarily in theoretical studies of the fallout process, in making planning estimates, and in the preparation of templates for use with analog prediction methods. Less detailed mathematical models which do not require the use of digital computers have been used to predict fallout patterns during nuclear tests.

9.62 The analog technique, which is essentially a comparison process, utilizes a pattern chosen from a catalog of fallout patterns covering a wide range of yields and wind conditions. The choice is determined by the similarity between the yield and wind in the given situation and those in the catalog pattern. The catalog can consist of actual fallout patterns and others interpolated and extrapolated from these, or of patterns obtained by calculation from a mathematical fallout model.

9.63 The danger sector forecast requires a minimum of detailed information in order to give a qualitative picture of the general fallout area and an idea of the arrival times. Although it provides a rough indication of the relative degree of hazard, there is little or no information concerning the actual dose rates to be expected at various locations. The method yields a prediction quickly and simply and is probably as accurate as the explosion yield and meteorological information will justify in an operational (field) situation. The fourth prediction method, based on the use of idealized fallout patterns, is described in some detail below.

IDEALIZED FALLOUT PATTERNS

Megaton-Range Explosions

9.64 Idealized fallout patterns have been developed which represent the average fallout field for a given yield and wind condition. No attempt is made to indicate irregularities which will undoubtedly occur in a real fallout pattern, because the conditions determining such irregularities are highly variable and uncertain. Nevertheless, in spite of their limitations, idealized patterns are useful for planning purposes, for example in estimating the overall effect of fallout from a large-scale nuclear attack. Although they will undoubtedly underestimate the fallout in some locations and overestimate it in others, the evaluation of the gross fallout problem over the whole area affected should not be greatly in error.

9.65 For a detailed fallout prediction, the winds from the surface to all levels in the radioactive cloud must be considered. However, for the idealized patterns, the actual complex wind system is replaced by an approximately equivalent "effective wind." This is taken as the mean value of the wind speed and direction from the surface to some representative level in the cloud. The level chosen generally lies between the base and middle of the mushroom head, where the concentration of radioactivity is believed to be a maximum.

9.66 By assuming little or no wind shear, that is, essentially no change in wind direction at different altitudes, the idealized fallout patterns have a regular cigar-like shape, as will be seen shortly. But if the wind direction changes with altitude, the fallout will spread over a wider angle, as in Fig. 9.58a, and the activity (or radiation dose rate) at a given distance from surface zero will be decreased because the same amount of radioactive contamination will cover a larger area. Lower wind speeds will make the pattern shorter in the downwind direction because the particles will not travel so far before descending to earth; the activity at some distance from the burst point will be lower and the high dose rates immediately downwind of ground zero will be increased. If the wind speed is higher, the contaminated area will be greater, and the radioactivity will be higher at large distances from surface zero and lower immediately downwind of ground zero.

9.67 Before showing an idealized fallout pattern it is important to understand how such a pattern develops over a large area during a period of several hours following a 1-megaton fission yield surface burst. This may be illustrated by the diagrams in Figs. 9.67 a and b. The effective wind speed was taken as 15 miles per hour. Fig. 9.67a shows a number of "contours" (or "isodose-rate" lines) for certain (arbitrary) round-number values of the dose rate, as would be observed on the ground, at 1, 6, and 18 hours, respectively, after the explosion. A series of total (or accumulated) dose contours (or "isodose" lines) for the same times are given in Fig. 9.67b. 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 continue to fall off over a greater distance.

9.68 Consider, first, a location 22 miles downwind from ground zero. At 1 hour after the detonation, the observed dose rate is seen to be about 10 roentgens per hour but is rising very rapidly and will reach a value over 1,000 r/hr sometime between 1 and 2 hours and will

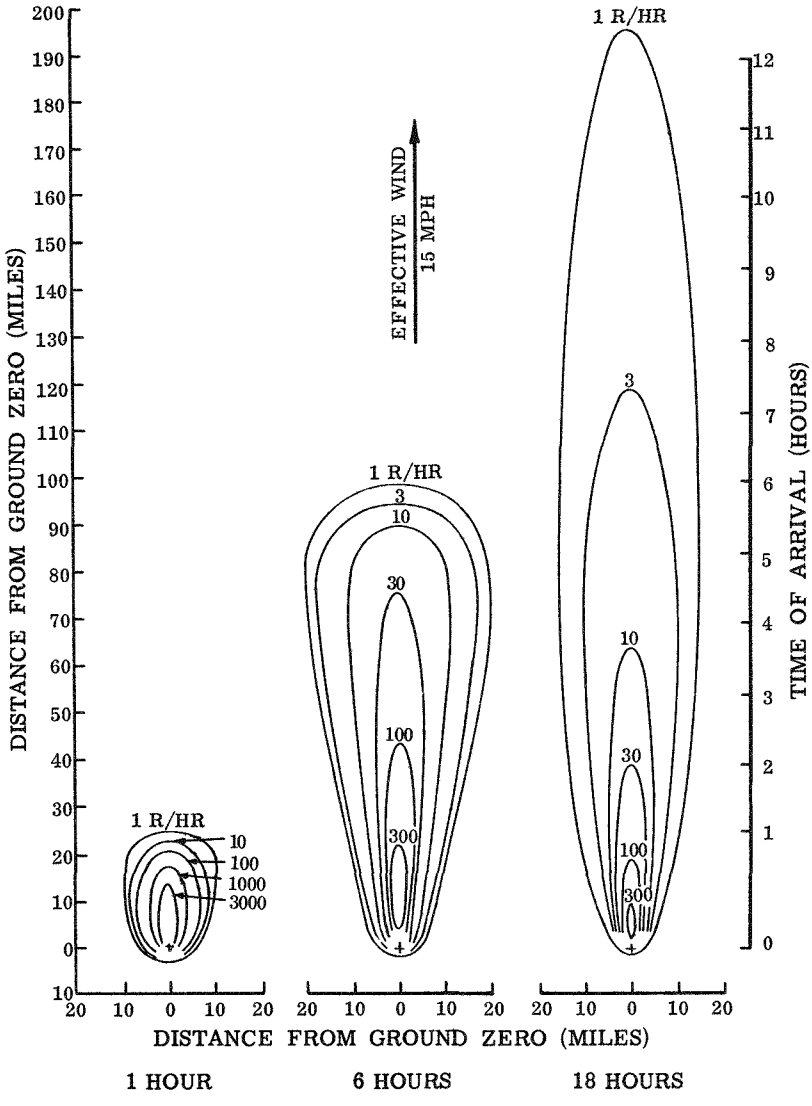

Figure 9.67a. Dose-rate contours from early fallout at 1, 6, and 18 hours after a surface burst with 1-megaton fission yield (15 mph effective wind speed).

then decay to about 300 r/hr at 6 hours. At 18 hours it is down to roughly 80 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

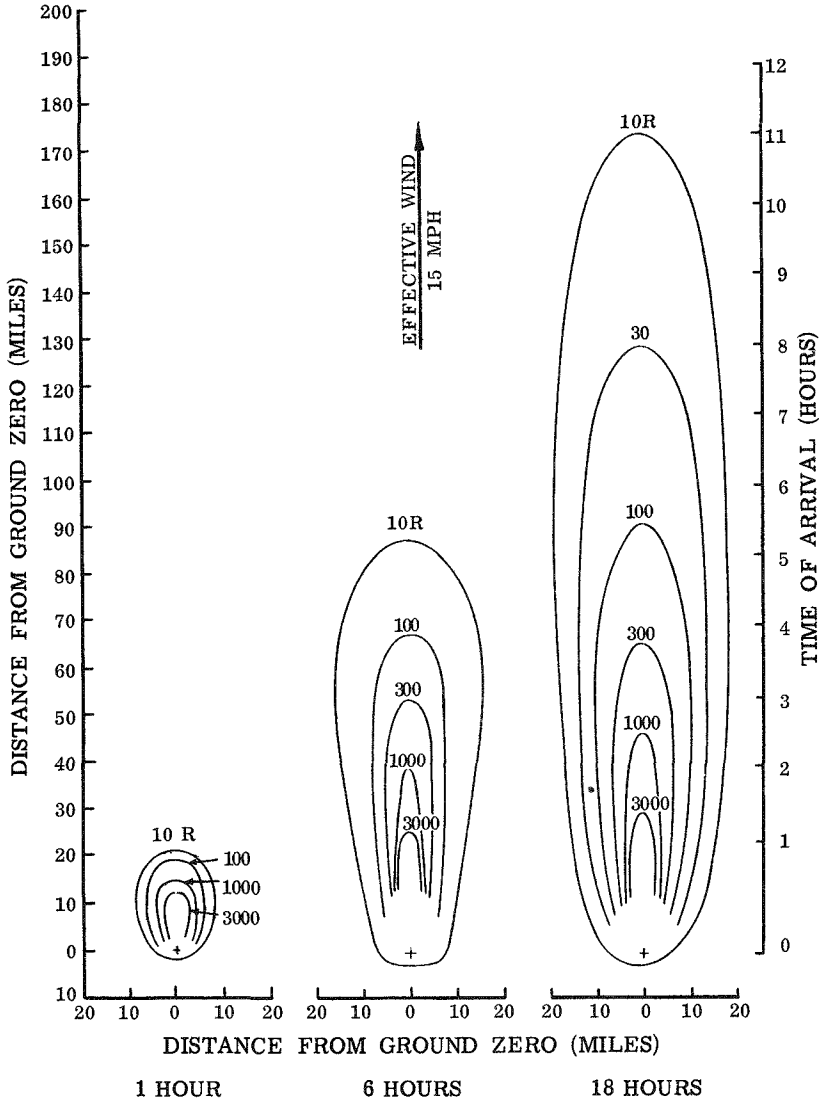

Figure 9.67b. Total-dose contours from early fallout at 1, 6, and 18 hours after surface burst with 1-megaton fission yield (15 mph effective wind speed).

is then due to the natural decay of the fission products. Turning to Fig. 9.67b, it is seen that the total radiation dose received at the given location by 1 hour after the explosion is small, because the fallout has only just started to arrive. By 6 hours, the total dose has

reached over 3,000 roentgens and by 18 hours a total dose of some 4,800 roentgens will have been accumulated. Subsequently, the total dose will continue to increase, toward the infinity value, but at a slower rate (§ 9.22).

9.69 Next, consider a point 100 miles downwind from ground zero. At 1 hour after the explosion the dose rate, as indicated in Fig. 9.67a, is zero, since the fallout will not have reached the specified location. At 6 hours, the dose rate is about 1 roentgen per hour and at 18 hours about 5 roentgens per hour. The fallout commences at somewhat less than 6 hours after the detonation and it is essentially complete at 9 hours, although this cannot be determined directly from the contours given. The total accumulated dose, from Fig. 9.67b, is seen to be zero at 1 hour after the explosion, less than 1 roentgen at 6 hours, and about 80 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.

9.70 In general, therefore, at any given location, at a distance from a surface burst, some time will elapse between the explosion and the arrival of the fallout. This time will depend on the distance from ground zero and the effective wind velocity. When the fallout first arrives, the dose rate is small, but it increases as more and more fallout descends. After the fallout is complete, the radioactive decay of the fission products will produce 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.

9.71 The curves in Figs. 9.71 a and b illustrate this behavior; they show the variation with time of the dose rate and the dose from fallout at points 35 and 150 miles downwind from a 5-megaton surface burst. Both the dose rate and the accumulated dose are zero until the fallout particles reach the given locations at 1 and 10 hours after the burst, respectively. At these times the dose rate commences to increase, reaches a maximum, and subsequently decreases, rapidly at first as the radioisotopes of short half-life decay, and then more slowly. The total dose increases continuously from the time of arrival of the fallout toward the limiting (infinite time) value.

9.72 The representation of dose rate and accumulated dose curves, of the form of Figs. 9.67 a and b, for all times following a nuclear detonation would obviously be a highly complicated matter. Fortunately, the situation can be simplified by utilizing an idealized

fallout pattern in terms of the unit-time reference dose rate, mentioned in §9.16 *et seq.* By means of the curves given earlier in the chapter (Figs. 9.16 a and b and Fig. 9.20) it is then possible to estimate dose rates and total doses from fallout at any given time for a specified distance downwind from the burst point. The calculations are valid only if all the early fallout has descended at that time.

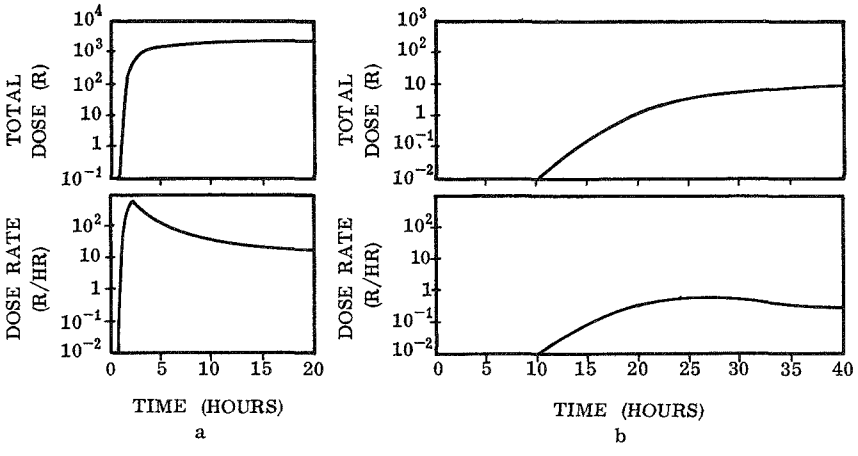

Figure 9.71a. Dose rate and accumulated dose from fallout as functions of time after the explosion at 35 miles downwind.

Figure 9.71b. Dose rate and accumulated dose from fallout as functions of time after the explosion at 150 miles downwind.

9.73 The idealized unit-time reference dose-rate contours for a 1-megaton fission yield surface burst, with an effective wind of 15 miles per hour, are represented in Fig. 9.73. This figure is based partly on observations made at various tests and partly on calculations. The maximum downwind distances and widths of the contours for various dose rates, down to 0.1 roentgen per hour, are recorded in Table 9.73. An example illustrating the use of Fig. 9.73 is given on the page facing the figure. No attempt is made here to express the upwind fallout pattern; this aspect of the problem will be considered later (§ 9.83).

9.74 It should be understood that the idealized dose rates and total dose calculations made from Fig. 9.73 would be those indicated by monitor instruments in open country in the complete absence of shielding from the residual nuclear radiations. Any kind of shelter would decrease the dose received from the early fallout.

Fallout Example

Given: A 10-megaton surface burst, with an effective wind speed from the surface to 80,000 feet of 25 miles per hour. Assume a fission yield of 50 percent.

Find: The unit-time reference dose rate, arrival time, and the dose received by an exposed person during the first week following fallout arrival at points 100, 200, and 300 miles downwind, and the upwind extent of the 1 r/hr unit-time reference dose rate.

Scaling procedures are described in § 9.75 *et seq.*; for upwind fallout distribution, see § 9.83 *et seq.* The scaling of the contours in Fig. 9.73 is explained in § 9.79.

Solution: The unit-time reference dose rates, scaled for wind speed, are found by plotting the scaled dose rates versus the scaled downwind distances, obtained from Fig. 9.73, to be 270 r/hr at 100 miles, 60 r/hr at 200 miles, and 24 r/hr at 300 miles. Scaling for the 5-megaton fission yield gives scaled unit-time dose rates of $5\times270=1{,}350$ r/hr, $5\times60=300$ r/hr, and $5\times24=120$ r/hr, respectively.

The cloud will be carried by the 25 mph wind to the 100 mile point in $100/25=4$ hours, to the 200 mile point in $200/25=8$ hours, and to the 300 mile point in $300/25=12$ hours.

In order to calculate the dose, an effective entry time equal to the arrival time may be assumed, giving effective entry times of 4, 8, and 12 hours for the 100, 200, and 300 mile points, respectively. Using Fig. 9.26, the total exposure doses for the first week are found to be about $1{,}350\times2=2{,}700$ r, $300\times1.50=405$ r, and $120\times1.2=144$ r, respectively.

From Fig. 9.85, the radius of the 1 r/hr contour for a 10-MT, 50-percent fission, burst is seen to be 21 miles. Because of the 25-mph wind, the downwind displacement of the center of the contours is $0.4\times25=10$ miles. Hence, the upwind extent of the 1 r/hr unit-time reference dose rate is $21-10=11$ miles.

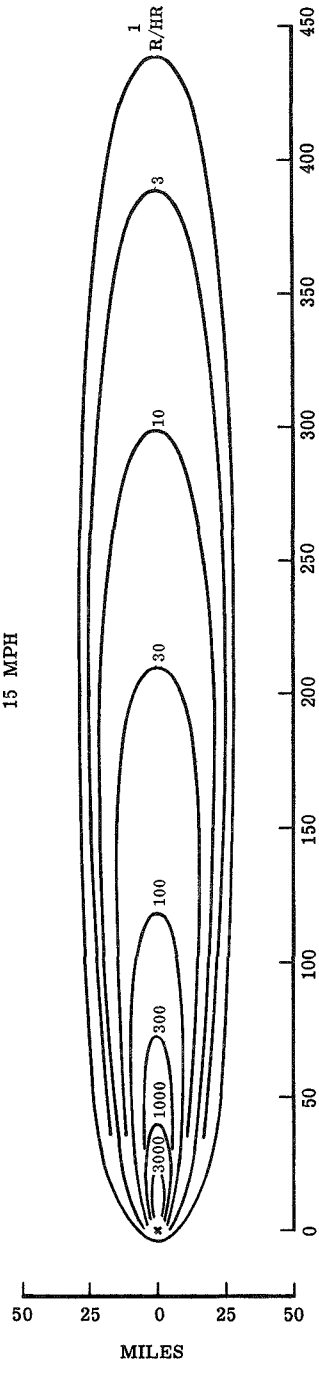

Figure 9.73. Idealized unit-time reference dose-rate pattern for early fallout from a 1-megaton fission yield surface burst (15 mph effective wind speed).

Table 9.73

DOWNWIND EXTENT OF UNIT-TIME REFERENCE DOSE-RATE CONTOURS FOR 1-MEGATON FISSION SURFACE BURST WITH 15 MPH WIND

Reference dose rate (roentgens/hour)	*Downwind distance (statute miles)*	*Maximum width (statute miles)*
3, 000	23	6
1, 000	42	10
300	74	12
100	120	18
30	210	30
10	300	42
3	390	50
1	440	56
0. 3	500	60
0. 1	530	62

Scaling

9.75 In order to obtain the idealized fallout pattern for a fission yield of F megatons, the values of the various contour lines in Fig. 9.73 may be multiplied by F. Thus, for a weapon having a total yield of M megatons with 50 percent of the energy derived from fission the factor would be 0.5 M. This scaling procedure, although highly simplified, gives reasonably good results for surface bursts from about 100 kilotons to 10 megatons fission yield. However, the higher values of dose rate (and dose) are probably overestimated for fission yields in excess of 1 megaton. Except for isolated points in the immediate vicinity of ground zero, observations indicate that unit-time reference dose rates greater than about 10,000 roentgens per hour are unlikely. A possible reason is that as the weapon yield increases so also does the initial volume of the radioactive cloud; hence, the maximum concentration of activity in the cloud does not change very much with the yield. The fallout contamination moderately near ground zero, where the dose rate is high, will thus not increase in proportion to the yield, as the simple scaling law given here implies. At greater distances downwind the law is much more reliable because, as a result of spreading by the wind, the initial cloud volume has relatively little influence on the concentration of fallout on the ground.

9.76 It should be noted that the proportional scaling procedure makes no allowance for the effect of the total, i.e., fission plus fusion, yield; thus it predicts the same fallout pattern for a 1-megaton all-

fission detonation as for a 2-megaton 50-percent fission explosion. Actually, the unit-time reference dose rate near ground zero might be somewhat smaller in the latter case because the same amount of radioactivity would be spread through a larger volume of the initial cloud. At greater distances downwind from the burst point the effect of the initial cloud concentration is small, as indicated above. Furthermore, at such locations the dilution effect may be compensated by the fact that the cloud from the 2-megaton explosion will probably rise higher, thus increasing the distances at which particles from the same relative position in the cloud will reach the ground.

9.77 As stated in § 9.65, the effective wind speed and direction are the mean values from the ground up to a certain level in the radioactive cloud, depending on the total yield of the explosion. As a very rough approximation, the atmospheric layers over which the wind is to be averaged as a function of the weapon yield, are as follows:

Total yield	*Layer*
Less than 1 MT	Surface to 40,000 feet.
1 MT to 5 MT	Surface to 60,000 feet.
More than 5 MT	Surface to 80,000 feet.

These values should be adequate for the rough evaluation of hypothetical fallout situations based on the idealized patterns. More elaborate prediction schemes take into consideration the winds at different levels instead of a single average effective wind.

9.78 If there is no directional wind shear, then doubling the wind speed would cause the particles of a given size to reach the ground at twice the distance from ground zero, so that they are spread over roughly twice the area. Based on this conclusion, the following scaling laws may be used in connection with the idealized fallout pattern: (*a*) the unit-time reference dose-rate value for each contour in the 15-mile-per-hour wind velocity pattern in Fig. 9.73 is multiplied by $15/v$, where v is the actual effective wind velocity in miles per hour and (*b*) the downwind distances in Fig. 9.73 are multiplied by $v/15$. For a 30-mile-per-hour wind, for example, the contour values would be halved and the distances doubled.

9.79 It will be apparent that in scaling for either yield or wind speed the values of the dose-rate contours are changed. The scaled downwind extent for any given contour value may readily be obtained by plotting the scaled dose rates versus the scaled downwind distances on logarithmic graph paper and reading downwind distances corresponding to the desired contour value from the resulting smooth curve.

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9.80 Both the idealized 15-mile-per-hour pattern in Fig. 9.73 and the wind scaling procedure tend to maximize the downwind extent of the dose-rate contours since they involve the postulate that there is very little (or no) wind shear. This is not an unreasonable assumption for the continental United States, since the wind shear is generally small at altitudes of interest from the standpoint of fallout. If there is considerable wind shear, e.g., 20° or more in the lower half of the mushroom head, the fallout pattern would be wider and shorter than that based on Fig. 9.73. The actual unit-time reference dose rate at a specified downwind distance from ground zero for a given effective wind speed would then be smaller than predicted. The crosswind values at certain distances might, however, be increased.

9.81 It may be noted that the method for wind scaling described in § 9.78 may be approximated by another procedure; the reference dose-rate contour values are left unchanged but the distances in Fig. 9.73 are multiplied by $(v/15)^{1/2}$. If considerable wind shear exists, a better approximation may be obtained by using the factor $(v/15)^{1/3}$. The results of this approximation are not reliable for dose rates greater than about 1,000 roentgens per hour for reasons similar to those given in § 9.75.

9.82 In order to emphasize the limitations of the idealized fallout patterns, Figs. 9.82 a and b are presented here. Figure 9.82a shows the idealized unit-time reference dose-rate contours for an 8-megaton, 50-percent fission surface burst and an effective wind speed of 40 miles per hour. Near ground zero the wind is from the southwest but the mean wind gradually changes to a westerly and then a northwesterly direction over a distance of a few hundred miles. In Fig. 9.82b an attempt is made to indicate what the actual situation might be like as a result of variations in local meteorological and surface conditions. The total contamination of the area is the same in both cases, but the details of the distribution, e.g., the occurrence of hot spots, which are shown shaded in Fig. 9.82b, is quite different. The pattern in Fig. 9.82b is hypothetical and not based on actual observations; its purpose is to call attention to the defects of the idealized fallout pattern. But since the factors causing deviations from the ideal vary from place to place and even from day to day, it is impossible to know them in advance. Consequently, the best that can be done here is to give an idealized pattern and show how it may be used to provide an overall picture of the contamination while, at the same time, indicating that in an actual situation there may be marked differences in the details of the distribution.

Upwind Fallout from Megaton-Range Explosions

9.83 A technique for predicting the ideal fallout contours in the upwind and crosswind directions has been developed from data obtained in connection with tests of devices in the megaton-energy range at the Eniwetok Proving Grounds. The treatment is based on the

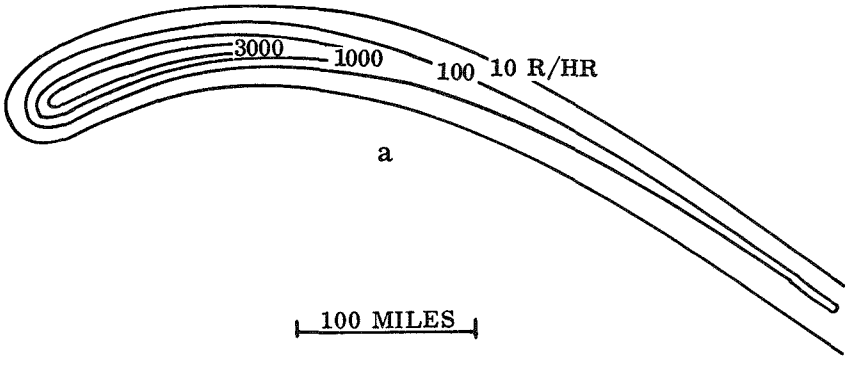

Figure 9.82a. Idealized unit-time reference dose-rate contours for an 8-megaton, 50-percent fission, surface burst (40 mph effective wind speed).

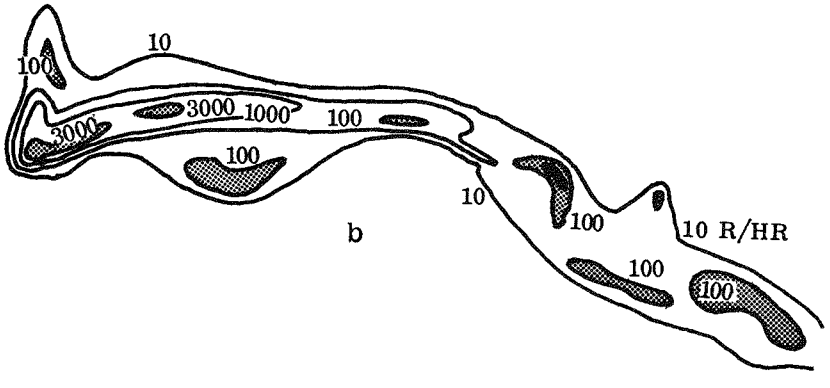

Figure 9.82b. Corresponding actual dose-rate contours (hypothetical).

expectation that the upwind extent of fallout will depend primarily on three factors: the maximum upwind extent of the radioactive cloud, the minimum time required for particles from the upwind edge of the cloud to reach the ground, and the mean effective wind from the ground to the altitude of the broadest part of the cloud.

9.84 Observations at Eniwetok have indicated that, for megaton-range detonations, the broad base of the cloud is generally stabilized

at almost the altitude of the tropopause, which is about 55,000 feet in the test area. The mean arrival time on the ground for upwind fallout was found to be about 30 minutes (0.5 hour). In the continental United States, the height of the tropopause is less and the estimated time of arrival is roughly 24 minutes (0.4 hour). Hence, while falling, particles from the upwind edge of the cloud would be carried downwind, i.e., back toward ground zero, a distance (in miles) equal to 0.5 times the mean effective wind speed (in miles per hour) at the Eniwetok Proving Grounds or 0.4 times the wind speed in the United States. The same reasoning may be applied to specific dose-rate contours. It may be assumed that if there were no wind, all the contours would be circles centered at ground zero. The radius of each contour would be determined only by the total yield and the fission percentage. Presumably, the radius of a contour would not be appreciably affected by the wind, but the center of the circles would be displaced in the downwind direction by the same distance the particles are carried downwind from the edge of the cloud.

9.85 From the available data on upwind and crosswind fallout in tests made at Eniwetok, contours for unit-time reference dose rates of 1, 10, and 100 roentgens/hour have been derived. These have been adjusted to zero wind speed and the radii of the corresponding circles are shown in Fig. 9.85 as a function of the total yield of the surface burst, assuming 50 percent fission. If the fission percentage is different from this value, then the indicated dose rates in Fig. 9.85 should be multiplied by the ratio ot the actual fission percentage to 50 percent. The figure also gives the radius for a peak blast overpressure of 7 pounds per square inch, representing the area of almost total destruction, and the dimensions of the visible cloud at 10 minutes after the explosion, this being the average time at which the cloud becomes stabilized (§ 2.15).

9.86 To convert these results into the idealized contours for an actual situation, it is necessary to know the effective wind speed and direction. In view of the uncertainty of the height of the cloud base, it is recommended that the speeds for altitudes of both 40,000 and 60,000 feet be considered and the smaller one be taken for the present purpose. The wind direction, however, would be that for 40,000 feet.[4] Multiplication of the mean wind speed by 0.4 would then give the displacement from ground zero of the centers of the circular contours in the downwind direction in the United States.

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[4] Mean wind speeds and expected direction of fall of particles, for various elevations, can be obtained from the "UF" (Upper-air Fallout) wind data reported regularly by the U.S. Weather Bureau.

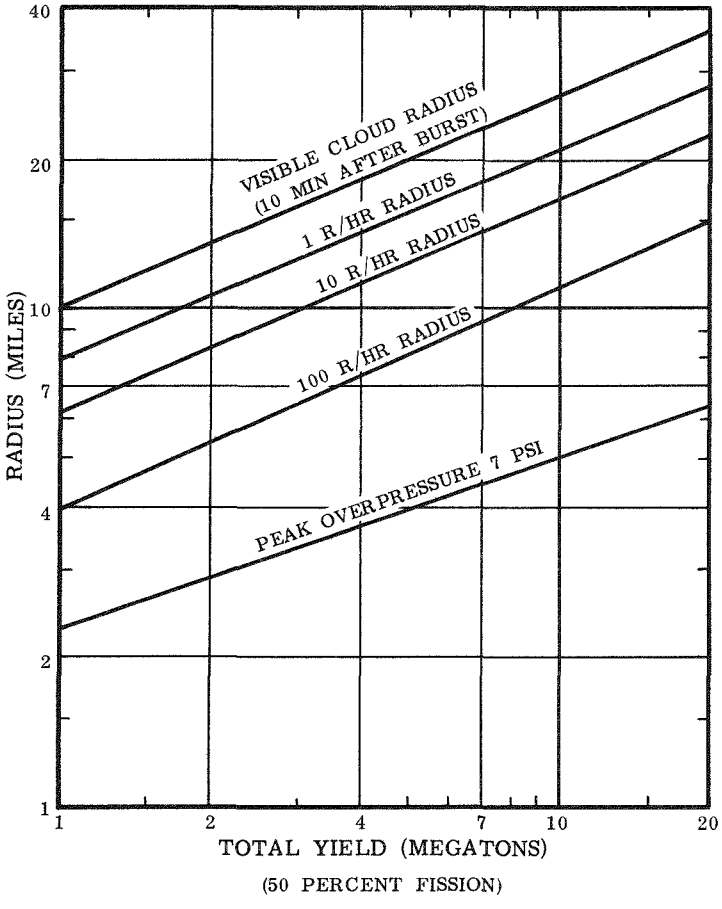

Figure 9.85. Radii for unit-time dose rates from early fallout, stabilized cloud, and 7-psi overpressure as function of total yield (50 percent fission) for surface bursts.

9.87 For purposes of illustration, consider a 10-megaton surface burst, with a 50-percent fission yield. Suppose that the mean wind from the surface to 40,000 feet is 25 miles per hour and its (downwind) direction is 30° east of north, and that the mean wind speed to 60,000 feet is 20 miles per hour. Hence, the effective wind to be used in constructing the upwind pattern is 20 miles per hour, but the direction is to be taken at 30° east of north. The displacement of the center of the contour circles is thus $0.4 \times 20 = 8$ miles, in the downwind direction.

From Fig. 9.85, the radii of the unit-time reference dose-rate contours for a 10-megaton burst are as follows:

1 roentgen/hour: 21 miles
10 roentgens/hour: 16.5 miles
100 roentgens/hour: 11 miles

Semicircles are now drawn having these radii with the point 8 miles downwind from ground zero as the center to give the actual upwind and crosswind contours, as shown in Fig. 9.87. Any contour, e.g., the one for 100 roentgens/hour, passing through the circle of severe blast damage (7 pounds per square inch overpressure), which has a radius of about 5 miles in the present case, may be regarded as uncertain. The area within the blast damage circle may be expected to be heavily contaminated by induced activity, stem fallout, and throwout, regardless of the wind speed.

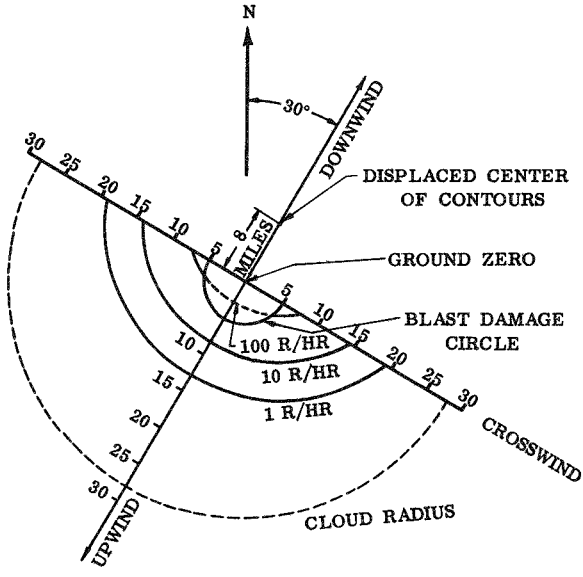

Figure 9.87. Illustration of calculation of upwind early fallout pattern.

9.88 The procedure described above is based on a number of assumptions, as are essentially all methods of fallout prediction. Nevertheless, it is felt that its shortcomings are outweighed by its simplicity and the fact that it can be used to provide a rapid, if approximate, estimate of the fallout contamination pattern in the upwind semicircle about ground zero.

Kiloton-Range Explosions

9.89 The basic fallout phenomena associated with a surface burst in the kiloton-energy range are essentially the same as for detonations of higher yield. The proportionately smaller quantity of fission products will, of course, mean that smaller areas are contaminated to a serious extent. Furthermore, the lower cloud height will result in fallout coming to earth sooner and at closer distances to the burst point. However, the peak dose rate at ground zero and for a short distance downwind may well be of the same order of magnitude as for explosions in the megaton range.

9.90 Representative dose-rate contour dimensions for a 20-kiloton surface burst, with a mean wind velocity of 15 miles per hour, and little wind shear, are recorded in Table 9.90. The downwind extent of a given contour may be scaled for yields from about 1 to 100 kilotons and for any effective wind speed in the same manner as described above for 1-megaton fission yield contours. However, the prediction method for upwind fallout from megaton-range detonations is not applicable to the kiloton-energy range. The upwind fallout associated with these lower yields will be much less extensive because of the smaller cloud radius, e.g., 3 miles or less. Dose rates in the region around ground zero will still be very high because of induced activity, stem fallout, throwout from the crater, and the fallout of larger particles from the cloud.

Table 9.90

DOWNWIND EXTENT OF UNIT-TIME REFERENCE DOSE-RATE CONTOURS FOR 20-KILOTON SURFACE BURST WITH 15 MPH WIND

Reference dose rate (roentgens/hour)	*Downwind distance (statute miles)*	*Maximum width (statute miles)*
3, 000	1	<0.5
1, 000	3	<1.0
300	7	1
100	14	2
30	32	4
10	60	6
3	100	11
1	150	16

9.91 On the average, fallout patterns from kiloton-range detonations will be more affected by wind shear than for megaton explosions because the particles spend a larger fraction of their fall times in the turbulent lower atmosphere. The effect of wind shear will be to reduce the areas enclosed by the high dose-rate contours, making

them shorter and wider. In addition, very large areas may be covered by contamination of a low order.

Uncertainties in Fallout Predictions

9.92 Although the procedures described above for developing idealized fallout patterns under various conditions are probably as good as can be expected, it must be emphasized that they are intended only for overall planning. There are several factors which will affect the details of the distribution of the early fallout and also the rate of decrease of the radioactivity. Near ground zero, activity induced by neutrons in the soil will be significant, apart from that due to the fallout. However, the extent of the induced activity is difficult to estimate, since it will depend on the type of weapon, e.g., the actual amounts of fission and fusion energy, the height of burst, and the nature of the soil. The existence of unpredictable hot spots will also affect the local radiation intensity. These are dependent upon a variety of conditions not all of which are fully understood. There is a possibility that the formation of a hot spot some distance downwind from ground zero is characteristic of high-yield explosions (§ 9.59). The nature of the terrain may also influence the dose rate at a given location as a result of incidential shielding. The data in Fig. 9.73 are applicable to moderately flat, uninhabited areas, such as those in which weapons tests are carried out. In a city, buildings, trees etc., might well reduce the average radiation intensity above the ground to 70 or 75 percent of this open-terrain value.

9.93 The rate of decay of the early fallout radioactivity, and hence the total dose accumulated over a period of time, will be affected by weathering. Wind may transfer the fallout from one location to another, thus causing local variations. Rain, on the other hand, may wash the fallout into the soil and this will tend to decrease the dose rate at a level a few feet above the ground. The extent of this decrease will, of course, depend on the climatic and surface conditions, but it has been estimated that, in temperate regions, the weathering effect will probably be negligible during the first month after the explosion, but that over a period of years the fallout dose rate would decrease to about half that which would otherwise be expected. If rain should occur at the time of the detonation, the fallout pattern might be changed considerably, as will be seen in § 9.95 *et seq.*

9.94 In attempting to predict the time that must elapse, after a nuclear explosion, for the radiation dose rate to decrease to a level that will permit reentry of a city or the resumption of agricultural

operations, use may be made of the (continuous) decay curves in Figs. 9.16a and b or of equivalent data. However, it is inadvisable to depend entirely on these estimates because of the uncertainties mentioned above. Moreover, even if the decay curve could be relied upon completely, which is by no means certain, the actual composition of the fallout is known to vary with distance from ground zero (§ 9.08) and the decay rate will vary accordingly. At 3 months after a nuclear explosion, the radiation intensity will have fallen to about 0.01 percent, i.e., one ten-thousandth part, of its value at 1 hour, so that almost any contaminated area will be safe enough to enter for the purposes of taking a measurement with a dose-rate meter, provided there has been no additional contamination in the interim.

Rainout of Radioactive Debris

9.95 If the airborne debris from a nuclear explosion should encounter a region where precipitation is occuring, a large proportion of the radioactive particles may be brought to earth with the rain. It should be noted, however, that the tops of rain-bearing clouds are generally below the 20,000-foot level, whereas the bulk of the radioactivity for detonations in excess of about 5-kilotons energy yield very soon attains a greater altitude. Hence, early fallout particles from a high-yield surface burst will spend only a fraction of their fallout time in the rain layer and the total amount of early fallout should not be significantly affected by the precipitation. The distribution of the fallout will probably be more irregular than in the absence of rain, with heavy showers producing local hot spots scattered within the contaminated area. Fallout from the cloud stem in an explosion of high yield should not be greatly influenced by precipitation since the particles in the stem will fall to earth in a relatively short time, regardless of whether there is precipitation or not.

9.96 In the surface detonation of a low-yield nuclear weapon in a rainy situation, the whole of the radioactive cloud might be within the rain layer. This would probably result in deposition on the ground of very nearly 100 percent of the fission product activity within a few hours after the explosion. The fallout (or rainout) pattern might cover a smaller area and the peak dose rates would be higher than in the absence of rain, but the difference would probably be less than an order of magnitude.

9.97 The fallout situation following an air burst of low total yield would be greatly altered by precipitation. If there were no precipitation, then this type of burst would produce virtually no local fallout.

Detonation in heavy rain, however, could result in almost as much early fallout (or rainout) as for a surface burst of the same fission yield.

9.98 In a high-yield air burst, essentially all the radioactive debris would generally be carried above the rain-bearing layer and there would be little or no early fallout. An important exception could arise if the airborne debris were to encounter thunderstorms, since precipitation may then originate as high as 60,000 feet. Should such an encounter take place within a few hours after the burst, localized hot spots of very high intensity might develop due to rainout. Although radioactive decay, wind shear, and diffusion all tend to reduce the concentration of activity in the cloud, thunderstorm scavenging of the weapon residues could still conceivably produce serious contamination of the ground many hours after detonation and hundreds of miles downwind from the point at which the air burst occurred.

9.99 It must be admitted that much of what has been stated above concerning the possible effects of rain on fallout from both surface and air bursts is based largely on theoretical considerations. Nuclear test operations have been conducted in such a manner as to avoid the danger of rainout. The few recorded cases of rainout which have occurred have involved very low levels of contamination and the possibility of severe contamination under suitable conditions has not been verified.

The High-Yield Explosion of March 1, 1954

9.100 The foregoing discussion of the distribution of the early fallout may be supplemented by a description of the observations made of the contamination of the Marshall Islands area following the high-yield test explosion (BRAVO) at Bikini Atoll on March 1, 1954.[5] The total yield of this explosion was approximately 15-megatons TNT equivalent. The device was detonated on a coral reef and the resulting fallout, consisting of radioactive particles ranging from about one-thousandth to one-fiftieth of an inch in diameter, contaminated an elongated area extending over 330 (statute) miles downwind and varying in width to over 60 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 avoidance of death or radiation

[5] "The Effects of High-Yield Nuclear Explosions." A report by the U.S. Atomic Energy Commission, Government Printing Office, February 1955.

injury would have depended upon evacuation of the area or taking protective measures.

9.101 The BRAVO shot is of particular interest because the predicted fallout patterns for megaton-range explosions, such as those given in §9.67 and §9.73, are largely based on inferences drawn from measurements made after this detonation. The available data, for the estimated total doses received at various locations at 96 hours after the explosion, are shown by the points in Fig. 9.101. Through these points there have been drawn a series of contour lines which appear to be in reasonably good agreement with the data. However, other patterns are possible; one, for example, ascribes the large radiation doses on the northern islands of Rongelap Atoll to a hot spot and brings the 3,000-roentgen contour line in much closer to Bikini Atoll. Because of the absence of observations from large areas of ocean, the choice of the fallout pattern, such as the one in Fig. 9.101, is largely a matter of guesswork. Nevertheless, one fact is certain: there was appreciable radioactive contamination at distances downwind of 300 miles or more from the explosion.

9.102 It should be noted that the doses to which the contours in Fig. 9.101 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 period longer than 96 hours after the explosion would have received larger doses of the residual radiation.

9.103 A radiation dose of 700 roentgens spread over a period of 96 hours would probably prove fatal in the great majority of 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 170 miles long and up to 35 miles wide to have seriously threatened the lives of nearly all persons who remained in the area for at least 96 hours following the detonation without taking protective measures of any kind. At distances of 300 miles or more downwind, the number of deaths due to short-term radiation effects would have been negligible, although there would probably have been many cases of sickness resulting in temporary incapacity.

9.104 The period of 96 hours after the explosion, for which Fig. 9.101 gives the accumulated radiation exposures, was chosen somewhat arbitrarily. It should be understood, however, as has been frequently stated earlier in this chapter, that the radiations from the

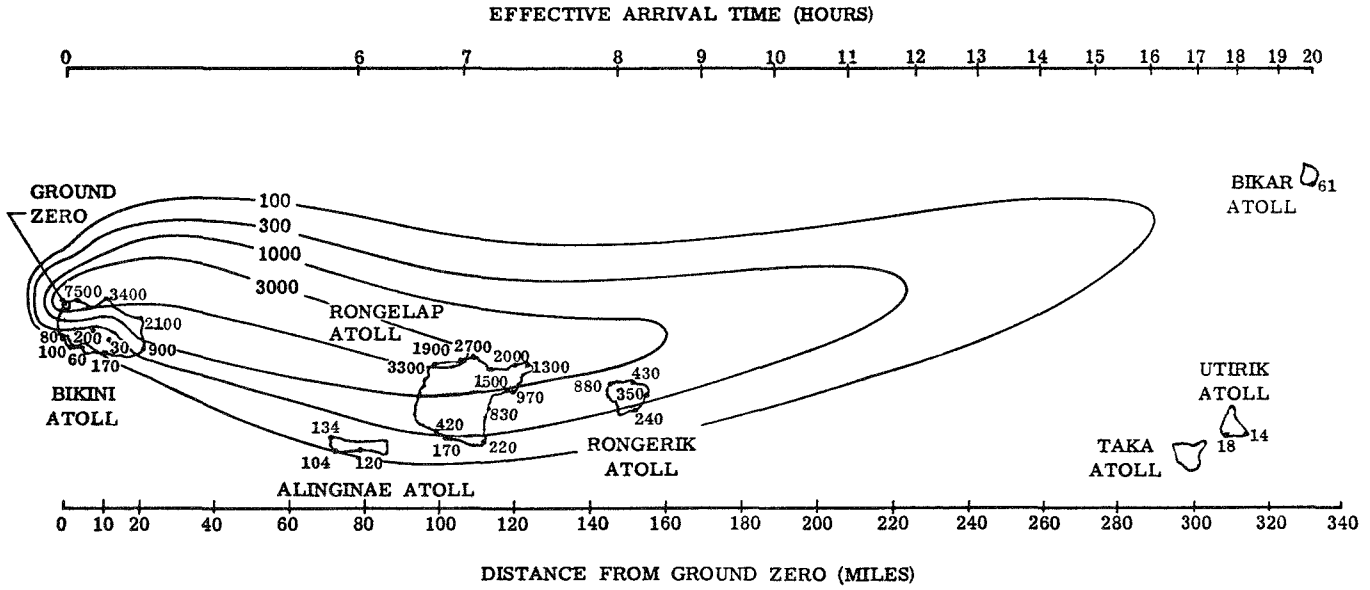

Figure 9.101. Estimated total-dose contours in roentgens at 96 hours after the BRAVO test explosion.

fallout will continue to be emitted for a long time, although at a gradually decreasing rate. The persistence of the external gamma radiation may be illustrated in connection with the BRAVO test by considering the situation at two different locations in Rongelap Atoll. Fallout began about 4 to 6 hours after the explosion and continued for several hours.

9.105 The northwestern tip of the atoll, 100 miles from the point of detonation, received 3,300 roentgens during the first 96 hours after the fallout started. This was the heaviest fallout recorded at the same distance from the explosion and may possibly have represented a hot spot, as mentioned above. About 25 miles south, and 115 miles from ground zero, the dose over the same period was only 220 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 § 11.126). The maximum theoretical exposures in these two areas of the atoll for various time intervals after the explosion, calculated from the decay curves given earlier in this chapter, are recorded in Table 9.105.

TABLE 9.105

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 96 hours	220	3, 300
96 hours to 1 week	35	530
1 week to 1 month	75	1, 080
1 month to 1 year	75	1, 100
Total to 1 year	405	6, 010
1 year to infinity	About 8	About 115

9.106 It must be emphasized that the calculated values in Table 9.105 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. Furthermore, no allowance is made for weathering 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 of the expected values. Rains were known to have occurred during the second week, and these were probably responsible for the major decrease in the contamination.

9.107 In concluding the present discussion of fallout contamination, it may be noted that the 96-hour dose contours shown in Fig. 9.101, representing the fallout pattern in the vicinity of Bikini Atoll after the high-yield explosion of March 1, 1954, as well as the unit-time reference dose-rate contours in Fig. 9.73, 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.

9.108 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 and 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.

9.109 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.

RADIOACTIVE CONTAMINATION FROM NUCLEAR EXPLOSIONS

Radiological Warfare

9.110 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.

9.111 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.

9.112 The situation has undergone a change with the development of weapons having high fission energy yields. The explosion of such devices 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 fission yield.

Contamination of Areas

9.113 It was suggested in § 9.110 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 fallout, assuming no protection, have been

given earlier in this chapter. 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 will vary, depending on the radiation history of the individual and the degree of hazard that he is willing to risk incurring under the existing conditions.

9.114 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 absorption of radioisotopes 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. Some aspects of this subject are considered further in § 11.174 *et seq.*

Contamination in Subsurface Bursts

9.115 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 weapon 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 fireball actually breaks through, the consequences, as regards fallout, will not be very greatly different from those following a surface burst.

9.116 There will, in fact, be a gradual transition in behavior from a high air burst, at one extreme, where all the radioactive residues are dissipated in the atmosphere, to a deep subsurface burst, at the other exteme, 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 early fallout. These merge into shallow subsurface bursts, for which the behavior is similar. With increasing depth of explosion, more of the radioactive 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.

9.117 Since a shallow subsurface burst, in which the fireball emerges from the ground, is essentially similar to a 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 in-

terest, however, is that of a subsurface burst at such a depth that the fireball does not emerge, yet a considerable amount of dirt (or water) is thrown up as a column into the air.

9.118 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 (§ 9.35), 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.

9.119 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 (§ 2.89) will remain suspended in the air and will descend as a fallout at some distance from ground zero.

9.120 The early 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 early fallout.

Underwater Explosions

9.121 In a shallow underwater explosion, radioactive contamination will arise from the visible and invisible base surge, which remains near the water surface, and from the radioactive, airborne cloud, which is produced by condensation of the vented weapon residues (Chapter II). The radioactive cloud does not ascend as high as it would for a surface (or low air) burst of the same yield and so a large proportion of the fission product activity rains out in a short time within a radius of a few thousand yards of surface zero. In the Bikini BAKER test (§ 2.61), the contaminated fallout (or rainout) consisted of both solid particles and of a slurry of salt crystals in drops of water. This contamination was difficult to dislodge and had there been personnel on board the ships used in the test, they would have been subjected to considerable doses of radiation if the fallout were not removed immediately.[6] Since the BAKER

[6] The technique of washdown of ships, by continuous flow of water over exposed surfaces to remove fallout as it settles, was developed as a result of the Bikini BAKER observations.

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shot was fired in shallow water, the bottom material may have helped in the scavenging of the radioactive cloud, thus adding to the contamination. It is expected that for shallow bursts in very deep water the fallout from the cloud will be less than observed at the test in Bikini lagoon, and in some cases there may be no cloud at all.

9.122 The base surge, both visible and invisible, created by the water from the plume as it falls back on the surface, will carry radioactive particles outward rapidly, enveloping nearby ships and land stations. The dose rate of the "transient" radiation, i.e., radiation from a source which is moving past a given location, from the base surge can be very high, e.g., of the order of 100,000 roentgens per hour, at early times. However, the radiation intensity declines rapidly as the concentration of the activity decreases as a result of radial expansion of the base surge ring and decay of the fission products. The total radiation dose delivered at a given distance from surface zero will depend on the direction and velocity of the wind which carries the base surge with it; for ships close to the explosion, the dose can be lethal.

9.123 The relative contributions of the base surge and the fallout (and rainout) from the cloud will depend upon the distance from surface zero, the depth of burst, and the environment. It is possible that shots at slightly greater depths than Bikini BAKER may produce no radioactive cloud and then all the contamination will come from the base surge. The nearness of the bottom may have an important bearing upon whether a detonation at a certain depth will create an airborne cloud or not. Furthermore, atmospheric conditions may also affect the rainout. For these reasons, the BAKER shot may not necessarily be entirely typical of a shallow underwater burst.

9.124 For a deep underwater shot there will generally be no airborne cloud (§ 2.82) and consequently no fallout and rainout. The radiation hazard will then arise only from the base surge, the characteristics of which are similar to those for a shallow underwater detonation. Whether the base surge from a deeper shot will be more or less radioactive than from one at a shallower depth, will depend on the scavenging action of the water on the fission debris in the interior of the underwater steam bubble created by the explosion. If all the debris is injected into the base surge, it will be considerably more radioactive than from a shallow shot, when much of the fission product residues goes into the airborne cloud. On the other hand, if the detonation takes place at a sufficiently great depth, it is possible that most of the fission debris will remain in the water and little will go into the base surge. In any event, the exact behavior of the fission products is

believed to depend to a great extent on the precise condition of the bubble of gas and steam as it vents at the surface (§ 2.84).

9.125 There will always be some gaseous products of the fission process that are more or less insoluble in water. These radioactive gases may jet out of the plume and drift skyward, for shots fired at a moderate depth. Hence, even in the absence of a regular cloud, they will constitute a radioactive hazard in addition to the base surge.

9.126 The phenomena associated with nuclear explosions on the surface of the water will probably be similar to those at shallow depth; however, the probability of creating a base surge has not been established. The fallout and rainout from the cloud will also be subject to many variations dependent upon atmospheric conditions.

9.127 Most of the radioactivity remaining in the water and on the bottom after an underwater or water surface burst will be found initially in the vicinity of the shot. For detonations occurring in deep water, activity will be left behind at layers where the hot gas and steam bubble was in a contraction phase during the course of its rise through the water (§ 2.84). Fallback from the plume and venting of the bubble will leave considerable amounts of contamination on the surface near the burst point. This will rapidly diffuse downward and outward, thus reducing the activity level to safe limits for ships' personnel within 15 minutes to an hour.

9.128 An indication of the rate of spread of the active material and the decrease in the dose rate following a shallow underwater burst is provided by the data in Table 9.128, obtained after the Bikini BAKER test. Although the dose rate in the water was still fairly high after 4 hours, there would be considerable attenuation in the interior of a ship, so that during the time required to cross the contaminated area the total dose received would be small. Within 2 or 3 days after the BAKER test the radioactivity had spread over an area of about 50 square miles, but the radiation dose rate in the water was so low that the region could be traversed in safety.

9.129 The radioactivity falling back on the sea from the high airborne cloud will extend downwind much farther than the base surge or that transported by the water. However, it will be much less significant than other sources of contamination, the level of activity seldom being such as to prohibit operation of modern ships. The fallout debris quickly mixes with the water and since the water absorbs (or attenuates) the radiation to a considerable extent, the hazard is much less than would result from the same fallout on land. The radioactive water will gradually be transported to other locations by the prevailing currents, and if these are known, the path of the contaminated water can be predicted.

TABLE 9.128

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

ATTENUATION OF RESIDUAL NUCLEAR RADIATION

ALPHA AND BETA PARTICLES

9.130 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.[7] 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 only just over 1½ inches in air. In more dense media, such as water or body tissue, the range is 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.

9.131 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.

9.132 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

[7] An alpha particle is identical with a nucleus of the element helium (§ 1.62). When it has lost most of its (kinetic) energy, it captures two electrons and becomes a harmless (neutral) helium atom.

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. Only beta radiation from material ingested or in contact with the skin poses a hazard (§ 11.148).

Gamma Radiation

9.133 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. Shielding will be required in most fallout situations to reduce the radiation dose to an acceptable level. Incidentally, any method used to decrease the gamma radiation will also result in a much greater attenuation of both alpha and beta particles.

9.134 The absorption of the residual gamma radiation from fission products and from radioisotopes produced by neutron capture, e.g., in sodium, manganese, and in the weapon residues, is based upon exactly the same principles as were described in Chapter VIII in connection with the initial gamma radiation. Except for the earliest stages of decay, however, the gamma rays from fallout have much less energy, on the average, than do those emitted in the first minute after a nuclear explosion. This means that the residual gamma rays are more easily attenuated; in other words, compared with the initial gamma radiation, a smaller thickness of a given material will produce the same degree of attenuation.

9.135 Calculation of the attenuation of the gamma radiation from fallout is different and in some ways more complicated than for the initial radiations. The latter emanate from the explosion point, but the residual radiations arise from contamination which is widely distributed on the ground, on roofs, trees, etc. The complication stems from the fact that the effectiveness of a given thickness of material is influenced by the fallout distribution (or geometry) and hence depends on the degree of contamination and its location relative to the position where protection is desired. Estimates of the attenuation of residual radiation in typical residential structures have been made, based partly on calculations and partly on measurements with simulated fallout.

9.136 Some of the results obtained for various locations are given in Table 9.136 for one- and two-story, brick-veneer and wood-frame

houses, respectively. The "protection factor" is the ratio of the dose which would be received outdoors, without any protection, to that received at the indicated location in the structure. It should be emphasized that, while the values in the table are considered to be fairly representative, they must not be regarded as being exact. Deviations are to be expected because of differences in constructional details and environment, e.g., effect of nearby buildings.

TABLE 9.136

PROTECTION FACTORS AT VARIOUS LOCATIONS IN TYPICAL RESIDENTIAL STRUCTURES

First floor area (*sq ft*)	Type of structure			
	One-story brick veneer		One-story frame	
	Location			
	Center of ground floor	Center of basement	Center of ground floor	Center of basement
1,000	3.4	22	2.3	20
1,200	3.1	18	2.2	17
1,500	3.1	16	2.3	15
2,000	3.0	14	2.2	13

First floor area (*sq ft*)	Type of structure			
	Two-story brick veneer		Two-story frame	
	Location			
	Center of ground floor	Center of basement	Center of ground floor	Center of basement
1,000	4.4	54	2.3	44
1,200	4.4	41	2.4	37
1,500	4.4	37	2.4	34
2,000	4.1	34	2.4	29

9.137 The data in the table show that the heavier type of construction (brick veneer) provides better protection than a frame dwelling. It will be noted, too, that the protection factors in the middle of the ground floor of a wood-frame house are approximately the same for one- and two-story structures, but are appreciably different for brick-veneer houses. The reason is that in the latter case

the fallout on the roof contributes a larger fraction of the overall dose than for the lighter walled construction. Consequently, reducing the radiation from the roof by increasing the separation distance, in the two-story house, produces a greater change in the dose (and protection factor) in the case of the brick-veneer house. In each type of dwelling the protection factor expected at the center of the ground floor does not change very much as the floor area is increased. This is because there is a compensation between the increase in dose received from fallout on the roof and the decrease due to the greater distance from the outside.

9.138 The advantages of a basement location in providing protection against fallout radiation in any type of house are obvious from Table 9.136. The values given apply only if no part of the basement wall is exposed; in other words, it must be completely covered by earth and there must be no window openings. Under these circumstances, greater protection can be obtained near the exterior wall than in the center of the basement, because there is a decrease in the radiation from fallout on the roof. This is one reason why it is generally recommended that fallout shelters be constructed in the basement adjacent to an outer wall which is not exposed in any way (§12.55).

9.139 Typical protection factor ranges for a wide variety of structures of different types are summarized in Table 9.139. All the structures are assumed to be isolated, so that the effects, if any, of adjacent buildings have been neglected. From these values, rough estimates can be made of the shielding from fallout radiation that might be expected under various conditions.

9.140 It is of interest to mention that a simple one-man foxhole, 3 feet in diameter and 4 feet deep, can provide a protection factor of about 40 if fallout is present up to the edge, but not inside. If an area 3 or 4 feet wide around the foxhole is kept free of fallout material, a protection factor of 100 or more is possible.

DELAYED FALLOUT

Introduction

9.141 Before proceeding to a description of delayed fallout, a general comparison may be made between the two types of fallout. In addition to corresponding to different physical situations, with regard to space and time, the early and delayed fallout represent different biological hazards. The principal hazard from early fallout

TABLE 9.139

PROTECTION FACTOR RANGES FOR VARIOUS STRUCTURES

Type of structure	*Protection factor range*
Underground shelters (3 ft earth cover or equivalent). Sub-basements of multistory buildings.*	1,000 or greater
Basement fallout shelters (heavy masonry residences). Basements without exposed walls of multistory masonry buildings. Central areas of upper floors (excluding top 3 floors) of high-rise buildings † with heavy floors and exterior walls.	250 to 1,000
Basement fallout shelters (frame and brick veneer residences). Central areas of basements with partially exposed walls in multistory buildings. Central areas of upper floors (excluding top floor) of multistory buildings with heavy floors and exterior walls.	50 to 250
Basements without exposed walls of small 1- or 2-story buildings. Central areas of upper floors (excluding top floor) of multistory buildings with light floors and exterior walls.	10 to 50
Basements (partially exposed) of small 1- or 2-story buildings. Central areas on ground floor in 1- or 2-story buildings with heavy masonry walls.	2 to 10
Above ground areas of light residential structures.	2 or less

* Multistory buildings are those having from 3 to about 10 stories.
† High-rise buildings have more than about 10 stories.

arises from the possible exposure to gamma rays from sources outside the body, with the effect of beta particles from fallout material in direct contact with the skin as secondary. Because most of the radioisotopes in the early fallout have relatively short half-lives, the activity decays fairly rapidly and will have decreased by a factor of several thousand after 6 months (or less). The delayed fallout hazard, on the other hand, is due to radioactive material, particularly strontium-90, which is ingested as food. The strontium-90 accumulates in the bone and part may remain there for many years, representing a prolonged internal hazard. Both early and delayed fallout can have long-term genetic effects, but they are probably of less significance than other deleterious effects to be expected. These and related aspects of fallout are discussed more fully in Chapter XI.

9.142 The very fine particles present in the radioactive cloud, with radii of a few microns or less (§ 9.47), fall extremely slowly under the influence of gravity. Consequently, they remain suspended in the

atmosphere for a considerable time and may be carried over great distances as a result of the movements of the air. Ultimately, the radioactive particles are brought to the ground, primarily by the scavenging action of rainfall, and so produce the delayed fallout. Essentially all of the residual nuclear radiation from an air burst contributes to the delayed fallout, for in explosions of this type there is very little early (or local) fallout. For land surface bursts, about 40 percent of the residual activity appears as delayed fallout, whereas for surface bursts over water the proportion has been estimated to be about 70 percent (§ 9.48).

9.143 There are two respects, in particular, in which the delayed fallout is of special importance. First, many of the small contaminated particles will remain aloft for a long time—weeks, months, and sometimes years—so that the delayed fallout will be spread over large areas of the earth's surface. Second, although the radioisotopes of short life will have decayed almost completely before most of the delayed fallout reaches the ground (see, however, § 9.160, footnote), those having a long life will remain. Among these there are two, namely, strontium-90 (half-life 27.7 years) and cesium-137 (half-life 30.5 years), having great biological significance. Not only do these isotopes decay fairly slowly, but they both constitute relatively large fractions of the fission products; thus, for every 1,000 atoms undergoing fission there are eventually formed from 30 to 40 atoms of strontium-90 and from 50 to 60 of cesium-137. Moreover, both of these isotopes have gaseous precursors (or ancestors), so that, as a result of the process of fractionation (§ 9.08), their proportions in the delayed fallout will tend to be greater, at least for surface bursts, than in the fission products as a whole. Although the strontium and cesium in the delayed fallout make a negligible contribution to the external radiation dose, compared with that from the early fallout, their importance lies in the possibility that they may get into the body by way of food.

9.144 The ultimate distribution of the delayed fallout over the earth's surface is not affected by the particular wind conditions at the time of the detonation nearly as much as that of the early fallout. What is more important is the manner in which the contaminated particles enter the upper atmosphere. In order to understand the situation, it is necessary to review some of the characteristic features of the atmosphere.

Structure of the Atmosphere

9.145 One of the most significant aspects of the atmosphere is the variation in temperature at different altitudes and its dependence on latitude and time. In ascending into the lower atmosphere, from the surface of the earth, the temperature of the air falls steadily, in general, toward a minimum value. This region of falling temperature is called the "troposphere" and its top, where the temperature ceases to decrease, is known as the "tropopause." Above the troposphere is the "stratosphere," where the temperature remains more or less constant with increasing altitude in the temperate and polar zones. Although all the atmosphere immediately over the tropopause is commonly referred to as the stratosphere, there are areas in which the structure varies (Fig. 9.145). In the equatorial regions, the temperature in the stratosphere increases with height. This inversion also occurs at the higher altitudes in the temperate and polar regions. In the "mesosphere" the temperature falls off again with increasing height. At still higher altitudes is the "thermosphere" where the temperature rises rapidly with increasing height.

9.146 Most of the visible phenomena associated with weather occur in the troposphere. The high moisture content, the relatively high temperature at the earth's surface, and the convective movement (or instability) of the air arising from temperature differences promote the formation of clouds and rainfall. In the temperate latitudes, at about 45° in the summer and 30° in the winter, where the cold polar air meets the warm air of the tropics, there are formed meandering, wavelike bands of storm fronts called "polar fronts" (Fig. 9.145). In these regions, the average rainfall is high.

9.147 The tropopause, that is the top of the troposphere, is lower in the polar and temperate zones than in the tropics; its height in the former regions varies from 25,000 to 45,000 feet, depending on latitude, time of year, and particular conditions of the day. In general, the altitude is lowest in the polar regions. The tropopause may disappear entirely at times in the polar winter night. In the tropics, the tropopause usually occurs near 55,000 feet at all seasons. It is more sharply defined than in the temperate and polar regions because in the tropics the temperature increases with height above the tropopause instead of remaining constant. There is a marked gap or discontinuity in the tropopause in each temperate zone, as may be seen in Fig. 9.145, that constitutes a region of unusual turbulence. This gap moves north and south seasonally, following the sun, and is usually located near a polar front. It is believed that considerable

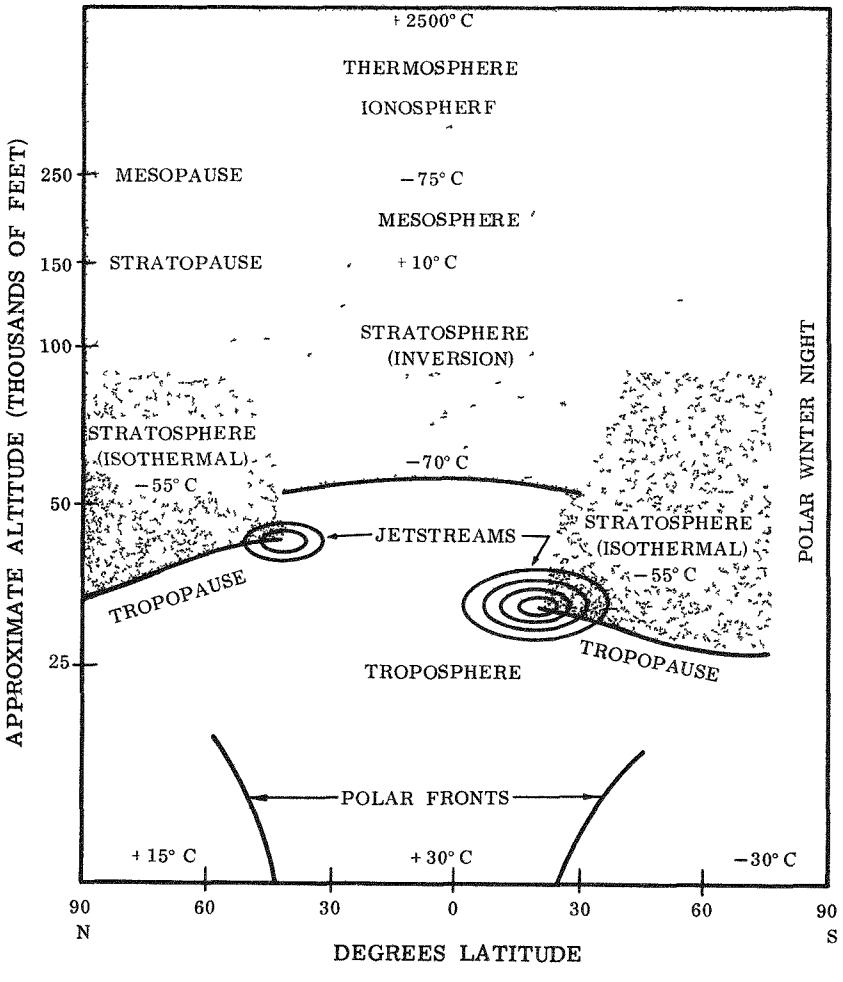

Figure 9 145 Structure of the atmosphere during July and August

interchange of air between the stratosphere and troposphere takes place at the gap A jet stream, forming a river of air moving with high speed and circulating about the earth, is located at the tropical edge of the polar tropopause in each hemisphere

9.148 Because of its temperature structure, there is very little convective motion in the stratosphere, and the air is exceptionally stable. This is especially noticeable in the tropics where the vertical movement of the radioactive cloud from a nuclear explosion has sometimes been less than 2 miles in three trips around the globe, i.e.,

approximately 70,000 miles. This stability continues up to the mesosphere where marked turbulence is again noted. The polar stratosphere is less stable than that in the tropics, particularly during the polar winter night when the stratospheric temperature structure changes to such an extent that the inversion may disappear. When this occurs there may be considerable convective mixing of the air to great heights.

Atmospheric Paths of Delayed Fallout: Tropospheric Fallout

9.149 The fallout pattern of the very small particles in the radioactive cloud which remain suspended in the atmosphere depends upon whether they were initially stabilized in the troposphere or in the stratosphere. The distribution of the radioactive material between the troposphere and the stratosphere depends mainly on the total energy yield of the explosion, the height of burst, the environment of the detonation, and the height of the tropopause. Additional complicating factors are scavenging by dirt or water and fractionation in surface bursts. Scavenging will tend to decrease the proportion of radioactive debris remaining in the cloud while increasing that in the early fallout, whereas fractionation will result in a relative increase in the amounts of strontium-90 and cesium-137 that remain suspended (§ 9.08). Consequently, it is difficult to predict the distribution between troposphere and stratosphere, but rough estimates have been made. Since strontium-90 is of particular interest in the delayed fallout, the calculated percentage of this isotope formed in a nuclear explosion that might enter the stratosphere under various conditions is shown in Fig. 9.149. The breadth of the bands is an indication of the uncertainty of the estimates.

9.150 In general, a larger proportion of strontium-90 will go into the stratosphere in an air burst than in a surface burst under the same conditions; for one thing, there is essentially no local or early fallout in the former case, and for another, surface material taken up into the cloud tends to depress the height attained in the latter case. In the temperate and polar regions, more strontium-90 enters the stratosphere from an air burst than for an equivalent burst in the tropics. The reason is that the tropopause is lower and the stratosphere is less stable in the non-tropic regions. For low-yield explosions, most of the radioactive material remains in the troposphere, with little entering the stratosphere. But since the altitude to which the cloud rises increases with the explosion energy yield, the proportion of strontium-90 passing into the stratosphere will increase correspondingly.

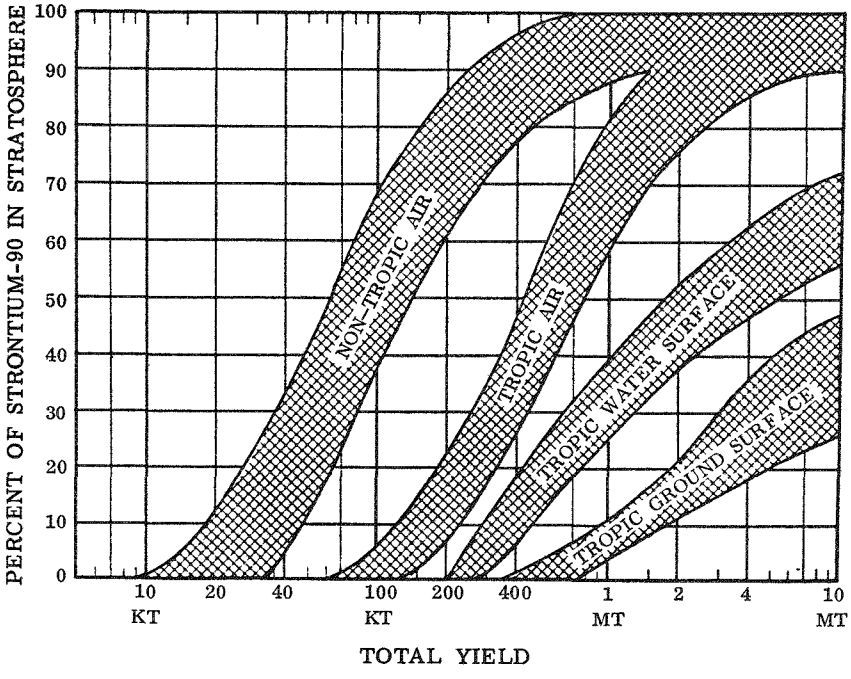

Figure 9.149. Theoretical percentage of strontium-90 injected into stratosphere as a function of total yield and burst conditions.

9.151 The small particles remaining in the troposphere descend to earth gradually over a period of time up to several months; this constitutes the "tropospheric fallout." The most important mechanism for causing this fallout appears to be the scavenging effect of rain and snow. The fine particles may be incorporated into the water droplets (or snow crystals) as they are formed and are thus brought down in the precipitation. Except for unusually dry or wet regions, the amount of delayed fallout deposited in adjacent areas is closely related to the amount of precipitation in those areas during the fallout period. Dry fallout has been recorded, but it probably represents a minor proportion of the tropospheric fallout in most instances.

9.152 The rate of removal of material from the troposphere at any time is roughly proportional to the amount still present at that time; consequently, the "half-residence time" concept is useful. It is defined as the period of time required at a given location for the removal of half the suspended material. If the cloud particles originally reached the upper part of the troposphere, the half-residence

time for tropospheric fallout is from 2 to 6 weeks. During the course of its residence in the atmosphere, the tropospheric debris is carried around the earth, by generally westerly winds, in perhaps a month's time. The bulk of the fallout on the average is then confined to a relatively narrow belt that spreads to a width of about 30° of latitude.

9.153 An idealized representation of the possible tropospheric fallout distribution from a detonation in the temperate zone is given in Fig. 9.153, in which the ordinates refer to the activity of isotopes having average lives of at least a month. One curve shows the variation of the relative activity of the deposited material with distance along the downwind fallout axis; it has a steep slope because the particles spread farther and farther from the axis, and so cover larger areas, as the distance from ground zero increases. If total activity were being considered, including that of isotopes of short life, the relative intensity would fall off even more sharply with distance because of the decay occurring before the particles descended to earth.

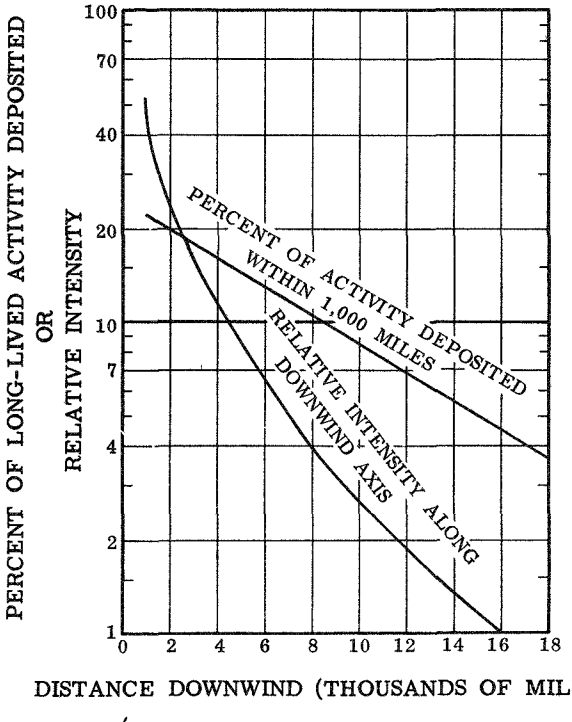

Figure 9.153. Percentage of long-lived activity deposited in troposphere and relative intensity downwind as function of distance.

The second curve indicates the peroentage of the longer lived activity that might be deposited within 1,000 miles of locations on the downwind fallout axis. The idealized curves are based on the assumptions of uniform wind and moderate rainfall patterms in the downwind direction. However, the weather pattern existing during the first few weeks following a nuclear detonation can markedly change the picture represented in Fig. 9.153. Since uniform winds and rainfall are not very probable, the tropospheric fallout patterns, like those of the early fallout, will vary and may be quite irregular.

Stratospheric Fallout

9.154 The radioactive cloud debris that enters the stratosphere descends much more slowly than does the tropospheric fallout. This is mainly due to the fact that vertical motions in the stratosphere are slow, as stated above, and little moisture is available to scavenge the particles. It appears that almost the only way for the removal of the radioactivity from the stratosphere is for the air masses carrying the particles to move first into the troposphere, where the particles can be brought down by precipitation. There are at least three ways in which this transfer of air from the stratosphere to the troposphere can occur, they are (1) direct downward movement across the tropopause, (2) upward movement of the tropopause or its reformation at a higher altitude, and (3) turbulent, large-scale meandering horizontal circulation through the tropopause gaps. The relative importance of these mechanisms depends upon the altitude, latitude, and time of year at which the injection into the stratosphere takes place. The first method may be important during the arctic winter and the second in the lower polar stratosphere in the early spring. The third mechanism is particularly applicable to material in the lower stratosphere near the gaps. Very little debris crosses the tropopause in equatorial regions.

9.155 The winds in the stratosphere are predominantly easterly or westerly, depending on the place and time. Hence, when the radioactive cloud is injected into the stratosphere it tends to move in the downwind direction and ultimately becomes a streak girdling the globe more or less at the latitude of injection. This cloud gradually widens in a north-south direction and, very much more slowly, in a vertical direction by turbulent diffusion. A slow meridional circulation may cause a gradual shift of the cloud towards the polar region. The relatively complicated structure of the stratosphere and the varied modes by which contaminated particles may leave it, make it impos-

sible to assign a single half-residence time for stratospheric debris. In fact, there is some doubt whether the concept of half-residence time is strictly applicable. However, an effective half-residence time may be calculated from the time required for the removal of 80 percent of the material suspended in the stratosphere.[8]

9.156 The effective half-residence times obtained in this manner vary with both latitude and altitude of injection, but reasonable success in predicting stratospheric delayed fallout rates has resulted from assigning effective half-residence times of 5 months to debris entering the polar stratosphere (up to 70,000 feet), 10 months for the lower tropical stratosphere (up to 70,000 feet), 30 months for the higher stratosphere (70,000 to 110,000 feet), and 60 months for the highest stratosphere and mesosphere (110,000 to 250,000 feet).

9.157 Because the U.S.S.R. tests of high-yield nuclear weapons have been carried out in the Arctic and north temperate regions, the stratospheric fallout has come to earth more rapidly, and is consequently relatively more radioactive, than that from U.S. tests in the tropical Pacific Ocean area. If all other factors are equal, the fallout time is greatest when injection occurs in the spring. The half-residence time of material injected into the polar stratosphere is especially susceptible to this seasonal effect; for the north polar region, the time has been estimated to range from 3 months to 8 months depending upon whether injection takes place in December or April, respectively.

9.158 Regardless of where it is injected, the major portion of the stratospheric fallout will reach the earth in the temperate latitudes. This is mainly due to high-rainfall regions near the polar fronts (§9.146). Since the half-residence time in the troposphere is so short, air coming down through the tropopause gap or on its poleward side and moving toward the equator will be depleted of its contaminated particles by scavenging before it can reach the tropics. Consequently, stratospheric fallout in the equatorial zone is low in spite of the heavy rainfall.

9.159 Stratospheric debris originating in a particular hemisphere will tend to fall out in that hemisphere. For example, material injected at 10° N latitude was found to be distributed in such a way that two-thirds remained in the Northern Hemisphere. Since most nuclear tests have been performed in this hemisphere, the amount of delayed fallout on the ground is considerably greater than in the Southern Hemisphere (§9.168). In the event that the radioactive cloud reached a height of 100,000 feet in the stratosphere, it is probable that there would be more effective mixing of the air between the two

[8] The time to remove 80 percent is 2 32 effective half-residence times.

hemispheres, provided the injection did not occur in the polar regions.

9.160 The particles in the stratosphere are effectively held in storage, for periods of several months up to a few years, at the time when their radioactivity is greatest. During this interval, the radioactive debris does not represent a direct hazard and, in fact, most of the activity of short life decays away almost completely.[9] On the other hand, isotopes with long half-lives, such as strontium-90 and cesium-137, are not materially reduced in amount. As mentioned earlier, this is one of the significant aspects of the delayed fallout.

Fallout from Nuclear Weapons Tests

9.161 During the course of major nuclear weapons testing, from 1945 through 1958, approximately 92 megatons of fission yield were introduced into the atmosphere, to constitute both early and delayed fallout. The distribution according to nations and types of burst is given in Table 9.161. This table does not include data for tests carried out since 1958. In estimating fission yields a value of 50 percent has been chosen for the fission fraction of all thermonuclear devices, including those of the U.S.S.R., since this is about the average for the U.S. and U.K. tests.

9.162 For making estimates of delayed fallout, it is the general practice to determine the amount of strontium-90, for several reasons. It has a long half-life compared to the residence time in the stratosphere, so that it does not decay to any great extent prior to its deposition on the earth; it is produced in relatively large quantities in fission, and it is fairly easy to identify and measure by standard radiochemical techniques. Furthermore, the concentration of strontium-90 is of special interest because it provides a measure of the hazard from delayed fallout (§ 11.178 *et seq*).

9.163 The activity of strontium-90, as of radioactive materials in general, is conveniently expressed in terms of a unit called the "curie." It is defined as the quantity of any radioactive substance undergoing 3.7×10^{10} disintegrations per second. (This particular rate was chosen because it is close to the rate of disintegration of 1 gram of radium.) Where large amounts of active material are involved, the "megacurie" unit is employed; this is equal to 1 million curies and corresponds to disintegrations at the rate of 3.7×10^{16} per second. A megacurie of

[9] During the period of high delayed fallout rate in the spring of 1959, which reached the ground relatively soon after the U.S.S.R. test series of October 1958, appreciable activity resulted from the presence of the relatively short-lived isotopes zirconium-95, ruthenium-103 and -106, and cerium-141 and -144.

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strontium-90 is that quantity of this isotope which emits 3.7×10^{16} beta particles per second.[10]

9.164 The strontium-90 produced by weapons testing has been apportioned approximately as follows: mesosphere, 0.4 megacurie; lower stratosphere, 5.5 megacurie (3.0 U.S. and U.K., 2.5 U.S.S.R.); troposphere, 0.6 megacurie; local Pacific Ocean, 2.7 megacurie. Of the 0.6-megacurie of tropospheric fallout, 0.5 megacurie probably fell into the sea within a few weeks, so that only about 0.1 megacurie descended on land areas. Consequently, any world-wide sampling of delayed fallout, which is made on land, will reflect mainly the 5.9 megacuries of strontium-90 from stratospheric fallout. Measurements in the continental United States west of the Mississippi River are

TABLE 9.161

FISSION AND TOTAL YIELDS FROM NUCLEAR TESTS MADE BY THE UNITED STATES, THE UNITED KINGDOM, AND THE U.S.S.R. (1945–1958)

United States and United Kingdom Nuclear Tests

Years	*Fission yield (kilotons)*	*Fission yield from events with total yields of 1 MT or greater (kilotons)*
1945	60	----------
1946	40	----------
1948	100	----------
1951	500	----------
1952–1954	37, 000	36, 000
1955	200	----------
1956	9, 000	8, 000
1957–1958	19, 000	14, 000

U.S.S.R. Nuclear Tests

Years (inclusive)	*Fission yield (kilotons)*
1945–1951	60
1952–1954	500
1955–1956	4, 000
1957–1958	21, 000

All Nuclear Tests

	Fission yield (kilotons)			*Total yield (kilotons)*	
Inclusive years	*Air burst*	*Ground surface burst*	*Water surface burst*	*Air burst*	*Surface burst*
1945–1951	190	550	20	190	570
1952–1954	1, 000	15, 000	22, 000	1, 000	59, 000
1955–1956	5, 600	1, 500	6, 000	11, 000	17, 000
1957–1958	31, 000	4, 400	4, 600	57, 000	28, 000

[10] One megaton of fission yield produces about 0.1 megacurie of strontium-90.

probably exceptional in this respect because of the tropospheric fallout of material originating at the Nevada Test Site. Thus, the strontium-90 content of the soil in this region is somewhat higher than that in other countries at the same latitude and with similar rainfall.

9.165 Since 1954, a number of sampling networks have been established in various parts of the world to determine the amounts of radioactive contamination in tropospheric and stratospheric air and in rainwater and soil, arising from weapons tests. The results obtained have shed a great deal of light on the possible mechanisms of the delayed fallout. The information so obtained, coupled with biological studies to determine the concentrations of certain radioisotopes in the diet and in human beings and animals, has permitted an evaluation to be made of the possible world-wide hazard (see Chapter XI).

9.166 The plots in Figs. 9.166 a and b show the variations over a period of years of the megacuries of strontium-90 present in the total stratospheric inventory, i.e., the amount still remaining in the stratosphere [11] at various times, and the ground inventory, i.e., the amount deposited on the ground. Calculations were made, using Fig. 9.149 to determine the quantity of strontium-90 injected into the stratosphere and the half-residence times given in § 9.156, together with weapons test yield data, for various scavenging conditions. It was found that best agreement with actual stratospheric and ground inventory determinations made since 1956 is obtained if it is assumed that on the average 50 percent of the strontium-90 activity from land surface bursts and 70 percent from water surface shots remains suspended in the atmosphere long enough to appear as delayed fallout. The plots in the two figures are based on these values.

9.167 The maximum amounts of strontium-90 in the earth's surface will be attained when the rate of natural radioactive decay just begins to exceed the rate at which the isotope reaches the ground in delayed fallout. While it appears that significant addition to the atmospheric inventory of strontium-90 may have been made during the latter part of 1961, it is estimated that the maximum surface accumulation from previous tests was attained in the summer of 1961. Subsequently, the surface inventory from these earlier tests will decrease. The estimated world-wide distribution of strontium-90 for the summer of 1961 is shown in Fig. 9.167. The quantities of this isotope are expressed in terms of its activity over a given area in units of millicuries per square mile, 1 millicurie being a one-thousandth part

[11] The stratospheric inventory does not include the material stabilized above 150,000 feet.

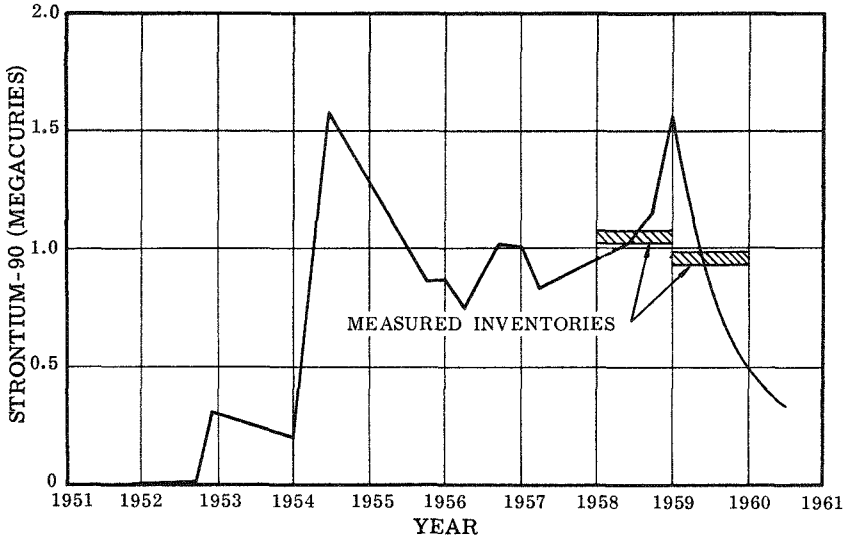

Figure 9.166a. Stratospheric burden (or inventory) of strontium-90.

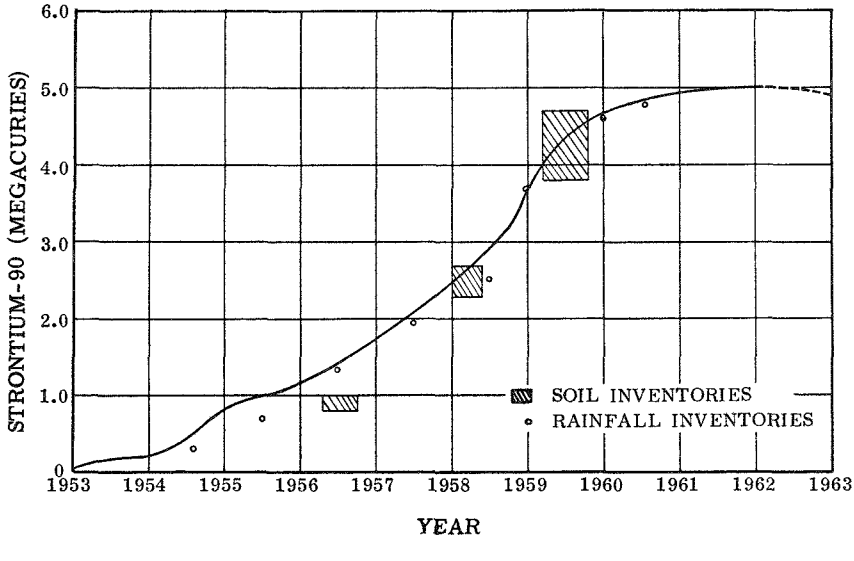

Figure 9.166b. Surface burden (or inventory) of strontium-90 from tests prior to September 1961.

of a curie [12] The mean annual rainfall for each 10° latitude is indicated at the top of the figure

9 168 The data illustrate some of the points relating to delayed stratospheric fallout mentioned earlier It is seen that most of the material, actually three-fourths of the total, is deposited in the Northern Hemisphere Moreover, in each hemisphere, the delayed fallout, as indicated by the strontium-90 activity, is greatest in the

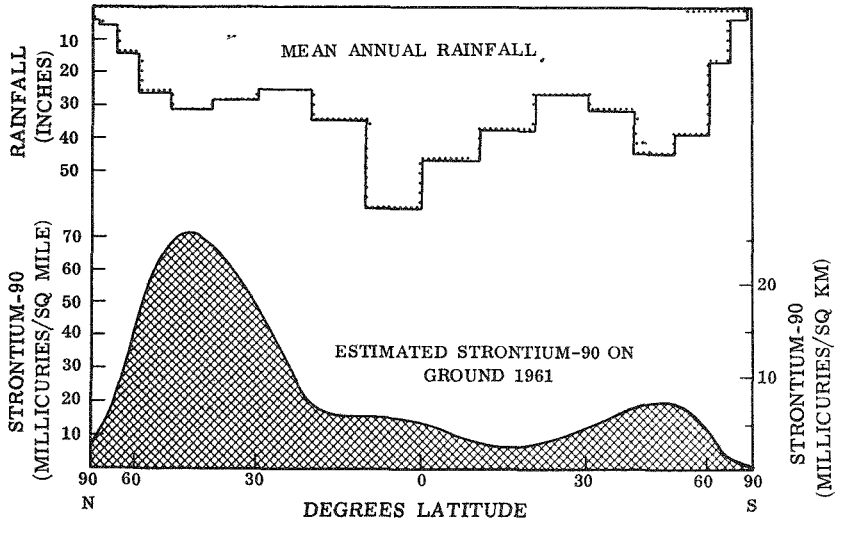

Figure 9 167 Estimated world-wide distribution of strontium-90 due to tests prior to September 1961, and mean annual rainfall

mid-latitudes (or temperate zone) where rainfall is high However, in the tropics, the strontium-90 activity is low, in spite of the very large mean annual rainfall for the reason given in § 9 158

9 169 *After strontium-90, the next most important radioisotope* from the biological standpoint is cesium-137 Fission products contain, after a short time, 1 8 times as many cesium-137 atoms as strontium-90 atoms Since there is essentially no fractionation relative to one another of these two isotopes and they have half lives which are not very different (§ 9 143), the activity of cesium-137 on the ground can be determined, to a good approximation, by multiplying the values for strontium-90, e g , Fig 9 176, by 1 8 The genetically

[12] If 1 megaton of fission yield were spread uniformly over one hemisphere of the earth the strontium 90 activity would be close to 1 millicurie per square mile

significant 30-year gamma ray dose from external cesium-137 in fallout from testing through the year 1958 will be no more than about 0.7 percent of the natural background radiation (§ 11.97). Isotopes of shorter half-life will increase the external dose to no more than about 1.7 percent of the background value (§ 11.190).

TECHNICAL ASPECTS OF RESIDUAL NUCLEAR RADIATION [13]

Rate of Decay of Fallout Activity

9.170 The continuous curves in Figs. 9.16 a and b, which represent the decrease in dose rate due to gamma radiation from radioactive fallout, have been obtained by summing the contributions of the more than 200 isotopes in the fission products and of the activity induced by neutrons in the weapons materials for various times after fission. The effects of fractionation, resulting from the partial loss of gaseous krypton and xenon (and their daughter elements) and from other circumstances, have also been taken into account (§ 9.08). The dose rates calculated in this manner vary with the nature of the weapon, but the values plotted in Figs. 9.16 a and b are reasonable averages for situations in which the fallout activity arises mainly from fission products. It is seen that the decrease in the dose rate with time cannot be represented by a simple equation which is valid at all times, but it can be approximated by the dashed straight lines labeled "$t^{-1.2}$", for times between 30 minutes to about 5,000 hours (200 days) after the explosion, to within 25 percent. For times longer than 200 days, the fallout decays more rapidly than indicated by the $t^{-1.2}$ line, so that the continuous curve may be used to estimate dose rates from fallout at these times.

9.171 During the interval in which the approximation is applicable, the decay of fallout activity at a given location may be represented by the simple expression

$$R_t \approx R_1 t^{-1.2}, \qquad (9.171.1)$$

where R_t is the gamma radiation dose rate at time t after the explosion and R_1 is the dose rate at unit time; this is the unit-time reference dose rate which has been used earlier, e.g., in Figs. 9.16 a

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

and b, and Figs. 9.20 and 9.26. The actual value of R_1 will depend on the units in which the time is expressed, e.g., minutes, hours, days, etc. In this chapter, time is generally expressed in hours, so that the unit time for the reference dose rate R_1 is 1 hour.[14]

9.172 It should be clearly understood that equation (9.171.1) is applicable provided there is no change in the quantity of fallout during the time interval under consideration. It cannot be used, therefore, at such times that the fallout is still descending, but only after it is essentially complete, at the particular location. If any fallout material is removed in any way, e.g., by weathering or by washing away during the time t, or if any additional material is brought to the given point by wind or by another nuclear detonation, equation (9.171.1) could not be employed to determine the rate of decay of the fallout activity.

9.173 By rearranging equation (9.171.1) and taking, logarithms it follows that

$$\log \frac{R_t}{R_1} \approx -1.2 \log t, \tag{9.173.1}$$

so that a logarithmic plot of R_t/R_1 against t should give a straight line with a slope of -1.2. When $t=1$, i.e., 1 hour after the explosion, $R_t=R_1$ or $R_t/R_1=1$; this is the basic reference point through which the straight line of slope -1.2 is drawn in Figs. 9.16 a and b.

9.174 The total dose received from a given quantity of fallout can be determined from Fig. 9.20 using the method described in § 9.21. The curve in Fig. 9.20 was obtained by numerical integration of the actual dose-rate (continuous) curve in Figs. 9.16 a and b. However, for times between 0.5 hour (30 minutes) and 5,000 hours (200 days) after the explosion, it is sometimes convenient to have an analytical expression for the dose received during a given time interval. Such an approximate expression can be obtained by direct integration of equation (9.171.1); thus if D is the total dose received between the times t_a and t_b, then

$$D \approx R_1 \int_{t_a}^{t_b} t^{-1.2}\, dt = 5R_1(t_a^{-0.2} - t_b^{-0.2}). \tag{9.174.1}$$

Hence if the unit-time reference dose rate R_1 is known, or is determined by using Figs. 9.16 a and b, and the observed dose rate at any known time after the explosion, the total (or accumulated) dose for

[14] Physically the unit-time reference dose rate is the dose rate that would have been received from the given (constant) amount of fallout at unit time, e.g., 1 hour after the explosion, although this quantity might actually have been in transit at that time and would not have reached the location under consideration.

any required period can be calculated, provided the fallout activity decays in accordance with the $t^{-1.2}$ relationship during this period.

9.175 Measurements made on actual fallout from weapons tests indicate that, although the $t^{-1.2}$ decay represents a reasonable average, there have been instances where exponents in the range of -0.9 to -2.0, rather than -1.2, are required to represent the rate of decay. In fact, different exponents are sometimes needed for different times after the explosion. These anomalies apparently arise from the particular circumstances of the explosion and are very difficult to predict, except possibly when a large quantity of neutron-induced activity is known to have been produced. Furthermore, fallout from two or more explosions occurring at different times will completely change the observed decay rate. In general, too, over a long period of time after the burst, weathering will tend to alter the dose rates in an unpredictable manner. Consequently, in an actual situation following a nuclear detonation, estimates based on either the $t^{-1.2}$ decay rule or even on the continuous curves in Figs. 9.16 a and b must be used with caution and should be verified by actual measurements as frequently as possible.

9.176 Within the limits of applicability of the $t^{-1.2}$ decay relationship, equation (9.171.1) or (9.173.1) can be used 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 (9.174.1), it is necessary to know the unit-time reference dose rate R_1. This can be obtained from equation (9.171.1) 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. 9.26 and 9.27.

9.177 In principle, equation (9.173.1) 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 (9.171.1) and (9.174.1) may be employed to make rough estimates of radiation doses over moderate periods of time, up to about 200 days after the explosion, provided one measurement of the dose rate is available.

Radiation Dose Over Contaminated Surfaces

9.178 It was seen in § 9.163 that the curie and megacurie are useful units for expressing the activity of radioactive material, and they will now be employed in connection with the contamination of areas. Because, as far as the external radiation dose is concerned, the gamma rays are more significant biologically than the beta particles, the early fallout activity may be stated in gamma-megacuries, as a measure of the rate of emission of gamma-ray photons, where 1 gamma-megacurie represents the production of 3.7×10^{16} photons per second.

9.179 If an area is uniformly contaminated with any radioactive material of known activity (in gamma-megacuries) at a given time, 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 various energies, are represented in Fig. 9.179. If the actual contamination density differs from 1 megacurie per square mile, the ordinates in the figure would be multiplied in proportion.

9.180 The calculations upon which Fig. 9.179 is based take into account the effects of "skyshine" (§ 8.40). Furthermore, it is assumed that the surface over which the contamination is distributed is perfectly smooth and infinite in extent. For actual terrain, which is moderately rough and may have a variety of radiation shielding, the dose rate at a specific height above the ground would be less than for an infinite, smooth plane. The actual reduction factor will, of course, depend on the terrain features and the extent of the contaminated area. As a rough approximation, a factor of 0.7 is commonly applied to the dose rates obtained from Fig. 9.179 to obtain average values for a moderately rough terrain.

9.181 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. 9.181. The curve gives approximate values of the attenuation factor for early fallout 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, i.e., 3 feet above, 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 at about 3 feet above the ground at that time.

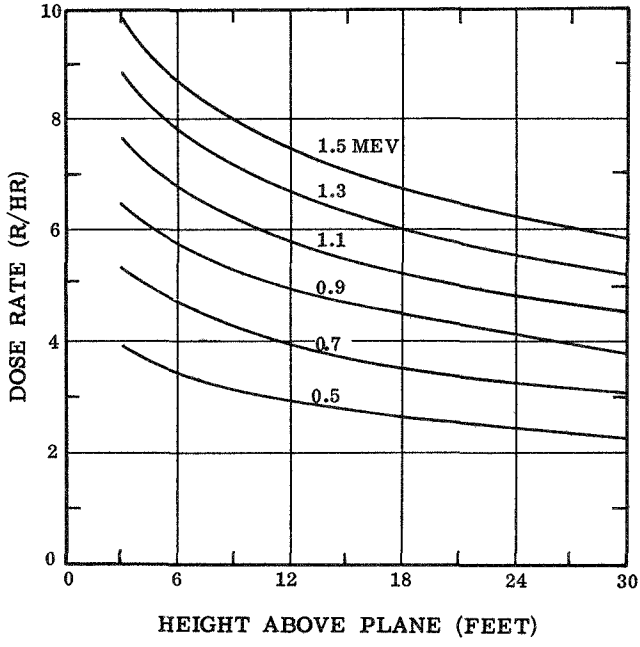

Figure 9.179. Dose rates above an ideal plane from gamma rays of various energies for a contamination density of 1 gamma-megacurie per square mile.

9.182 A possible use of the curve in Fig. 9.181 is to determine the dose rate near the ground and contamination density from data obtained by means of an aerial survey (see § 12.59). For example, suppose a radiation measuring instrument suspended from an aircraft at a height of 1,000 feet showed a radiation dose of 0.24 roentgen per hour (r/hr) and that, from the known time after the explosion, the average energy of the gamma-ray photons was estimated to be 0.8 Mev. The attenuation factor for an altitude of 1,000 feet is approximately 27 and so the dose rate at 3 feet above ground at the time of the observation is roughly $0.24 \times 27 = 6.5$ r/hr. It is seen from Fig. 9.179 that for a contamination density of 1 megacurie per square mile and a photon energy of 0.8 Mev, the dose rate 3 feet above the ground would be about 5.9 r/hr. Hence, in the present case, the contamination density of the ground is approximately $6.5/5.9 = 1.1$ gamma-megacurie per square mile.

9.183 It has been calculated that, on the average, the total gamma-ray activity from the fission products produced by a 1-kiloton TNT equivalent fission explosion would be about 550 gamma-megacuries

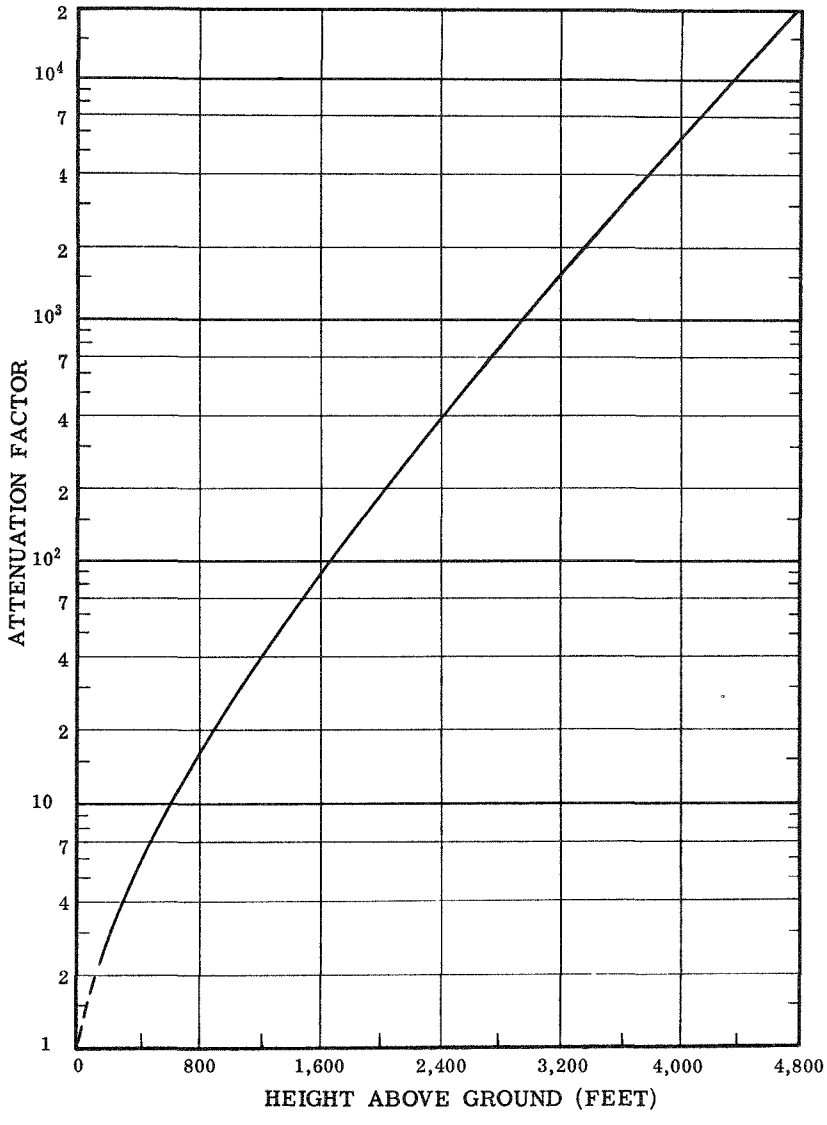

Figure 9.181. Altitude attenuation factor for early fallout radiation dose rate 3 feet above the ground.

at 1 hour after the explosion. If this activity were spread uniformly over a smooth plane 1 square mile in area then, assuming a mean photon energy of 0.95 Mev, the radiation dose received at a point 3 feet above the plane can be estimated from Fig. 9.179 as roughly

6.8×550, i.e., approximately 3,700 r/hr. Activity induced by neutron capture in the weapon materials may add about 200 r/hr to this figure. Hence, if 100 percent of the radioactivity present in the weapon debris were deposited uniformly over a smooth surface of area 1 square mile, the 1-hour dose rate above this area would be about 3,900 r/hr per kiloton of fission yield. This means that if the same residues were spread uniformly over a smooth surface of A square miles in area, the 1-hour dose rate would be $3{,}900/A$ r/hr; consequently, the product of the 1-hour dose rate and the area in square miles would be equal to 3,900 in units of (r/hr)(sq mi) per kiloton. If all the residues from 1-kiloton fission yield were deposited on a smooth surface in varying concentrations typical of an early fallout pattern, instead of uniformly, the product of the dose rate at 1 hour and the area would be replaced by the "area integral" of the 1-hour dose rate defined by

$$\text{Area Integral} = \int_A R_1 dA,$$

where R_1 is the 1-hour dose rate over an element of area dA and A square miles is the total area covered by the residues. Hence, regardless of the concentration pattern, the area integral of the 1-hour dose rate over a smooth surface would always be 3,900 in units of (r/hr)(sq mi) per kiloton of fission, assuming that the fallout particles had been completely deposited at that time.

9.184 Measurements of the early fallout pattern resulting from the BRAVO test (§ 9.100), made with radiation monitoring instruments 1 week after the detonation, are consistent with values in the range of 1,000 to 1,500 (r/hr)(sq mi) per kiloton of fission yield for the 1-hour dose rate area integral. This differs from 3,900 (r/hr)(sq mi)/kt given above, for two main reasons: first, only part of the radioactivity of the weapon residues appears in the early fallout, and second, corrections must be applied to the measured value for instrument response and terrain shielding. A typical ionization-chamber monitoring instrument, calibrated and used in the usual manner, will read about 25 percent too low, because of its directional response and shielding provided by the operator. This correction increases the observed mean of the area integral to 1,700 (r/hr)(sq mi)/kt. An average value of the terrain shielding factor, i.e., the ratio of the actual dose rate to that which would exist above an ideal smooth surface, is taken to be 0.7. On this basis, the 1-hour dose rate area integral over an ideal smooth plane, with no shielding, would be approximately 2,400 (rh/hr)(sq mi)/kt. The ratio of this number to the theoretical 3,900 (rh/hr)(sq mi)/kt indicates that some 60 percent of the total

gamma-ray activity of the weapon residues is deposited in the early fallout from a land surface burst (§ 9.48). This value must be recognized as an estimate because the data available are somewhat limited.

9.185 It should be noted that integration over the whole area of the idealized fallout pattern in Fig. 9.73 gives a value of approximately 1,700 (rh/hr)(sq mi)/kt for the 1-hour dose rate. The data thus refer to actual dose rates, i.e., after instrument correction, which would be expected over moderately flat terrain with a shielding factor of 0.7. In a city, the values might be 70 or 75 percent of those in Fig. 9.73, because of the increased shielding of buildings, trees, etc. (§ 9.92).

Rate of Particle Fall

9.186 The time at which particles of a given size and density will arrive at the ground from specified heights in the nuclear cloud may be calculated from aerodynamic equations of motion. The effects of vertical air motions are generally ignored since they cannot be predicted, especially as they are believed to be generally small for particles which fall within 24 hours. However, field test data sometimes indicate times of arrival which are quite different from those predicted by the theoretical calculations; hence, it is probable that vertical wind components and other factors may sometimes significantly influence the particle fall.

9.187 Some typical results of time of fall calculations are shown in Fig. 9.187. The curves give the times required for particles of different sizes to fall to earth from various initial altitudes. The density of the fallout material is taken to be 2.5 grams per cubic centimeter, which is roughly that of dry sand; the falling particles are assumed to be spherical, their radii being given in microns (μ). Actual fallout particles are sometimes quite irregular and angular in shape, although a large percentage tend to be fairly smooth and globular since they result from the solidification of fused spherical droplets of earth and of weapon debris. Even if the particles are irregular, they can be assigned an effective radius and then treated as spheres for calculating times of fall.

9.188 The percentages given in Fig. 9.187 represent estimates of the proportions of the total activity deposited by particles with sizes lying between pairs of lines. Thus, particles with radii larger than 200 microns carry 1 percent of the activity; those between 150 and 200 microns carry 3 percent, and so on; at the other extreme, particles less than 20 microns in radius carry 12 percent of the activity. This distribution of activity is known as "log-normal" because it obeys the

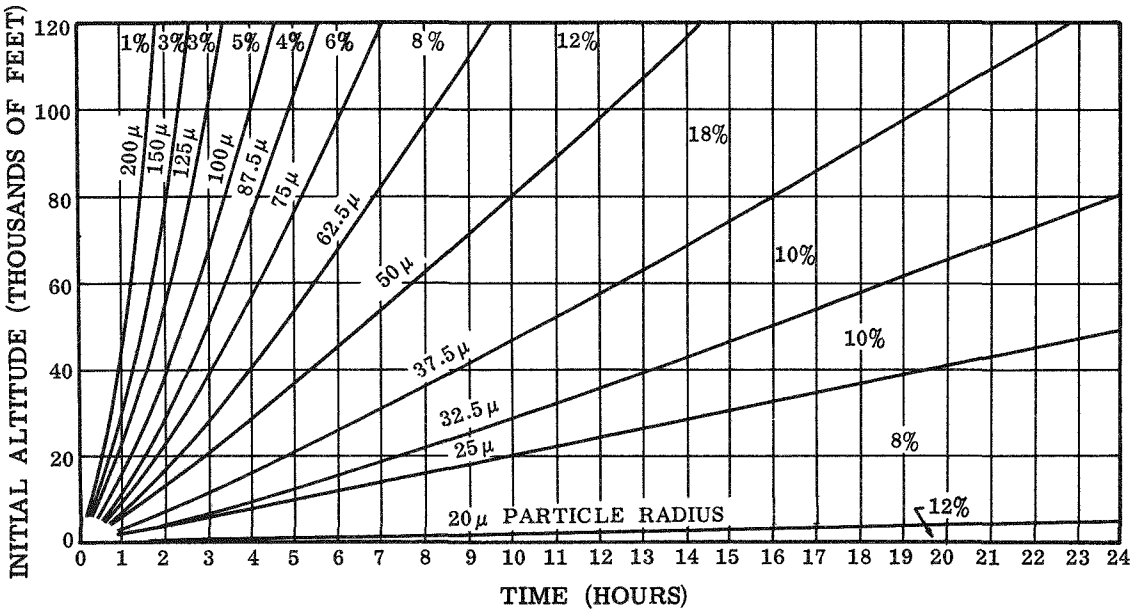

Figure 9.187. Times of fall of particles of different sizes from various altitudes and percentages of total activity carried.

normal (Gaussian) distribution law with the logarithm of the particle radius as the variable. It may not be strictly valid in any given case, since the activity distribution varies with the type of burst, the nature of the terrain at ground zero, etc. Nevertheless, it is characteristic of the activity distributions assumed for the theoretical analysis of fallout.

9.189 The arrival time at a location downwind from a nuclear explosion may be estimated if the effective wind velocity in the intervening space is known. It is equal to the downwind distance from the near edge of the stabilized radioactive cloud divided by the effective wind speed. Consider, for example, a point located 300 miles downwind from the explosion and suppose the effective wind speed is 15 miles per hour. The time of arrival of fallout at the point under consideration would then be 300/15=20 hours. If the mushroom cloud stabilizes at 60,000 feet, then it follows from Fig. 9.187 that, by this time, only particles with radii less than about 30 microns will still be present, and that they carry roughly 25 percent of the total activity deposited in the early fallout. It is evident that, in spite of the decay which will have occurred in transit, fallout of appreciable activity may be expected 300 miles downwind at about 20 hours after the detonation.

9.190 At the time of arrival at a downwind location, the dose rate will begin to rise, as shown in Figs. 9.71 a and b. Subsequently, the dose rate will fall and, when the early fallout is essentially complete, decay will occur roughly in accordance with the $t^{-1.2}$ rule. Exceptions to this behavior could result from unusual wind shears or precipitation after the maximum dose rate has been reached; these could produce a second, possibly higher, maximum at a later time. It is this kind of phenomenon which is responsible for the production of hot spots in the early fallout distribution.

Prediction of Early Fallout Path

9.191 In addition to the methods for estimating fallout dosage patterns mentioned in § 9.60 *et seq.*, simple procedures have been developed for rapidly determining the expected path and approximate times of arrival of the fallout. One of these, which has proved quite useful in weapon tests, will be described here. The basic information required is an observation (or forecast) 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 radioactive cloud.

9.192 Starting at a point O, representing ground zero, in Fig. 9.192, a vector OA is drawn, indicating the direction and velocity (in miles

per hour) of the wind in the first 5,000-foot layer from the ground. This is followed by vectors *AB*, *BC*, . . ., *GH*, for successive layers up to the limit of observation, e.g., the top of the cloud, in this case, $8 \times 5{,}000 = 40{,}000$ 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 layers, i.e., eight in this case.

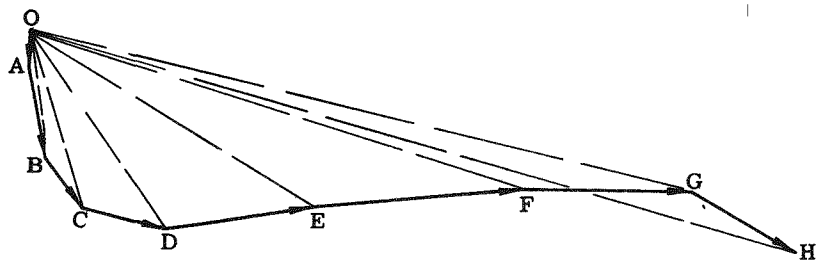

Figure 9.192. Prediction of approximate path of fallout based on wind pattern

9.193 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. To account for the physical dimensions of the radioactive cloud, the vectors should be extended by one cloud radius (see Fig. 2.16) in all directions.

9.194 Although Fig. 9.192 gives a general idea of the shape of the fallout area, it does not indicate its overall extent. If, as in the case considered above, the wind vectors, expressed in miles per hour, are drawn at 5,000-foot intervals, *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. 9.192, although it covers a larger area.

9.195 It will be apparent that the procedure just described can provide only a rough guide concerning the probable early fallout area. In actuality, the particle size distribution will not be known, and the height of the radioactive 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. 9.192 applies to the whole area of significant contamination which may extend hundreds of miles from ground zero. Precipitation occuring at the time of (or soon after) the detonation may also change the fallout situation, since radioactive particles may become attached to the drops and descend from various heights at rates which are characteristic of the rain or snow.

9.196 Similar fallout area plots may be constructed from the UF (Upper-air Fallout) wind data which are reported by U.S. Weather Bureau upper-air observing stations two to four times daily. The UF method, developed by the Weather Bureau to meet civil defense requirements, has the great merit of simplicity and speed which make it ideal for use even under emergency conditions.

9.197 The UF "winds" indicate the direction and distance from ground zero where particles, falling from various levels in a nuclear explosion cloud (10, 20, 40, 60, and 80 thousand feet) and requiring 3 hours to reach the ground, will land. These "fallout vectors" are computed from the current upper wind observations. The estimated fallout area may be obtained by plotting the UF vectors from the burst point as shown in Fig. 9.197. The 3-hour isochrone, i.e., the locus of particles which take 3 hours to reach the ground from the various altitudes, may be drawn through the 3-hour points given in the UF wind report. The time of arrival of fallout at any point can be approximated by linear extrapolation of the distance from the burst point to the 3-hour line. It is recommended that extrapolations beyond 3 hours be made only for particles originating at 40,000 feet and above. Extrapolation beyond 12 hours is not recommended since the UF method does not take into account the time and space changes in the wind.

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9.198 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.

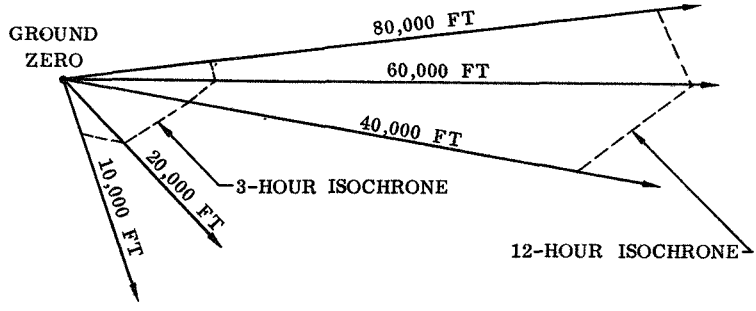

Figure 9.197. Simplified UF fallout area plot (radial lines indicate where fallout from the various levels is expected to occur).

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CHAPTER X

RADIO AND RADAR EFFECTS

INTRODUCTION

10.01 A nuclear explosion is accompanied by two principal types of electromagnetic effects.[1] These are entirely different from each other in nature, but both involve the whole spectral region of wavelengths longer than infrared, i.e., from about 1 millimeter on up to very large values. One involves the actual emission of an electromagnetic pulse of short duration from the explosion itself (or from the disturbed region in its vicinity), whereas the other, through alterations to the electrical properties of the atmosphere, can result in serious disturbance of electromagnetic waves, such as are used in communications and for radar, passing in the vicinity of the nuclear detonation. This disturbance may be caused by debris or water vapor introduced into the atmosphere by the burst, or by the unusual conditions created by the ionizing radiations from the exploding device. The latter mechanism may cause some radio and radar systems to be "blacked out" for several hours following the explosion. What little is known about the origin and characteristics of the electromagnetic pulse will be described first; the bulk of this chapter will then be concerned with a discussion of the changes in the normal ionization of the atmosphere brought about by a nuclear explosion and of the consequences of these changes.

THE ELECTROMAGNETIC PULSE

Origin of the Electromagnetic Pulse

10.02 The electromagnetic pulse or "radioflash" which is produced at the time of a nuclear detonation is of considerable interest. It is fairly well known that even small detonations of ordinary chemical

[1] The term "electromagnetic" as used in this chapter applies to radiations of the longer wavelengths and not to the entire spectrum described in § 1.69 *et seq.*, which is strictly included in the term.

explosives can produce electromagnetic signals, so it is not surprising that substantial pulses of this type accompany nuclear explosions.

10.03 There appear to be at least two different mechanisms whereby an electromagnetic pulse may be produced by a nuclear explosion. The first is associated with the creation by radiations from the burst of some kind of asymmetry in the electric charge distribution in the region surrounding the detonation; the second is the result of the rapid expansion of the essentially perfectly-conducting plasma of weapon residues in the earth's magnetic field. The first mechanism, often called the "Compton-electron model" for reasons which will be seen below, is believed to be the principal means for generation of electromagnetic pulses by detonations on or slightly above the earth's surface and by those near the "top" of the sensible atmosphere. The other, called the "field displacement" model, might be responsible for electromagnetic signals from underground bursts where the expansion is restrained in a more or less spherically symmetrical manner by the surrounding material, or from those at such great altitudes that the only immediate interaction of the explosion is with the geomagnetic field.

10.04 In the Compton-electron model the photons of the initial gamma radiation leave the exploding weapon with high energies, very soon collide with electrons in the atoms and molecules of the surrounding air, and transfer to them most of their energy. These Compton electrons (§ 8.68) move rapidly away, on the average, from the center of the burst. Provided some kind of asymmetry exists, this motion is apparently one of the main sources of the electromagnetic pulse. If the explosion were perfectly symmetrical, in a uniform atmosphere, the effects would be equal in all directions; the opposite components would then compensate each other exactly and there would be no electromagnetic signal. However, there are invariably a number of unrelated factors associated with a nuclear explosion which insures the presence of an asymmetry and, hence, of an electromagnetic pulse.

10.05 The most obvious asymmetric situation is that arising from a surface or near-surface (within 350 feet or so) burst, where the presence of the earth itself confines expansion of the weapon residues and radiation emission to the upward hemisphere. At the other extreme, where the explosion takes place high in the atmosphere, there will be very little interaction by upward-moving gamma rays because of the low air density, whereas those going downward will produce Compton electrons within a moderate distance. In both these cases, though their detailed behavior is probably different and their directions are opposite, the effective Compton-electron pulse is essentially

vertical. Moreover, no matter where the burst occurs, there is inevitably some asymmetry in the emission and interaction of the photons. For example, the gamma-ray flux from an exploding weapon is itself never fully symmetric because of the presence of auxiliary apparatus, external structure, or the carrying vehicle. It should be noted that, while the "natural" asymmetries tend to be vertical, the other type may be oriented in any direction.

10.06 The Compton electrons created by the initial gamma radiation thus move away asymmetrically, at high velocity, from the exploding weapon. Since the remaining symmetrical components still compensate each other's effects, this motion appears from a distance to be a practically instantaneously accelerated pulse of current in one direction; it is, in other words, something like an "electric dipole" radiator of classical electrodynamics. The current pulse in the air radiates electromagnetic energy just as it would if it were flowing in a wire transmitting antenna, and this radiation constitutes the first part of the characteristic signal of the explosion.

10.07 When the Compton electrons move away from the explosion they leave behind the much slower moving positive ions, which are the other component of the ion pairs (§ 8.16). This relative displacement of positive and negative charges produces a radial electric field. In addition, in its passage through the air each Compton electron itself produces a large number of electron-ion pairs, perhaps 30,000, mostly toward the end of its path of 10 to 15 feet. Under the influence of the radial electric field, the large number of electrons now present will be driven back toward the burst point. This initiates a second pulse of current, but it is rapidly terminated by recombination of electrons with ions and by attachment of the electrons to neutral atoms and molecules in the air, even before the electric field is neutralized. The negative ions produced in the attachment process, and a corresponding number of positive ions, remain free a while longer because the ions, being heavier and less mobile than electrons, collide less frequently. This large volume of ionized gas (or "plasma") undergoes oscillations at characteristic frequencies similar to those observed in experimental plasmas in the laboratory. The oscillations damp out in a short time, as the negative particles (ions and electrons) combine with positive ions, but while they last they produce electromagnetic waves in the radiofrequency range.

Characteristics of the Compton-Electron Signal

10.08 The effective rise-time of the main part of the initial signal pulse (produced by the Compton electrons) from surface or near-

surface bursts is of the order of 10^{-8} second, so that oscillation frequencies as high as 100 megacycles (10^8 cycles) per second may be expected. However, only a very small part of the total electromagnetic energy radiated is carried at such high frequencies. In addition, the higher frequencies are attenuated much more rapidly than the lower ones in normal propagation through the atmosphere. The frequencies of the plasma oscillations, which continue for several milliseconds and radiate considerably more energy, are much lower. These frequencies are attenuated hardly at all in normal propagation. At the lower end of the spectrum are the extremely low frequencies (in the very low kilocycle region) which might be detected very close to any such excited radiating dipole; they would exist principally in the "induction" and "quasi-static" fields and not be radiated at all.

10.09 The electromagnetic signal, as detected at a range of a hundred miles or so, thus consists of a continuous spectrum with most of its energy distributed about a median frequency (10 to 15 kilocycles per second) which is related inversely to the yield. At much longer distances, of many hundreds or thousands of miles, the form and spectrum of the pulse are determined largely by the characteristics of the medium of propagation, i.e., the "duct" between the surface of the earth and the D- or E-region of the ionosphere (see § 10.16).

10.10 A somewhat similar explosively-excited vertical dipole radiator which is frequently encountered in nature is lightning, and the electromagnetic signal (or static) associated with lightning also has a peak in the region of 10 kilocycles. This must not be taken, however, to mean that there is a detailed similarity in the modes of generation of the electromagnetic signals from lightning discharges and from nuclear explosions. The transmission path largely obliterates the characteristics of the original signal in both cases.

The Field-Displacement Mechanism

10.11 The second possibility which has been mentioned for the generation of radiofrequency signals by a nuclear explosion is considered to be of particular significance for extremely-high-altitude bursts. Immediately after the detonation has occurred, the hot weapon debris is essentially a highly ionized vapor (or plasma) which is expanding rapidly. A property possessed by all plasmas is a tendency to exclude a magnetic field, such as that of the earth, from its interior. The expanding plasma of weapon residues thus

causes a violent distortion of the earth's magnetic field. As a result of the interaction between the geomagnetic field and the charged particles in the expanding plasma and in the very tenuous, largely ionized, surrounding gases, this disturbance propagates away from the burst region as a "hydromagnetic wave".

10.12 The hydromagnetic wave retains its identity and characteristics in propagating over very long distances at high altitudes, but at lower levels, where it interacts with the denser atmosphere, it is detected as an ordinary electromagnetic wave or magnetic disturbance. The field-displacement mechanism is believed to be especially important at very high altitudes where the air density is low and the expansion of the debris is not impeded by the atmospheric pressure. It is probable that the same mechanism may operate to produce an electromagnetic signal from an underground burst. The expansion of the debris is here limited to a few yards and the signal is therefore small, but it may be detectable at short ranges.

ATMOSPHERIC IONIZATION PHENOMENA

Effects of Ionization on Radio Signals

10.13 Ionization, that is, the formation of ion pairs consisting of separated electrons and positive ions (§ 8.16), can be produced, either directly or indirectly, by the gamma rays and neutrons of the initial nuclear radiation, by the beta particles and gamma rays of the residual nuclear radiation, and also by the X-rays and even the ultraviolet light present in the primary thermal radiation (§ 2.38). Hence, after a nuclear explosion, the density of electrons in the atmosphere in the vicinity is greatly increased. These electrons can affect electromagnetic (radio and radar) signals in at least two ways. First, under suitable conditions, they can remove energy from the wave and thus attenuate the signal; second, a wave front traveling from one region into another in which the electron density is different will be refracted, i.e., its direction of propagation will be changed. It is evident, therefore, that the ionized regions of the atmosphere created by a nuclear explosion can influence the behavior of communications or radar signals whose transmission paths encounter these regions.

10.14 When a free electron is exposed to a radiofrequency wave, some of the energy of the wave is transferred to the electron as energy of vibration. If the electron does not lose this energy as the result of a collision with a neutral particle (atom or molecule) in the air, it will

radiate a new electromagnetic signal at the same frequency. Thus the energy is restored to the wave without loss. If, however, the air density is appreciable, e.g., more than about one ten-thousandth of the sea-level value, collisions between electrons and neutral particles will take place at a significant rate. In such collisions, most of the excess (vibrational) energy of the electron is transformed into random kinetic energy and cannot be re-radiated. The result is that energy is absorbed from the wave and the electromagnetic signal is attenuated.

10.15 It is apparent, therefore, that marked loss of signal strength will occur only when the electron density and air density are both moderately large. Other conditions being held constant, more energy is absorbed by an ionized gas as the frequency of the signal is decreased. Both positive and negative ions can, in principle, absorb electromagnetic energy in the same way as do electrons, but their larger mass makes them much less effective. It is permissible, therefore, to disregard the ions in this connection.

Ionization in the Normal Atmosphere

10.16 In order to understand the effects of free electrons on radio and radar systems, it is necessary to review briefly the ionization in the normal, undisturbed atmosphere. Below an altitude of about 40 miles, there is little ionization, but above this level there is a region called the "ionosphere", in which the density of free electrons (and ions) is appreciable (see Fig. 9.145). The ionosphere consists of three, more or less distinct, layers, called the D-, E-, and F-regions. In the daytime, especially in summer, the F-region is split up into two layers, called F_1 and F_2; for the present purpose, however, this division may be disregarded. The electron density does not increase gradually from one region to the next, but in each region there is a broad maximum (or peak) density; the value of this maximum increases from the D- to E- to F-regions, that is, with increasing altitude (Fig. 10.16).

10.17 The electrons (and ions) in the normal ionosphere are produced by interaction of solar radiations with various atomic and molecular species in the atmosphere, and they are removed either by recombination with positive ions or by attachment to neutral particles. The former process is the more important when the electron density is high, but the latter is favored by an increase in the density of the air.

10.18 For altitudes below 30 or 35 miles, the air is relatively dense and the probability of collisions between free electrons and atmospheric

atoms and molecules is large. As a result, the electrons are rapidly removed by attachment to neutral particles and the average lifetime of a free electron in this region is less than a millionth of a second, i.e., a microsecond. Any ionization produced will thus disappear very rapidly, and the electron density will be small and the effect on electromagnetic signals negligible.

10.19 In the altitude range from roughly 40 to 50 miles (D-region of the ionosphere), the density of neutral particles (molecular nitrogen

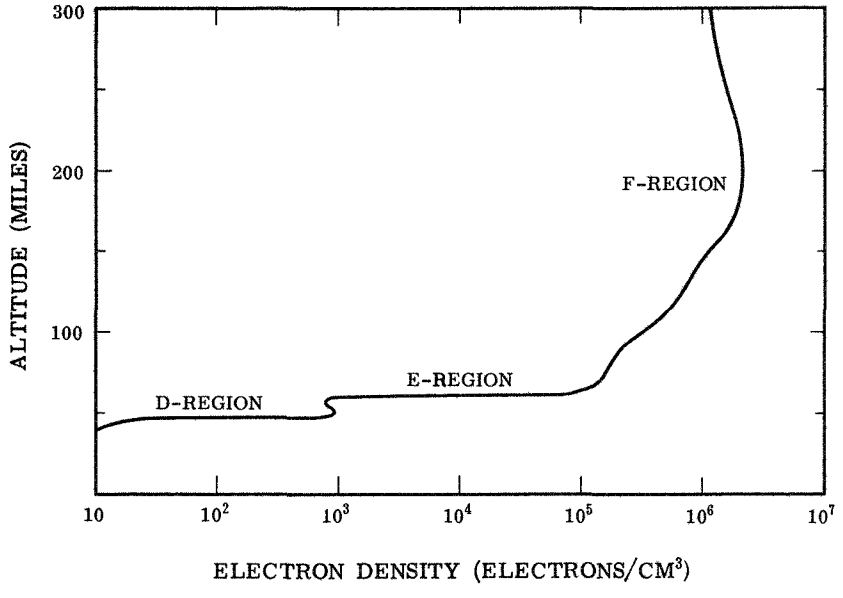

Figure 10.16. Electron densities in D-, E-, and F-regions of the ionosphere in the daytime.

and oxygen mainly, and some nitric oxide and atomic oxygen) is sufficiently small—about 10^{-4} times the sea-level density of the air—to allow electrons to remain free for several minutes. The average lifetime varies with location and the time of the year, but it is long enough for the radiation from the sun to maintain a peak density of about 10^3 electrons per cubic centimeter in the daytime. At night, when electrons are no longer being generated by solar radiations, the free electrons disappear. Although the density of neutral particles is small enough to permit the electrons (in the daytime) to have an appreciable average life, it is nevertheless sufficiently large for col-

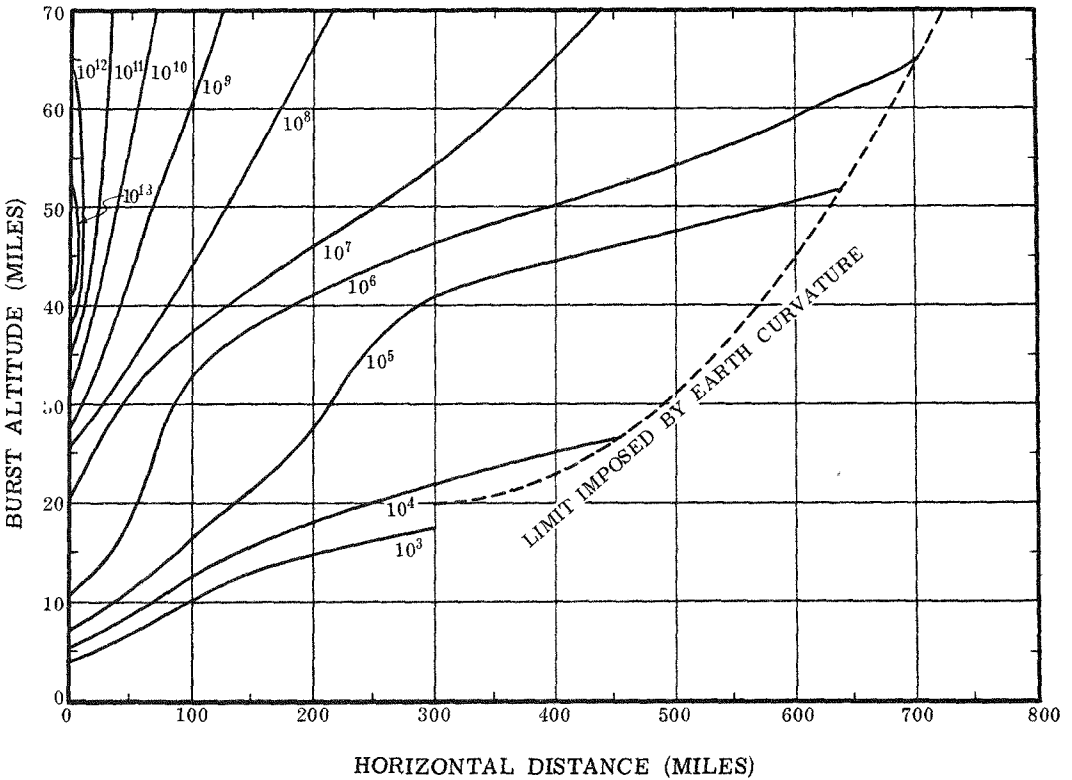

Figure 10.29. Calculated electron densities at an altitude of 45 miles produced by 1-megaton fission yield explosion at various burst heights as a function of horizontal distance.

of several thousand miles; as stated above, the distance over which ionization occurs is limited, however, by the curvature of the earth. For a detonation at 70 miles, for example, the earth's curvature prevents radiation from reaching the D-region at horizontal distances greater than about 700 miles.

10.34 The ionization produced by thermal X-ray and ultraviolet light, which is small at lower levels, becomes significant for nuclear detonations in the 40- to 70-mile altitude range. The X-rays, which carry as much as two-thirds of the explosion energy, have a tenth-value thickness of several miles in the air at these altitudes;[3] hence, the electron densities they produce will be high and will extend out to some distance from the point of burst. Figure 10.29, which shows the calculated electron densities at an altitude of 45 miles, produced from a 1-megaton fission yield explosion at various burst heights, includes the effects of X-rays as well as of initial gamma rays and neutrons. For bursts above 40 miles, the X-rays make the major contribution to the ionization.

10.35 Small amounts of ionization, which have been observed at distances up to 5,000 miles, within seconds of a high-altitude burst, have been attributed to the protons and electrons formed by the natural decay of neutrons (half-life about 13 minutes). The protons and electrons, being charged particles, follow the earth's magnetic field lines (§ 2.126), and produce ionization when they enter the atmosphere. Despite the fact that only a small percentage of the neutrons decay in the very short time they spend in the region of interest, the ionization is sufficient to cause a momentarily measurable effect in the lower ionosphere.

10.36 The ionization caused by delayed gamma and beta radiation is important for bursts in the 40- to 70-mile altitude range. Its intensity and location is determined by the location of the fission debris cloud, and the motion of the cloud for bursts in this altitude range is quite different from that for detonations at lower altitudes. Immediately after the time of burst, the thermal X-rays deposit about half of the total energy of the detonation within a few miles of the burst point. If the energy yield is in the megaton range, this energy will be sufficient to dissociate and ionize essentially all the molecules of oxygen and nitrogen in the air and raise the temperature of the region by several thousand degrees.

10.37 Prior to the burst, the air pressure in this region changes with altitude by an amount just sufficient to balance the force of grav-

[3] Because the thermal X-rays cover a wide range of energies (§ 7.80), they do not have a single tenth-value thickness (see § 10.83).

ity. The sudden increase in the temperature of the air causes a proportional increase in the pressure; hence, the pressure is no longer in balance with the gravitational force. This unbalance of forces causes the fireball to be hurled upward at high velocity, possibly as much as a mile per second. Consequently, the weapon debris reaches altitudes of several hundred miles, which are much higher than those to be expected if the rise were caused by buoyancy forces alone. Since the density of the air is extremely low, the particles will fall rapidly from these heights and within an hour will have reached an altitude of about 85 miles. Further fall will be much slower because of the increasing atmospheric density. The upward motion of the debris carries the radioactive particles into the regions where the gamma radiation has extremely long ranges. Thus, the gamma rays from fission residues will produce widespread ionization, although the electron concentration will be low because of the large volume involved. From a height of 300 miles, for example, the gamma rays will produce appreciable ionization in the D-region as far out as 3,000 miles, which is as far as the curvature of the earth will permit.

10.38 For the beta particles emitted by the radioisotopes in the weapon residues, a new situation arises for detonations at high altitudes. Because they carry an electrical charge, these particles follow a spiral path along the earth's magnetic field lines. As the radioactive debris from the burst rises and spreads, the beta particles will travel along the earth's magnetic field lines, about half moving toward the conjugate point in one hemisphere and the other half toward the corresponding point in the other hemisphere (§ 2.127). The particles will travel freely along the field lines at high altitudes, but will suffer collisions with atoms and molecules when they reach the denser air of lower altitudes. At about the D-region (45 miles altitude), the beta particles encounter air at a sufficient density to permit their absorption with accompanying ionization. There will thus be produced two (conjugate) volumes of ionization, one in each hemisphere, where the earth's magnetic field lines passing through the radioactive cloud encounter the D-region (see Fig. 2.127). Each of the volumes will be of roughly the same extent as the cloud and its effective vertical thickness will be about 10 miles, centered at an altitude of 45 miles. The electron density in each ionization volume will be approximately half that to be expected if the radioactive cloud were actually present at that particular location.

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Detonations Above 70 Miles Altitude

10.39 If the burst altitude is from 70 miles up to a few hundred miles, still another behavior pattern can be expected. The initial nuclear radiation and thermal ultraviolet and X-rays traveling downward will cause ionization over a large extent of the D-region, in the manner described above. The radiations going upward, however, will not encounter enough air molecules (or atoms) to be absorbed and most will escape the earth's atmosphere completely. Some widespread ionization of low intensity will be caused, however, by neutrons which decay in the earth's magnetic field, as described in § 10.35.

10.40 The effect of the residual beta and gamma radiation will be determined, as in other cases, by the location of the radioactive debris. The motion of these residues is difficult to predict exactly, but a qualitative picture can be presented. Immediately after the explosion, the weapon debris travels radially outward from the burst point at high velocity, most of the material consisting of fission product (and other) ions and free electrons because of the very high temperatures. At the lower altitudes, the radial motion is quickly stopped by the surrounding atmosphere and the ions and electrons soon re-combine to form neutral atoms. But at the extreme altitudes under consideration, the air density is too low, i.e., collisions between debris and ambient air atoms are too infrequent, to cause any appreciable deceleration of the outward motion of the radioactive particles. However, since the material consists largely of free ions and electrons, i.e., a plasma, the earth's magnetic field plays a significant part in stopping the radial expansion.

10.41 As stated earlier (§ 10.11), a plasma in a magnetic field always tends to exclude the field lines from its interior. Hence, when the weapon debris expands it will cause the earth's field lines to be "stretched" in such a way that they remain outside the conducting volume. This stretching of the lines of force requires that work be done on the field by the expanding debris and the expansion stops when the pressure has decreased to such a point that it is equal to the magnetic pressure (or energy density) of the field. For a 1-megaton fission explosion it is estimated that this would occur at a radius of 600 miles, whereas for a 1-kiloton weapon the radius would be 60 miles.

10.42 If the burst point is not too high, the weapon residues in moving downward will reach a region of appreciable air density, at an altitude of about 85 miles, before the earth's magnetic field halts the expansion; part of the debris will then be stopped and neutralized.

Because of the heating of the air by the thermal X-rays (§ 2.100), the radioactive material will probably be carried upward a short distance by the rising heated air. But it will settle again to an altitude of about 85 miles and be deposited in a circular layer, the radius of which is determined by the fission yield and altitude of the burst. This sheet will irradiate the D-region, the gamma rays producing widespread ionization of low intensity and the beta particles two regions of more intense ionization at locations on the magnetic field lines passing through the radioactive layer (§ 10.38).

10.43 The behavior of that part of the weapon debris which has been stopped by the magnetic field is somewhat uncertain. The distorted magnetic field will begin to recover and, in returning to their normal position, the field lines will probably cause turbulence and will tend to mix ambient air into the debris. Part of the debris will become electrically neutral, by recombination of the ions and electrons, and will no longer be affected by the magnetic field, so that it escapes from the region of confinement; the remainder, which is still charged, will be recompressed. Neutral particles of radioactive debris with sufficient energy and proper direction of motion will escape from the earth's gravitational field. The others will eventually settle to an altitude of about 85 miles and irradiate the D-region with the residual beta and gamma radiation, as described earlier.

10.44 The part of the debris which retains its charge for a longer time, and is confined by the magnetic field, will be in a position to release beta particles in locations and directions suitable for trapping in the earth's magnetic field. These particles, traveling back and forth, as described in § 2.129, and drifting eastward in longitude around the earth, will, within a few hours, spread to form a shell of high-energy beta particles, i.e., electrons, completely around the earth. In the ARGUS experiments, in which the bursts occurred at altitudes of about 300 miles (§ 2.54), well-defined shells, about 60 miles in thickness, were established and remained in place with measurable electron densities for many days. This has become known as the "Argus effect."

Time History of Ionization

10.45 After the ionization in the D-region has increased as the result of a nuclear detonation, the electron density will decay toward the normal value by electron-ion recombination and by electron-neutral particle attachment. If the electron density in the D-region exceeds about 10^6 electrons per cubic centimeter, recombination will

be the dominant process for electron removal both day and night; but if the density is below this value, recombination will predominate in the daytime and attachment at night (§ 10.85 *et seq.*).

10.46 The times required for various electron densities in the D-region to be decreased by a factor of 10 have been calculated and the results are summarized in Table 10.46. The significance of these times is as follows: after 1 second, day or night, all electron densities

TABLE 10.46

CALCULATED RECOVERY TIMES IN D-REGION OF IONOSPHERE

Electron Density (electrons/cm³)	*Time for density to decrease by factor of 10*	
	Day (sec)	*Night (sec)*
10^8 or greater decreased to 10^7	less than 1	less than 1
10^7	10	10
10^6	100	15
10^5	1,000	15
10^4	10,000	15

of 10^8 or more will have decreased to 10^7; densities of 10^7 or less will remain essentially unchanged. At 10 seconds later, day or night, the density of 10^7 will have dropped to 10^6, but densities of 10^6 or less will not be appreciably affected. Below a density of about 10^6, the recovery times for day and night are different; during the day, it takes 100 seconds for the electron density to decrease from 10^6 to 10^5, whereas at night the same change requires only 15 seconds. Densities below 10^5 will decrease relatively slowly in the daytime. Since the normal electron density in the D-region is 10^3 in the daytime and almost zero at night, the data in Table 10.46 show that it would take about 3 hours in the day and about 100 seconds at night for this region to recover completely from a sudden increase in the electron density.

10.47 By using the recovery times in Table 10.46 in connection with the curves in Fig. 10.29, it is possible to determine the time history of the ionization produced by the initial nuclear radiation and the thermal radiation from a 1-megaton fission explosion taking place at various altitudes. However, because of simplifications made in the calculations, the results, at best, represent orders of magnitude only. Furthermore, in regions where the ionosphere has been severely disturbed by the nuclear burst, electron densities may remain above 10^7 electrons per cubic centimeter for much longer than the 1 second indicated in Table 10.46.

10.48 The density of electrons produced by the residual beta and gamma radiations decreases at a rate which is somewhat more difficult

to estimate, because the ionization continues over an extended period of time. However, by combining the rates of removal of electrons by recombination and attachment with the rate of decay of the activity of the weapon residues, the results in Figs. 10.48 a and b have been obtained; they refer to 1-megaton fission detonations at altitude ranges of 10 to 40 miles and 40 to 70 miles, respectively. Two quantities are displayed on each figure: the radius to which the debris has expanded (which determines the region in which enhanced electron concentrations occur), and the associated D-region electron densities.

10.49 It is seen, for example, that at 1 hour after a 1-megaton burst in the 10- to 40-mile altitude range, an electron density of about 10^6 will extend over a region of radius 100 miles around the burst point, day or night. At 3 hours after the explosion, a density of 2×10^5 will be found out to a radius of 300 miles in the daytime, but at night the electron density out to this distance would be about 3×10^4 electrons per cubic centimeter.

EFFECTS ON RADIO AND RADAR SIGNALS

Introduction

10.50 The effects on radio communications systems of the atmospheric ionization produced by nuclear explosions at various altitudes depend on the type of system and in the particular manner in which the ionosphere is involved in transmitting the signals. The latter is determined, in turn, by the operating frequency of the system. It is convenient, therefore, to divide the discussion into sections corresponding to the conventional division of the communications spectrum into various decade frequency ranges. These ranges, with associated frequencies and wavelengths, are enumerated in Table 10.50.

Table 10.50

COMMUNICATIONS SPECTRUM

Name of Range	*Frequency Range**	*Wavelength Range*
Very-Low-Frequency (VLF)	3–30 kc	10^7–10^6 cm.
Low-Frequency (LF)	30–300 kc	10^6–10^5 cm.
Medium-Frequency (MF)	300 kc–3 Mc	10^5–10^4 cm.
High-Frequency (HF)	3–30 Mc	10^4–10^3 cm.
Very-High-Frequency (VHF)	30–300 Mc	10^3–10^2 cm.
Ultra-High-Frequency (UHF)	300 Mc–3 kMc	10^2–10 cm.

*The abbreviations kc, Mc and kMc refer to kilocycles (10^3 cycles/sec), megacycles (10^6 cycles/sec), and kilomegacycles (10^9 cycles/sec), respectively.

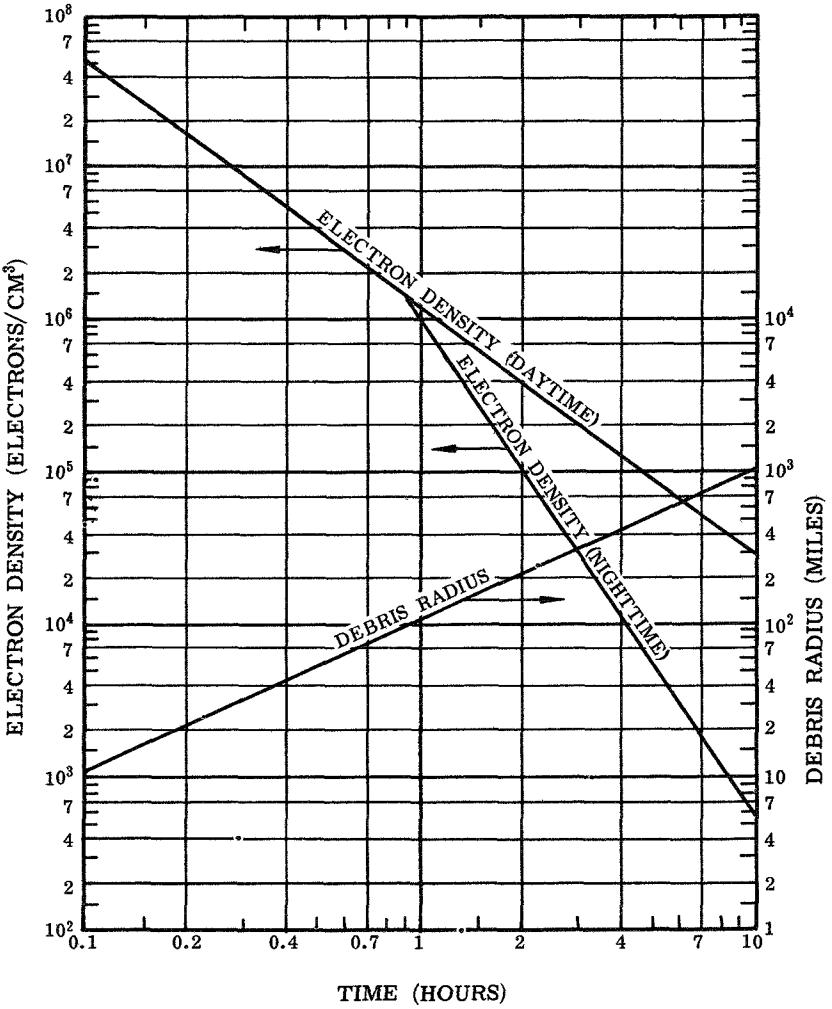

Figure 10.48a. Radius of debris expansion and corresponding D-region electron density as functions of time for a 1-megaton fission detonation in the altitude range of 10 to 40 miles.

Radar systems, which normally employ the frequency range of VHF or higher, are treated separately in § 10.64 *et seq.*

Very-Low-Frequency Range

10.51 Signals in the VLF range are transmitted by reflection

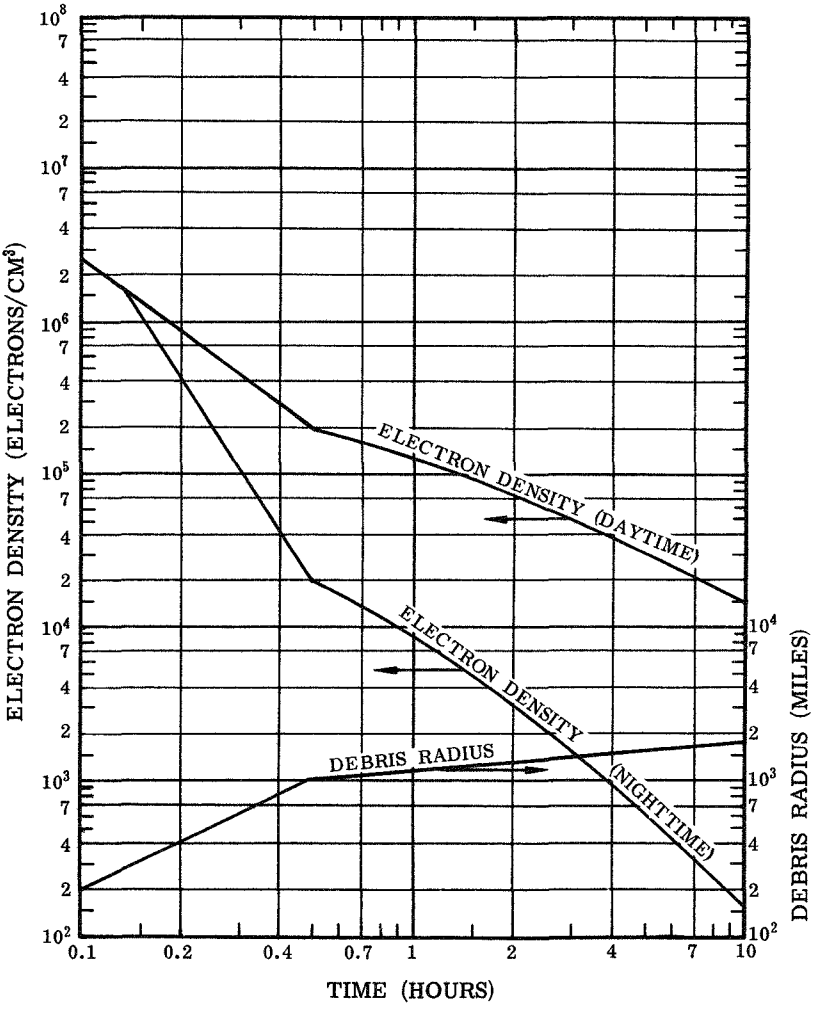

Figure 10.48b. Radius of debris expansion and corresponding D-region electron density as functions of time for a 1-megaton fission detonation in the altitude range of 40 to 70 miles.

between the surface of the earth and the extreme lower boundary of the ionosphere. At these frequencies, signals are reflected by such a slight change in electron density that they do not ordinarily penetrate into the ionosphere past the point where the electron density reaches 10^3 electrons per cubic centimeter. The wave may be regarded as traveling down a duct (or guide) whose boundaries are the earth and that level in the atmosphere at which the electron density is about

10^3 per cubic centimeter. Communication over distances of thousands of miles is possible by this mode.

10.52 Since the signal does not penetrate appreciably into the ionosphere, the additional ionization produced by a nuclear detonation does not cause any serious amount of attenuation. However, the actual distance the signal will travel between transmitter and receiver depends on the height at which the signal is reflected. If the electron density is rapidly increased, the waves will be reflected from a lower altitude and will travel a shorter total distance between transmitter and receiver; hence, the wave will arrive with a shift in phase. The most noticeable effect of a nuclear explosion on a VLF system will thus be a sudden phase shift of the signal at the time the ionosphere is disturbed. This will be followed by gradual recovery as the ionosphere returns to its normal state. Long-range gamma ray and neutron-decay beta ionization may alter VLF propagation conditions at very large distances from the detonation. In fact, after the TEAK and ORANGE high-altitude shots described in Chapter II, the 18.6-kilocycle signal transmitted from the Naval Radio Station at Seattle, Washington, to Cambridge, Massachusetts, suffered an abrupt 40° phase shift. The entire path was at least 3,000 miles from the burst point.

Low- and Medium-Frequency Ranges

10.53 For communications systems operating in the LF and MF regions of the spectrum, a different mode of propagation is normally utilized. Although there is a sky-wave mode, in which the signal is reflected repeatedly by the ionosphere and the ground, it is not normally relied upon for communication because of strong absorption. In the ground-wave mode, the signal is transmitted along the surface of the earth; it tends to bend and follow the curvature of the earth, particularly in regions where the surface is a good conductor of electricity. With reasonable amounts of transmitter power, it is possible to use this method for communication over distances of a few hundred miles. Thus, a high-altitude nuclear burst which changes the conditions in the ionosphere might have drastic effects on the sky-wave transmission but would not be expected to have any appreciable influence on the normally used ground-wave mode, in the LF and MF ranges of the radio spectrum.

The High-Frequency Range

10.54 The HF band is used extensively for long-range communications; the frequencies are high enough to accept information at a rapid rate and yet are sufficiently low to be turned back by the ionosphere. The signals are thus propagated from transmitter to receiver 500 to 5,000 miles away by successive reflections from the ionosphere and the surface of the earth. Each reflection results in some energy loss and so satisfactory operation can be achieved only if there are no more than three reflections from the ionosphere. Frequencies toward the lower end of the range, i.e., around 5 megacycles, are reflected by an electron density of 10^5 electrons per cubic centimeter, which is typical of the E-region, whereas the higher frequencies, e.g., about 20 megacycles, are reflected by the densities of 10^6 electrons per cubic centimeter normally found in the F-region of the ionosphere.

10.55 There are two main ways in which a HF system can be affected by the ionization produced by a nuclear explosion. First, if the signal passes through the D-region at a point where sufficient ionization is present, severe attenuation can result (§ 10.97) and communication will be interrupted. A density of about 10^3 electrons per cubic centimeter in this region is usually sufficient to affect transmission of the lower frequencies of the HF band, whereas about 10^4 electrons per cubic centimeter will interfere with the higher frequency end. From the results given earlier, it can be concluded that for bursts at altitudes below 10 miles no serious interference with HF communications is to be expected. For megaton-range detonations above 10 miles, it is seen from Fig. 10.29 that the initial nuclear radiation and thermal X-rays are sufficient to cause instantaneous disruption of HF signals passing sufficiently close to the burst point. For example, for a megaton burst at a height of 50 miles in the daytime, the effect would be felt out to distances of 600 miles. According to the data in Table 10.46, recovery from this effect would require from about 1,000 seconds (17 minutes) to roughly 10,000 seconds (3 hours), according to the frequency.

10.56 In addition to the initial radiations, the ionization due to the delayed nuclear radiation must be considered. It follows from Fig. 10.48a that a signal passing 500 miles from a megaton burst in the altitude range from 10 to 40 miles will be disrupted by radiation from the debris cloud 5 hours after the burst in the daytime and will not recover until several hours later. For a burst at an altitude of 40 to 70 miles, Fig. 10.48b indicates that a signal 500 miles distant will be affected within 15 minutes and will not recover for 10 hours

or more. At night, the electron density would drop below 10^4 electrons per cubic centimeter in 1 hour and below 10^3 in 4 hours, so that recovery would be expected in 1 to 4 hours. Comparison of Figs. 10.48 a and b shows that, as far as the delayed nuclear radiation is concerned, bursts at higher altitudes influence larger areas but the effects are of shorter duration. It should be remembered, too, that for bursts at 40 to 70 miles altitude there are two similar "blackout" regions due to beta particles, one in each hemisphere (§ 10.38).

10.57 In addition to those specifically considered above, there are other factors which in all cases can affect the duration of HF signal interruptions. Some examples of these other factors are: (1) communication circuit characteristics, e.g., power margin, (2) ionization produced by gamma rays from the weapon residues, (3) ionization at altitudes other than the D-region, and (4) miscellaneous aspects of propagation, e.g., signal refraction by electron density variations. Although some of these factors are important, so that predictions which ignore their influence are not accurate, it is probable that the general nature of the effects, at least, is in accord with the foregoing description.

10.58 The second and quite different manner in which HF communications may be affected by a nuclear explosion is the disturbance of the ionosphere by hydrodynamic motions. If the ionosphere is disturbed in any manner in the vicinity of one of the control points of an HF circuit, i.e., one of the locations in the ionosphere where the signal is reflected, disruption of communications over that circuit may be anticipated. For burst altitudes above 40 miles such disturbances can be expected to occur, despite the low atmospheric density. Just as for lower altitude bursts, a shock wave will be formed and transmitted radially in all directions from the burst. When that part of the shock front traveling upward and outward reaches altitudes corresponding to the E- and lower F-regions, it will encounter air of such low density that further propagation can occur with very little loss of energy. Thus, although the shock contains only a small fraction of the explosion energy, it will move outward for very long distances—possibly thousands of miles for a megaton burst—carrying with it most of the atmosphere in the upper E- and lower F-regions. The disturbance travels at about 2,000 miles per hour and after its passage the ionosphere will require from one to several hours to recover. If a HF system has one of its control points within 1,000 miles of a megaton burst in the altitude range from 40 to 70 miles, it will probably be disrupted for a period of an hour or more. Many instances of the interruption of HF propagation were observed in connection

with the TEAK and ORANGE shots. For example, a 15-megacycle signal from WWVH, Hawaii, which was being received at Hiraiso, Japan, was lost for several hours following the burst. The signal path in this case passed within about 600 miles of the point of detonation.

Very-High-Frequency Range

10.59 Signals in the VHF range are sufficiently penetrating to be able to pierce the normal ionosphere and escape from earth completely. This frequency range is primarily used for line-of-sight communications over short distances, e.g., commercial television channels and FM radio, but long-range communication is possible by making use of the small amount of transmitted energy that is scattered back to earth by patches of unusually intense ionization. The so-called "forward propagation ionospheric scatter" systems are inefficient, since only a minute fraction of the energy of the transmitter reaches the receiver, but they are nevertheless employed, to some extent, because of the demands on the electromagnetic spectrum.

10.60 The ionization from a nuclear burst affects ionospheric scatter systems in two ways. The enhanced electron density will tend to increase the fraction of the signal that is scattered and will thus improve reception; on the other hand, it will also absorb more of the signal energy and so tend to weaken it. No evidence is available from weapons tests concerning the relationship between these two effects, but theoretical studies and observations made during natural disturbances of the ionosphere indicate that they will roughly counterbalance one another, so that no net change is to be expected.

10.61 A side effect of the increased ionization in the ionosphere may be important for long-range scatter links. Transmitter and receiver are usually 500 to 1,500 miles apart and scattering occurs from ionized regions at heights of about 60 miles. If electron densities in the D-region reach 10^4 electrons per cubic centimeter, scattering will take place at altitudes of some 40 miles. Because of the curvature of the earth, a signal which reaches an altitude of only 40 miles will return to the surface at a maximum distance of 1,200 miles from the transmitter. Hence, communication over longer distances than this may be cut off for the time during which the D-region has a density of 10^4 electrons per cubic centimeter or more. The distances and times for which this density is exceeded may be obtained from Figs. 10.48 a and b.

Ultra-High-Frequency Range and Above

10.62 Frequencies in the UHF range and above are little affected by the electron densities normally occurring in the ionosphere. They are used for point-to-point (line-of-sight) communications between ground stations, aircraft stations, and between ground stations and satellites. The wavelength at a frequency of 300 megacycles is 1 meter, and signals of such wavelengths are scattered in the atmosphere, possibly because of variations in water vapor content, the presence of particulate matter, or other properties of the air. Use is made of this scattering, in the so-called "tropospheric scatter" systems, for communication over ranges up to 600 miles around the curve of the earth. Such systems, as well as those involving line-of-sight stations below the ionosphere, are essentially unaffected by nuclear bursts which disturb the ionosphere. They might be disrupted for a short time by a surface or low-altitude burst directly between the stations, but the effect would probably last no more than seconds.

10.63 For line-of-sight communication with satellites, the situation is different because the UHF signal does have to penetrate the ionosphere. The amount of attenuation caused by free electrons is less than for frequencies in the HF band. Consequently, it is expected that communications will not be greatly affected, provided the electron density does not exceed 10^7 electrons per cubic centimeter. It is seen from Table 10.46 that such high densities will not exist for more than about 1 second, except in the immediate vicinity of the burst where the atmosphere is disturbed. Nuclear blackout of ground-to-satellite communication will not be so serious as for some of the other systems which have been considered.

Effects on Radar

10.64 Radar systems are similar to radio communications systems in the respect that a transmitter and receiver of electromagnetic waves are used. However, in radar the receiver is located near the transmitter and may use the same antenna, which may be highly directional. The transmitted signal, consisting of a series of pulses, is in part reflected back to the receiver, like an echo, by objects in the path of the pulsed beam. From the direction of the antenna and the travel time of the signal, information can be obtained concerning the location and movement of the source of the echo. Frequencies normally employed in this connection are in the VHF range and above. As was seen in the discussion of effects on communica-

tion, there is little effect on signals of these frequencies so long as both the radar and the target are below the ionosphere.

10.65 If the signal must pass through the ionosphere, however, the interference from nuclear detonations becomes important. Radar signals traversing the ionosphere will, like radio signals, be subject to attenuation. Although any additional attenuation is undesirable, the amount which can be tolerated varies widely with the type of radar and the purpose of the system. In search radars, for example, where it is desired to detect each target at the greatest possible range, i.e., just as soon as the target return becomes observable against the background noise, even the smallest additional signal loss results directly in shortening of the range at which a given target can be detected. A tracking or guidance radar in a weapon system, on the other hand, usually takes over its target, well inside its maximum detection range, from another (search) radar which has already detected and tracked the object. In this case the signal may be attenuated to a much greater degree before the radar loses its ability to acquire or track. For this reason, subsequent discussion will be limited to estimating the amounts of attenuation to be expected without making any attempt to assess their significance.

10.66. Signal attenuation is expressed in terms of decibels (§ 10.76), where 1 decibel corresponds to a decrease in strength to roughly 0.8 of the original value; 2 decibels to about $(0.8)^2$, i.e., 0.64; 3 decibels to $(0.8)^3$, i.e., 0.51; 10 decibels to exactly 0.1; 20 decibels to 0.01; 30 decibels to 0.001 of the original value, and so on. For a radar system, a 12-decibel drop in power would result in a decrease in effective range by a factor of two.

10.67. As mentioned in §10.25, maximum attenuation effects occur mainly within a 10-mile range centered around an altitude of about 45 miles. In this region, which coincides with the D-region of the normal ionosphere, an electron density of 1 electron per cubic centimeter will cause a 10-megacycle signal to suffer an attenuation of about 4×10^{-5} decibel per mile of travel. For other electron densities and for higher signal frequencies, the attenuation is directly proportional to the electron density and inversely proportional to the square of the signal frequency. For frequencies below 10 megacycles, the frequency dependence is more complicated. The electron density information given in Fig. 10.29 and Figs. 10.48 a and b can thus be used to calculate attenuation effects for radar systems for frequencies of 10 megacycles or more.

10.68. As an example of the calculation of attenuation for a radar system, consider a 100-megacycle radar tracking a target above the

D-region 1.5 hours after a 1-megaton daytime explosion in the 10- to 40-mile altitude range. According to Fig. 10.48a, at this time an electron density of about 5×10^5 per cubic centimeter exists in the D-region within a 150-mile radius of the burst point. If the radar beam passes through this region, attenuation will occur. For a 10 megacycle signal and 1 electron per cubic centimeter, the attenuation would be 4×10^{-5} decibel per mile. For a frequency 10 times as great, this must be divided by 10^2. For an electron density of 5×10^5, and a frequency of 100 megacycles, therefore, the attenuation is $4\times10^{-5}\times5\times10^5/10^2=0.2$ decibel per mile. Since the region is 10 miles thick, a radar signal traversing the region and returning, in a vertical direction, will travel a distance of 20 miles through the attenuating region, so that the total attenuation for a signal traveling in the vertical direction would be $20\times0.2=4$ decibels.

10.69. If the signal makes an angle θ with the vertical, the distance traveled through the attenuating layer will be increased by a factor of $1/\cos\theta$, i.e., $\sec\theta$, and the attenuation in decibels is obtained upon multiplying the value for the vertical signal by this factor. For example, if the radar beam is at 80° to the vertical direction, the correction factor is $1/\cos 80°$, i.e., roughly 6. Hence, the total attenuation would be $6\times4=24$ decibels.

10.70. In many instances, refraction of a radar beam, as a result of variation in electron density, can be as important as attenuation. Figure 10.70 shows the amount of bending (or refraction) which will occur when a 100-megacycle radar beam encounters an electron density *change* of 10^6 electrons per cubic centimeter. The amount of bending is directly proportional to the electron density change and inversely proportional to the square of the signal frequency, so the figure may be used for other electron density changes and signal frequencies. It applies, however, only for frequencies greater than 10 megacycles, and angles of refraction less than 5°. Since the electron density below the D-region is essentially zero, Fig. 10.70 will provide a rough estimate of the amount of bending suffered by a radar beam entering the D-region from below. For example, if the D-region electron density were 10^6, and if a 100-megacycle beam were incident at an angle of 70°, i.e., 70° angle with the vertical, the bending would be about 0.8°.

10.71. For some large angles of incidence, θ, reflection will occur and the radar signal will be turned back without passing through the attenuating region. The values of the angle θ for various electron densities and signal frequencies are given in Fig. 10.71. It can be used in conjunction with Fig. 10.29 and Figs. 10.48 a and b to deter-

mine whether a radar beam will suffer total reflection under particular circumstances associated with a 1-megaton, high-altitude explosion.

10.72. Other disruptions of radar signals may occur as a result of ionization from a nuclear detonation. The ionization produced tends to become nonuniform and to align itself in columns of differing density along the direction of the earth's magnetic field. These irregu-

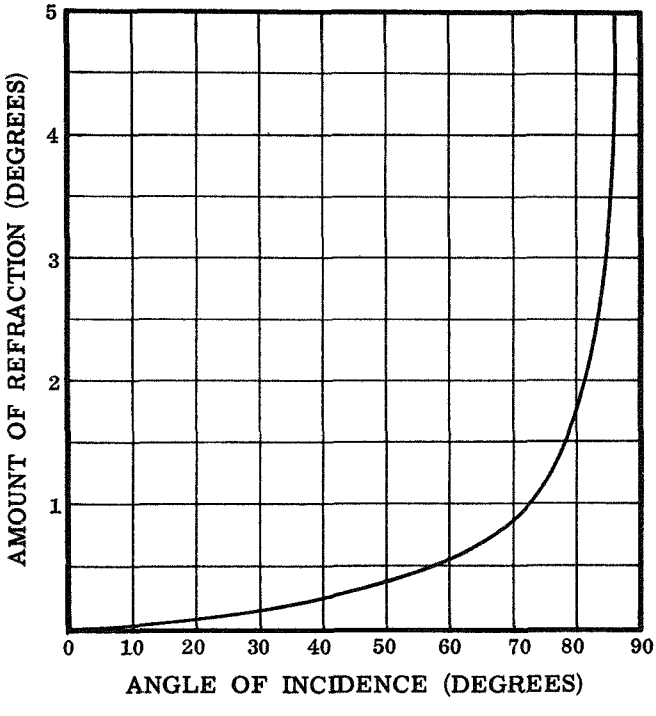

Figure 10.70. Refraction of 100-megacycle radar beam by an electron density change of 10^6 electrons/cm^3 as function of angle of incidence.

larities can disrupt the radar beam causing an effect similar to the "twinkling" of stars, and "clutter" or false echoes from ionized patches. However, not enough is known of these phenomena to permit a quantitative description.

Effects of Surface and Subsurface Bursts

10.73 It has already been seen that bursts at altitudes below 10 miles do not produce sufficient quantities of persistent ionization to

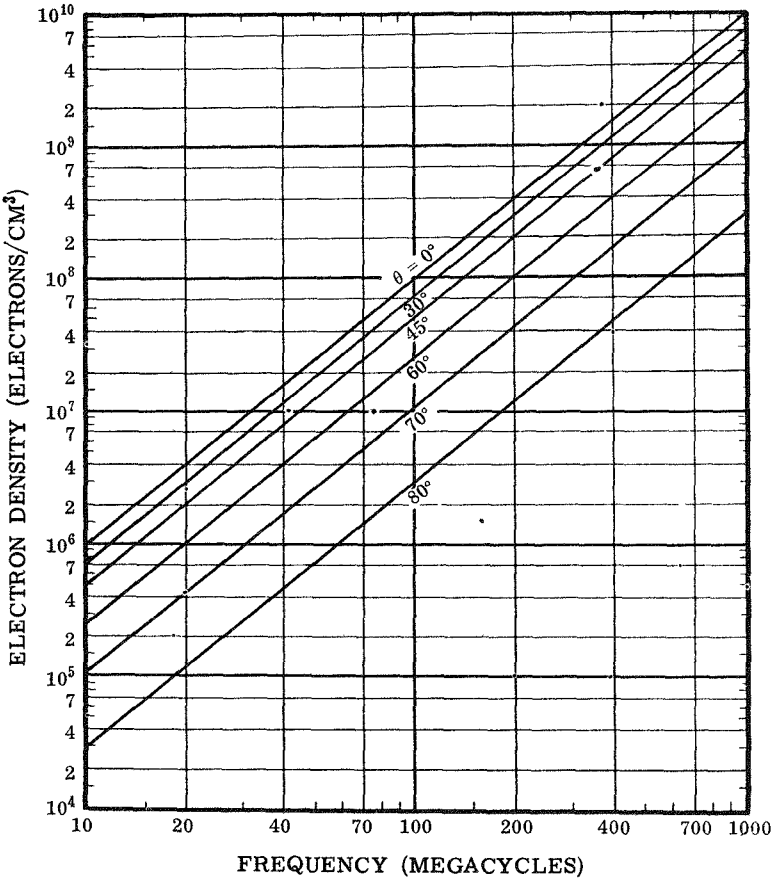

Figure 10.71. Angles of incidence for reflection of radar beam as function of frequency and electron density.

cause serious effects on radio or radar systems. For surface and subsurface (land or water) bursts, particulate matter or water introduced into the atmosphere by the nuclear explosion can cause some disturbance of radio wave propagation. Particles of dust, debris, water droplets, or ice crystals in the cloud formed by a detonation can act as reflectors for some electromagnetic signals. A particle is an efficient reflector of an electromagnetic wave if its size is somewhat comparable to the wavelength. Most of the particles are quite small (1 mm or less in diameter), whereas the shortest wavelengths for radars in general use (X and K bands) are 1 to 6 centimeters. Nevertheless, there are sufficient numbers of particles of the appropriate

size present in the early stages after an explosion to produce echoes in X- or K-band radars. This condition may last for minutes or hours, depending on the weapon yield, the nature of the particles picked up by the burst, and the rate at which the cloud spreads in the atmosphere. Because of the small size of the particles, electromagnetic radiation of longer wavelengths, associated with lower frequency radar or with radio communications systems, will not be affected.

TECHNICAL ASPECTS OF RADIO AND RADAR EFFECTS[4]

Density of Atmosphere and Altitude

10.74 The density of the atmosphere from the surface of the earth up to an altitude of about 80 miles can be represented with fair accuracy by the formula

$$\rho \approx \rho_0 e^{-z/4.3}, \qquad (10.74.1)$$

where ρ_0 is the sea-level density and ρ is the value, in the same units, at an altitude of z miles. For higher altitudes, the density decreases somewhat more slowly than is implied by equation (10.74.1), but since altitudes below 80 miles are of primary interest for the present purpose, the simple exponential relationship will be employed.

10.75 It follows from equation (10.74.1) that the air density decreases by a factor of e, i.e., 2.72, for every 4.3 miles increase in altitude. By writing the expression in the alternative form

$$\rho \approx \rho_0 10^{-z/10},$$

it is seen that the density changes by a factor of roughly 10 for every 10 miles of altitude. Thus, any property of the atmosphere which is proportional to the air density changes by an order of magnitude for a change of 10 miles in altitude.

Signal Attenuation

10.76 The decibel, which is used to express electromagnetic (and other) signal attenuation, is defined by

$$\text{Attenuation in decibels} = 10 \log \left(\frac{P_{\text{in}}}{P_{\text{out}}} \right),$$

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

where P_{in} is the signal power before attenuation and P_{out} that after attenuation. When an electromagnetic signal travels through an ionized medium, the attenuation A, expressed in decibels per mile of path, is

$$A=\frac{2.9\times10^4 N\nu}{\omega^2+\nu^2}, \tag{10.76.1}$$

where N is the electron density, i.e., number of electrons per cubic centimeter, ν is the number of collisions per second which an electron makes with ions or atoms, and ω is the (angular) frequency of the wave (in radians per second). It follows from equation (10.76.1) that if the collision frequency ν is small then, for a given wave frequency, A will be small because of the ν in the numerator. On the other hand, if ν is very large, A will again be small because of the ν^2 in the denominator. Thus, the attenuation passes through a maximum for a particular value of the collision frequency.

10.77 Since the collision frequency is proportional to the density of the air, it will decrease exponentially with altitude. It is to be expected, therefore, that the values of ν for which attenuation of signals is important would occur only within a relatively narrow altitude region. More complete theoretical studies show that the attenuation occurs mainly within a 10-mile range centered about an altitude of about 45 miles. In addition, it has been found that the greatest electron densities accompanying nuclear detonations generally occur at approximately this same altitude. Hence, by confining attention to the situation in the neighborhood of a 45-mile altitude, it is possible to avoid complexities and yet present a reasonably accurate picture of the effects of the burst on electromagnetic signals.

Electron Densities From Initial Radiations

10.78 An estimate of the electron density produced at a given distance from a nuclear burst by gamma radiation can be obtained by utilizing a slight modification of equation (8.98.1); as before, the weapon is treated as a point source. Let W kilotons be the total energy yield of the explosion and k the fraction which appears as initial gamma radiation; then the gamma-ray energy, E kilotons per unit area, arriving at a given point at a distance (slant range) D from the detonation is

$$E=\frac{kW}{4\pi R^2}\, e^{-\bar{\mu}D}, \tag{10.78.1}$$

where $\bar{\mu}$ is an effective (or average) linear absorption coefficient along the path of the radiation.

10.79 The average coefficient, $\bar{\mu}$, may be expressed in terms of the linear absorption coefficient, μ, at any point distant D' from the explosion by

$$\bar{\mu}=\frac{1}{D}\int_0^D \mu dD'. \tag{10.79.1}$$

The mass absorption coefficient, μ_m, is equal to μ divided by the density (§ 8.79); that is,

$$\mu=\mu_m\rho.$$

Upon substituting this result, together with equation (10.74.1), into equation (10.79.1), it is found that

$$\bar{\mu}=\frac{\mu_m\rho_0}{D}\int_0^D e^{-z/4.3}\,dD'. \tag{10.79.2}$$

If the detonation occurs at an altitude H_0, and H is the altitude of the observation point at a slant distance D from the explosion, where H may be either above or below H_0, then changing the variable in equation (10.79.2) leads to

$$\bar{\mu}=\frac{\mu_m\rho_0}{H-H_0}\int_{H_0}^H e^{-z/4.3}\,dz.$$

Replacing $\mu_m\rho_0$ by its equivalent, μ_0, the linear absorption coefficient of air at sea level, and performing the integration, the result is

$$\bar{\mu}=\frac{4.3\mu_0}{H-H_0}\,(e^{-H_0/4.3}-e^{-H/4.3}). \tag{10.79.3}$$

10.80 The gamma-ray energy absorbed per unit volume of air at the point under consideration, i.e., altitude H, is equal to $E\mu$, where E is given by equation (10.78.1) and μ is the absorption coefficient [5] at altitude H. As seen above, μ may be written as $\mu_m\rho$, and ρ may be expressed in terms of ρ_0 by equation (10.74.1); hence,

$$\text{Energy absorbed per unit volume}=E\mu_m\rho_0e^{-H/4.3}$$
$$=E\mu_0e^{-H/4.3}.$$

[5] Since all the gamma-ray photons are ultimately absorbed in the atmosphere, μ is employed here instead of the conventional energy absorption coefficient.

Since 1 kiloton of explosion energy is equivalent to 4.2×10^{19} ergs (Table 1.41) and 1 electron volt is 1.6×10^{-12} erg (§ 1.39), it follows that 1 kiloton is equal to 2.6×10^{31} electron volts. It requires 34 electron volts to produce one ion pair, and hence one electron, in air; consequently, the number of free electrons, N, produced per unit volume is

$$N=\frac{2.6\times10^{31}}{34}E\mu_0e^{-H/4.3},$$

where E is expressed in kilotons per unit area, i.e., by equation (10.78.1). Upon substituting from equations (10.78.1) and (10.79.3), the result is

$$N=\frac{6.2\times10^{28}\mu_0kW}{D^2}e^{-(x+H/4.3)}, \tag{10.80.1}$$

where

$$x\equiv\left[\frac{4.3\mu_0D}{H-H_0}(e^{-H_0/4.3}-e^{-H/4.3})\right].$$

In equation (10.80.1), H and H_0 are in miles, W in kilotons, μ_0 in reciprocal centimeters, and D in centimeters, to give N in electrons per cubic centimeter. It was seen in § 8.100 (footnote) that, for the initial gamma radiations, the relaxation length, λ, which is equivalent to $1/\mu_0$, is about 325 yards for sea-level air density; hence, μ_0 is close to 3.0×10^{-5} reciprocal centimeters. The energy of the initial gamma radiation leaving the exploding weapon is estimated to be about 0.03 percent of the total energy so that k is 3×10^{-4}. Hence, all the information is available to permit the use of equation (10.80.1) for calculating the electron density produced by the initial gamma rays.

10.81 Equation (10.80.1) can also be employed, in principle, to estimate the electron density produced by the neutrons present in the initial radiation. However, the situation is somewhat complicated for various reasons. In the first place, the proportion of the total energy yield which appears as energy of the escaping neutrons varies widely with the nature and design of the weapon. Furthermore, neutrons produce ionization in air as the result of a number of indirect processes, which vary with the altitude. Since the sea-level mean free path for weapon neutrons is not greatly different from that for the initial gamma radiation, and since the ultimate result of the neutron processes is the production of ionization, a very crude estimate of electron density produced by the neutrons in the initial nuclear radiation may be made as follows. From the data in Chapter VIII, it is known that the amount of energy carried by the neutrons leaving

an exploding weapon may range from 1 to 40 times the energy in the initial gamma radiation. For the purpose of making an order-of-magnitude estimate, it is assumed that the electron density produced by both gamma rays and neutrons present in the initial nuclear radiation is equal to 10 times that resulting from the gamma rays alone.

10.82 The electron density produced by the gamma rays can be determined from equation (10.80.1) and the results obtained in this manner were multiplied by 10 to give the data used to plot the curves in Fig. 10.82. These curves give approximate electron densities produced by the initial nuclear radiation at various horizontal distances at a height (H) of 45 miles for a 1-megaton weapon detonated at various altitudes (H_0). The broken cut-off line indicates where the curvature of the earth prevents the nuclear radiations from reaching the 45-mile altitude.[6]

10.83 For altitudes which are sufficiently high for the thermal X-rays to have appreciable mean free paths (or relaxation lengths) the electron densities produced may also be calculated by means of equation (10.80.1). However, since these radiations cover a wide range of frequencies (or wavelengths), there is not a single relaxation length (or absorption coefficient), since the latter varies with energy of the photon in accordance with equation (7.84.1). To make an order-of-magnitude estimate of the ionization produced by thermal X-rays, a round-number temperature of 10^7 degrees Kelvin was assumed for simplicity, as in § 7.84. The radiant power distribution as a function of wavelength (or photon energy) was then obtained from Fig. 7.79. The photons over the whole spectrum were divided into five energy groups, and each group was assigned a separate mean free path in accordance with equation (7.84.1). Then equation (10.80.1) was applied to each individual group and the results added; the value of k was taken to be 0.67, i.e., two-thirds of the explosion energy was assumed to be emitted as the initial thermal radiation capable of producing ionization in air. In this way, the curves in Fig. 10.83 were obtained for the electron densities produced at an altitude of 45 miles by the thermal X-rays from a 1-megaton fission yield explosion.[7]

10.84 The curves in Fig. 10.29 were obtained by addition of the data in Figs. 10.82 and 10.83. Hence, they represent the electron densities that may be expected at an altitude of 45 miles from all

[6] The calculations are based on the so-called "flat earth" model, but with the horizontal distance limited by the earth's curvature. It is assumed that the initial nuclear radiations do not penetrate the atmosphere below an altitude of 15 miles.

[7] The same model was used as for the initial nuclear radiations except that the cut-off due to the earth's curvature was taken at an altitude of 20 miles, rather than 15 miles, because the thermal X-rays are more readily absorbed by the atmosphere.

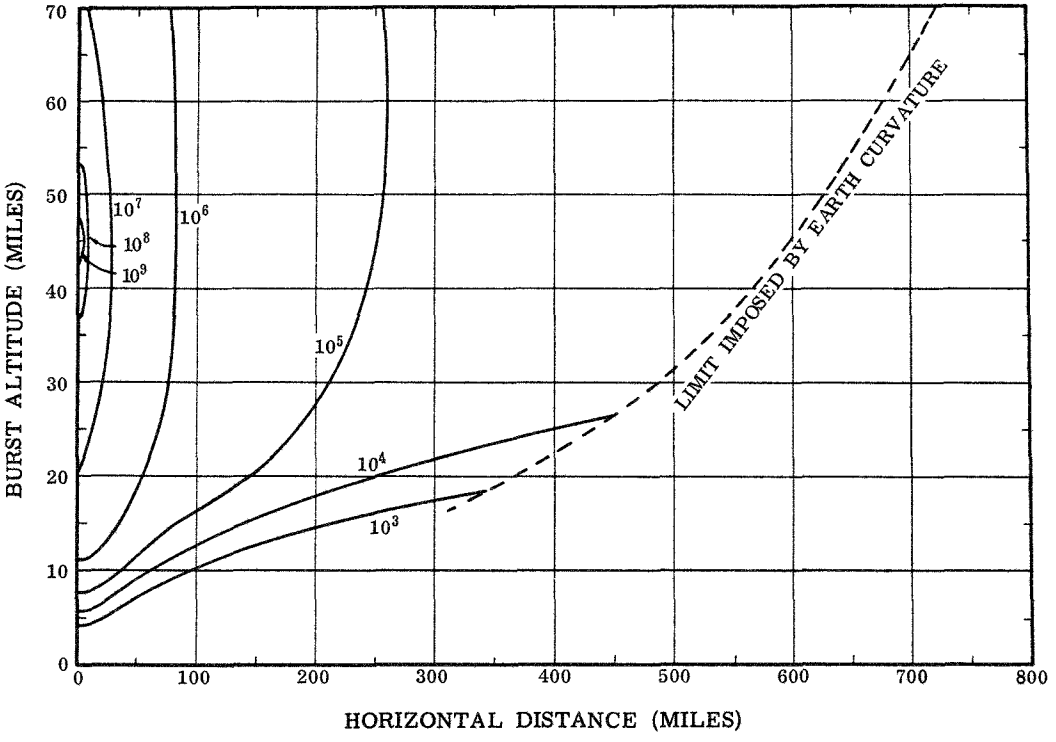

FIGURE 10.82. Calculated electron densities at an altitude of 45 miles produced by the initial nuclear radiations from a 1-megaton fission yield explosion at various burst heights as a function of horizontal distance.

lisions to cause considerable attenuation of the electromagnetic waves, in the manner described in §10.14.

10.20 In the E-region of the ionosphere (50 to 80 miles altitude), the air density is quite low, about 10^{-5} to 10^{-8} of the sea-level value, and the average lifetime of electrons is even longer than in the D-region. The peak daytime electron density is about 10^5 electrons per cubic centimeter, but most of the ionization, as in the D-region, disappears at night. However, because of the very low density of neutral particles, the frequency of collisions between them and electrons is so small that there is relatively little attenuation of electromagnetic signals.

10.21 Above an altitude of 80 miles is the F-region of the ionosphere. Here the neutral particle density is so low that free electrons have extremely long lifetimes. At an altitude of about 160 miles, the peak daytime density is about 10^6 electrons per cubic centimeter, decreasing to about 10^5 at night. At lower altitudes, the nighttime density is somewhat less than this value. Attenuation of electromagnetic signals in the F-region is small despite the high electron density, because of the very low electron-neutral collision frequency, but refraction effects are important.

10.22 When a radio (or radar) wave travels upward, it commences to be refracted (or bent) when it reaches the D-region, where the first increase in electron density is encountered. As it penetrates into this region, where the electron density increases toward the peak value, more and more bending occurs so that, if the angle of incidence is not too small, the wave may actually be refracted back toward the earth. This process is frequently referred to as "reflection", although it is not the same as true reflection, in which there is no penetration of the ionized layer of air. True (or specular) reflection does occur, to some extent, especially for the lowest radiofrequencies; there will be reflection, as for visible light, when the sine of the angle of incidence is equal to (or exceeds) the refractive index of the ionized region. If the angle of incidence is fairly small, the electromagnetic wave will not be refracted sufficiently in the D-region to be returned to earth, but it will penetrate into the E-region or even into the F-region where the peak electron densities are higher and then be turned back. Normally there is very little reflection in the D-region; electromagnetic waves of higher frequencies, e.g., about 1 megacycle or more, used for communication purposes are generally reflected in the E- and F-regions.

IONIZATION PRODUCED BY NUCLEAR EXPLOSIONS

Introduction

10.23 Both nuclear and thermal radiations from a nuclear explosion can produce ionization in the air, and anywhere from 10 to 75 percent of the total energy yield, depending on the height of burst, may be expended in this respect. Utilizing the value of 34 ev as the amount of energy required to produce one ion pair in air, it is found that if only 10 percent of the energy of a megaton weapon were utilized for this purpose, a total of about 10^{32} free electrons would be formed. This is approximately equal to the number of free electrons in the entire normal ionosphere. Since many communications systems are profoundly affected by, or are even dependent upon, the ionospheric ionization, it is apparent that major consequences to such systems are possible as the result of a nuclear explosion.

10.24 In the subsequent treatment of the manner in which the electron density in the ionosphere can be affected by nuclear detonations, various burst height ranges, associated with different mechanisms, will be considered. It should be understood, however, that these ranges are somewhat arbitrary and are chosen for convenience in bringing out the changes in behavior that occur with burst height. Actually, there are no lines of demarcation between the various altitude ranges; the changes are continuous, but one type of mechanism gradually supersedes another and becomes the dominating one in each of the indicated regions.

10.25 For electromagnetic waves in the radio and radar range, circumstances are such that the maximum attenuation effects occur mainly within a 10-mile range centered around an altitude of about 45 miles. Hence most of the subsequent discussions pertain to this relatively narrow altitude region, which coincides with the D-region of the normal ionosphere.

Detonations Below 10 Miles Altitude

10.26 For nuclear detonations at altitudes below about 10 miles, much of the ionization produced in the surrounding air by the initial gamma radiation and neutrons and also by the thermal X-rays will be contained within a few hundred yards of the fireball. These free electrons will attach themselves almost immediately to neutral particles in the atmosphere, so that they will have a very short lifetime.

Within the fireball, the high temperature, of the order of a million degrees or so, will produce considerable ionization for a small fraction of a second. During this short period the free electron density in the fireball region will be sufficient to cause some attenuation of electromagnetic signals in the immediate vicinity of the burst. This effect will, however, disappear in a matter of seconds.

10.27 As the fireball rises, the residual nuclear radiation, mainly beta particles and gamma rays from the fission products and other weapon debris, will produce ionization in the immediate vicinity. Since the air density is quite appreciable, the free electrons will be rapidly removed by attachment to neutral particles and so their density will remain low. Consequently, unless the radioactive cloud rises to considerable heights, e.g., 20 miles or more, there will be little effect on radiofrequency wave propagation, in spite of the continuous emission of beta particles and gamma rays.

10.28 For explosions with yields in the megaton range, the radioactive cloud may rise to heights of more than 20 miles. The gamma radiation is emitted in all directions and although that going downward is of little consequence, as stated above, the situation is different for the rays traveling upward, into regions of low air density. The tenth-value thickness (§ 8.34) for absorption of the residual gamma radiation at altitudes of over 20 miles is more than 12 miles. Consequently, an appreciable proportion of the gamma rays will reach the D-region of the ionosphere and free electrons produced there will persist for several minutes. The continued emission of gamma radiation from the weapon residues in the radioactive cloud will then result in the build-up of a considerable concentration of electrons. Hence, a large-yield explosion at a fairly low altitude can cause abnormally high electron densities in the D-region that persist for several hours after the burst.

Detonations at 10 to 40 Miles Altitude

10.29 If the burst occurs in the altitude range of roughly 10 to 40 miles, where the air density is low, some of the initial nuclear radiations (gamma ray and neutrons) and, to a minor extent, the thermal X-rays will reach the D-region and cause significant amounts of ionization there. The approximate calculated electron densities at an altitude of 45 miles, where the densities are expected to be maximal (§ 10.77), resulting from a 1-megaton fission yield explosion at various burst heights, are shown in Fig. 10.29 as a function of

horizontal distance.[2] For example, for a 1-megaton burst at a height of 30 miles, the electron density in the D-region (45 mile altitude) is 10^7 electrons per cubic centimeter at a horizontal distance of 40 miles, 10^6 at 80 miles, and so on. The horizontal distance over which the ionization occurs is limited by the curvature of the earth to the portion of the D-region that is in line-of-sight of the explosion, as shown by the broken curve in Fig. 10.29.

10.30 The lifetime of the electrons produced in the D-region is not known with any degree of accuracy, but it will probably be a few minutes (see § 10.46). As the electrons are removed, by attachment to neutral particles or by recombination with ions, more free electrons are produced by the beta particles and gamma rays from the fission products, etc., in the rising fireball. The electron density will depend on the altitude attained by the weapon residues and this will vary with the explosion yield and the height of burst.

10.31 The fission debris cloud from a 1-megaton detonation in the lower atmosphere will attain a height of 20 miles or so; hence, from a burst of the same yield at an altitude of 20 miles, the cloud may be expected to reach a height of about 40 miles above the earth's surface. The air density at this altitude is so low that the tenth-value thickness of the residual gamma rays will be over 2,000 miles, and hence ionization will be produced over a large area extending horizontally a great distance from the radioactive cloud. The beta particles will have a total range of about 20 miles, so that the ionization accompanying their absorption will occur in the vicinity of the cloud. The resulting electron density will depend on the density of the radioactive debris, on the time since the explosion, and on the lifetime of the free electrons. Some estimates of the electron densities are given in § 10.48.

10.32 Outside the cloud, except in that portion of the D-region below it, the electron densities produced by the gamma radiation will be small. However, the gamma rays traveling downward enter a region of somewhat higher air density. They are consequently absorbed within a shorter distance and may produce significant electron densities.

Detonation at 40 to 70 Miles Altitude

10.33 For bursts at altitudes of approximately 40 to 70 miles, the initial gamma rays and neutrons have tenth-value thicknesses

[2] It should be noted that the curves show only the electron densities produced by the nuclear explosion and do not include the ionization caused by sunlight or arising from other natural causes.

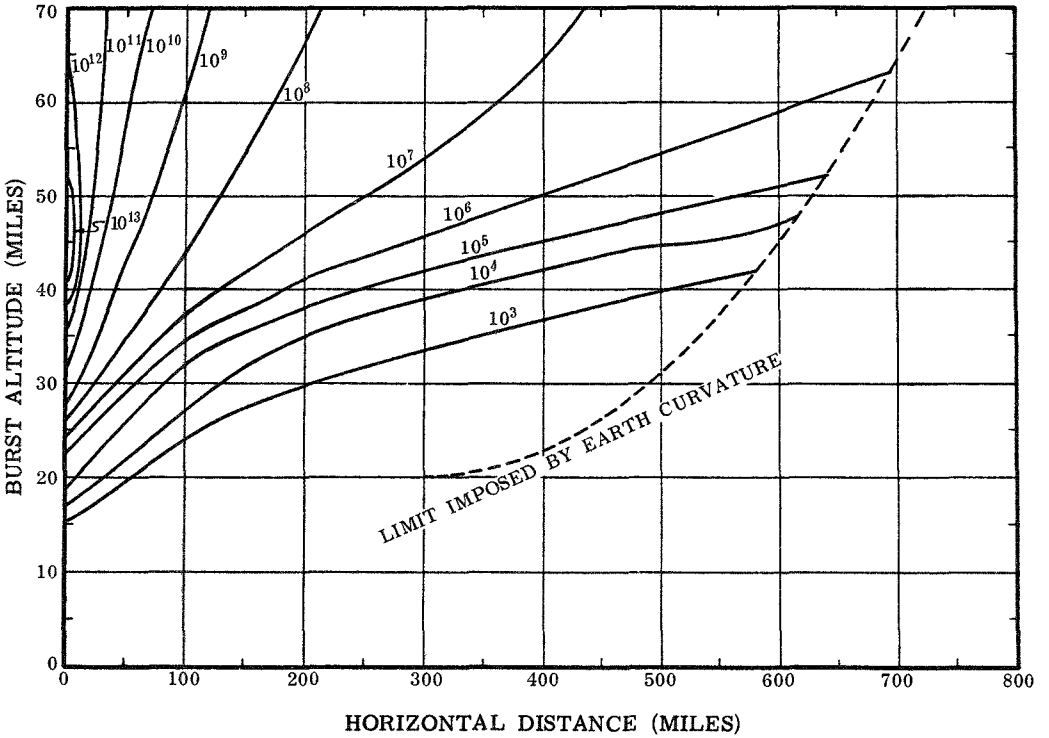

Figure 10.83. Calculated electron densities at an altitude or 45 miles produced by the thermal X-rays from a 1-megaton fission yield explosion at various burst heights as a function of horizontal distance.

the ionizing radiations emitted at the time of the explosion of a 1-megaton weapon at various heights. Comparison of the three figures shows that for burst heights below about 40 miles the ionizing effect of the initial nuclear radiations is predominant, but at higher burst altitudes the thermal X-rays produce essentially all the electrons.

Rate of Disappearance of Free Electrons

10.85 Free electrons are removed either by attachment to neutral atoms or molecules or by recombination with positive ions. In the daytime, recombination is the only significant mechanism because sunlight tends to remove an electron immediately it becomes attached to a neutral particle. The recombination rate is proportional to the densities of both electrons (N) and ions (N_i) so that

$$\text{Recombination rate} = \alpha N N_i, \qquad (10.85.1)$$

where α is the proportionality constant, called the "recombination coefficient." The numbers of electrons and positive ions per unit volume are essentially equal, since the region of the atmosphere is electrically neutral as a whole; hence, N_i is equal to N and equation (10.85.1) may be written

$$\text{Recombination rate} = \alpha N^2. \qquad (10.85.2)$$

For the normal ionosphere, e.g., at an altitude of about 45 miles, α is approximately 10^{-7} in second per cubic centimeter units, and so the number of recombinations per cubic centimeter per second is given by

$$\text{Recombination rate} = 10^{-7} N^2. \qquad (10.85.3)$$

10.86 At night, electron attachment to neutral particles becomes significant. The attachment rate is proportional to the densities of electrons (N) and of neutral particles (N_n) so that

$$\text{Attachment rate} = \beta N N_n,$$

where β is the "attachment coefficient"; for an altitude of 45 miles, β is about 10^{-16} second per cubic centimeter. At this altitude, there are some 1.6×10^{15} neutral particles per cubic centimeter, and so the nighttime attachment rate, expressed as number of attachments per cubic centimeter per second, is

$$\text{Attachment rate} = 10^{-16} \times 1.6 \times 10^{15} N = 0.16N. \qquad (10.86.1)$$

By comparison with equation (10.85.3) it is seen that attachment is the chief mode of electron removal at night if N is less than 1.6×10^6, but recombination is the more important when N exceeds 1.6×10^6 electrons per cubic centimeter. Hence, for electron densities greater than 1.6×10^6, equation (10.85.3) should be used for nighttime as well as daytime.

10.87 If N_0 is the electron density produced by the initial nuclear radiations and thermal X-rays at the instant of the nuclear explosion, and no further ionization occurs, it follows from equation (10.85.3) that the electron density N at a time t seconds later is

$$N=\frac{N_0}{1+10^{-7}N_0t}. \qquad (10.87.1)$$

Provided no additional ionization occurs, this expression is applicable if N_0 is the density at any arbitrary starting time. If N_0 is very large, e.g., greater than 10^8, then at times of 1 second or later, unity in the denominator of equation (10.87.1) can be neglected, so that

$$N\approx10^7t^{-1}.$$

At the end of 1 second, therefore, i.e., when $t=1$, the electron density will have fallen to 10^7 electrons per cubic centimeter, no matter what its initial (high) value. Furthermore, it can be shown from equation (10.87.1) that, in the daytime, it requires 10 seconds for the density to decrease from 10^7 to 10^6; 100 seconds from 10^5 to 10^4, and so on; these are the values given in Table 10.46.

10.88 If the initial electron density at night is greater than 1.6×10^6, the results derived above for daytime are applicable, but for lower densities equation (10.86.1) must be used; the nighttime electron density at any time t is then given by

$$N=N_0e^{-0.16t}\approx N_010^{-0.070t}.$$

This formula shows that, after the electron density falls to 1.6×10^6 at night, the density subsequently decreases by a factor of e every 6 seconds or by a factor of 10 every (roughly) 15 seconds. Thus, the electron density will drop at night from its initial high value to 10^7 in about 1 second, according to the daytime formula, then to 10^6 in roughly 10 seconds, and subsequently by a factor of 10 every 15 seconds, as shown in Table 10.46.

Electron Densities From Delayed Radiation

10.89 At 1 hour after a nuclear explosion, the total delayed beta-particle activity is estimated to be about 400 beta-megacuries per kiloton of fission energy, and since 1 beta-megacurie represents 3.7×10^{16} decays per second (§9.163), the rate of beta-particle emission is 1.5×10^{19} per second per kiloton. If the $t^{-1.2}$ rule for the decay of weapon residues is assumed to be applicable (§ 9.171), it follows that for a W-kiloton fission explosion

$$\text{Rate of beta-particle emission} = 1.5\times10^{19}Wt^{-1.2} \text{ per second}, \tag{10.89.1}$$

where t is the time in hours after the explosion. The average energy per particle may be taken as approximately 1 Mev, i.e., 10^6 ev, and since it requires 34 ev to produce one ion pair, i.e., one electron and one positive ion, in air, it follows that

$$\text{Rate of production of free electrons} = 4.4\times10^{23}Wt^{-1.2} \text{ per second}. \tag{10.89.2}$$

The energy of the delayed gamma rays from the weapon residues is approximately equal to that of the beta particles and if it is assumed that the $t^{-1.2}$ decay rule is obeyed, the rate of production of free electrons by the gamma rays is also given roughly by equation (10.89.2).

10.90 The actual electron densities established will depend on where the free electrons are produced and on how long they remain free. If a fairly steady source produces S electrons per cubic centimeter per second, the electron density will increase until the rate of removal, e.g., by recombination in the daytime, will just equal the rate of production and then will remain at that value; thus, using equation (10.85.2) for the recombination rate, it follows that, in the daytime,

$$S=\alpha N^2,$$

where N is the steady-state electron density attained.

10.91 It was seen in §10.38 that when the cloud of radioactive residues is above 45 miles altitude, the bulk of the ionization will be produced within a 10-mile altitude range around a height of 45 miles in two conjugate regions. If the regions are assumed to be circular with a radius R miles, so that the area of each is πR^2 square miles, then the rate of formation of free electrons, due to ionization by beta particles, can be derived from equation (10.89.2) as

$$S=\frac{4.4\times10^{23}Wt^{-1.2}}{10\pi R^2(1.6\times10^5)^3}=\alpha N^2$$

where 1.6×10^5 is the factor for converting miles into centimeters. Since, α is 10^{-7}, it follows that

$$N\approx4\times10^6\left(\frac{W}{R^2t^{1.2}}\right)^{1/2} \text{ electrons per cubic centimeter.} \qquad (10.91.1)$$

This relation gives the free electron density, at 45 miles altitude, produced by the delayed beta particles at t hours after a burst of W kilotons fission yield if the debris is spread uniformly over a circular area of radius R miles. The result is applicable to daytime conditions and also at night if the electron density exceeds 1.6×10^6.

10.92 If the electron density is less than 1.6×10^6 at night, the predominant loss rate will be due to attachment of electrons to neutral particles, as given by equation (10.86.1), i.e., $0.16N$. For the same conditions as above, setting S equal to $0.16N$, it follows that the steady-state electron density will be given by

$$N\approx10^7\frac{W}{R^2t^{1.2}} \text{ electrons per cubic centimeter,} \qquad (10.92.1)$$

where t is in hours. The electrons disappear at night by forming negative ions and at sunrise the light will detach the electrons from these ions and the electron density will adjust quickly to the daytime value given by equation (10.91.1).

10.93 If the source of beta particles does not change appreciably in magnitude at the given location, the relationship of electron densities just before and just after sunrise is obtained from equations (10.91.1) and (10.92.1) as

$$N_{\text{day}}\approx1.3\times10^3\sqrt{N_{\text{night}}},$$

provided N_{night} is less than 1.6×10^6 electrons per cubic centimeter at sunrise. It is seen that, in these circumstances, N_{day} will be greater than N_{night}, so that there is an increase in the free electron density at sunrise. This effect was observed at the TEAK and ORANGE high-altitude shots. If the electron density before sunrise is greater than 1.6×10^6, no marked increase will be observed after the sun has risen.

10.94 In order to utilize equations (10.91.1) and (10.92.1) to calculate the steady-state electron densities produced by beta particles in the radioactive cloud, throughout which the weapon debris is supposed to be spread uniformly, it is necessary to know the radius R. The determination of this quantity requires a knowledge of the processes taking place as the cloud rises and spreads horizontally. Since

there is not much known about these processes, models will be used which roughly parallel the behavior observed at high-altitude tests. For a megaton-range burst at an altitude from 15 to 40 miles, it is postulated that the cloud rises to a height of 20 miles above the burst height (§ 10.31), and that its radius increases at a rate of 100 miles per hour. In this case, the radius in miles at any time t hours after the explosion is given by

$$R=100t.$$

With this model the radius at any time can be calculated and the value used, in conjunction with equations (10.91.1) and (10.92.1), to determine the electron density, day or night, as a function of time. The data for the curves in Fig. 10.48a were obtained in this manner, for a 1-megaton fission yield explosion.

10.95 For a megaton burst in the 40- to 70-mile altitude range, it is assumed that the cloud rises to a height of over 100 miles and then drops to 85 miles within a few minutes. The rate of increase of the radius is taken to be 2,000 miles per hour for 30 minutes and 100 miles per hour thereafter. Hence, R in miles is expressed by

$$R=2000t \text{ for } t\leq 0.5 \text{ hour}$$

$$R=950+100t \text{ for } t>0.5 \text{ hour}.$$

These values were used in deriving the results in Fig. 10.48b.

Attenuation of Signals in Decibels

10.96 By combining the data in Fig. 10.29 with equation (10.76.1), it is possible to calculate the extent of attenuation of electromagnetic signals of various frequencies as the result of a 1-megaton fission yield explosion. For an altitude of 45 miles, the collision frequency ν is about 6×10^6 per second. For radio frequencies above 5 megacycles, which are the only ones that will be considered, the value of ω^2 is much greater than ν^2, so that equation (10.76.1) then reduces to

$$A=4\times10^{-3}\frac{N}{f^2} \text{ decibels per mile},$$

where f is the wave frequency in megacycles, i.e., $10^{-6}\omega/2\pi$. If the signal beam makes an angle (of incidence) θ with the vertical and traverses a layer 10 miles thick, the total attenuation is

$$A=4\times10^{-2}\frac{N}{f^2}\sec\theta \text{ decibels}. \qquad (10.96.1)$$

The results of equation (10.96.1) are expressed graphically in Fig. 10.96 which shows the signal attenuation in decibels, as a function of frequency, for several values of the angle θ and an electron density of 1 electron per cubic centimeter. The attenuation in any particular situation may be obtained upon multiplying by the actual density N as derived from Fig. 10.29.

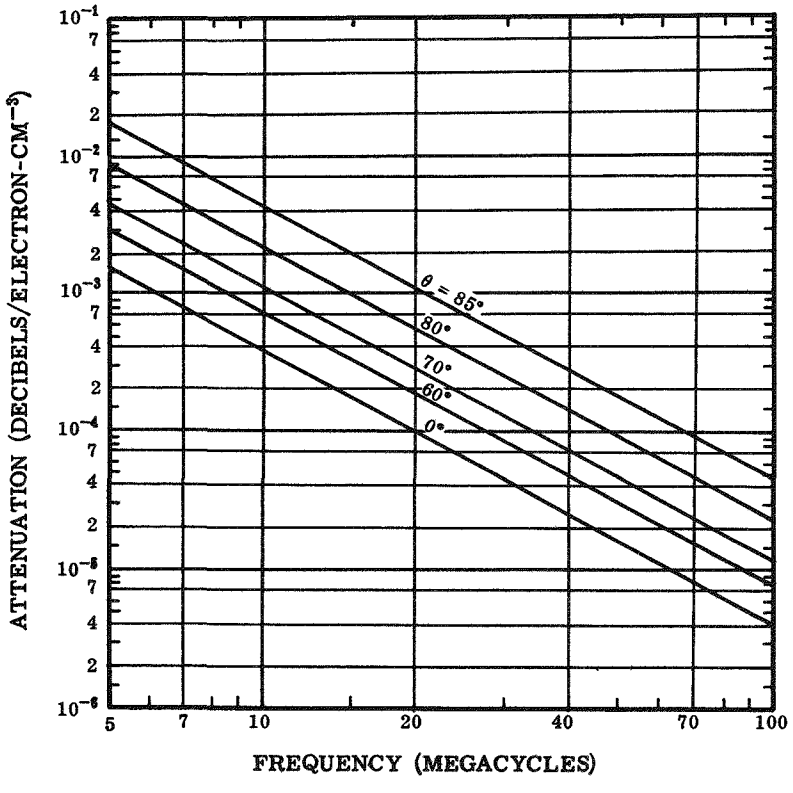

Figure 10.96. Signal attenuation as a function of frequency for various values of the angle of incidence.

10.97 For operational HF circuits the value of sec θ is about 5 under normal conditions, and so it follows from equation (10.96.1) that, for a frequency of 5 megacycles, an electron density of about 5×10^3 electrons per cubic centimeter will produce about 40 decibels of signal attenuation. For a frequency of 20 megacycles, an electron density of almost 10^5 is required to produce the same attenuation. These

densities may be taken as indications of the values required to make an HF circuit inoperative; they were used in this connection in § 10.55 *et seq.*

Refraction of Radiofrequency Signals

10.98 The index of refraction n of a medium is related to the density of free electrons (N per cubic centimeter); if there are no collisions, then

$$n=\left(1-\frac{Ne^2}{\pi mf^2}\right)^{1/2}, \tag{10.98.1}$$

where e is the charge (in electrostatic units) and m (in grams) is the mass of the electron; f is here the frequency in cycles per second. By inserting numerical values for e and m and expressing f in megacycles, it is found that

$$n=\left(1-\frac{0.8N}{10^4f^2}\right)^{1/2} \tag{10.98.2}$$

or, since electron densities are not known very accurately,

$$n\approx\left(1-\frac{N}{10^4f^2}\right)^{1/2}. \tag{10.98.3}$$

If an appreciable number of neutral particles are present with which the electrons can collide, the collision frequency ν enters the expression for the refractive index in a complex manner. However, if the wave (angular) frequency, ω, is greater than ν, the latter may be ignored.

10.99 At an altitude of 45 miles, where ν is 6×10^6 per second, the expressions given for the refractive index may be used for signal frequencies greater than 10 megacycles. For lower frequencies, the results may be seriously in error. Furthermore, if the electron density exceeds about 10^9, the collision frequency may become much larger than the value given above, and equations (10.98.2) and (10.98.3) will no longer be applicable.

10.100 If an electromagnetic wave crosses a plane interface where the index of refraction changes from 1 to n, the beam will be bent by an amount given by the familiar Snell's law, i.e.,

$$\frac{\sin\theta}{\sin r}=n, \tag{10.100.1}$$

where θ is the angle of incidence and r the angle of refraction. In the passage from the lower atmosphere, where there are essentially no free electrons, into the D-region, where the electron density is N, the bending of the beam can be calculated using equation (10.98.3) to derive the refractive index. This procedure is strictly justifiable only if there is a single, sharp interface where the electron density changes. However, even if the density change is gradual rather than abrupt, the method may be utilized to obtain a rough idea of the amount of bending of the beam.

10.101 Since sin r cannot exceed unity, it follows from equation (10.100.1) that true reflection will take place when sin θ is equal to or greater than n. The values of the angle of incidence, θ, for critical reflection for various values of N and f are given in Fig. 10.71. If N is less than $10^3 f^2$, equations (10.98.2) and (10.100.1) can be approximated by

$$\Delta\theta \approx 3 \times 10^{-3} \frac{N \tan \theta}{f^2},$$

where $\Delta\theta$ is the angular change (in degrees) of the ray in passing from electron density zero to density N. If the beam passes on through a 10-mile thick ionized layer into a region of negligible electron density, the signal will once again be traveling in its original direction, but the path will be offset by a horizontal distance given approximately by

$$\text{Offset} \approx \frac{N \sin \theta}{2 \times 10^3 f^2 \cos^2 \theta} \text{ miles.}$$

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CHAPTER XI

EFFECTS ON PERSONNEL

INTRODUCTION

Types of Injuries

11.01 The three main types of physical effects associated with a nuclear explosion, namely, blast and shock, thermal radiation, and nuclear radiation, each have the potentiality for causing death and injury to exposed persons. Blast injuries may be direct or indirect; the former are caused by the high air pressure and the latter by missiles and by displacement of the body. For a given overpressure, a nuclear device is more effective in producing direct blast injuries than is a conventional, high-explosive weapon because, as will be seen later, the human body is sensitive to the duration of the pressure phase and this is relatively long in a nuclear explosion. On the whole, indirect blast injuries, especially those caused by missiles, such as glass, wood, debris, etc., are similar for nuclear and conventional weapons. However, because of its longer duration, the blast wave from a nuclear explosion produces missile and displacement injuries, at much lower overpressures than in a chemical explosion.

11.02 The frequency of burn injuries due to a nuclear explosion is exceptionally high. Most of these are flash burns caused by direct exposure to the thermal radiation, although individuals trapped by spreading fires may be subjected to flame burns. In addition, persons in buildings or tunnels close to ground zero may be burned by hot gases and dust entering the structure even though they are shielded adequately from direct or scattered thermal radiation. Finally, mention must be made of the harmful effects of the nuclear radiations on the body. These represent a source of casualties entirely new to warfare.

11.03 A nuclear explosion in the air or near the ground will inevitably be accompanied by damage and destruction of buildings, by blast, shock, and fire, over a considerable area. Consequently, a correspondingly larger number of casualties among personnel is to be expected. However, the actual number, as well as their distribution

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among the different kinds of injuries mentioned above, will be greatly dependent upon circumstances. All other things being equal, the range of each of the major immediate effects—blast, thermal radiation, and initial nuclear radiation—increases with the explosive yield of the weapon. But the relative importance of the various effects does not remain the same. The initial nuclear radiation, for example, is much more significant in comparison with blast and thermal radiation for nuclear explosions of low energy yield than it is for those of high yield. In other words, although the total number of casualties will increase with the energy of the explosion, under similar circumstances, the percentage of injuries due to initial nuclear radiation may be expected to decrease whereas the proportions of blast and thermal injuries will increase (see Fig. 12.08 and Table 12.44).

11.04 For a given total energy yield of the nuclear explosion, the number and distribution of casualties of various kinds will be determined by the type of burst, e.g., air, surface, or subsurface. Moreover, for an air burst, the height of burst will have an important influence. With other factors constant, there is an optimum height of burst which maximizes the range on the ground for a given overpressure in the blast wave (§ 3.67). This optimum height differs for each yield and for each value of the overpressure. Similarly, there are particular heights of burst, usually different from that for blast effects, which maximize the ranges for either thermal radiation or the initial nuclear radiation. It is evident, therefore, that considerable variations are possible both in the number and in the nature of the injuries associated with an air burst.

11.05 The effects of a surface or of a shallow subsurface burst will not be greatly different from those accompanying a low air burst. However, as increasing amounts of contaminated earth and debris are sucked up into the radioactive cloud the hazard from the residual nuclear radiation in the early fallout increases. For an underground burst at a certain depth, the injuries from blast and from thermal and initial nuclear radiations would be much less than from an air burst or even from a surface burst of the same yield. On the other hand, the effects of ground shock and the delayed nuclear radiation hazard would be greatly increased. In the case of a deep (completely contained) underground burst, casualties would result only from ground shock.

11.06 Apart from the explosion yield and burst conditions, local environmental circumstances can be a significant factor in the casualty potential of a nuclear weapon. Conditions of terrain and weather, for example, can influence the injuries caused by blast and by thermal

radiation. Structures may have an important, although variable, effect. For example, the shielding in ordinary houses may markedly reduce the range over which significant casualties from flash burns can occur. This is particularly the case for heavier structures extending below as well as above ground; persons properly located in such buildings could be protected from blast and initial nuclear radiations as well as from thermal radiations. On the other hand, in certain buildings the frequency of indirect blast injuries may be greatly increased by the presence of large numbers of missiles.

11.07 As regards direct injuries resulting from the overpressure of the air in the blast wave, the effects of a structure are also quite variable. In some situations it is known that the magnitude of the peak overpressure inside a structure can be appreciably less than the free-field (open terrain) value. On the other hand, there is a possibility that, as a result of reflection at walls, etc., the air overpressure in the interior of a building may be increased twofold or more, depending on the geometry involved. There will also be changes in wind velocity inside structures, so that the magnitudes may differ markedly from those existing in the free field as the blast wave spreads outward from the burst point.

Japanese Casualties

11.08 The only direct information concerning human casualties resulting from a nuclear explosion is that obtained following the air bursts over Japan and this will be used as the basis for much of the discussion presented here. It should be pointed out, however, that the Japanese experience applies only to an energy yield of about 20 kilotons, to the particular burst heights employed (1,850 feet), and to the weather, terrain, and other conditions existing at the times and locations of the explosions. While it is true that almost any kind of nuclear explosion, except perhaps one deep under the surface, would be accompanied by a large number of deaths and injuries in a short interval of time, the actual number of casualties and their distribution among blast (and shock), thermal, and nuclear radiation effects could vary markedly with the circumstances, as explained earlier.

11.09 The data in Table 11.09 are the best available estimates [1]

[1] Computed from data in A. W. Oughterson and S. Warren (Editors), "Medical Effects of the Atomic Bomb in Japan," McGraw-Hill Book Co., Inc., Chapter 4, 1956. For further information, see also "Medical Effects of the Atomic Bomb," Report of the Joint Commission for the Investigation of the Effects of the Atomic Bomb in Japan, Office of the Air Surgeon NP-3041; "Medical Report on Atomic Bomb Effects," The Medical Section, Special Committee for the Investigation of the Effects of the Atomic Bomb, National Research Council of Japan, 1953; and the U.S. Strategic Bombing Survey, "The Effects of Atomic Bombs on Hiroshima and Nagasaki," 1946.

for civilian casualties resulting from all effects of the explosions over Hiroshima and Nagasaki. The population estimates are only for civilians within the affected area in each city and do not include an unknown number of military personnel. Three zones, representing different distances from ground zero, are considered: the first is a circular area of 0.6 mile radius about ground zero, the second is a ring from 0.6 to 1.6 miles from ground zero, and the third is from 1.6 to 3.1 miles from ground zero. In each case there is given the total population in a particular zone, the population density, i.e., number per square mile, and the percentages of killed and injured, in that zone. Also included are the total population "at risk" in the city, the average population density, and the total numbers of killed and injured. The standardized casualty rates are values calculated by proportion on the basis of a population density of one person per 1,000 square feet (or about 28,000 per square mile) of vulnerable area. The accepted standardized casualty rate for a 1-ton chemical high-explosive bomb is about 40.

TABLE 11.09

CASUALTIES AT HIROSHIMA AND NAGASAKI

Zone	*Population*	*Density (per square mile)*	*Killed*	*Injured*
	HIROSHIMA			
0 to 0.6 mile	31, 200	25, 800	26, 700	3, 000
0.6 to 1.6 miles	144, 800	22, 700	39, 600	53, 000
1.6 to 3.1 miles	80, 300	3, 500	1, 700	20, 000
Totals	256, 300	8, 400	68, 000	76, 000
Standardized Casualty Rate: 261,000 (Vulnerable area 9.36 square miles).				
	NAGASAKI			
0 to 0.6 mile	30, 900	25, 500	27, 200	1, 900
0.6 to 1.6 miles	27, 700	4, 400	9, 500	8, 100
1.6 to 3.1 miles	115, 200	5, 100	1, 300	11, 000
Totals	173, 800	5, 700	38, 000	21, 000
Standardized Casualty Rate: 195,000 (Vulnerable area 7.01 square miles).				

11.10 It is important to note that, although the average population densities in Hiroshima and Nagasaki were 8,400 and 5,700 per square mile, respectively, densities of over 25,000 per square mile existed in areas close to ground zero. For comparison, the average population density for the five boroughs of New York City, based on the 1960 census, is about 24,700 per square mile and for Manhattan alone it is 74,800 per square mile. The population density for the latter borough during the working day is, of course, much higher.

The 10 next largest U.S. cities have average population densities ranging from 15,670 to 5,350 persons per square mile.

11.11 The numbers in Table 11.09 serve to emphasize the high casualty potential of nuclear weapons. There are several reasons for this situation. In the first place, the explosive energy yield is very much higher than is possible with conventional weapons, so that both area and degree of destruction are greatly increased. Second, because of the high energy yields, the duration of the overpressure and winds associated with the blast wave, for a given peak overpressure, is so long that injuries occur at overpressures which would not be effective in a chemical explosion. Third, the proportion of the explosive energy released as thermal radiation is very much greater for a nuclear weapon, so that there is a considerably larger incidence of flash burns. Finally, nuclear radiation injuries are completely absent from conventional explosions.

11.12 The data in the table also show that some 95 percent of the population within a half mile from ground zero were casualties. In this area the blast wave energy, thermal exposure, and initial nuclear radiation were each sufficient to cause serious injury or death. Beyond about 1.5 miles, however, the chances of survival were very greatly improved. Between 0.5 and 1.5 miles from ground zero a larger proportion of the population would probably have survived if immediate medical attention had been available. Although the particular distances mentioned apply to the yield and conditions of the Japanese explosions, it is to be expected quite generally that close to ground zero the casualty rate will be high, but it will drop sharply beyond a certain distance which scales with the energy yield of the explosion.

Causes of Fatalities

11.13 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 estimated that some 50 percent of the deaths were caused by burns of one kind or another, but 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 many deaths from burns during the first week.

11.14 The high incidence of flash burns caused by thermal radiation among both fatalities and survivors in Japan was undoubtedly related to the light and scanty clothing being worn, because of the

warm summer weather prevailing at the time of the attacks. If there had been an appreciable cloud cover or haze below the burst point, the thermal radiation would have been attenuated somewhat and the frequency of flash burns would have been much less. Alternatively, had the weather been cold, fewer people would have been outdoors and they would have been wearing more extensive clothing. Both the number of people and individual skin areas exposed to thermal radiation would then have been greatly reduced so that there would have been fewer casualties from flash burns.

11.15 None of the estimates of the causes of death bear directly on the incidence of those blast effects which result in early death, e.g., air (emboli) in the arteries, lung damage, and heart injury which tolerate very little post-injury activity, various bone fractures, severing of major blood vessels by sharp missiles, violent impact, and others. One of the difficulties in assessing the importance of injuries of various types lies in the fact that many people who suffered fatal blast injuries were also burned. As seen earlier, within half a mile of ground zero in the Japanese explosions, either blast, burns, or nuclear radiation injury alone was lethal in numerous instances.

11.16 It should be pointed out, however, that, due to various circumstances, not everyone within a radius of half a mile was killed immediately. Among those who survived the first few days after the explosions at Hiroshima and Nagasaki, a number died two or more weeks later with symptoms which were ascribed to nuclear radiation injuries (see § 11.109 *et seq.*). These were believed to represent from 5 to 15 percent of the total fatalities. 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.

11.17 The death rate in Japan was greatest among individuals 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 of all for those in concrete buildings. These facts emphasize the influence of circumstances of exposure on the casualties produced by a nuclear weapon and indicate that shielding of some type can be an important factor in survival. For example, it has been estimated that within a range of 0.6 mile from ground zero over 50 percent of individuals in Japanese-type homes died of nuclear radiation effects, but such deaths were rare among persons in concrete buildings at the same range. The effectiveness of concrete structures in providing protection from injuries of all kinds is apparent from the data in Table 11.17; this gives the respective average distances from ground

zero at which there was 50-percent survival (for at least 20 days) among the occupants of a number of buildings in Hiroshima. School personnel who were indoors had a much higher survival probability than those who were outdoors at the times of the explosions.

TABLE 11.17

AVERAGE DISTANCES FOR 50-PERCENT SURVIVAL AFTER 20 DAYS IN HIROSHIMA

Conditions	*Approximate distance (miles)*
Overall	0.8
Concrete buildings	0.12
School personnel:	
Indoors	0.45
Outdoors	1.3

CAUSES OF INJURIES AMONG SURVIVORS

11.18 From surveys made of 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 survived the nuclear attacks. The results are quoted in Table 11.18. It will be observed that the totals add up to more than 100 percent, since many individuals suffered multiple injuries.

TABLE 11.18

DISTRIBUTION OF TYPES OF INJURY AMONG SURVIVORS

Injury	*Percent of survivors*
Blast (mechanical)	70
Burns (flash and flame)	65
Nuclear radiation (initial)	30

11.19 Among survivors the proportion of indirect blast (mechanical) injuries due to flying missiles and movement of other debris was smallest outdoors and largest in certain types of industrial buildings. Patients were treated for lacerations received out to 10,500 feet (2 miles) from ground zero in Hiroshima and out to 12,500 feet (2.2 miles) in Nagasaki. These distances correspond roughly to those at which moderate damage occurred to wood-frame houses, including the shattering of window glass.

11.20 An interesting observation made among the Japanese survivors was the relatively low incidence of serious mechanical injuries.

For example, fractures were found in only about 4 percent of survivors. In one hospital among 675 patients, there were no cases of fracture of the skull or back and only one fractured femur although many injuries must have undoubtedly occurred. This was attributed to the fact that persons who suffered severe concussion or fractures were rendered helpless, particularly if leg injuries occurred, and, along with those who were pinned beneath the wreckage, were trapped by the flames. Such individuals, of course, did not survive.

BLAST INJURIES

Direct Blast Injuries: Biological Factors

11.21 Blast injuries are of two main types, namely, direct (or primary) injuries associated with exposure of the body to the environmental pressure variations accompanying a blast wave, and indirect injuries resulting from impact of missiles on the body or as the consequences of displacement of the body as a whole. There are also miscellaneous blast injuries, such as burns from the gases and debris, and irritation, and possibly suffocation, caused by airborne dust. The present section will treat direct injuries, and indirect blast effects will be discussed later.

11.22 The general interactions of a human body with a blast wave are somewhat similar to that of a structure as described in Chapter IV. Because of the relatively small size of the body, the diffraction process is quickly over, the body being rapidly engulfed and subjected to severe compression. This continues with decreasing intensity for the duration of the positive phase of the blast wave. At the same time the blast wind exerts a drag force of considerable magnitude which contributes to the displacement hazard to be discussed subsequently.

11.23 Due to the compression and subsequent decompression of the body and the transmission of pressure waves through the organism, damage occurs mainly at junctions between tissues and air-containing organs and at areas of union between tissues of different density, such as where cartilage and bone join soft tissue. The chief consequences are hemorrhage and occasional rupture of abdominal and thoracic organs. The lungs are particularly prone to hemorrhage and edema (liquid extrusion), and if the injury is severe, air reaches the veins of the lungs and hence the heart and arterial circulation. Death occurs in a few minutes from air embolic obstruction of the vessels of the heart or brain, but may also ensue from suffocation

caused by lung hemorrhage or edema into the lung tissues. It is important to note also that bodily activity after blast damage to the lungs and heart is extremely hazardous, and lethality can result quickly where recovery might otherwise have occurred. Damage to the brain due to overpressure is improbable, but it can be caused by arterial air emboli arising in the lung. Otherwise, any effects on the brain arising from blast are a result of injury to the head caused by missiles, debris, or displacement, and so are indirect.

11.24 The direct blast effect was not specifically recognized as a cause of fatality in Japan, but it no doubt contributed significantly to early mortality even though most of the lethally injured individuals may also have received mortal injury from debris, displacement, fire, and thermal and nuclear radiations. Primary blast casualties have been reported after large-scale air attacks with conventional high-explosive bombs, mainly because of the provision of medical care for those who otherwise would have suffered the early death that is characteristic of serious blast injury to the lungs. However, persons who spontaneously survive for 24 to 48 hours in the absence of treatment, complications, and other injury usually recover and show little remaining lung hemorrhage after 7 to 10 days. In very severe injuries under treatment, recurring lung hemorrhage has been reported as long as 5 to 10 days after injury. In view of such facts and the overwhelming disruptive effects of the Japanese bombings on medical and rescue services, it can be concluded that individuals with significant direct blast injuries did not survive. Those with relatively minor blast injuries who did survive, did so without getting into medical channels, or if they did require medical care it was for causes other than blast injury to the lungs. For these reasons primary blast effects, except for eardrum rupture, were not commonly seen among Japanese survivors.

11.25 Many persons who apparently suffered no serious injury reported temporary loss of consciousness. This symptom can be due to the direct action of the blast wave, resulting from transient disturbance of the blood circulation in the brain by air emboli. However, it can also be an indirect effect arising from impact injury to the head caused by missiles or by violent displacement of the body by the air pressure wave.

11.26 A number of cases of ruptured eardrums were reported among the survivors in Hiroshima and Nagasaki, but the incidence was not high even for those who were fairly close to ground zero. Within a circle of 0.31 mile (1,640 feet) radius about 9 percent of a group of about 200 survivors in Nagasaki had ruptured eardrums,

and some 8 percent in the ring from 0.31 to 0.62 mile from ground zero. In Hiroshima the incidence of ruptured eardrums was somewhat less. In both cities very few cases were observed beyond 0.62 mile.

Direct Blast Injuries: Physical Factors [2]

11.27 Tests have demonstrated that three parameters of the blast wave affect the extent of the direct injuries to the body; these are (1) the rate of pressure rise (or "rise time") at the blast wave front, (2) the peak overpressure attained, and (3) the duration of the positive phase of the overpressure (see Chapter III). If the rise time is short, as it is in nuclear explosions under appropriate burst and terrain conditions, the damaging effect of a given overpressure is greater than for a more slowly increasing pressure. At low burst heights a precursor wave may form (§§ 3.43, 3.72); in this case the rate of pressure increase is less than for an ideal (or nearly-ideal) situation and the injury potential is decreased. A step-wise increase of pressure, sometimes called "step loading," to a specified peak value is less hazardous than a sharp increase in a single step. Such step loading may be associated with a precursor and also with reflection in certain situations (§ 11.32).

11.28 For a sharply rising pressure wave, the duration of the positive phase is a significant factor for direct blast injuries. Up to a point, an increase in the duration increases the probability of injury for a given peak overpressure. Beyond this point, which may be of the order of several tens to a few hundred milliseconds, depending on the body size, it is only the magnitude of the peak pressure that is important for a blast wave with a short rise time. The duration of the positive phase for a given peak overpressure varies with energy yield and height of burst (see § 3.69 *et seq.*). But for most conditions associated with nuclear explosions, especially for energy yields in excess of about 10 kilotons, the duration of the positive phase of the sharp-rising blast wave is so long that the peak overpressure is the main factor determining the potential for direct injury.

11.29 Laboratory and field studies with animals indicate that, provided the rise time is short, a peak overpressure (incident or reflected) as low as 35 pounds per square inch, with a positive phase duration of 400 milliseconds (0.4 second), could cause death in human beings. The estimated peak overpressures required to produce various probabilities of fatality under these conditions are given in

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[2] C. S. White and D. R. Richmond, "Blast Biology," U.S. AEC Report TID-5764, September 1959.

Table 11.29. Damage to the lung can occur at overpressures as low as 15 pounds per square inch, which may develop from reflection of an incident peak overpressure of 6 or 7 pounds per square inch.

TABLE 11.29

ESTIMATED PEAK OVERPRESSURES FOR DIRECT BLAST WAVE FATALITIES

Probability of fatality (percent)	*Peak overpressure (pounds per sq in)*
1	35 to 45
50	45 to 55
99	55 to 65

11.30 The situation as regards direct blast injury is different for conventional high explosives, mainly because of the short duration of the positive pressure phase. From observations made with such explosives, it is estimated that death in humans would require sharp-rising peak overpressures as high as 80 to 300 (or more) pounds per square inch, because the positive phase durations range from about 1 to 15 milliseconds.

11.31 Rupture of the normal human eardrum is apparently a function of the age of the individual as well as of the peak overpressure. Failures have been recorded at overpressures as low as 5 pounds per square inch, ranging up to 40 or 45 pounds per square inch. The best value of the overpressure for 50-percent probability of eardrum rupture appears to be between 20 and 30 pounds per square inch. Sinus hemorrhage and bleeding from the nose is common in animals exposed to blast, but no reliable quantitative information is available. Fracture of the thin orbital bones into the adjacent sinus cavities has been observed. A relatively fast-rising pulse with a high peak overpressure is apparently necessary, but the appropriate values for man are not known.

11.32 The geometry[3] in which a person is exposed to the fast-rising blast wave, for a particular free-field overpressure, may have a large effect on his response. When the pressure wave reaches an individual in the open or in a long hallway or tunnel, much of it is reflected from his body surface. The reflected pressure, and hence the effective pressure, may then be more than double the incident (free-field) pressure. Depending upon the dimensions of entry-way

[3] The word "geometry" is used here as a composite term to describe the location of an individual in relation to the details of his environment that may affect the blast wave characteristics.

openings and internal volume, the overpressure inside a structure may be much less, equal to, or much greater than the free-field pressure; there may also be alterations in the rate of pressure rise and the duration of the positive pulse. Under certain circumstances an individual inside a structure would not only be exposed to the initial overpressure, but, in addition, to reflections of the blast wave from the walls. Since these would reach him at different times, the result would be a step loading. However, a location against a wall is the most hazardous position as regards direct blast effects because the overpressure from the initial reflection is then maximal.[4] In addition, oscillating pressures often exist inside structures due to reverberating reflections from the inside walls.

Indirect Blast Injuries

11.33 Indirect blast injuries are associated with (1) the impact of missiles, either penetrating or non-penetrating, and (2) the physical displacement of the body as a whole. The wounding potential of blast debris depends upon a number of factors, such as impact (or striking) velocity and the angle at which impact occurs, and the size, shape, density, mass, and nature of the moving objects. Furthermore, consideration must be given to the portion of the body involved in the missile impact, and the events which may occur at and after the time of impact, namely, simple contusions and lacerations, at one extreme, or more serious penetrations, fractures, and critical damage to vital organs, at the other extreme.

11.34 The hazard from displacement depends mainly upon the time and distance over which acceleration and deceleration of the body occur. Injury is more likely to result during the latter phase when the body strikes a solid object, e.g., a wall or the ground. The velocity which has been attained before impact is then significant. This is determined by certain physical parameters of the blast wave, as mentioned below, as well as by the orientation of the body with respect to the direction of motion of the pressure wave. The severity of the damage depends, of course, on the particular portion of the body that has received the decelerative impact, e.g., head, back, extremeties, thoracic and abdominal organs, body wall, etc.

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[4] Although a location away from a wall decreases the direct hazard due to overpressure, the hazard from displacement of the body may well increase sharply.

Displacement Velocity of Missiles [5]

11.35 Because the effects of both missiles and body displacement depend on the velocity attained before impact, it is convenient to consider the relationships between displacement velocity and the blast parameters for objects as small as tiny pieces of glass and as large as man. The significant physical factors in all cases are the magnitude and duration of the blast overpressure and the accompanying winds, the acceleration coefficient of the displaced object,[6] ground shock, gravity, and the distance traveled by the object. The latter is important because, as a result of the action of the blast wave, the velocity of the object increases with the time and distance of travel until it attains that of the blast wind. Subsequently, the velocity falls because of negative winds or impact with the ground or other material.

11.36 As a result of the interaction of the various factors, small and light objects reach their maximum velocity fairly quickly, often after only a small portion of the blast wave has passed over them. The maximum velocity is thus not too sensitive to the duration of the overpressure and winds. Large, heavy objects, on the other hand, gain velocity more slowly and attain their maximum only after most of the blast wave has passed. The velocity is consequently influenced by the duration of the winds and overpressure.

11.37 The variations of the overpressure and dynamic pressure with time (see § 3.51 *et seq.*) at the location of interest also have a bearing on the behavior of a displaced object. The results given here were obtained at nuclear weapons tests under such conditions that the blast wave was approximately ideal in behavior. Some of the median velocities, masses, and spatial densities (number of fragments per square foot) of window glass, from houses exposed to the blast, and of natural stones are summarized in Table 11.37. For glass, the velocities refer to those attained after 10 feet of travel; for the stones the distances are unknown, but the velocities given in the table may be regarded as applicable to optimum distances of missile travel.

11.38 Studies have also been made of the displacement produced by the blast from a nuclear explosion on anthropomorphic dummies weighing 165 pounds. A dummy standing with its back to the blast

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[5] I. G. Bowen, *et al.*, "A Model Designed to Predict the Motion of Objects Translated by Classical Blast Waves," Civil Effects Test Operations, U.S. AEC Report CEX-58.9, 1961; E. R. Fletcher, *et al.*, "Determination of Aerodynamic Drag Parameters of Small Irregular Objects," Civil Effects Test Operations, U.S. AEC Report CEX-59.14, 1961.

[6] The acceleration coefficient is the product of the projected area presented to the blast wave and the drag coefficient (§ 4.69) divided by the mass of the object.

TABLE 11.37

VELOCITIES, MASSES, AND DENSITIES OF MISSILES

Missile	*Peak overpressure (psi)*	*Median velocity (ft/sec)*	*Median mass (grams)*	*Maximum number per sq ft*
Glass	1. 9	108	1. 45	4. 3
Glass	3. 8	168	0. 58	159
Glass	3. 9	140	0. 32	108
Glass	5. 0	170	0. 13	388
Stones	8. 5	286	0. 22	40

attained its maximum velocity, which was about 21 feet per second, after a displacement of 9 feet within 0.5 second after the arrival of the blast wave. The free-field overpressure at the test location was 5.3 pounds per square inch. The dummy traveled 13 feet before striking the ground and then slid or rolled a further 9 feet. It is of interest to note that a prone dummy did not move under the same conditions. The foregoing results were obtained in a situation where the blast wave was nearly ideal, but in another test, at a peak overpressure of 6.6 pounds per square inch, where the blast wave was nonideal (§ 3.43), both standing and prone dummies suffered considerably greater displacements. Even in these circumstances, however, the displacement of the prone dummy was less than that of the standing one.

MISSILE AND DISPLACEMENT INJURY CRITERIA [7]

11.39 Velocity criteria for the production of skin lacerations by penetrating missiles, e.g., glass fragments, are not known with certainty. However, some reliable information is available concerning the probability of penetration of the abdominal cavity by glass. The impact velocities, for glass fragments of different masses, corresponding to 1, 50, and 99 percent probability are recorded in Table 11.39. Any wound involving a serous cavity can have dangerous consequences; the threshold for such injury can be taken to be about 100 feet per second for a 10-gram glass missile. For smaller fragments, the threshold velocity is higher.

11.40 Little is known concerning the relationship between missile mass and velocity of nonpenetrating missiles that will cause injury after impact with the body wall near the liver and spleen. It appears, however, that a missile with a mass of 10 pounds striking the head at

[7] D. R. Richmond, I. G. Bowen, and C. S. White, "Tertiary Blast Effects. The Effect of Impact on Mice, Rats, Guinea Pigs, and Rabbits," *Aerospace Medicine*, **32**, 789 (1961).

TABLE 11.39

PROBABILITIES OF GLASS FRAGMENTS PENETRATING ABDOMINAL CAVITY

Mass of glass fragments (grams)	*Probability of penetration (percent)*		
	1	50	99
	Impact velocity (ft/sec)		
0. 1	235	410	730
0. 5	160	275	485
1. 0	140	245	430
10. 0	115	180	355

a velocity of 12 to 13 feet per second or more can cause skull fracture. For such missiles it is unlikely that a significant number of dangerous injuries will occur at impact velocities of less than 10 feet per second.

11.41 Although there may be some hazard associated with the accelerative phase of body displacement by a blast wave, the deceleration, particularly if impact with a solid object is involved, is by far the more significant. Since a hard surface will cause more serious injury than a soft one, the damage criteria given below refer to impact of the displaced body with a hard object. From various data, it is concluded that an impact velocity of 10 feet per second is unlikely to be associated with a significant number of serious injuries; between 10 and 20 feet per second some fatalities may occur; and above 20 feet per second the probability of fatal injury increases rapidly with increasing displacement velocity.

11. 42 From the results of field work and laboratory studies it is possible to predict the ranges at which missiles (and man) will attain specified velocities for different nuclear explosion yields and burst conditions. The values are dependent upon the acceleration coefficient (§ 11.35) of the moving object, and two special cases of interest have been chosen for representation in Fig. 11.42: one is for glass missiles ranging in mass from 0.1 to 10 grams (acceleration coefficient 0.72 sq ft/lb), and the other is for man in random orientation (average acceleration coefficient 0.03 sq ft/lb); in both cases the displacement is arbitrarily fixed at the reasonable value of 10 feet. The curves in Fig. 11.42 give the velocities as a function of range for a 1-kiloton explosion assuming (1) a surface burst and (2) air burst conditions which yield the maximum range for each velocity. In order to determine the velocities for any specified energy yield, the scaling expressions given on the page facing the figure are to be used.

The curves in Fig. 11.42 give the velocity attained after 10 feet displacement of (*a*) 0.1- to 10-gram pieces of double-strength window glass (acceleration coefficient 0.72 sq ft/lb) and (*b*) a 165-pound man standing in an open area (acceleration coefficient 0.03 sq ft/lb), as a function of distance from ground zero in air and surface bursts of a 1-kiloton weapon. (The burst heights for the air burst are such as to maximize the range for each velocity.)

Scaling. The respective distances scale approximately as follows:

$$(a)\ R \approx R_1 W^{0.35} \text{ and } (b)\ R \approx R_1 W^{0.4},$$

where R_1 is the range for a 1-kiloton explosion, as given in Fig. 11.42, and R is the range for the same velocity for a W-kiloton burst.

Example

Given: A 1 MT air burst.

Find: (*a*) The distance from ground zero at which a small piece of double-strength window glass will attain a velocity of 100 feet per second at a location 10 feet from the window.

(*b*) The velocity of a 165-pound man, standing in the open 5 miles from ground zero, after a displacement of 10 feet.

Solution: (*a*) For a 1 KT air burst, the range for a 100-ft/sec velocity for glass fragments is found from Fig. 11.42 to be 0.68 mile; hence, for 1 MT, i.e., 1,000 KT, the corresponding range from ground zero is

$$R = R_1 W^{0.35} = 0.68 \times (1{,}000)^{0.35} = 7.5 \text{ miles.} \quad \textit{Answer}$$

(*b*) The range R_1 for 1 KT which is equivalent to 5 miles for 1 MT for the velocity of a man is given by

$$R_1 = \frac{R}{W^{0.4}} = \frac{5}{(1{,}000)^{0.4}} = 0.31 \text{ mile.}$$

For a 1 KT air burst at this range, the velocity is found from Fig. 11.42 to be 21 feet per second; this is consequently the value for 5 miles from a 5 MT air burst. *Answer.*

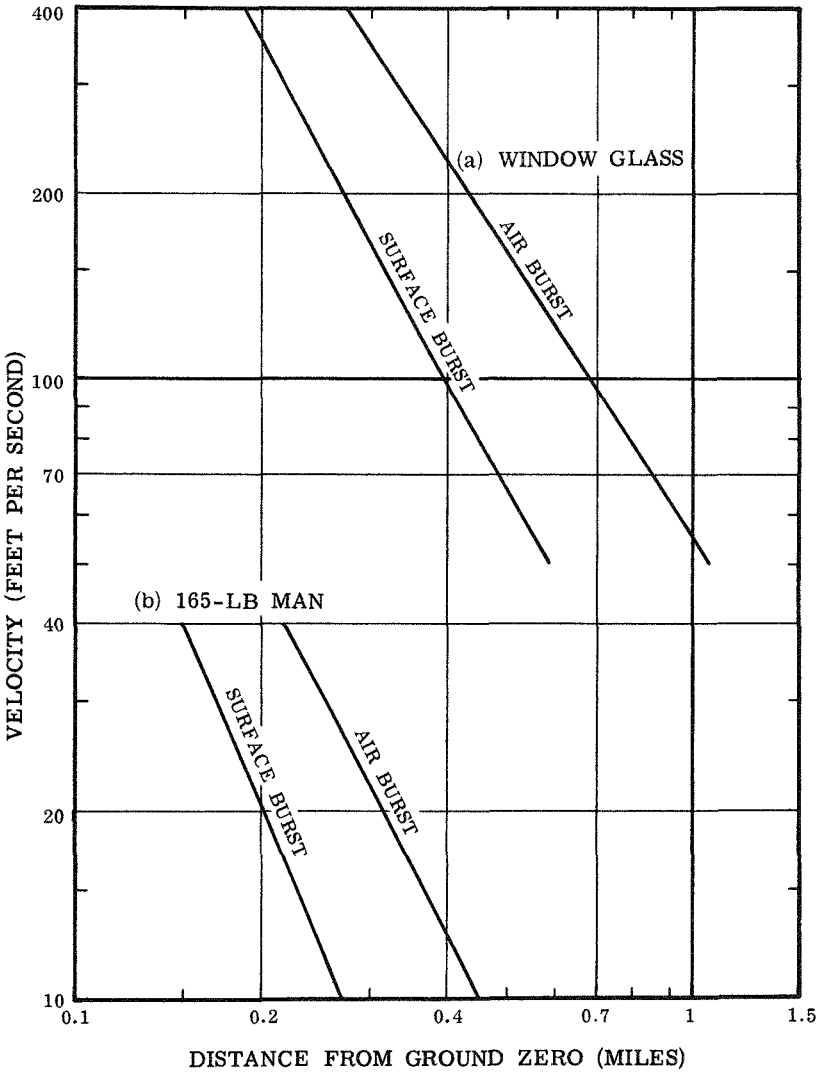

Figure 11.42. Velocities attained after 10 feet displacement by (*a*) 0.1- to 10-gram pieces of window glass, and (*b*) a 165-pound man in 1-kiloton surface and optimized air bursts.

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BURN INJURIES

Classification of Burns

11.43 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 fireball. 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. In addition, individuals in buildings or tunnels close to ground zero may be burned from hot gases and dust, as stated in §11.02.

11.44 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.

11.45 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.

11.46 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. Furthermore, there are certain critical, local regions, such as the hands, where almost any degree of burn will incapacitate the individual.

Flame and Flash Burns in Japan

11.47 Among the survivors of the nuclear explosions in Japan, the incidence of flame burns appeared to be very small. In fact, they constituted 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 was similar to that of burns caused by other conflagrations. The clothing usually caught fire, and so large parts of the body were frequently burned. By contrast, as will be seen below, flash burns were generally restricted to exposed skin areas, e.g., face, arms, hands, and legs.

11.48 One of the most striking consequences of the nuclear bombings of Japan was the large number of casualties due to flash burns caused by the thermal radiation. As mentioned earlier, the situation was aggravated by the clear atmosphere and warm weather which prevailed at the time. It was estimated that 20 to 30 percent of the fatal casualties in Hiroshima and Nagasaki were caused by flash burns. In the former city alone, some 40,000 fairly serious burn cases were reported. Apart from other injuries, thermal radiation 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 such burns which were bad enough to require treatment.

Effects of Thermal Radiation in Japan

11.49 A distinctive feature of the thermal radiation burns was their sharp limitation to exposed areas of the skin facing the center of the explosion. For this reason they are sometimes called "profile burns" (Fig. 11.49). The phenomenon was due to the fact that most of the radiation received had traveled in a straight line from the fireball and so only regions that were directly exposed were affected. A striking illustration of this behavior was that of a man writing before a window. His hands were seriously burned, but his face and neck, which were not covered, suffered only slight burns because the angle of entry of the thermal radiation through the window was such as to place them in partial shadow.

11.50 Although flash burns were largely confined to exposed parts of the body, there were a few cases where such burns occurred through one, and very occasionally more, layers of clothing. Instances of this

Figure 11.49. Partial protection against thermal radiation produced "profile" burns (1.23 miles from ground zero). The cap was sufficient to protect the top of the head against flash burn.

kind, however, were observed only near to ground zero where the radiant exposure was fairly large. When burns did occur through clothing, they generally involved regions where the clothes were tightly drawn over the skin, at the elbows and shoulders, for example. Such burns may have been due to contact with the hot fabric, as described below, 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 thermal radiation (Fig. 11.50).

11.51 There were many instances in which burns occurred through black clothing, but not through white material worn by the same individual (Fig. 11.51). 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 mentioned, however, 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.

11 52 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 because 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, some shielding was provided by the natural promontories of the body, e g , the nose, supraorbital (eye socket) ridges, and the chin.

General Characteristics of Flash Burns

11.53 In spite of the thousands of flash burns experienced after the nuclear attacks on Japan, only their general features were reported.

Figure 11 50 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

Figure 11.51. The patient's skin is burned in a pattern corresponding to the dark portions of a kimono worn at the time of the explosion.

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.

11.54 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 less than 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 air burst in the megaton range.

11.55 Severity of the flash burns in Japan ranged from mild erythema (reddening) to charring of the outermost layers of the skin. 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."

11.56 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 because of the decrease in resistance of the body to infection.

11.57 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.

11.58 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 appears

to have been influenced by infections, which complicated healing of the burns, and by malnutrition. A secondary factor is the known disposition for keloid formation to occur among the Japanese and other dark-skinned people 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.

Burn Injury Energies and Ranges

11.59 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.

11.60 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, but can be obtained from Fig. 7.105. Second, information must be available concerning the radiant exposure 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. The 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.

11.61 The approximate thermal radiation energies required to produce moderate first- and second-degree burns as a result of exposure to air bursts of various total yields are shown in Fig. 11.61. As in Chapter VII, the thermal radiation (or radiant) exposures are expressed in calories per square centimeter (cal/cm^2) 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.

11.62 It will be seen from Fig. 11.61 that the radiant exposure required to produce a burn of any particular degree of severity increases with the total energy yield of the explosion. The reason for this difference lies in the fact that with air bursts of lower energy yield the thermal energy is received in a short time, e.g., not more than a few tenths of a second, but with high energy yields, the effective delivery time may extend to several seconds (see Fig. 7.95). The greater the exposure time, the larger, in general, is the amount of thermal energy required to produce a particular effect (§ 7.35).

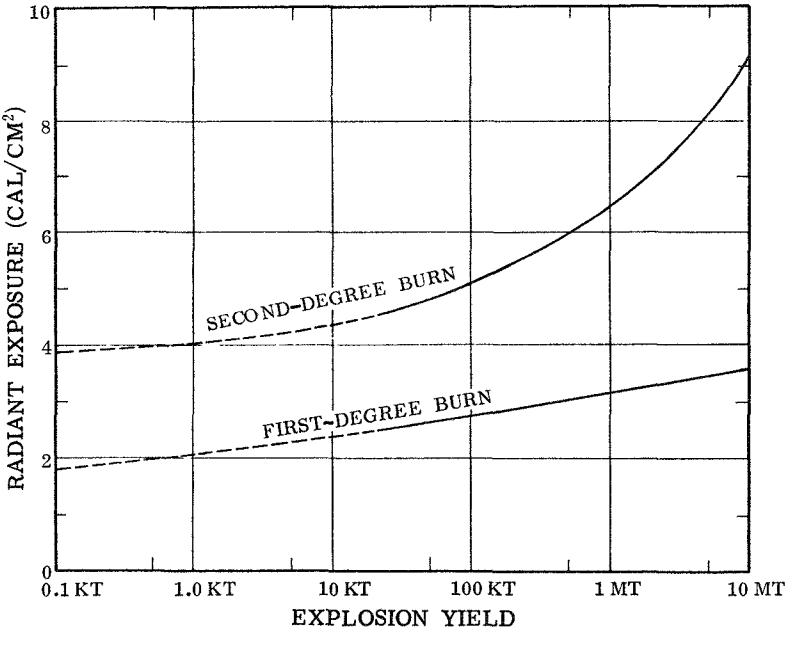

Figure 11.61. Radiant exposures required to produce first- and second-degree burns as a function of total energy yield.

11.63 Taking into consideration the variation of the thermal energy requirement with the energy yield of the explosion, Fig. 11.63 has been prepared to show the ranges for moderate first- and second-degree burns for nuclear explosions from 1 kiloton to 10 megatons total energy yield. In deriving the curves, two particular assumptions have been made. First, it is supposed that the explosion occurs in the air at such a height that the atmospheric pressure is not very greatly different from that at sea level. For a surface burst, the

distances would be scaled down to about 80 percent of those in the figure. If the detonation takes place at a high altitude, i.e., above 100,000 feet, where the air pressure is quite low, the situation is different. 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 hazy, the distances predicted in Fig. 11.63, 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. On the other hand, the distances may be too small if clouds above the burst point or snow on the ground reflect the thermal radiation.

11.64 The application of Fig. 11.63 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 curve representing the second-degree burn formation. The value on the horizontal (distance) scale corresponding to this point is seen to be 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 about 4 miles from the burst point, under average atmospheric conditions.

Effects of Thermal Radiation on the Eyes

11.65 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 instances of temporary blindness, occasionally lasting up to 2 or 3 hours, but only one case of retinal injury was reported.

11.66 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.

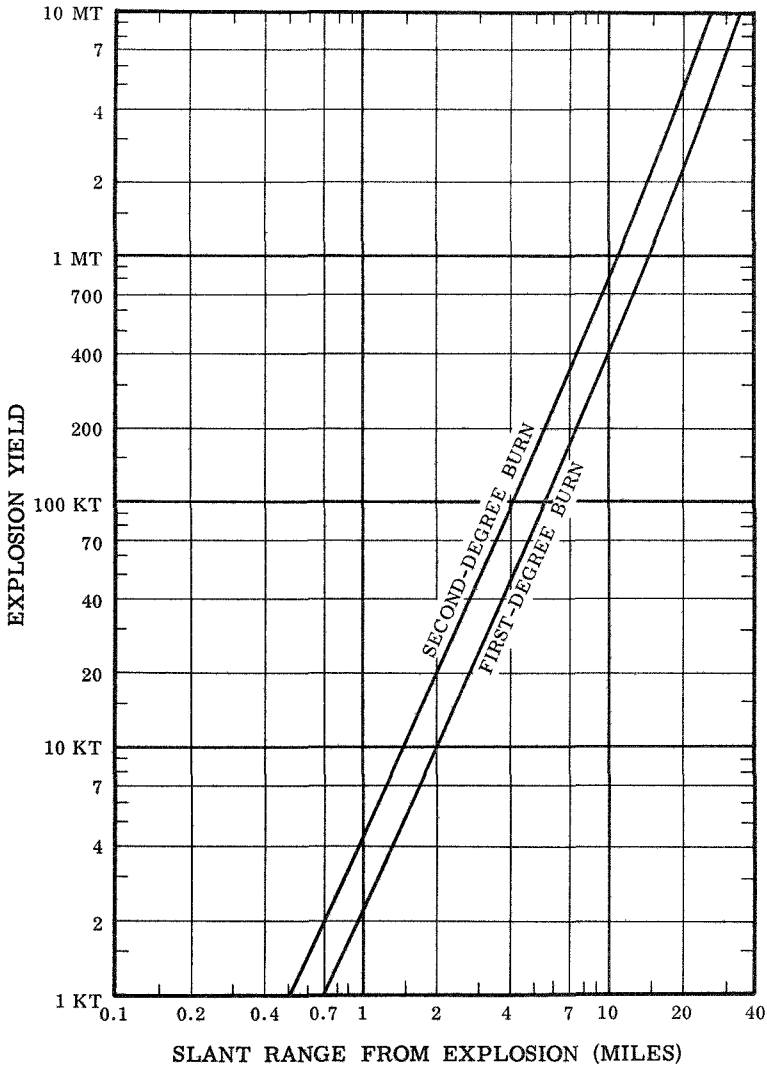

Figure 11.63. Ranges for first- and second-degree burns as a function of the total energy yield.

11.67 Investigators have reported that in no case, among 1,400 examined, was the thermal radiation exposure of the eyes apparently sufficient to produce permanent opacity of the cornea. This observation is not surprising since the cornea is transparent to the major portion of the thermal energy which is received in the visible and longer

wavelength (infrared) parts of the spectrum. In approximately one-quarter of the cases studied there had been facial burns and often singeing of the eyebrows and eyelashes. Nevertheless, some 3 years later the corneas were found to be normal.

11.68 Several reasons have been suggested for the scarcity of severe eye injuries in Japan. For example, the detonations occurred in the morning in broad daylight when the eye pupil would be expected to be small. 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. Furthermore, on the basis of probability, it is likely that only a small proportion of individuals would be facing the explosions in such a way that the fireball would actually be in their field of vision.

11.69 The effects of thermal radiation on the eyes fall into two main categories: (1) permanent (chorioretinal burns) and (2) temporary (flash blindness). Concentration of sufficient direct thermal energy, due to the focusing action of the eye lens, can cause the permanent damage. The focusing occurs, however, only if the fireball is in the individual's field of view. When this happens, chorioretinal burns may be experienced at distances from the explosion which exceed those where the thermal radiation produces skin burns. As a result of accidental exposures at nuclear weapons tests, a few burns of this type have been received at distances up to 10 miles from explosions of approximately 20-kilotons energy yield.

11.70 Experiments have been made with rabbits in an attempt to estimate the susceptibility of the human eye to thermal radiation. Although the rabbit eye is smaller, it is similar to the human eye in many respects including pupillary opening. However, under the same exposure conditions, the rabbit retina receives a larger amount of radiant energy per unit area because the rabbit eye, being smaller and having a shorter focal length, produces a smaller image. Estimates of the limiting distances are given in Table 11.70 for chorioretinal burns associated with a 20-kiloton low air burst, based on tests with rabbits and the assumption that, in humans, an exposure of 0.1 calorie per square centimeter for a period of about 0.15 second would produce a minimal eye burn. It should be noted, however, that research suggests this assumption may not be entirely correct. The distances are given for various degrees of atmospheric visibility, as defined in § 7.12, and for different pupil diameters. The importance of the air visibility and the brightness to which the eye is adapted are apparent.

TABLE 11.70

ESTIMATED LIMITING DISTANCES FOR CHORIORETINAL BURNS IN HUMANS FOR A 20-KILOTON LOW AIR BURST

	Pupil Opening Diameter		
	2 mm (Bright sunlight adapted	*4 mm (Cloudy day)*	*8 mm (Completely dark adapted)*
Visibility (miles)	*Distance (miles)*		
25	23	31	40
12	11	16	20
6	6	8	10
2	2	3	4

11.71 The size of the eye lesion produced is uncertain since it depends on the distance from the explosion and severity of the damage. The lesions contain areas of different types and degrees of damage; their relations to yield depend on a variety of factors and cannot be established with the information available at present. In all instances, however, there will be some temporary loss of visual acuity, at least, but the ultimate effect will depend upon the severity of the exposure and, to a greater extent, upon its location. If a chorioretinal burn is mild, or on the periphery of the visual field, the acuity may hardly be affected, but in more serious or centrally located cases there may be considerable loss of vision.

11.72 In a high-altitude detonation, the thermal radiation will generally traverse less of the atmosphere than for an air burst at the same slant range. Consequently, the atmospheric attenuation will be less in the former case in the absence of clouds, and chorioretinal burns may be expected at greater distances from the point of burst for similar energy yields. In order to obtain data concerning the possibility of eye injury, rabbits were exposed to the radiation from the TEAK shot of a megaton-range weapon at an altitude of 252,000 feet (§§ 2.53, 2.123 *et seq.*). Under nighttime conditions, chorioretinal burns occurred at slant distances up to about 345 miles; however, no measurements were made at greater distances and so this cannot be considered as a threshold range for eye damage.

11.73 Although extrapolation of the rabbit data to man is uncertain for high-altitude shots, it is felt that there would be some danger to human beings at distances greater than 200 miles under similar circumstances, and possibly as far as the eye can see at high altitude. It may be concluded from the Japanese situations that the number of individuals who will be looking directly at the fireball in the event of an unexpected air burst will not be large. High-altitude detonations

will be visible over greater distances and so it is probable that more people would actually observe an explosion of this type.

11.74 The size of the fireball image on the retina decreases with increasing slant range from the burst point and hence the radiant energy is received on a smaller area of the retina. The decrease in area largely compensates for the decrease in thermal energy, which varies inversely as the square of the distance from the explosion. In these circumstances, therefore, the thermal energy received per unit area of the retina decreases only as the atmospheric transmittance decreases with increasing distance (§ 7.104). However, because of chromatic aberration, the image on the retina does not become much less than about 10 microns (0.001 cm) in diameter. Consequently, beyond a certain distance from the explosion, the image of the fireball does not decrease further. The radiant exposure then decreases rapidly with increasing distance since it is dependent on both the inverse square of the distance and the atmospheric transmittance.

11.75 Temporary "flash blindness" or "dazzle" can occur in persons who are too far from the explosion to suffer chorioretinal injury or who do not view the fireball directly. Flash blindness results when more thermal energy is received on the retina than is necessary for image perception, but less than is required for burn. The effect is a localized bleaching of the visual elements, with image persistence, after-image formation, halo, etc. From a few seconds to several days may be required for the eye to recover its functions. Dazzle is essentially the same as flash blindness although some authorities reserve the term dazzle for the effect of scattered light reaching the eye in which recovery is much more rapid than with "line of sight" flash blindness. Flash blindness occurs at greater ranges at night, when the eye is dark adapted, than in daylight; however, the range of these effects is highly dependent on atmospheric conditions prevailing at the time of detonation.

11.76 Much of the thermal radiation responsible for chorioretinal burns and flash blindness would arrive so soon after the explosion of a weapon in the kiloton energy range that reflex actions, such as blinking and contraction of the eye pupil, can give only limited protection. The same holds true for high-altitude, kiloton and megaton yield detonations, in which most of the thermal energy is emitted in very short times (§ 7.96). In certain situations with air bursts of high yield, however, the thermal pulse is long enough to permit some protection by the blink reflex.

NUCLEAR RADIATION INJURY

Introduction

11.77 The injurious effects of nuclear radiations from a nuclear explosion 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. It should be understood, however, that the extended discussion does not necessarily 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 detonations occurred 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 radiation, in the form of early fallout and induced radioactivity, was negligible. However, as was seen in Chapter IX, the situation could be very different in the event of a surface burst.

11.78 It has long been known that exposure to radiations, such as X-rays, alpha and beta particles, gamma rays, and neutrons, which are capable of producing ionization, either directly or indirectly (§ 8.16), can cause injury to living organisms. After the discovery of X-rays and radioactivity, toward the end of the nineteenth century, it became increasingly apparent that an element of danger was associated with exposure to ionizing radiations. In spite of the growing awareness by both scientists and physicians of the hazards inherent in many radiation sources, there were some excessive exposures. 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 and hospitals, cyclotrons, and nuclear reactors, or working with radioactive materials.

11.79 The harmful effects of nuclear radiations appear to be caused by the ionization (and excitation) produced in the cells composing living tissue. As a result of ionization, some of the constituents, which are essential to the normal functioning of the cells, are altered or destroyed. In addition, the products formed may act as poisons. Among the observed consequences of the action of ionizing [8] radiations on cells are breaking of the chromosomes, swelling of the nucleus and

[8] The more general expression "ionizing radiations" is often employed, since this permits the inclusion of radiations of non-nuclear origin, e.g., X-rays, having similar biological effects.

of the entire cell, increase in viscosity of the cell fluid, increased permeability of the cell membrane, and destruction of cells. 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.

Radiation Dose Units

11.80 The radiation unit known as the roentgen was described in § 8.21. By definition, it is applicable only to gamma rays or X-rays and not to other types of ionizing radiation, such as alpha and beta particles and neutrons. Since the roentgen refers to a specific result in air accompanying the passage of an amount of radiation through air, it does not imply any effect which it would produce in a biological system. Because of this, the roentgen is, strictly speaking, a measure of radiation "exposure dose." The effect on a biological system, however, is expressed in terms of an "absorbed dose." By comparing the actual biological effects of different types of ionizing radiation, it is possible to convert the absorbed dose into a "biologically significant dose" which provides an index of the biological injury that might be expected.

11.81 The absorbed dose of radiation was originally expressed in terms of a unit called the "rep," the name being derived from the initial letters of "roentgen equivalent physical." It was used to denote a dose of about 97 ergs of any nuclear radiation absorbed per gram of body tissue; however, for various reasons this unit has proved to be somewhat unsatisfactory. In order to avoid difficulties arising in the use of the rep, a new unit of radiation absorption, called the "rad," has come into general use. 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 small, and numerical values of absorbed dose formerly expressed in reps are essentially unchanged when converted to rads.

11.82 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. This difference in behavior is expressed by means of 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)[9] to the absorbed dose in rads of the given radiation having the same biological effect.

11.83 The value of the RBE for a particular type of nuclear radiation depends upon several factors, including the dose rate, 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 nuclear weapons are concerned, the important criteria are disabling sickness and death.

11.84 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 dose unit of biological effect, whereas the rad is a unit of absorbed energy dose and the roentgen (for X- and gamma rays) is one of exposure dose.

11.85 All radiations capable of producing ionization (or excitation) directly or indirectly, e.g., alpha and beta particles, X-rays, gamma rays, and neutrons, 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 seen above, the latter difference is expressed by means of the RBE.

11.86 The RBE for gamma rays is approximately unity, by definition, although it varies somewhat with the energy of the radiation as stated previously. For beta particles, the RBE is also close to unity; this means that for a given 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.[10] 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 weapon neutrons, the RBE for acute radiation injury is now

[9] Because 1 roentgen exposure dose gives rise to about 1 rad absorbed dose in tissue for photons of intermediate energies (0.3 to 3 Mev), the absorbed dose for gamma (or X-) rays is often stated, somewhat loosely, in "roentgens." However, for photon energies outside the range from 0.3 to 3 Mev, the exposure dose in roentgens is no longer simply related to the absorbed dose in rads.

[10] Beta particles from sources on or near the body can also cause skin lesions, called "beta burns" (§ 11.148).

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taken as 1.0 (see § 11.88), but it is appreciably larger where the formation of opacities of the lens of the eye (cataracts) is concerned. In other words, neutrons are much more effective than gamma rays in causing cataracts.

Determination of Neutron Dose

11.87 The absorbed neutron dose in rads, at a particular location, can be determined by applying certain calculations to the measurements of foil activation described in § 8.58. In estimating the dose received from a nuclear explosion it is necessary to know the contribution of neutrons in various energy ranges and for this purpose threshold (foil type) detectors are employed. Instruments based on ionization (§ 8.57) are usually calibrated by means of foil activation data, and so they can also be used to indicate the absorbed dose in rads of neutrons of specific energies (or energy ranges).

11.88 To determine the biological dose in rems, from the measured absorbed dose in rads, the RBE for neutrons must be known. Since the information available for the effects of nuclear weapon neutrons on man is inadequate for the RBE for acute radiation injury to be evaluated, recourse must be had to experiments with animals. From such studies it has been found that the RBE varies with the neutron density and energy, the particular biological response under investigation, and other factors. Moreover, since the results must be extrapolated from the experimental animals to man, it is evident that there are considerable uncertainties involved. It appears, however, that the RBE value for acute radiation effects of weapon neutrons in man is close to unity and it is assumed to be 1.0 in all biological dose data given below.[11] As a consequence, the acute neutron biological dose in rems is numerically equal to the absorbed dose in rads, so that the values are interchangeable, just as they are for gamma rays and beta particles.

11.89 From a study of the energy spectrum of the neutrons in the initial nuclear radiation (§ 8.93 *et seq.*), it has been found that slow (low-energy) 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 fact, some 75 percent of the dose is derived

[11] The RBE values for neutrons recorded in the literature range from 1 to 30. This variation is partly due to errors in determination of absorbed dose and partly to the choice of different biological effects as the basis of comparison. Thus, the RBE values for identical exposure conditions are very different for cataracts, on the one hand, and hematological effects on the other hand. The figure of 1.0 for the RBE of nuclear weapon neutrons may not be exact, but in the opinion of several authorities it is the best estimate that can be made at the present time.

from those fast neutrons having energies above 0.75 Mev. In the majority of significant situations, therefore, it appears, that as a first approximation, the slow neutrons can be neglected in estimating the total radiation hazard. This simplification is further justified by the fact that the absorbed dose per neutron increases with the neutron energy. Consequently, in calculating the absorbed dose in rads from measurements of integrated neutron flux, only neutrons with energies above the plutonium-239 (shielded with boron) fission threshold, i.e., more than 200 ev energy, are included (§ 8.96).

11.90 The factors used to convert the integrated neutron flux into absorbed dose are derived from single-collision theory; in essence, this implies that the neutron delivers all its energy to the body in one collision with an atomic nucleus. The results obtained may be expressed by the equation

$$\text{Dose (in rads)} = [(N_1 - N_2) + 2.5\ (N_2 - N_3) + 3.2\ (N_3 - N_4) + 3.9\ N_4] \times 10^{-9},$$

where the N's are the integrated neutron fluxes, in neutrons per square centimeter, in the following energy ranges:

N_1: above 200 ev, the plutonium-239 (boron-shielded) fission threshold
N_2: above 0.75 Mev, the neptunium-237 fission threshold
N_3: above 1.5 Mev, the uranium 238-fission threshold
N_4: above 3.0 Mev, the sulfur activation threshold

From this expression and the values of $N_1 - N_2$, $N_2 - N_3$, etc., obtained from the neutron energy spectrum, such as the one in Fig. 8.95, it is found that, for a typical fission weapon, an integrated flux of 1 neutron per square centimeter is equivalent to an absorbed dose of 1.8×10^{-9} rad, for neutrons with energies in excess of 200 electron volts.

Absorbed Doses from Nuclear Explosions

11.91 In Chapter VIII there were given curves showing the exposure doses of initial gamma rays (in roentgens) and of neutrons (in neutrons per square centimeter) at various distances from a nuclear explosion. Since gamma rays and neutrons cause similar injury to human beings, it is of interest to compare the biological doses (in rems) received from these radiations and to consider their combined effect. Using the conversion factors given above, the data in Figs. 8.27a and 8.61 have been replotted in Fig. 11.91 in terms of rems

for a 1-kiloton air burst. A curve giving the total biological dose, obtained by adding the separate initial gamma-ray and neutron doses at each distance from the explosion, is also included. 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.

11.92 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 negligible in comparison with the gamma radiations. At distances where marked biological effects are to be expected, 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.

11.93 The slant distances from the explosion at which total initial nuclear radiation (gamma-ray plus neutron) doses of 100, 500, and 1,000 rems, respectively, would be received for various explosion yields are shown in Fig. 11.93. For the higher doses, i.e., at shorter distances from ground zero, the neutrons make an increasingly greater percentage contribution to the total dose. The reason, as will be apparent from Fig. 11.91, is that, for a given yield, the neutron dose is larger than the gamma-ray dose at the shorter distances, whereas the reverse is true at greater distances from the explosion. The character of the initial nuclear radiation received at a given location will thus be determined by both the slant range and the energy yield.

Natural Background Radiation

11.94 In considering the possible 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" (or extended) 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. It is not possible to define an acute dose precisely, but it may be somewhat arbitrarily taken to be the dose received during a 24-hour period. Although the delayed radiations from early fallout persist for longer times, it is during the first day that the main exposure would be received and

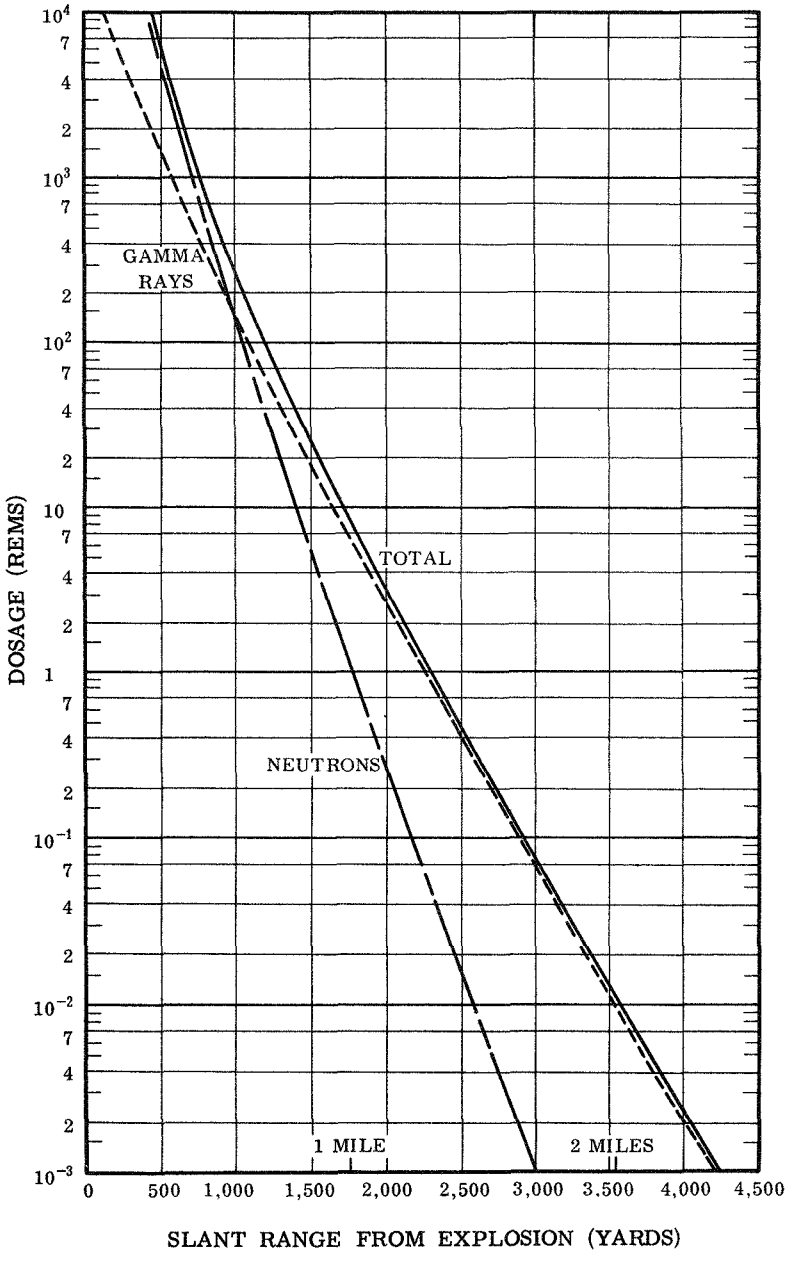

Figure 11.91. Initial gamma-ray and neutron doses as a function of range for a 1-kiloton air burst.

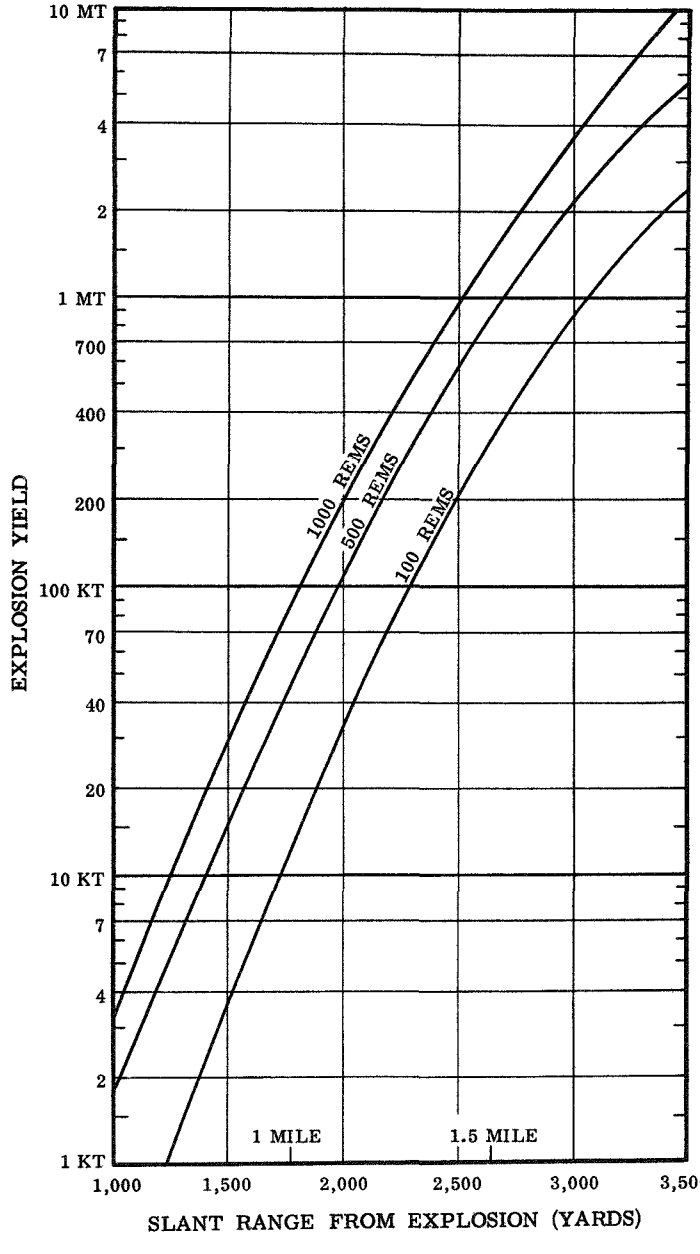

Figure 11.93. Ranges for total doses of 100, 500, and 1,000 rems of initial nuclear radiation as a function of the energy yield.

so it is regarded as being acute. On the other hand, an individual entering a fallout area after the first day or so and remaining for some time would be considered to have been subjected to a chronic exposure.

11.95 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 later, a larger total gamma-radiation dose would be required to produce a certain degree of injury if the dose were spread over a period of several weeks than if the same dose were received within a minute or so.

11.96 All living creatures are always exposed to ionizing radiations from various natural sources, both inside and outside the body. These are chronic exposures continuing for a lifetime. 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. Some potassium-40, as well as radioactive uranium, thorium, and radium in varying amounts, is also present in soil and rocks. The so-called "cosmic rays," originating in space, are another important source of ionizing radiations in nature. The radiation dose received from these rays increases with altitude up to about 90,000 feet; at 15,000 feet, it is more than five times as great as at sea level. The high radiation levels encountered in the Van Allen belts at much higher altitudes do not contribute to the background radiation on earth.

11.97 An estimate of the total radiation dose, due to purely natural sources, received per annum by human beings is given in Table 11.97 in millirems, i.e., in thousandths of a rem. The dose to the lungs from the radioactive gas radon present in the atmosphere varies with the type of building, the degree of ventilation, and atmospheric conditions. Brick and concrete construction materials, for example, contain more naturally occurring radioactive substances, which produce radon upon decay, than does wood.

11.98 It follows from the data in Table 11.97 that, during the average lifetime, every human being receives a total of about 10 rems (or more) of nuclear radiation over the whole body from natural sources. This exposure has undoubtedly continued during the whole period of man's existence on earth. In addition, there may be exposures associated with dental and chest X-rays, and similar treatments, and even from the luminous dials of wrist watches and instruments.

TABLE 11. 97

ESTIMATED DOSE PER ANNUM FROM NATURAL BACKGROUND RADIATION

Source	Dose in millirems			
	Soft tissue	*Lungs*	*Bone*	*Bone marrow*
Cosmic rays:				
Sea level	30	30	30	30
5,000 feet	70	70	70	70
Terrestrial radiations	50	50	50	50
Internal emitters:				
Potassium-40	20	20	9	9
Carbon-14	2	2	2	2
Radon	2	100 to 1,000	2	2
Radium	----	----	40	*

* Uncertain but probably small.

RADIOACTIVITY CONCENTRATION AND RADIATION PROTECTION GUIDES [12]

11.99 As seen above, human beings are continually exposed to ionizing radiations, from sources both inside and outside the body. This fact suggests that there is a certain chronic radiation dose over which the body has partial power of recovery or at which no detectable damage results. As to what this chronic dose is, there is no definite knowledge; however, in order for radioactive material to be used by industry, estimates must be made based on the best information available at the time.

11.100 Much effort has been expended in recent years in establishing criteria which can be used to measure hazards involved in the exposure to radiations from various radioactive materials. In 1960, the Federal Radiation Council established Radioactivity Concentration Guides (RCG) for the more important radioisotopes in air and water. These guides are for persons whose occupation causes them to be exposed frequently to radioactive substances. It is expected that, in the light of present knowledge, keeping within the recommended RCG values will result in no appreciable risk to the individual; in other words, the hazard will be no more severe than those commonly accepted in other present-day occupations. These guides are for normal peacetime operations and generally correspond to the old maximum permissible concentrations (MPC) which they replace.

11.101 The term "maximum permissible concentration" was misleading, since it was frequently taken to imply that concentrations

[12] National Bureau of Standards Handbook 59 ("Permissible Dose from External Sources of Ionizing Radiations") and recommendations of the Federal Radiation Council, approved by the President on May 13, 1960 and published in the Federal Register (May 18, 1960, pages 4802-3).

below the MPC will insure immunity from deleterious effects whereas concentrations greater than the MPC will inevitably lead to harmful consequences. This misconception is one of the main reasons that the term was replaced by Radioactivity Concentration Guide. In an emergency situation, such as could arise from a nuclear explosion, weapons tests, or an accident in an industry where radioisotopes are involved, it might be necessary to receive exposures in excess of the guides.

11.102 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 Radiation Protection Guide (RPG) of 5 rems per year beyond the age of 18 (or an average of approximately 0.1 rem per week), with a further provision that not more than 3 rems be received in any 13 consecutive weeks, has been established. In addition, it is recommended that the radiation or radioactive material outside of a controlled area, attributable to normal operations within the controlled area, shall be such that it is improbable that any individual will receive a dose of more than 0.5 rem in any one year from external radiation; and that the internal body burden of radioisotopes of the same group should not exceed one-tenth that recommended for occupational exposure. Exposures received from medical diagnostic and therapeutic procedures are not included in these guides. The figures (or guides) may be revised from time to time as further data on the effects of various ionizing radiations on living organisms become available.

11.103 The Radiation Protection Guides recommended for workers in industry are felt to include a factor of safety. There are individuals, in fact, 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.

General Radiation Effects

11.104 The effect of nuclear radiations on living organisms depends 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. A few radiation phenomena, such as genetic effects (see § 11.191 *et seq.*), apparently

depend primarily upon the total dose received and to a lesser extent on the rate of delivery. The injury caused by radiation to the germ cells under certain conditions appears to be 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, 1,000 rems in a single dose would be fatal if the whole body were exposed, but it would probably not have any noticeable external effects in the majority of persons if supplied more or less evenly over a period of 30 years.

11.105 The injury caused by a certain dose of radiation will depend upon the extent and part of the body that is exposed. One reason for this 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.

11.106 Different portions of the body show different sensitivities to ionizing radiations, and there are variations in degree of sensitivity among individuals. In general, the most radiosensitive parts include the lymphoid tissue, bone marrow, spleen, organs of reproduction, and gastrointestinal tract. Of intermediate sensitivity are the skin, lungs, and liver, whereas muscle, nerve, and adult bones are the least sensitive.

Effects of Acute Radiation Doses [13]

11.107 Before the nuclear bombings of Hiroshima and Nagasaki, radiation injury was a rare occurrence and relatively little was known of the phenomena associated with whole-body exposure and radiation injury. 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. Because of the great number of patients and the lack of facilities after the explosions, it was 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.

11.108 Since 1945, further information on this subject has been gathered from other sources. These include a few laboratory accidents

[13] Based on work and analysis by H. B. Gerstner, M.D., Oak Ridge Institute of Nuclear Studies.

involving a small number of human beings, whole-body irradiation used in treating various diseases and malignancies, and extrapolation to man of observations on animals. In addition, detailed knowledge has been 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 (§ 9.100 *et seq.*). The exposed individuals included both Marshallese and a small group of American servicemen. The whole-body radiation doses ranged from relatively small values (14 rems), which produce no obvious symptoms, to amounts (175 rems) which caused marked changes in the blood-forming system.

11.109 No single source of data directly yields the relationship between the physical dose of ionizing radiation and the clinical effect in man. Hence, there is no complete agreement concerning the effect associated with a specific dose or dose range. Attempts in the past have been made to relate particular symptoms to certain narrow ranges of exposure; however, the data are incomplete and associated with many complicating factors that make interpretation difficult. For instance, the observations in Japan were very sketchy until 2 weeks following the exposures, and the people at that time were suffering from malnutrition and pre-existing bacterial and parasitic infections. Consequently, their sickness was often erroneously attributed to the effects of ionizing radiation when such was not necessarily the case. The existing conditions may have been aggravated by the radiation, but to what extent it is impossible to estimate in retrospect.

11.110 In attempting to relate the radiation dose to the effect on man, it should be mentioned that reliable information has been obtained for doses up to 200 rems. As the dose increases from 200 to 600 rems, the data from exposed humans decrease rapidly and must be supplemented more and more by extrapolations based on animal studies. Nevertheless, the conclusions drawn can be accepted with a reasonable degree of confidence. Beyond 600 rems, however, observations on man are so sporadic that the relationship between dose and biological effect must be inferred or conjectured almost entirely from observations made on animals exposed to ionizing radiations.

11.111 With the foregoing facts in mind, Table 11.111 is presented as the best available summary of the effects of various whole-body dose ranges of ionizing radiation on human beings. Below 100 rems, the response is almost completely subclinical; that is to say, there is no sickness requiring special attention. Changes may, nevertheless, be occurring in the blood, as will be seen later (§ 11.126). Between

100 and 1,000 rems is the range in which therapy, i.e., proper medical treatment, will be successful at the lower end and may be successful at the upper end. The earliest symptoms of radiation injury are nausea and vomiting, which may commence within about 1 to 3 hours of exposure, accompanied by discomfort (malaise), loss of appetite, and fatigue. The most significant, although not immediately obvious, effect in the range under consideration, is that on the hematopoietic tissue, i.e., of the organs concerned with the formation of blood. An important manifestation of the changes in the functioning of these organs is leukopenia, that is, a decline in the number of leukocytes (white blood cells). Loss of hair (epilation) will be apparent about 2 weeks or so after receipt of a dose exceeding 300 rems.

11.112 Because of the increase in the severity of the radiation injury and the variability in response to treatment in the range from 100 to 1,000 rems, it is convenient to subdivide it into three subsections, as shown in Table 11.111. For whole-body exposures from 100 to 200 rems, hospitalization is generally not required, but above 200 rems admission to a hospital is necessary so that the patient may receive such treatment as may be indicated. Up to 600 rems, there is reasonable confidence in the clinical events and appropriate therapy, but for doses in excess of this amount there is considerable uncertainty and variability in response.

11.113 Beyond 1,000 rems, the prospects of recovery are so poor that therapy may be restricted largely to palliative measures. It is of interest, however, to subdivide this lethal range into two parts in which the characteristic clinical effects are different. Although the dividing line has been somewhat arbitrarily set at 5,000 rems in Table 11.111, human data are so limited that this dose level might well have any value from 2,000 to 6,000 rems. In the range from 1,000 to (roughly) 5,000 rems, the pathological changes are most marked in the gastrointestinal tract, whereas in the range above 5,000 rems, it is the central nervous system which exhibits the major injury.

11.114 The superposition of radiation effects 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 nuclear radiation 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.

TABLE 11.111

SUMMARY OF CLINICAL EFFECTS OF ACUTE IONIZING RADIATION DOSES

Range	0 to 100 rems Subclinical range	100 to 1,000 rems Therapeutic range			Over 1,000 rems Lethal range	
		100 to 200 rems	200 to 600 rems	600 to 1,000 rems	1,000 to 5,000 rems	Over 5,000 rems
		Clinical surveillance	Therapy effective	Therapy promising	Therapy palliative	
Incidence of vomiting	None	100 rems: 5% 200 rems: 50%	300 rems: 100%	100%	100%	
Delay time	—	3 hours	2 hours	1 hour	30 minutes	
Leading organ	None	Hematopoietic tissue			Gastrointestinal tract	Central nervous system
Characteristic signs	None	Moderate leukopenia	Severe leukopenia; purpura; hemorrhage; infection. Epilation above 300 rems.		Diarrhea; fever; disturbance of electrolyte balance.	Convulsions; tremor; ataxia; lethargy.
Critical period post-exposure.	—	—	4 to 6 weeks		5 to 14 days	1 to 48 hours
Therapy	Reassurance	Reassurance; hematologic surveillance.	Blood transfusion; antibiotics.	Consider bone marrow transplantation.	Maintenance of electrolyte balance.	Sedatives
Prognosis	Excellent	Excellent	Good	Guarded	Hopeless	
Convalescent period Incidence of death	None None	Several weeks None	1 to 12 months 0 to 80% (variable)	Long 80 to 100% (variable)	— 90 to 100%	
Death occurs within	—	—	2 months		2 weeks	2 days
Cause of death	—	—	Hemorrhage; infection		Circulatory collapse	Respiratory failure; brain edema.

CHARACTERISTICS OF ACUTE WHOLE BODY RADIATION INJURY

Doses of 25 to 100 Rems: No Illness

11.115 Single doses in the range of from 25 to 100 rems over the whole body will produce nothing other than blood changes. These changes do not usually occur below this range and are not produced consistently at doses below 50 rems. Disabling sickness does not occur and exposed individuals should be able to proceed with their usual duties.

Doses of 100 to 200 Rems: Slight or No Illness

11.116 Exposure of the whole body to a radiation dose in the range of 100 to 200 rems will result in a certain amount of illness but it will rarely be 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 267 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, 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 similar to those to be expected from an acute exposure of the same amount.

11.117 The illness from radiation doses in this range does not present a serious problem in that most patients will suffer little more than discomfort and fatigue and others may have no symptoms at all. There may be some nausea and vomiting on the first day or so following irradiation, but subsequently there is a so-called "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 and malaise, may reappear, but if they do, they are mild. 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 infection, there will be recovery in essentially all cases. In general, the more severe the early stages of the radiation sickness, the longer will be the process of recovery. Adequate care and the use of antibiotics, as may be indicated clinically,

can greatly expedite complete recovery of the small proportion of more serious cases.

Doses of 200 to 1,000 Rems: Survival Possible

11.118 For doses between 200 and 1,000 rems the probability of survival is good at the lower end of the range but poor at the upper end. The initial symptoms are similar to those common in radiation injury, namely, nausea, vomiting, diarrhea, loss of appetite, and malaise. The larger the dose, the sooner will these symptoms develop, generally during the initial day of the exposure. After the first day or two the symptoms disappear and there may be a latent period of several days to 2 weeks during which the patient feels relatively well, although important changes are occurring in the blood. Subsequently, there is a return of symptoms, including fever, diarrhea, and a step-like rise in temperature which may be due to accompanying infection.

11.119 Commencing about 2 or 3 weeks after exposure, there is a tendency to bleed into various organs, and small hemorrhages under the skin (petechiae) are observed. This tendency may be marked. Particularly common are spontaneous bleeding in the mouth and from the lining of the intestinal tract. There may be blood in the urine due to bleeding in the kidney. The hemorrhagic tendency depends mainly upon depletion of the platelets in the blood, resulting in defects in the blood-clotting mechanism (see § 11.131). Loss of hair, which is a prominent consequence of radiation exposure, also starts after about 2 weeks, immediately following the latent period, for doses over 300 rems (Fig. 11.119).

11.120 Susceptibility to infection of wounds, burns, and other lesions, can be a serious complicating factor. This would result to a large degree from loss of the white blood cells, and a marked depression in the body's immunological process. For example, ulceration about the lips may commence after the latent period and spread from the mouth through the entire gastrointestinal tract in the terminal stage of the sickness. The multiplication of bacteria, made possible by the decrease in the white cells of the blood and injury to other immune mechanisms of the body, allows an overwhelming infection to develop.

11.121 Among other effects observed in Japan was a tendency to spontaneous internal bleeding toward the end of the first week. At the same time, swelling and inflammation of the throat was not uncommon. The development of severe radiation illness among the Japanese was accompanied by an increase in the body temperature,

which was probably due to secondary infection. Generally there was a step-like rise between the fifth and seventh days, sometimes as early as the third day following exposure, and usually continuing until the day of death.

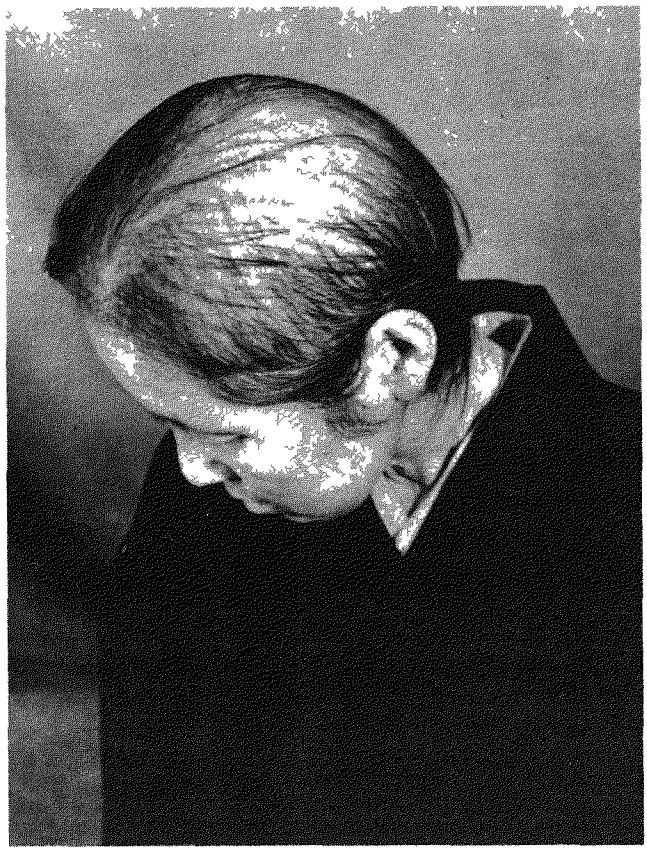

Figure 11.119. An example of epilation due to radiation exposure.

11.122 In addition to fever, the more serious cases exhibited severe emaciation and delirium, and death occurred within 2 to 8 weeks. Examination after death revealed a decrease in size of and degenerative changes in testes and ovaries. Ulceration of the mucous membrane of the large intestine, which is generally indicative of doses of 1,000 rems or more, was also noted in some cases.

11.123 Those patients in Japan 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.

Large Dose (Over 1,000 Rems): Survival Improbable

11.124. Very large doses of whole-body radiation (approximately 5,000 rems or more) result in prompt changes in 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 from 1,000 to roughly 5,000 rems, it is the gastrointestinal system which exhibits the earliest severe clinical effects. There is the usual vomiting and nausea 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 detonations in Japan, the diarrhea was frequent and severe in character, being watery at first and tending to become bloody later; however, this may have been related to pre-existing disease.

11.125 The sooner the foregoing symptoms of radiation injury develop the sooner is death likely to result. Although there may be no pain during the first few days, patients experience malaise, accompanied by marked depression and fatigue. At the lower end of the dose range, the early stages of the severe radiation illness are followed by a 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 a few days to 2 weeks.

Effects of Radiation on Blood Constituents

11.126 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 and blood-forming organs. Normally, these changes will occur only for doses greater than 25 rems. Much information on the he-

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matological 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 rems) 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.

11.127 One of the most striking hematological changes associated with radiation injury is in the number of white blood cells. Among these cells are the neutrophils, formed chiefly in the bone marrow, which are concerned with resisting bacterial invasion of the body. The number of neutrophils in the blood increases rapidly during the course of certain types of bacterial infection to combat the invading organisms. Loss of 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 neutrophils can then multiply rapidly, causing serious consequences. There are several types of white blood cells with different specialized functions, but which have in common the general property of resisting infection or removing toxic products from the body, or both.

11.128 After the body has been exposed to radiation in the sublethal range, i.e., about 200 rems or less, the total number of white blood cells may show a transitory increase during the first 2 days or so, and then decrease below normal levels. Subsequently the white count may fluctuate and possibly rise above normal on occasions. During the seventh or eighth weeks, the white cell 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.

11.129 The neutrophil count parallels the total white blood cell count, so that the initial increase observed in the latter is apparently due to increased mobilization of neutrophils. Complete return of the number of neutrophils to normal does not occur for several months.

11.130 In contrast to the behavior of the neutrophils, 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. The lymphocyte count continues to remain considerably below normal 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 indi-

viduals 3 or 4 years after exposure was not appreciably different from that of unexposed persons.

11.131 A significant hematological change also occurs in the platelets, a constituent of the blood which plays an important role in blood clotting. Unlike the fluctuating total white count, the number of platelets begins to decrease soon after exposure and falls steadily and reaches a minimum at the end of about a month. The decrease in the number of platelets is followed by 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 count which partly explains the appearance of hemorrhage and purpura in radiation injury.

11.132 The red blood cell (erythrocyte) count also undergoes a decrease as a result of radiation exposure and hemorrhage, so that symptoms of anemia, e.g., pallor, become apparent. However, the change in the number of erythrocytes is much less striking than that which occurs in the white blood cells and platelets, especially for radiation doses in the range of 200 to 400 rems. 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, followed by a gradual increase in individuals who survive.

11.133 As an index of severity of radiation exposure, particularly in the sublethal range, the total white cell or neutrophil counts are of limited usefulness because of the wide fluctuations and the fact that 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 is observed even with low doses and there is relatively little difference with large doses.

11.134 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. Furthermore, in this range, the degree of depression from the normal value is roughly proportional to the estimated whole-body 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 IONIZING RADIATION

Introduction

11.135 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, non-specific life shortening, leukemia, other forms of malignant disease, and retarded development of children *in utero* at the time of the exposure. Information concerning these late effects has been obtained from continued studies of various types, including those in Japan made chiefly under the direction of the Atomic Bomb Casualty Commission.[14]

11.136 The effects which occur later in life, like the acute reactions observed within a few weeks or months after irradiation, arise from changes in cells and tissues at the time of exposure. If an exposed individual survives the acute reaction, cell replacement may be complete, but the cells may not necessarily be quite normal; however, the causes for the late effects are largely unknown although many theories have been proposed.

Cataracts

11.137 An examination for the incidence of cataracts among the survivors of the bombings of Hiroshima and Nagasaki has revealed about 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. Only in a small proportion 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 were probably due to the initial nuclear radiation from the explosions. Because of the relatively high biological effectiveness of fast neutrons for the formation of lens opacities, as compared with gamma rays (§ 11.88), it is probable that this radiation was largely responsible for the Japanese cases.

11.138 Most persons in the same zone, with respect to the center of the explosion, died either from thermal or mechanical injuries or from radiation illness. Consequently, it is probable that all (or nearly all) the survivors who later developed cataracts must have received at

[14] The Atomic Bomb Casualty Commission of the U.S. National Academy of Sciences-National Research Council is sponsored by the Atomic Energy Commission and administered in cooperation with the Japanese National Institute of Health. One of its purposes is to study the long-term effects of exposure to nuclear radiation.

least moderate doses (300 rems or more) 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 injury.

Life Shortening

11.139 Laboratory experiments with animals indicate that shortening of the life span, apart from the effects of leukemia and other forms of malignant disease, can result from partial or whole-body exposure to radiation. Such shortening may be the result of a number of factors, including decreased immunity to infection, damage to connective tissues, and premature aging. The life shortening in a given animal, for a specific radiation dose, apparently depends on such factors as genetic constitution and on the age and physical condition at the time of the exposure.

11.140 During 1960 a study was made, under the direction of the Atomic Bomb Casualty Commission, on a large group of people in Hiroshima and Nagasaki to determine if there was any evidence of increased aging among survivors of the 1945 nuclear detonations. The results indicated that there is, at present, no support for the concept of general nonspecific aging acceleration, exemplified by aging of skin and hair, as a late radiation effect. However, it is still too early to make any definitive statement on the influence of radiation exposure of the Japanese with respect to life shortening.

Leukemia

11.141 It has been suggested that chronic exposure to moderate doses of nuclear radiation is conducive to leukemia, a disease associated with an overproduction of white blood cells. It 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 cases among the inhabitants of Hiroshima and Nagasaki was obtained in 1947. The peak apparently occurred between 1950 and 1952 and the incidence has subsequently decreased.

11.142 Essentially all of the cases of leukemia, which might be attributed to radiation because of other associated 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, has been estimated to be 400 to 500 rads air dose, although the actual dose received by the tissues was probably less than this.

11.143 From a survey of the exposed populations in Japan, it has been concluded that chronic granulocytic leukemia shows the greatest increase. There appears to be a direct relationship between the radiation dose and high dose-rate exposures, such as occurred in Japan, and the probability of leukemia development. Furthermore, there are indications of a trend toward onset of the disease at an earlier age among exposed individuals.

11.144 In addition to the Japanese study on the relation of radiation to the development of leukemia, other studies have been made although there are serious uncertainties associated with several of them. Some interpretations of mortality rates imply that leukemia is much more common among radiologists than other physicians; however, other interpretations of the same data indicate that the opposite is true. A slightly more clear relationship has been shown in patients irradiated with very large doses of X-rays to the spine, for rheumatoid spondylitis, to the subsequent development of leukemia or aplastic anemia. It should be noted, however, that out of over 17,000 patients radiated, only 49 cases of these two diseases were found. In addition, it has been suggested that there may be an increased incidence of leukemia in infants receiving large doses of X-rays about the head and neck primarily for enlarged thymus glands. In this particular study there is a more definite relationship to subsequent development of thyroid gland cancer. Up to 1960, there have been a total of only 226 cases of leukemia in the entire world in which radiation has been implicated; consequently, considerable uncertainty still remains.

Neoplasms

11.145 A special research initiated in 1957 in Hiroshima, to compare the frequency of malignant neoplasms, other than leukemia, in people exposed within about a mile of ground zero in 1945 with the incidence in unexposed populations, has yielded some interesting information. Although the study covers only a two-year period, the results suggest a two- to four-fold increase over the expected frequency for neoplastic disease in some organs (lung, stomach, breast, and ovary) in exposed persons. However, a similar study made in Nagasaki does not show the same relationship. The investigation is being continued through the Hiroshima Medical Society Tumor Registry

and future reports may shed more light on the incidence of neoplastic disease following exposure to ionizing radiation.

Retarded Development of Children

11.146 Among the mothers who were pregnant at the time 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 showed a slightly increased frequency of mental retardation. 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 rems of nuclear radiation. Maldevelopment of the teeth, attributed to injury of the roots, was also noted in many of the children.

11.147 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. It should be mentioned that those who were conceived in Japan after the nuclear attacks, even by irradiated parents, appear, for the most part, to be normal. The fear expressed at one time that there would be a sharp increase in the frequency of abnormalities has not been substantiated.

EFFECTS OF EARLY FALLOUT

External Hazard: Beta Burns

11.148 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 early 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 whole body could receive a large dose from beta particles which might be significant.

11.149 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 the hair and skin and remained there for a considerable time. Moreover, since the islanders, as a rule, did not wear shoes, their bare feet were continually subjected to contamination from fallout on the ground.

11.150 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 early fallout. 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.

11.151 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. 11.151 a and b).

11.152 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 dark-skinned patients undergoing X-ray treatment in clinical practice.

11.153 Most of the lesions were superficial without blistering. Microscopic examination at 3 to 6 weeks showed that the damage

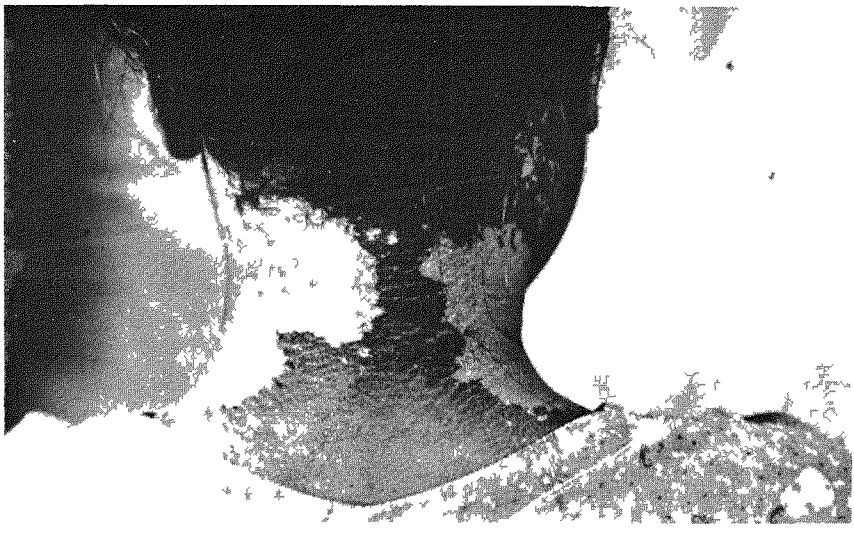

Figure 11 151a Beta burn on neck 1 month after exposure

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.

11.154 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 11 154 a and b).

11 155 Regrowth of hair, of the usual color (in contrast to the skin pigmentation) and texture, began about 9 weeks after contamination and was complete in 6 months. By the same time, nail discoloration had grown out in all but a few individuals. Seven years later, there were only 10 cases which continued to show any effects of beta burns, and there was no evidence of malignant changes.

Figure 11.151b. Beta burn on feet 1 month after exposure.

Blood studies of platelets and red blood cells indicated levels lower than average at 5 years after exposure; at 7 years after exposure the platelets continued to be slightly depressed. It thus appears that repair of bone marrow injury was not complete at this time. In the 1961 examination of the Marshallese people there was a possible indication of bone growth retardation in children who were babies at the time of the explosion.

Internal Hazard

11.156 Wherever fallout occurs there is a chance that radioactive material will enter the body through the digestive tract (due to the

Figure 11 154a Beta burn on neck 1 year after exposure (see Fig 11.151a)

consumption of food and water contaminated with fission products), through the lungs (by breathing air containing fallout particles), or through wounds or abrasions It should be noted that even a very small quantity of radioactive material present in the body can produce considerable injury. 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 Furthermore, internal sources of alpha emitters, e g , plutonium, or of beta

Figure 11 154b. Beta burn on feet 6 months after exposure (see Fig 11 151b).

particles, or soft (low-energy) gamma-ray emitters, can dissipate their entire energy within a small, possibly sensitive, volume of body tissue, thus causing considerable damage.

11.157 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 radioactive element 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) iso-

topes of the same element. This is the case, for example, with iodine which tends to concentrate in the thyroid gland.

11.158 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 absorbed 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 smaller extent and in other parts of the bone than are strontium and barium. 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 affects the entire body adversely.

11.159 The extent to which early fallout contamination can get into the blood stream will depend upon two main factors: (1) the size of the particles, and (2) their solubility in the body fluids. Whether the material is subsequently deposited in some specific tissue or not will be determined by the chemical properties of the elements present, as indicated previously. Elements which do not tend to concentrate in a particular part of the body are eliminated fairly rapidly by natural processes.

11.160 The amount of radioactive material absorbed from early fallout by inhalation appears to be relatively small. 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 (§ 9.186 *et seq*). Consequently, only a small proportion of the early fallout particles present in the air will succeed in reaching the lungs. Furthermore, the optimum size for passage from the alveolar (air) space of the lungs to the blood stream is as small as 1 to 2 microns. The probability of entry into the circulating blood of fission products and other weapon residues present in the early fallout, as a result of inhalation, is thus low. Any very small particles reaching the alveolar spaces may be retained there or they may be removed either by physical means, e.g., by coughing, or by the lymphatic system to lymph nodes in the mediastinal (middle chest) area, where they may accumulate.

11.161 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 early 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 enter the blood stream more readily and find their way into the bones.[15] The element iodine is also chiefly present in a soluble form and so it soon enters the blood and is concentrated in the thyroid gland.

11.162 In addition to the tendency of a particular element to be taken up by a specific organ, the main consideration in determining the hazard from a given radioactive isotope inside the body is the total radiation dose delivered while it is in the body (or specific organ). The most important factors in determining this dose are the mass and half-life (§ 1.60) 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 the "biological half-time" which is 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 half-life and biological half-time gives rise to the "effective half-life," defined as 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. For some isotopes it is difficult to express the behavior in terms of a single effective half-life because of their complicated metabolic mechanisms in the human body (see § 11.178, footnote).

11.163 The isotopes representing the greatest potential internal hazard are those with relatively short radioactive half-lives and comparatively long biological half-times. 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. Moreover, the long biological half-time means that the active material will not be readily eliminated from the body by natural processes. For example, the element iodine has a fairly long biological half-time in many individuals. The actual value varies over a wide range, from a few days in some people to many

[15] Even under these conditions, only about 10 percent of the strontium or barium is actually absorbed.

years in others, but on the average it is about 90 days. Iodine is quickly taken up by the thyroid gland from which it is generally 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, because it remains there during essentially the whole of its radioactive life.

11.164 At short times after a detonation, other radioisotopes of iodine, e.g., iodine-133 and -135, would contribute materially to the total dose to the thyroid gland. However, their radioactive half-lives are measured in hours, and so they decay to insignificant levels within a few days of their formation. 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.

11.165 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, cesium-137, 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.

11.166 Another potentially hazardous element, which may be present to some extent in the early fallout, is plutonium, in the form of the alpha-particle emitting isotope plutonium-239. This isotope has a long radioactive half-life (24,000 years) as well as a long biological half-time (about 200 years). Consequently, once it is deposited in the body, mainly on certain surfaces of the bone, 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.

11.167 Experimental evidence indicates that nearly all, if not all, inhaled plutonium deposits in the lungs where a certain portion, less than 10 percent, remains. Some of this is found in the bronchial lymph nodes. For this reason, the primary hazard from inhaled plutonium is to the lungs and bronchial lymph nodes. It is of interest to note that despite the large amounts of radioactive material which 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.

11.168 Early fallout accompanying the nuclear air bursts over Japan was so insignificant that it was not observed. Consequently, no information was available concerning the potentialities of fission products and other weapon residues as internal sources of radiation. Following the incident in the Marshall Islands in March 1954, however, data of great 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.

11.169 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 gastrointestinal tract, its contents, and the liver were found to be more highly contaminated than lung tissue.

11.170 From radiochemical analysis of the urine of the Marshallese subjected to the early 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 levels of the strontium isotopes were more persistent. Not only do these isotopes have longer radioactive half-lives, but the biological half-time of the element is also relatively long.

11.171 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 weapon residue activities were rapidly eliminated, because of either the shorteffective half-lives of the radioisotopes, the sparing solubility of the oxides, or the relatively large size of the fallout particles.

11.172 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 half-lives 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.

11.173 In spite of the fact that the Marshallese people lived approximately 2 days under conditions where maximum probability of contamination of food and water supplies existed, and that they took few steps to protect themselves, the amount of internally deposited radioactivity from early 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 early fallout due to internal sources can be quite minor in comparison with that due to the external radiation. If reasonable precautions are taken, the short-term, internal hazard can probably be greatly reduced.

LONG-TERM HAZARD FROM DELAYED FALLOUT [16]

CESIUM-137

11.174 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 delayed fallout. The process of fractionation will tend to increase the proportions of strontium and cesium still further, as explained in § 9.08. Of course, the activity level due to these isotopes at late times in the early fallout pattern in the area close to a surface or subsurface burst will be considerably larger than in the delayed fallout from a given explosion. However, the special interest in the delayed fallout arises from the fact that it may occur in significant amounts in many parts of the globe remote from the point of the nuclear detonation, as explained in Chapter IX, as well as in close by areas.

11.175 Cesium-137 has a radioactive half-life of 30.5 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.[17] The chemical and biochemical

[16] Much valuable information on delayed fallout and related problems is to be found in the published Hearings before the Special Committee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States: "The Nature of Radioactive Fallout and its Effects on Man," May 27 to June 7, 1957; "Fallout from Nuclear Weapons Tests," May 5 to 8, 1959; and "Biological and Environmental Effects of Nuclear War," June 22 to 26, 1959 (U.S. Government Printing Office).

[17] The gamma rays are actually emitted, within a very short time, by a high-energy state of the decay product, barium-137.

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properties of cesium resemble those of potassium. The compounds of these elements are generally more soluble than the corresponding compounds of strontium and calcium and the details of the transfer of these two pairs of elements from the soil to the human body are quite different. The element cesium is relatively rare 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 distributes itself within living cells in a way similar to potassium, so that it is found mostly in muscle.

11.176 Based on one experiment with several human subjects, the current estimate of the biological half-time of cesium 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. In spite of the gamma-ray emission, the biological half-time of cesium is so relatively short that, for the same amount of delayed fallout, the residual cesium-137 is less of a general biological hazard than the residual strontium-90.

11.177 The amount of internal exposure to cesium-137 is determined by the quantity of this isotope in the diet. If the major mechanism for its incorporation into the diet is through the root systems of plants, then the dose will be more or less proportional to the total amount of cesium-137 accumulated on the ground. On the other hand, if this isotope enters the diet mainly through material deposited directly on the leaves of plants, the internal dose will be more nearly proportional to the rate of descent of delayed fallout. It has been calculated that if the former mechanism prevails, the internal 30-year dose to the gonads, which is of interest in connection with possible genetic effects (§ 11.191), would be much higher than if the alternative mechanism were of major importance. The best data presently available on cesium-137 levels in food suggest that, up to the present time, the fallout rate has been the dominant factor; but in the future a larger proportion of the cesium may get into food via the soil, provided no considerable amounts of cesium-137 are added to the atmosphere.

Strontium-90

11.178 Strontium-90, because of its relatively long radioactive half-life of 27.7 years and its appreciable yield in the fission process, accounts for a considerable fraction of the total activity of fission products which are several years old. Strontium is chemically similar to calcium, an element essential to both plant and animal life; an

adult human being, for example, contains over 2 pounds of calcium, mainly in bone. However, the relationship between strontium and calcium is not a simple one as will be seen in subsequent sections and, because of its complex metabolism in the body, the behavior of strontium-90 cannot be stated in terms of a single effective half-life.[18]

11.179 The probability of serious pathological change in the body of a particular individual, due to the effects of internal radiation material, depends upon the intensity and energy of the radioactivity and upon the length of time the source remains in the body. Although strontium-90 emits only beta particles of fairly low energy, a sufficient amount of this isotope can produce damage because once it gets into the skeleton it will stay there for a long time.[19] Experiments with animals indicate that the pathological effects which result from damaging quantities (§ 11.184) of strontium-90 may be anemia, bone necrosis, cancer, and possibly leukemia.

11.180 Most of the strontium-90 in the delayed fallout is ultimately brought to earth by rain or snow, and it makes its way into the human body primarily through plants. At first thought, it might appear that the ratio of strontium to calcium in man would be equal to that in the soil from which he obtains his food. Fortunately, however, a number of processes in the chain of biological transfer of these elements to the human body operate collectively to decrease the relative quantity of strontium that is stored in man by an overall factor of two to ten. The processes which influence the strontium-90 which gets into the human body include availability and proximity of strontium to the root system of the plant, strontium-90 uptake by the plant, transfer from plant to animal, and transfer (where relevant) from animal to man.

11.181 Greenhouse experiments show a slight discrimination in favor of calcium and against strontium when these elements are taken up by most plants from homogeneous soils. However, several factors make it difficult to generalize concerning the ratio of strontium to calcium in the plant compared to that in field soils. First, plants

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[18] Data from strontium-90 excretion by the Marshallese people and studies in a case of accidental inhalation indicate that for an acute intake the major portion of the absorbed strontium-90 is excreted with a biological half-time of 40 days during the first year. During the next 2 years, at least, a smaller fraction is excreted with a biological half-time of 500 days. The remaining portion (less than 10 percent) is tightly bound to bone and is excreted very slowly with a long biological half-time of about 50 years. In this latter case, the effective half-life would be about 18 years. The situation for a chronic intake, e.g., from delayed fallout, although not the same, would be similar.

[19] The energy of the strontium-90 beta particles is 0.54 Mev. However, its daughter isotope, yttrium-90, which has the short half-life of only 64 hours, emits 2.27-Mev beta particles (no gamma rays); the decay product is stable zirconium-90. Thus, both 0.54- and 2.27-Mev beta particles (and the associated bremsstrahlung or secondary X-radiation) accompany the decay of strontium-90.

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 deposited in undisturbed soil has been found close to the surface, so that the uptake of this isotope may be expected to vary with the root 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 available for assimilation. Some natural calcium compounds in soil are insoluble and are not available as plant food until they have been converted into soluble compounds. Most of the strontium-90 in the delayed fallout, however, is in a water-soluble form. Third, in addition to the strontium-90 which plants derive from the soil, growing plants retain a certain amount of strontium-90 from fallout deposited directly on the surface of the plant.

11.182 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 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.

11.183 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. In addition to the fact that the human metabolism discriminates against strontium, it will be noted that, in each link of 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.

11.184 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. Tentative conclusions 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 § 9.163) 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 Radioactivity Concentration Guide (RCG) recommendation is that the maximum amount of strontium-90 in the body of any individual who is exposed in the course of his occupation be taken as 2 microcuries. Since the average amount of calcium in the skeleton of an adult human is about 1 kilogram (or a little over 2 pounds), this corresponds to a concentration in the skeleton of 2 microcuries of strontium-90 per kilogram of calcium. Moreover, the limit generally considered to be acceptable for any member of the general population is 0.2 microcurie of strontium-90 per kilogram of calcium. This is in accord with the recommendations made in 1960 by the U.S. National Academy of Sciences. The International Commission on Radiological Protection has suggested, further, that the concentration of strontium-90 averaged over the whole population should not exceed 0.067 microcurie per kilogram of calcium.

11.185 As a result of nuclear test explosions in various countries, there has been an increase in the strontium-90 content of the soil, plants, and the bones of animals and man. This increase is worldwide 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 (early) fallout.[20] As the fine particles descend from the stratosphere over a period of years, and are brought down by rain and snow in the troposphere, the amount of strontium-90 falling to the earth each year had reached a maximum in the summer of 1961 and had started to decline (§ 9.167). However, the subsequent addition of strontium-90 to the stratospheric reservoir may be expected to cause a temporary increase.

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[20] It is to be expected that areas near the explosion will be more highly contaminated in strontium-90 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. Because of the phenomenon of fractionation, the proportion of strontium-90 in the local (early) fallout will generally be less than that in the worldwide (delayed) fallout (§ 9.08). It is of interest to mention, too, that the strontium-90 in early fallout appears to be in a less soluble form, and hence probably less readily accessible to plants, than that present in the delayed fallout.

11.186. In the event that nuclear weapons with high fission yields were to be used extensively in warfare, calculations, based on somewhat uncertain premises, suggest that debris from many thousands of megatons of fission would have to be added to the stratosphere before the delayed fallout from these weapons would lead to an average concentration equal to the RCG value, for occupationally exposed persons, of 2 microcuries of strontium-90 per kilogram of calcium in human beings.

Carbon-14 and Other Isotopes

11.187 In addition to the effects of internal cesium-137 and strontium-90 considered above, consideration must be given to whole-body exposure from ingested carbon-14,[21] which is a beta-particle emitter, and from the gamma rays emitted by cesium-137 and isotopes of shorter half-life, such as zirconium-90, ruthenium-103 and -106, and cerium-141 and -144, deposited on the ground.

11.188 Weapons testing through the year 1958 had increased the amount of carbon-14 in the troposphere by about 30 percent (§ 9.34). If there had been no more nuclear explosions in the atmosphere, the additional carbon-14 would have dropped to 1 percent of the natural level in 50 to 100 years. Calculations indicate that the total dose from carbon-14 over the next two generations (50 years) will be a small fraction of that received from internal cesium-137. After a few hundred years, essentially all of the cesium-137 will have decayed, but the carbon-14, with its radioactive half-life of 5,760 years, will have diminished very little.

11.189 It has been estimated that, from the standpoint of the genetic impact of weapons tests upon the next 200 generations of mankind, the total dose from carbon-14 may be about equal to that from cesium-137, but the former will be delivered at an extremely low level during the whole 200 generations whereas that from cesium-137 will be received almost entirely within the first few generations. It should be noted, however, that the calculations for carbon-14 take into account only the ionization produced by the beta particles emitted during decay. An additional genetic effect can result from the detrimental biochemical consequences of the replacement of all the carbon-14 incorporated into genetic material by its decay product nitrogen-14. Present estimates suggest that the genetic damage from the transmutation of carbon-14 into nitrogen-14 might be as much as that caused by the emitted beta particles.

[21] Carbon-14 is not strictly a component of fallout but it is convenient to include it here since it is a possible long-term hazard arising from nuclear explosions.

11.190 The amounts of radiation, expressed in millirems, received from weapons tests through the year 1958 are summarized in Table 11.190. The first column gives the total dose for the year 1959, the second is an estimate for the 30 years between 1955 and 1985, and the third column for 70 years between 1955 and 2025. The reasons for choosing these two periods is that evaluation of the genetic effects of radiation on human beings (§ 11.191 *et seq.*) is generally based on the amount received by the gonads (or the whole body if uniformly irradiated) during the first 30 years of life, whereas the somatic effects are determined by the exposure during the whole lifetime (70 years). In most cases, the values listed in the table are conservative and are probably higher than would be received by the average person in the United States. It should be noted that both the 30-year whole-body (genetic) dose of 75 millirems and the 70-year whole-body (somatic) plus strontium-90 (bone marrow) dose of 201 millirems are less than 3 percent of the accumulated natural background doses over the same periods.

TABLE 11.190

ACCUMULATED DOSES FROM DELAYED FALLOUT FROM WEAPONS TESTS THROUGH 1958*

	Whole-body dose (millirems)		
Source	*1959*	*1955 to 1985*	*1955 to 2025*
Internal carbon-14	0.3	5	8
Internal cesium-137	2	20	30
External cesium-137	1	20	30
External short half-life	20	30	30
Total	23	75	98
Bone marrow dose from strontium-90	7	75	103
Natural background radiation (sea level)	100	3,000	7,000

*Additional doses from weapons tests which have been carried out subsequent to September 1, 1961 are not included.

GENETIC EFFECTS OF NUCLEAR RADIATIONS

SPONTANEOUS AND INDUCED MUTATIONS

11.191 The genetic effects of nuclear radiation consist of changes produced in the hereditary components of the reproductive cells; they are accompanied by no visible injury in the exposed individual but they may have notable consequences in future generations.

Although genetic damage is cumulative, it is now recognized that the rate at which changes result from exposure to radiation is somewhat dependent on the dose rate. Prompt, high dose rate exposures (greater than 25 rads per minute) may be at least four times as effective as are continuous exposures at low dose rates (1 rad or less per minute), for the same total dose. Thus, the protracted exposure that could result from a low-dose fallout field would presumably not carry the same threat of genetic change as would exposure to a single high-intensity dose, e.g., from the initial nuclear radiation, although the total dose delivered may be the same in both cases.

11.192 The mechanism of heredity, which is basically similar in sexually reproducing plants and animals, including man, is somewhat as follows. The nuclei of dividing cells contain a definite number of thread-like entities called "chromosomes" which 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, present in the reproductive organs, that are important.

11.193 Human body cells normally contain 46 chromosomes, made up of two similar (but not identical) sets of 23 chromosomes each. One of these sets was inherited from the mother, for the egg cell (produced in the ovaries) carries a set of 23 chromosomes, whereas the other set came from the father, for the sperm cell (produced in the testes) carries a set of 23 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.

11.194 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. However, if the mutation occurs in a germ cell of either parent, a new characteristic may appear in a later generation. The mutations which occur naturally, without any definitely assignable cause or human intervention, are called "spontaneous mutations."

11.195 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 ova-

ries, to ionizing 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 a result of exposure to radiation. It is only the frequency with which the mutations occur that is increased by ionizing radiation.

11.196 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.

11.197 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 observable in the next generation even if the particular gene is inherited from only one parent. Furthermore, in the great majority of cases, mutations have deleterious effects of some kind. A very few of the mutations are undoubtedly beneficial, but their consequences become apparent only in the slow process of biological evolution.

11.198 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

11.199 Experiments with fruit flies and mice have shown that the increased frequency of the occurrence of gene mutations, as a result of

exposure to large amounts of ionizing radiation (greater than 25 rads), is approximately proportional to the total radiation dose absorbed by the gonads of the parents from the beginning of their development to the time of conception of the progeny. Geneticists are of the general opinion that even the smallest amount of radiation will cause some increase in the normal mutation frequency; in other words, there is no threshold for genetic mutations resulting from exposure to nuclear (or ionizing) radiations. There is ample experimental proof from laboratory studies that, for an acute dose in the range of 37 to 600 rads, the mutation frequency increases in proportion to the radiation dose received by the gonads. However, 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 would be of the same general type as for a small dose, or as those which occur spontaneously, but there would be more of them in proportion to the dose.

11.200 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 carbon-14 and of strontium-90, cesium-137, and other radioisotopes in the delayed fallout. With regard to the initial nuclear radiation, it has been estimated that the amount, in addition to that received from natural background sources, required to double the rate at which spontaneous mutations are already occurring in humans is a dose to the gonads of probably between 30 and 80 rads, prior to conception, for each member of the population.

11.201 Genetic effects due to strontium-90 are relatively insignificant. In the first place, because of their very short range in the body, the beta particles from this isotope in the skeleton do not penetrate to the reproductive organs. In addition, the intensity of the secondary X-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.

11.202 The situation is somewhat different for cesium-137 and carbon-14, since they are distributed throughout the body and so can cause irradiation of the gonads. Furthermore, the decay of cesium-137 is accompanied by fairly long-range gamma rays, from a high-energy state of its daughter, barium-137. In addition, there must be taken into consideration the gamma rays from various isotopes of short half-life present in fallout deposited on the ground. However, the data in Table 11.190 show that the accumulated 30-year dose from all these sources would be no more than 75 millirems, that is,

less than 0.1 rem, so that the genetic effects will probably not be large.

PATHOLOGY OF ACUTE RADIATION INJURY [22]

Cellular Sensitivity

11.203 The discussion presented above has been concerned chiefly with general symptoms and the clinical effects of radiation injury. These effects are due directly to the action of nuclear radiation upon individual organs and tissues. The changes in the peripheral blood, for example, reflect the damage done by nuclear radiation to the bone marrow and lymphatic tissue. The pathologic changes in other systems and organs caused by ionizing radiation, which are the basis of the clinical radiation syndrome, are discussed here briefly.

11.204 Radiation damage is the result of changes induced in individual cells. Morphologically demonstrable changes, such as chromosome breaks, nuclear swelling, increased cytoplasmic viscosity, cellular permeability, and cellular death, are manifested as altered bodily function when enough cells are affected to reduce the total function of the organ made up of these cells. Cells of different types and organs have quite different degrees of radiosensitivity. In general, rapidly multiplying or actively proliferating cells are more radiosensitive than resting or intermitotic cells. The most striking early effect of irradiation is the rapid disappearance of dividing cells as further cell division is prevented by the exposure.

11.205 Of the more common tissues, the radiosensitivity decreases in the following order: lymphoid tissue and bone marrow, epithelial tissues (testes and ovaries, skin, basal layer of squamous epithelium, columnar epithelial crypts); endothelial cells of blood vessels, serosal cells of peritoneum and pleura, fibroblasts, osteocytes, smooth muscle, striated muscle, and differentiated nerve cells. Although nerves are the most radioresistant cells in the adult body, nervous tissue of the embryo and the adult granular cells of the adult cerebellum are radiosensitive. Disorientation and coma are induced by brain damage at dose levels of thousands of rems.

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

Lymphoid Tissue

11.206 Lymphoid tissue composes the lymph nodes, tonsils, adenoids, spleen, and the submucosal islands of the intestine. The lymphocytes of the peripheral blood arise in these various sites. Wherever these cells occur, they are the most radiosensitive cells of the whole body.

11.207 When a tissue is exposed to radiation, the lymphoid cells are killed and can be seen microscopically undergoing pyknosis and subsequent disintegration. As these cells die, their remnants are removed and the lymph nodes atrophy. This change was common among the victims of the nuclear bombs in Japan. After damage by radiation, the lymph nodes do not produce new lymphocytes for periods that vary with the radiation dose. As a result of this cessation of production, combined with death of circulating lymphocytes, there is a rapid fall in the number of the latter. This easily measurable change in the peripheral blood has been found to be one of the most sensitive and reliable means of prognosis following radiation exposure. A rapid, almost complete, disappearance of lymphocytes implies certain death, while no change within 72 hours is indicative of an inconsequential exposure.

11.208 Atrophic lymph nodes, tonsils, adenoids, Peyer's patches of the intestine, appendices, and spleens were common findings among the radiation casualties in Japan.

Bone Marrow

11.209 Since all the other formed blood cells, except the lymphocytes, arise from radiosensitive marrow cells, the radiation exposure syndrome is accompanied by severe changes in cellular composition of the blood. Under normal circumstances, the mature blood cells leave the marrow and enter the blood stream where they remain until destroyed by natural processes and in defense against infection. The different kinds of cells have different spans of natural life. The shorter the life of a particular cell, the more quickly will radiation damage to the parents of that particular cell be revealed by a decrease in number of such cells in the circulation. The red blood cells, which have the longest life span (about 120 days), are the last to show a reduction in number even though their parent cell, the erythroblast, is as radiosensitive as the lymphocyte.

11.210 Bone marrow exhibits striking changes soon after irradiation. There is at once a temporary cessation of cell division. Those

cells in the process of dividing go on and complete the process, after which all the cells in the marrow mature progressively. Since they leave the marrow as rapidly as maturity is reached, the marrow becomes depleted at once of adult forms and the more immature ones. As time passes, the marrow, barring regeneration, becomes progressively more atrophic until in the final stage it consists of dilated blood-filled sinuses, with gelatinous edema of the spaces left empty by the loss of marrow cells, and large macrophages containing the debris of dead cells removed from the circulation. Such extreme atrophy of the marrow was common among those dying of radiation injury in Japan up to 4 months after exposure. In some of these delayed radiation deaths, the bone marrow showed a return of cellular reproductive activity.

Reproductive Organs

11.211 Cell division in the germinative epithelium of the testes stops at once with lethal exposure to ionizing irradiation. The first change is pyknosis or nuclear death of the spermatogonia, the most primitive of the male germinative epithelium. Following this change, the more developed cells undergo maturation without further division, so that the testicular germinal cells leave the testis as adult sperm, and the most primitive cells disappear sequentially as they mature.

11.212 Although the ovaries are also highly radiosensitive, the changes are less striking than those in the testis. The primordial ova can be found in progressive stages of post irradiation atrophy and degeneration. In some Japanese irradiation victims, the ovarian follicles failed to develop normally and menstrual irregularities resulted. There was an increased incidence of miscarriages and premature births, along with an increased death rate among expectant mothers. These changes were related to the radiation dose, as determined by the distance from ground zero.

11.213 Morphologic changes in the human reproductive organs, compatible with sterility, are thought to occur with doses of 450 to 600 rems. Various degrees of temporary sterility were found among surviving Japanese men and women. Many supposedly sterile from exposure to significant doses of radiation have since produced children who are normal by ordinary measurements.

Loss of Hair

11.214 Epilation was common among Japanese surviving more than 2 weeks after the explosion. The onset of epilation was between

the 13th and 14th days after exposure in both sexes. Combing accentuated this change, although copious amounts of hair were lost spontaneously for about 2 weeks.

11.215 The distribution of the radio-epilation conformed in general with that expected from the senile changes of male ancestors. The hair of the eyebrows, eyelashes, and beard, however, came out much less easily. In severely exposed but surviving cases, hair began to return within a few months, and epilation was never permanent.

Gastrointestinal Tract

11.216 Some of the first gross changes noted in the Japanese were ulcerations of the intestinal lining. The mucosa of the first part of the small intestine is the most radiosensitive but usually does not ulcerate deeply. Ulcers are most commonly found after irradiation in the lower ileum in Peyer's patches and in the caecum, where bacterial invasion is common.

11.217 Microscopically profound changes are found throughout the gastrointestinal tract. The acid-secreting cells of the stomach are lost. Mitosis stops in the crypts of the intestinal glands. As a result, the cells covering the villi of the intestine are not replaced and the villi become swollen, turgid, and denuded. When bacterial invasion occurs, ulcers covered by a shaggy, fecally contaminated exudate develop. Since the white blood cells are simultaneously depleted and too few in number to combat infection, these intestinal ulcerations are often the point of entry of bacteria that kill the victim of heavy radiation exposure.

Hemorrhage and Infection

11.218 Hemorrhage is a common phenomenon after radiation exposure because the megakaryocytes, from which the blood platelets necessary for clotting are formed, are destroyed and the platelets are not replenished. If hemorrhage occurs in vital centers, death can result. Often the hemorrhages are so widespread that severe anemia and death are the consequences.

11.219 The loss of the epithelial coverings of tissues, together with the loss of white cells and antibodies, lowers the resistance of the body to bacterial and viral invasion. If death does not take place in the first few days after a large dose of radiation, bacterial invasion of the blood stream usually occurs and the patient dies of infection. Often

such infections are caused by bacteria which, under normal circumstances, are harmless.

11.220 Very often in whole-body irradiation the outward signs of severe damage to the bone marrow, lymphatic organs, and epithelial linings are gangrenous ulcerations of the tonsils and pharynx. This condition (agranulocytic anemia) is also found in cases of chemical poisoning of the bone marrow that resemble the effect of radiation exposure. Such ulcerations and the pneumonia that often accompanies them are unusual in that very little suppuration is found because of the paucity of leucocyte cells. Although most of the bacteria in such ulcerations can usually be controlled by antibiotic drugs, the viruses and fungi which also invade such damaged tissues are not affected by treatment, and fatal septicemia is common.

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CHAPTER XII

PRINCIPLES OF PROTECTION

BASIS FOR PROTECTIVE ACTION

Introduction

12.01 In the preceding chapters the phenomena and the destructive effects of nuclear explosions have been described in terms that are reasonably exact. In addition, the best available assessment of these effects on man have been presented. But in planning protection from the consequences of a nuclear explosion, so many uncertainties are encountered that precise analysis of a particular situation is impractical. For example, it is impossible to know in advance where or when a weapon will be detonated and what will be the explosive energy or the kind of burst. Nevertheless, there are some basic principles which, if properly understood and applied, could provide a measure of protection to a large proportion of the population in the event of a nuclear attack.

12.02 The most fruitful application of the principles of protection requires considerable preplanning on the part of individuals; however, some protection may be possible even in certain emergency situations if the principles are understood beforehand. It is the purpose of this chapter to present the quantitative aspects of weapons effects in a simplified form and to use them to explain the principles of protection. The information provided should be helpful in indicating the nature of the protection required and what steps must be taken in advance to achieve such protection. However, details of specific measures are not included since they are described in other publications.[1]

12.03 In the following sections the various effects of a nuclear explosion will be reviewed, with special reference to their ranges, and the principles of protection against each of these effects will be examined. At the same time, it will be shown how the measures used to provide protection from one particular effect can furnish protection against

[1] See the bibliography at the end of the chapter.

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others, so that the problem is less complicated than it might at first appear. Finally, a brief discussion will be presented of the planning needed to implement the principles of protection so as to make them effective.

Immediate and Delayed Effects

12.04 The effects of a nuclear explosion may be divided into two broad categories, namely, immediate and delayed. The immediate effects are those which occur within a few minutes of the actual explosion. These include air blast and ground shock, thermal radiation (light and heat), and initial nuclear radiation.

12.05 The delayed effects are associated with the radioactivity present in fallout and neutron-induced radioactivity. The early fallout from a surface burst will begin to reach the ground within a few minutes after the explosion at close-in locations, and at increasingly later times at greater distances from ground zero, depending on the effective wind speed and direction. At distances of several hundred miles from the explosion, the fallout may not commence until as late as 24 hours after the burst time. Furthermore, several hours may elapse between the time of arrival of the fallout at any point and the time when deposition is essentially complete. A significant early fallout is associated with a surface burst or a subsurface burst which vents to the atmosphere, but not with an air burst or with a completely contained underground burst. Neutron-induced radioactivity, apart from that in the weapons residues, extends only a short distance from ground zero and it decays more rapidly than fallout.

12.06 Except for a contained burst, all presently known nuclear weapons produce delayed (world-wide) fallout. However, this part of the fallout is generally not apparent until several weeks or months have elapsed; it will not be treated here, since the present discussion refers to protection which is effective at the time of, and soon after, an explosion.

Ranges of Various Immediate Effects

12.07 When a nuclear weapon of known yield is detonated on the surface, at a particular height in the air, or at a particular depth below the surface, the ranges of the immediate effects are fairly well defined. For example, there will be an area surrounding ground zero within which the destruction due to blast and shock, and accompanying fires, will be so great that the survival of inhabitants in conventional structures is improbable. At considerably greater distances the immediate

effects will be weaker and damage to structures will be minor, e.g., broken windows and damage to window frames and doors. The radiation from fallout may be significant in this region, but this is a delayed effect which will be considered later (§12.48 *et seq.*). Between the zone of total destruction and the area at which damage is not significant, there is a region in which protective measures can determine whether inhabitants survive, with little or no injury, or whether they become serious casualties.

12.08 The distances from ground zero within which various degrees of destruction may be expected depend primarily upon the energy yield of the explosion and the conditions of the burst, i.e., air, surface, etc. The topography and weather also influence these distances. By using the data presented in the earlier chapters, it is possible to draw a series of circles, as depicted in Fig. 12.08, representing areas within which effects of different types are to be expected for air bursts of various yields from 10 kilotons to 10 megatons TNT equivalent. The height of burst is such as to maximize the distance to which each effect extends; in other words, the radii of the circles give the greatest ranges at which the indicated thermal radiation, initial nuclear radiation, and overpressure levels will occur for any air burst of the given energy yield. It should be mentioned that the circular areas depict an idealized situation. Actually, as was the case in Japan, the pattern would be distorted by the conditions of the terrain, weather, etc. Two or more weapons detonated within a short distance can, of course, change the situation considerably.

12.09 Within the ring at which the blast overpressure is 5 pounds per square inch (5 psi), nearly all conventional houses will be damaged beyond repair. Even strong buildings, such as reinforced concrete and steel structures, will suffer damage and, without protective measures, the casualties to the inhabitants of this area will be high. In the central zone of heavy damage, there will alsa be a great fire hazard. Individuals in this area will be exposed not only to the effects of blast, but also to nuclear and thermal radiation. Apart from fortuitous circumstances, few persons will survive who have not sought protection in strong structures or shelters which will withstand the fire, blast, and shock and which will attenuate the radiation.

12.10 At distances from the burst where the blast overpreseure is 1 psi, the destructive effect of the air blast wave is minor. Window frames, doors, and plaster will suffer light damage. Window panes will be broken at much greater distances. The initial nuclear radiation dose will be so small that its immediate consequences are negligible, but thermal radiation may still be a significant source of

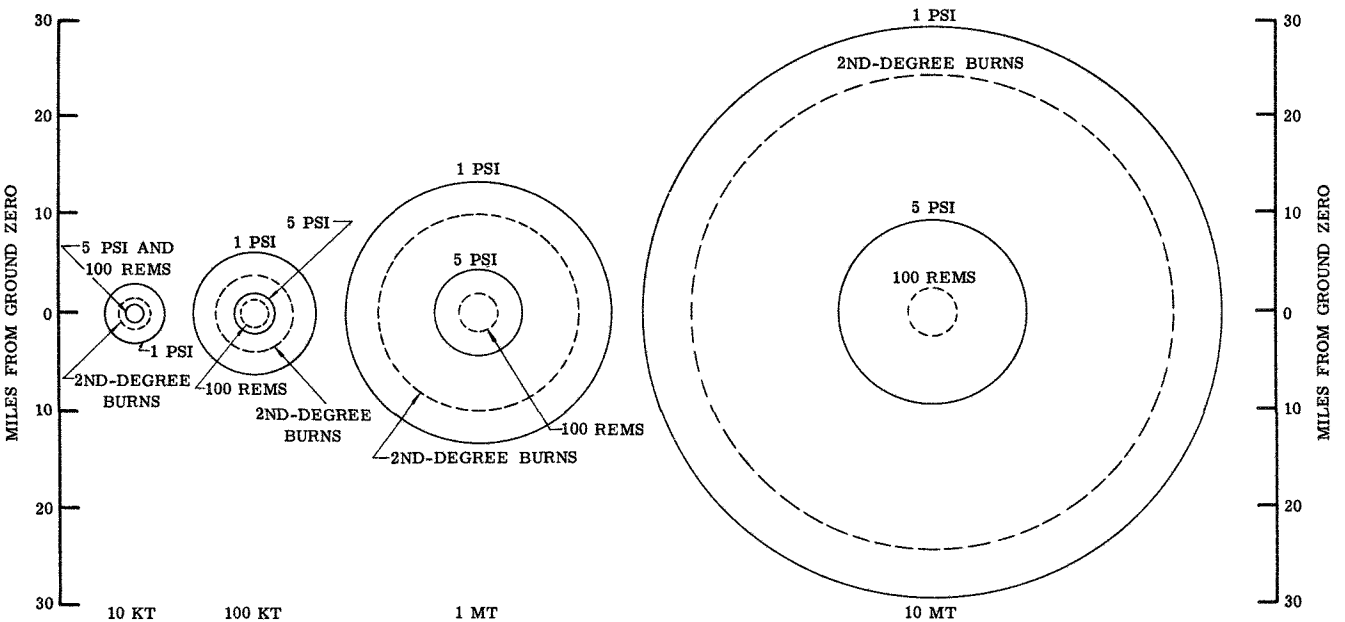

Figure 12.08. Idealized ranges for effects of air burst with the heights of burst optimized to give the maximum range for each individual effect.

casualties. Second-degree burns may be experienced at distances approaching those for 1 psi overpressure and less severe burns may be suffered at much greater distances from ground zero. Eye injury may also occur at even greater ranges and for high-altitude bursts of megaton weapons, this distance may be as much as several hundred miles. Furthermore, in dry, clear weather, many small fires would probably be ignited in newspapers and other thin combustible materials both within and outside of buildings.

Effective Protection Areas

12.11 In Japan, where little evasive action was taken, the survival probability depended upon whether the individual was outdoors or inside a building and, in the latter case, upon the type of structure. At distances between 0.3 and 0.4 mile (530 and 700 yards) from ground zero in Hiroshima the average survival rate, for at least 20 days after the nuclear explosion, was less than 20 percent. Yet in two reinforced-concrete office buildings, at these distances, almost 90 percent of the nearly 800 occupants survived more than 20 days, although some died later from radiation injury. Furthermore, of approximately 3,000 school students who were in the open and unshielded within a mile of ground zero at Hiroshima, about 90 percent were dead or missing after the explosion. But of nearly 5,000 students in the same zone who were shielded in one way or another, only 26 percent were fatalities. These facts bring out clearly the greatly improved chances of survival from a nuclear explosion that could result from the adoption of suitable warning and protective measures.

12.12 As a rough guide, the inner range at which protection in conventional structures could be achieved may be supposed to be that where the overpressure is 5 pounds per square inch and the outer range, beyond which casualties will be small *for an air burst*, is at 1 pound per square inch (or the limit for second-degree burns). As seen above, survival in Hiroshima was possible in buildings at such distances that the overpressure in the open was 15 to 20 pounds per square inch. The somewhat arbitrary choice of an overpressure of 5 pounds per square inch, which was experienced at a little over a mile from ground zero in Japan, is thus very conservative. In any case, it is evident from the circles in Fig. 12.08 that the area over which protection could be effective in saving lives is roughly eight to ten times as great as that in which the chances of survival are small. It may be concluded, therefore, that a considerable proportion of the population "at risk" from a nuclear explosion would be in an area in

which the casualty rate from the immediate effects may be significantly reduced provided protective measures are employed.

12.13 The various circles in Fig. 12.08 refer to an air burst, in which case there is essentially no early fallout. In the event of a burst at or near the surface, the situation would be different. The overpressure ranges would be reduced to roughly three-fourths and the second-degree burn range to about four-fifths of those shown in Fig. 12.08. However, there would be early fallout which might cover very extensive areas, from about 7 square miles for a 1-kiloton explosion to several thousand square miles for a 10-megaton yield (§9.100). Data that can be used for planning purposes are given in Chapter IX, but the conclusions concerning the extent of the hazard from early fallout cannot be expressed in simple diagrammatic form. However, it can be stated quite definitely that, following a surface burst of a high-yield weapon, a very large region extending possibly to three or four hundred miles downwind from the explosion center may become contaminated by the early radioactive fallout. The area affected will be influenced both by the total energy yield of the nuclear weapon and the proportion that is due to fission. The distance at which significant fallout will descend depends on the direction and speed of the wind at all levels from the radioactive cloud down to the ground.

12.14 From the standpoint of the present discussion, it cannot be too strongly emphasized that it is within this possibly large area of early fallout that preplanning of protective measures is of the utmost importance. At locations far from the point of attack, where the immediate effects of the nuclear explosion, i.e., blast, shock, initial nuclear radiation, and thermal radiation, are of absolutely no consequence, the delayed effect of fallout can be extremely serious unless steps are taken, in advance, to achieve protection when the emergency arises.

Relative Importance and Time Scale of Effects

12.15 It is not possible to arrange a single burst which maximizes the potential damage from each of the various immediate and delayed effects of a nuclear explosion. Thus, in a surface burst, the areas affected by blast, thermal radiation, and the initial nuclear radiation are appreciably less than for an air burst of similar energy yield. But, on the other hand, the surface burst is accompanied by early fallout whereas the air burst is not. Even with air bursts, the relative importance of the various effects depends on the height of burst.

12.16 In the following analysis an attempt is made to indicate the relative hazards associated with the various effects, as experienced by

a ground observer, under different burst conditions for a given energy yield. The phenomena are given roughly in the order of their appearance. First, there is the flash of brilliant light accompanied and followed by heat, both of which are part of the thermal radiation. The initial nuclear radiation starts at the same time but may continue after the thermal radiation has ceased. Then ground and water shock, if any, will arrive, followed very soon by the air blast (and sound) wave; then will come the early fallout, if any, which may continue for several hours. The general conclusions are summarized in Table 12.16, the degree (or severity) of a particular effect being indicated by the number of asterisks. The various degrees are relative to each other for a given burst type, and are best interpreted in terms of the descriptions given below.

HIGH-ALTITUDE BURST

Light: Very intense.
Heat: Moderate, decreases with increasing burst altitude.
Initial nuclear radiation: Negligible.
Shock: Negligible.
Air blast: Small on the ground, decreasing with increasing burst altitude.
Early fallout: None.

Summary: The most significant effect will be flash blindness over a very large area; eye burns will occur in persons looking directly at the explosion. Other effects will be relatively unimportant.

AIR BURST

Light: Fairly intense, but much less than for high-altitude burst.
Heat: Intense out to considerable distances.
Initial nuclear radiation: Intense, but generally hazardous out to shorter distance than heat.
Shock: Negligible except for very low air bursts.
Air blast: Considerable out to distances similar to heat effects.
Early fallout: Negligible.

Summary: Blast will cause considerable structural damage; burns to exposed skin are possible over a large area and eye effects over a still larger area; initial nuclear radiation will be a hazard at closer distances; but the early fallout hazard will be negligible.

GROUND SURFACE BURST

Light: Less than for an air burst, but still appreciable.
Heat: Less than for an air burst, but significant.
Initial nuclear radiation: Less than for an air burst.

Shock: Will cause damage within about three crater radii, but little beyond.

Air blast: Greater than for an air burst at close-in distances, but considerably less at farther distances.

Early fallout. May be considerable (for a high-yield weapon) and extend over a large area.

Summary: Except in the region close to ground zero, where destruction would be virtually complete, the effects of blast, thermal radiation, and initial nuclear radiation will be less extensive than for an air burst; however, early fallout may be a very serious hazard over a large area which is unaffected by blast, etc.

SHALLOW UNDERGROUND BURST

Light, heat, and initial nuclear radiation: Less than for a ground surface burst, depending on the extent to which the fireball breaks through the surface.

Shock: Ground shock will cause damage within about three crater radii, but little beyond.

Air blast: Less than for surface burst, depending upon depth of burst.

Early fallout: May be considerable, if the depth of burst is not too large, and in addition there may be a highly radioactive base surge.

Summary: Light, heat, and initial nuclear radiation will be less than for a ground surface burst; early fallout can be significant, and at distances not too far from the explosion the base surge will be an important hazard.

WATER SURFACE BURST

Light: Somewhat more intense than for a ground surface burst.

Heat: Similar to ground surface burst.

Initial nuclear radiation: Similar to ground surface burst.

Shock: Water shock can cause damage to ships and underwater structures to a considerable distance.

Air blast: Similar to ground surface burst.

Early fallout: May be considerable.

Summary: The general effects of a water surface burst are similar to those for a ground surface burst, except that the effect of the shock wave in water will extend farther than ground shock. In addition, water waves can cause damage on a nearby shore by the force of the waves and by inundation.

SHALLOW UNDERWATER BURST

Light, heat, and initial nuclear radiation: Less than for a water surface burst, depending upon how much of the fireball breaks through the surface.

Shock: Water shock will extend farther than for a water surface burst.

Air blast: Less than for a surface burst, depending on the depth of burst.

Early fallout: May be considerable, if the depth of burst is not too large, and in addition there may be a highly radioactive base surge.

Summary: Light, heat, initial nuclear radiation, and blast effects will be less than for a surface burst; early fallout can be significant, but at distances not too far from the explosion the radioactive base surge will be an important hazard. Water waves can also cause damage, as in the case of a water surface burst.

CONFINED SUBSURFACE BURSTS

Light, heat, and initial nuclear radiation: Negligible or none.

Shock: Severe, especially at fairly close distances from the burst point.

Air blast: Negligible or none.

Early fallout: None.

Summary: If the burst does not penetrate the surface, either of the ground or water, the only hazard will be from ground or water shock. No other effects will be significant.

TABLE 12.16

RELATIVE DEGREES OF WEAPON EFFECTS FOR VARIOUS BURST CONDITIONS†

Burst conditions	Thermal radiation		Initial nuclear radiation	Ground or water shock	Air blast	Early fallout
	Light	Heat				
High altitude	****	**	*		*	
Air	***	****	****	*	****	
Ground surface	**	***	***	**	***	****
Water surface	***	***	***	**	***	****
Confined subsurface				****		

†The number of asterisks provides a rough indication of the relative importance of the indicated effect to a ground observer. Four asterisks imply that the effect is the most extensive for the given burst type; a blank space means that the effect is negligible or absent. For a more complete interpretation, see the accompanying text.

12.17 The time sequence referred to in § 12.16 brings up another aspect of nuclear weapons effects that has a bearing on protection. Except very close to ground zero, even the immediate effects do not occur simultaneously. The first, almost instantaneous, indication of a nuclear explosion in the air or on the earth's surface is a brilliant flash of light. In many circumstances, it may be feasible, after observing the flash, to take some appropriate protective action that could greatly minimize the degree of injury suffered. At distances beyond those at which the immediate blast, thermal, and initial nuclear effects of the explosion are significant, there may be some time to make final preparations to decrease the early fallout.

12.18 As a general guide for planning purposes, it is useful to know the magnitudes of the respective immediate effects at a range of distances from an explosion of given yield. This information can be obtained from various figures and tables given in earlier chapters and can be identified from the list in the table of contents at the beginning of the book. A tabular summary of part of the data for air bursts, which may be more convenient for some purposes, is given in Table 12.18. The heights of burst are such as to maximize the various effects. An asterisk indicates that the particular distance is within the fireball; otherwise a blank space implies that the value is too small to be significant. The initial nuclear radiation doses are not given for distances of 5 miles or more for they are extremely small even for a 10-megaton explosion.

BLAST EFFECTS

Effects on Structures

12.19 Injury to individuals both inside and outside a structure may occur because of the blast damage to that structure. Persons in the interior of the building can be injured and trapped by collapse and fire, and those outside can be hurt by flying debris. For these and other reasons, an important aspect of protection is an understanding of the relative ability of different structures to withstand damage from air blast. Both the peak overpressure and the peak dynamic (or wind) pressure determine the amount of the damage, but for certain structures one or the other of these pressures has the dominant effect. For most office-type and residential buildings, including ordinary houses, the extent of destruction is mainly dependent on the peak overpressure, and an approximate correlation between the overpressure and the expected physical damage is given in Table 12.19.

TABLE 12.18

WEAPON EFFECTS FOR AIR BURSTS WITH MAXIMIZED RANGES

Distances from ground zero	Explosion yield				
	1 KT	10 KT	100 KT	1 MT	10 MT
½ mile				(*)	(*)
Overpressure (psi)	4.1	13	46		
Thermal radiation (cal/cm²)	3.8	38	380		
Initial nuclear radiation (rems)	670	6.7×10^3	7.6×10^4		
1 mile				(*)	(*)
Overpressure (psi)	1.5	4.5	14		
Thermal radiation (cal/cm²)	0.9	9.1	91		
Initial nuclear radiation (rems)	9.1	91	1100		
2 miles					(*)
Overpressure (psi)	<1.0	1.7	5.0	16	
Thermal radiation (cal/cm²)	0.2	2.1	21	210	
Initial nuclear radiation (rems)		0.2	1.9	35	
3 miles					
Overpressure (psi)		1.0	2.8	8.6	29
Thermal radiation (cal/cm²)		0.9	9.0	90	900
Initial nuclear radiation (rems)				<1.0	2.6
5 miles					
Overpressure (psi)		<1.0	1.4	4.1	13
Thermal radiation (cal/cm²)		<1.0	3.0	30	300
10 miles					
Overpressure (psi)			<1.0	1.5	4.5
Thermal radiation (cal/cm²)			<1.0	6.6	66
20 miles					
Overpressure (psi)				<1.0	1.7
Thermal radiation (cal/cm²)				1.4	14
50 miles					
Overpressure (psi)					<1.0
Thermal radiation (cal/cm²)				<1.0	1.7

*Inside or close to fireball.

TABLE 12.19

RELATION BETWEEN PEAK OVERPRESSURE AND DAMAGE TO STRUCTURES

Structure type	*Damage*	*Overpressure (psi)*
Wood-frame building, residential type.	Moderate	2 to 3
	Severe	3 to 4
Wall-bearing, masonry building, apartment-house type.	Moderate	3 to 4
	Severe	5 to 6
Multistory, wall-bearing building, monumental type.	Moderate	6 to 7
	Severe	8 to 11
Reinforced-concrete (not earthquake-resistant) building, concrete walls, small window area.	Moderate	8 to 10
	Severe	11 to 15

12.20 This information can be utilized, in conjunction with the overpressure-distance data in Table 12.18, or with the curves in Chapter III, to determine approximately how far from ground zero the respective degrees of damage would be experienced for air bursts of various yields. The height of burst is assumed to be such as to maximize the area of structural damage. For example, it is seen from Table 12.18 that for a 1-megaton air burst a peak overpressure of 3 to 4 pounds per square inch is attained at about 5 miles from ground zero. This is consequently the approximate limit of moderate damage to brick, apartment-house type buildings and of severe damage to wood-frame dwellings.

12.21 The results of a more detailed analysis, based on the nomograph in Fig. 4.58a, are given in Table 12.21. The maximum distances from ground zero for moderate and severe damage to the four types of structures referred to above are recorded for air bursts (at optimum heights) of weapons with yields from 1 kiloton to 10 megatons. For a surface burst, the damage range is three-quarters that for an air burst of the same yield.

TABLE 12.21

MAXIMUM RANGES FROM GROUND ZERO FOR STRUCTURAL DAMAGE FROM AIR BURSTS*

		Explosion yield				
		1 KT	*10 KT*	*100 KT*	*1 MT*	*10 MT*
Structure type	*Damage*	*(Distance in miles)*				
Wood-frame building, residential type.	Moderate	0. 66	1. 5	3. 2	6. 6	14
	Severe	0. 47	1. 1	2. 4	5. 5	12
Wall-bearing, masonry building, apartment-house type.	Moderate	0. 53	1. 1	2. 4	4. 7	10
	Severe	0. 34	0. 76	1. 7	3. 5	8. 7
Multistory, wall-bearing building, monumental type.	Moderate	0. 36	0. 76	1. 6	3. 5	7. 4
	Severe	0. 23	0. 55	1. 3	2. 8	6. 1
Reinforced-concrete (not earthquake-resistant) building, concrete walls, small window area.	Moderate	0. 28	0. 61	1. 5	3. 4	7. 2
	Severe	0. 19	0. 44	1. 1	2. 5	5. 9

*For a surface burst the respective distances are three-quarters of those for an air burst of the same yield.

12.22 Information on the effects of 20-kiloton and 1-megaton air bursts on a variety of structures, including many which are damaged by dynamic loading, is given in Tables 12.22 a and b. These refer to "typical" air bursts at heights of 1,850 and 6,800 feet, respectively,

TABLE 12.22a

DAMAGE RANGES FOR 20-KT TYPICAL AIR BURST

Peak Wind Velocity (mph)	Positive Phase Duration (sec)	Peak Dynamic Pressure (psi)	Peak Over-Pressure (psi)	Range from Ground Zero	
				2 MILES	Light damage to window frames and doors, moderate plaster damage out to about 4 miles; glass breakage possible out to 8 miles.
70	0.95	0.09	2.0	10 1000 FT	
				1.8	Fine kindling fuels: ignited.
79	0.94	0.12	2.3	9	Wood-frame buildings: moderate damage. Smoke stacks: slight damage.
				1.6	
93	0.92	0.17	2.7	8	
				1.4	
112	0.90	0.27	3.2	7	Wood-frame buildings: severe damage. Radio and TV transmitting towers: moderate damage. Wall-bearing, brick building (apartment house type): moderate damage.
				1.2	
139	0.86	0.42	4.2	6	Wall-bearing, brick buildings (apartment house type): severe damage.
				1.0	Telephone & power lines: limit of significant damage.
190	0.80	0.80	6.0	5	Multistory, wall-bearing buildings (monumental type): moderate damage. Light steel-frame, industrial buildings: moderate damage.
				0.8	
291	0.72	1.50	10.0	4	Multistory, wall-bearing buildings (monumental type): severe damage. Light steel-frame industrial buildings: severe damage. Highway and RR truss bridges: moderate damage.
				0.6	
431	0.63	3.90	16.3	3	Multistory, steel-frame building (office type): severe Transportation vehicles: moderate damage. damage. Multistory, blast-resistant designed, reinforced-concrete building: moderate damage.
				0.4	
459	0.54	7.50	22.5	2	Multistory, reinforced-concrete, frame building (office type): severe damage. Multistory, blast-resistant designed, reinforced-concrete buildings: severe damage. All other (above ground) structures: severely damaged or destroyed.
260	0.44	2.70	30.0	0.2 1 MILES 1000 FT	
				0 0	Ground zero for 20 KT air burst.

TABLE 12.22b

DAMAGE RANGES FOR 1-MT TYPICAL AIR BURST

Peak Wind Velocity (mph)	Positive Phase Duration (sec)	Peak Dynamic Pressure (psi)	Peak Over-Pressure (psi)	Range from Ground Zero	
					Light damage to window frames and doors, moderate plaster damage out to about 15 miles; glass breakage possible out to 30 miles.
				10 MILES	
44	3.45	0.036	1.2	50	
				9 1000 FT	
51	3.45	0.049	1.4	45	Fine kindling fuels: ignited.
				8	
60	3.44	0.072	1.7	40	
				7	
72	3.43	0.11	2.1	35	Smokestacks: slight damage.
				6	
89	3.40	0.16	2.6	30	Wood-frame buildings: moderate damage. Radio and TV transmitting towers: moderate damage.
				5	
117	3.24	0.28	3.5	25	Wood-frame buildings: severe damage. Telephone & power lines: limit of significant damage.
					Wall-bearing, brick buildings (apartment house type): moderate damage.
				4	Wall-bearing, brick buildings (apartment house type): severe damage.
177	3.02	0.60	5.5	20	Light steel-frame, industrial buildings: moderate damage. Light steel-frame, industrial buildings: severe damage. Multistory, wall-bearing buildings (monumental type): moderate damage.
				3	
278	2.69	1.40	9.4	15	Multistory, wall-bearing buildings (monumental type): severe damage. Highway and RR truss bridges: moderate damage. Multistory, steel-frame building (office type): severe damage. Transportation vehicles: moderate damage.
				2	
464	2.25	5.22	18.0	10	Multistory, reinforced-concrete frame buildings (office type): severe damage.
					Multistory, blast-resistant designed, reinforced-concrete buildings: moderate.
307	1.75	3.60	27.0	1 5	Multistory, blast-resistant designed, reinforced-concrete buildings: severe. All other (above ground) structures: severely damaged or destroyed.
				MILES 1000 FT	
				0 0	Ground zero for 1 MT air burst.

whereas the results in Table 12.21 and in Figs. 4.58 a and b are for heights of burst which produce a maximum area of damage for each type of structure.

Effects on Personnel

12.23 For ease of understanding, the effects of air blast on personnel are referred to as either direct or indirect. Among the direct effects are those due to overpressure, such as damage to the ear drums and the lungs (§§ 11.29, 11.31). These occur at close-in distances. An indirect type of injury can arise from displacement of the body as a whole by dynamic (or wind) pressure and its resulting impact with a hard surface (§ 11.33 *et seq.*). This can be experienced at distances where the overpressure (and dynamic pressure) are relatively low, because the maximum wind velocities in the open can still be quite high (Tables 12.22 a and b). Indirect blast injuries can also arise from broken glass and flying debris of various kinds produced by the destruction of buildings. These injuries could be quite numerous over the area in which the overpressure is about 2 pounds per square inch or more.

Protective Construction and Evasive Action

12.24 It is impractical to construct an aboveground conventional building, e.g., office, apartment, or warehouse, that will resist overpressures greater than 25 psi or more, but by taking certain precautions the blast resistance of any structure can be increased somewhat without adding seriously to its cost. The building should be designed for a prescribed overpressure of a certain duration in order that the structure may have essentially uniform strength in different parts. In this connection, it should be borne in mind that the reflected pressure on a wall facing the blast wave will be more than twice as great as on a side wall (§ 3.71). Sturdy connections between beams and columns, such as are commonly used in earthquake-resistant design, and the extensive use of bracing will generally increase the strength of the structure.

12.25 For large buildings, walls of reinforced concrete, which also contain the frame, will give a structure having maximum blast resistance. Such buildings withstood the blast from a nuclear bomb in Japan (Chapter V), although the interiors were badly damaged by fire. Unreinforced block construction, with brick, concrete, or

glass, is not only much less able to withstand blast than is a reinforced-concrete structure, but produces more flying debris when it is damaged.

12.26 In industrial-type structures, e.g., for housing machine tools, which have walls made of a frangible material, such as asbestos sheet, rather than of metal, the blast wave will destroy the siding with the result that the loading on the frame will be reduced mainly to that from wind drag. The lightweight debris produced will cause little damage to the machines inside the building. However, shelters are necessary to protect personnel in such buildings from flying pieces of frangible material.

12.27 Blast resistant personnel shelters have been tested at nuclear weapon tests at overpressure levels up to 200 pounds per square inch. Animals exposed at overpressures up to 90 pounds per square inch in such shelters have survived. Similar or more modest shelters can be constructed at relatively low cost if they are planned and built concurrently with new construction. Essential features of blast-resistant shelters are structural strength to resist blast loads to the selected overpressure level, an access door of corresponding strength, a protected ventilation system to permit occupancy of the shelter until fires have subsided, and adequate nuclear radiation shielding.

12.28 Where a blast-resistant shelter is not available, protection should be sought in the strongest building that is accessible. Protection against flying debris can be obtained by taking refuge in a location, preferably selected in advance, that is least likely to be entered by blast debris. In addition, individuals should stay away from windows and easily breakable materials, such as plaster walls or ceilings. In the collapse of buildings as a result of blast, heavy members and pieces of structural materials and contents will fall or be hurled about. There is a dual hazard of being hit and trapped; therefore, positions next to walls in basements offer the best protection. Above ground, however, the safest locations are generally near, but not against, walls and away from doors and windows.

12.29 Even if there is no prior warning of a nuclear attack and the first indication is the flash of light, there may still be the opportunity to take some protective action against the effects of blast. In Table 12.29 are given some approximate values of the times which elapse between the instant of the explosion and the arrival of the blast wave front at various distances from ground zero for air bursts of energy yields from 1 kiloton to 10 megatons TNT equivalent. For distances at which the peak overpressure is small, e.g., 1 pound per square inch or less, the times are not included.

TABLE 12.29—ARRIVAL TIME FOR PEAK OVERPRESSURE

Distance (miles)	Explosion yield				
	1 KT	10 KT	100 KT	1 MT	10 MT
	(Time in seconds)				
1	4. 3	3. 6	3. 7	2. 5	1. 5
2	>9	8. 1	7. 4	6. 5	5. 0
3	--------	>13	12	11	9. 5
5	--------	--------	21	20	16
7	--------	--------	>30	28	26
10	--------	--------	--------	42	37
20	--------	--------	--------	>90	83
30	--------	--------	--------	--------	>130

12.30 It is seen that at 10 miles from a 10-megaton air burst, which is within the area where protection against blast could be effective, some 37 seconds would elapse before arrival of the blast wave. If prompt action is taken, a person in a building could reach a position of the type indicated above. In the open, some protection against the blast may be obtained by falling prone, and remaining in that position until the wave has passed. In the prone position, with the head directly toward or directly away from the explosion, the area of the body exposed to the onrushing blast wave is relatively small and the danger of displacement is thereby decreased (cf. § 11.38).

THERMAL RADIATION EFFECTS

EFFECTS ON PERSONNEL

12.31 The main direct effects of thermal radiation on human beings are skin burns, generally called flash burns to distinguish them from flame burns, and permanent or temporary eye damage. Burns are classified by "degree"; first-degree burns being mild in nature, roughly similar to moderate sunburn; they should heal without special treatment. Second-degree burns are associated with blister formation and if a significant area of the body is involved, medical attention is necessary (§ 11.44 *et seq.*). The approximate limiting distances from air bursts of various total yields at which first- and second-degree burns of exposed (light-colored) skin may be expected are given in Table 12.31. Third-degree burns, which involve the entire thickness of the skin, can occur at shorter ranges. For a surface burst, the respective distances are decreased to about four-fifths of the values in the table. The ranges shown are actually from the burst point

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rather than from ground zero, but at the heights of burst that maximize the distances over which burns are experienced, the differences are small.

TABLE 12.31

RANGES FROM GROUND ZERO FOR BURNS TO BARE SKIN FROM AIR BURSTS*

	Explosion yield				
	1 KT	*10 KT*	*100 KT*	*1 MT*	*10 MT*
	(*Distance in miles*)				
First-degree burn	0. 7	1. 9	5. 3	14	>30
Second-degree burn	0. 5	1. 5	4. 0	11	24

*For a surface burst the distances are about four-fifths those for an air burst of the same yield.

12.32 The data presented in Table 12.31 are applicable to reasonably clear atmospheric conditions. Fog or mist near the ground or a layer of cloud between the point of the explosion and the ground would attenuate the thermal radiation and thus decrease the ranges at which flash burns may be experienced by exposed persons. However, snow on the ground or cloud layers above the explosion provide reflecting surfaces which increase these ranges.

12.33 Eye injuries are of two main types: temporary (flash blindness) and permanent (chorioretinal burns), as described in § 11.69 *et seq.* Both kinds of injury can occur at great distances from the explosion, considerably greater even than those for first-degree burns given in Table 12.31. The nature and extent of the eye injury depends on the yield and type of burst, on the orientation of the observer to the burst, on the clarity of the atmosphere, and on the size of the pupil opening. As a general rule, permanent eye injury would be expected only in those persons who were looking directly at the fireball. Flash blindness, on the other hand, could be quite general over a large area.

PROTECTIVE MEASURES

12.34 In an air or surface burst, the thermal radiation is received in two pulses, in each of which there is a maximum of intensity followed by a decrease. If an individual is caught in the open or is near a window in a building at the time of a nuclear explosion, evasive action to minimize flash burn injury should be taken, if possible, before the maximum in the second pulse. At this time only 20 percent of the thermal energy will have been received, so that a large proportion can be avoided if shelter is obtained before or soon after

the second thermal maximum. The elapsed times between the instant of the explosion and the second thermal maximum for air and surface bursts of various energy yields are recorded in Table 12.34. From this table it is seen that the prospects of being able to take evasive action are not good for air or surface bursts of low energy yield, but some possibility may exist for explosions in the megaton range.

TABLE 12.34

TIME TO SECOND THERMAL MAXIMUM

	Explosion yield				
	1 KT	*10 KT*	*100 KT*	*1 MT*	*10 MT*
Time (seconds)	0. 03	0. 1	0. 3	1. 0	3. 2

12.35. The major part of the thermal radiation travels in straight lines, and so any opaque object interposed between the fireball and the exposed skin will give some protection. This is true even if the object is subsequently destroyed by the blast, since the main thermal radiation pulse is over before the arrival of the blast wave.

12.36 At the first indication of a nuclear explosion, by a sudden increase in the general illumination, a person inside a building should immediately fall prone, as described in § 12.30, and, if possible, crawl behind or beneath a table or desk or to a planned vantage point. Even if this action is not taken soon enough to reduce the thermal radiation exposure greatly, it will minimize the displacement effect of the blast wave and provide a partial shield against splintered glass and other flying debris. An individual caught in the open should fall prone to the ground in the same way, while making an effort to shade exposed parts of the body. Getting behind a tree, building, fence, ditch, bank, or any structure which prevents a direct line of sight between the person and the fireball, if possible, will give a major degree of protection. If no substantial object is at hand, the clothed parts of the body should be used to shield parts which are exposed. There will still be some hazard from scattered thermal radiation, especially from high-yield weapons at long range, but the decrease in the direct radiation will be substantial.

12.37 Clothing of the proper kind provides good protection against flash burns. Materials of light color are usually preferable to dark materials because the former reflect the radiation. Clothing of dark shades absorbs the thermal radiation and may become hot enough to ignite, so that severe flame burns, which are more serious that the flash burns, may result. Woolen materials give better protection than those of cotton of the same color, and the heavier the fabric the

greater the protection. An air space between two layers of clothing is very effective in reducing the danger of flash burns.

12.38 *Protection against eye injury is difficult, especially for those* persons who happen to be facing the burst point. The blink reflex, i.e., the automatic blinking of the eye, which requires 0.15 second, may be helpful in providing some protection from air and surface bursts in the megaton range. It is doubtful, however, if much can be done at those distances where the same total amount of thermal energy is received from weapons of lower energy. In a nuclear explosion at high altitude, that is, at heights above 20 miles, the thermal radiation is emitted in a single rapid pulse. Assuming the total thermal energy received by a person at a particular location is sufficient to cause flash burns or eye injury, it seems improbable that any evasive action will be effective, as even the involuntary blink will not be in time to help very much. Ordinary sunglasses will provide little or no protection against eye damage, since much more opaque material would be required to decrease the radiation intensity. In all cases individuals should make every effort to avoid looking toward the fireball.

Fire Protection

12.39 After a nuclear attack on an urban area, extensive fires may develop as they did in Japan. Such fires were started both directly by thermal radiation and by secondary blast effects, i.e., overturning of stoves, short circuiting of electrical wires, etc. (§ 7.69). Appropriate fire control action may be directed along three lines, namely, (1) reduction of potential ignition points, (2) provision for isolation or rapid extinction of ignitions to prevent formation of large fires, and (3) minimization of the consequences should large-scale fires develop.

12.40 Since the elimination of wood as a construction material for houses is virtually impossible, potential ignition points can be decreased by continuous upkeep of existing wood structures and by taking steps to keep yards free from all combustible trash. As stated in § 7.57 *et seq.*, it was clearly demonstrated at the 1953 tests in Nevada that a well-maintained house, with a yard free from trash, is much more capable of withstanding the thermal effects of a nuclear explosion than is a poorly-maintained house or one with an unkept yard. Fire-resistive furnishings, e.g., draperies, rugs, etc., made of vinyl plastic or wool, also proved to be advantageous in these tests.

12.41 The second aspect of fire control action is to plan and train for the elimination of small fires before they can grow into serious ones.

In Japan the fires were so numerous and spread so rapidly that it would have been beyond the capability of regular fire departments to deal with them even if the latter had survived the bombings. The training of private individuals in emergency methods of firefighting, such as were developed in Europe during World War II, is therefore desirable. By extinguishing small fires soon enough, the number of serious fires may be sufficiently small to be dealt with by professional firefighters.

12.42 Conventional methods for preventing the spread of large fires, by the use of natural and artificial fire breaks, were not too successful in Japan, for the reasons mentioned in § 7.72. Nevertheless, consideration should be given to the provision of adequate fire breaks and to the zoning and planning of urban areas. As seen in § 7.55, the potential for the development and spread of fires is greatest in wholesale distribution and slum residential areas. Dispersal and protection of utilities and emergency services should be included in such planning.

INITIAL NUCLEAR RADIATION

Effects on Personnel

12.43 The initial nuclear radiation consists of gamma rays and neutrons received during the first minute after the explosion. Doses of this radiation up to 100 rems, over the whole body, would have little or no immediate observable effects on exposed individuals. The only effect expected might be a slight feeling of fatigue in some people. Many persons receiving larger doses, up to 200 rems, would not be greatly affected by the radiation, except for blood changes. For the present purpose, however, it will be supposed that a whole-body dose of 100 rems will cause few, if any, casualties requiring medical attention. At the other extreme, it is probable that every person receiving 1,000 rems over the whole body will become sick within 4 hours (or less) of exposure and will die in 2 or 3 weeks. Between these extremes there is a great deal of variation in the expected effects on personnel, but at an exposure of around 400 to 500 rems, all will be nauseated and vomit on the first day, and most will require medical care. However at this exposure, at least one-half of the people will probably recover.

12.44 The actual distances from air bursts of various yields at which the initial nuclear radiation will produce doses of 100, 500, and 1,000 rems, respectively, to completely unprotected individuals are

shown in Table 12.44. However, the heights of burst which maximize these distances are such that the latter are not very different from the ground zero ranges. For purposes of comparison, the distances for an overpressure of 5 pounds per square inch and for second-degree flash burns of exposed skin are included. It is seen that the hazards from blast and thermal radiation extend to much greater distances than do those from initial nuclear radiation, especially for weapons of yields in excess of 10 kilotons. For example, an individual 2 miles from a 1-megaton burst probably would show no significant symptoms of nuclear radiation sickness, but the thermal radiation exposure would be 210 calories per square centimeter (see Table 12.18). Less than 7 calories per square centimeter are sufficient to produce a second-degree skin burn from an explosion of 1 megaton. The corresponding blast wave overpressure of 18 pounds per square inch would cause severe damage to the strongest conventional structures (cf. Table 12.19).

TABLE 12.44

RANGES FROM GROUND ZERO FOR VARIOUS INITIAL NUCLEAR RADIATION DOSES FROM AIR BURSTS*

	Explosion yield				
	1 KT	*10 KT*	*100 KT*	*1 MT*	*10 MT*
Radiation Dose	(*Distances in miles*)				
100 rems	0.7	1.0	1.3	1.8	2.4
500 rems	0.6	0.8	1.1	1.5	2.1
1,000 rems	0.5	0.7	1.0	1.4	2.0
Other Effects					
5 psi	0.4	0.9	2.0	4.3	9.2
Second-degree burns	0.5	1.5	4.0	11	22

*The distances for a specified radiation dose are slightly less for a surface burst.

PROTECTION FROM INITIAL NUCLEAR RADIATION

12.45 It is apparent that for weapons with yields greater than 10 kilotons, the regions in which large doses of initial nuclear radiation could be received are those of high blast pressure and intense thermal radiation. Protection against all three effects would be provided by a massive reinforced, fire-resistant building. An 18-inch thickness of concrete, for example, would reduce the fatal dose of 1,000 rems to the tolerable one of about 100 rems. Thus, aboveground buildings of massive construction would provide some protection against the initial nuclear radiation. Additional protection may be obtained in basements beneath substantial concrete floor slabs. The surrounding

earth also helps in this connection; a 26-inch thickness of earth attenuates the radiation by a factor of about ten and 3 feet by about thirty.

12.46 The immediate evasive action suggested earlier for limiting the effects of thermal radiation and blast to a person in the open may assist, to a lesser extent, in reducing the dose of initial nuclear radiation. From high-yield weapons, in particular, a second or two elapses before much of the nuclear radiation is delivered at distances where survival is possible (§ 8.43). Table 12.46 gives the percentage of the total initial gamma-radiation dose received at given distances from 20-kiloton and 5-megaton explosions as a function of time. The total unshielded dose would be about 4,500 roentgens in each case.

TABLE 12.46

INITIAL GAMMA-RADIATION DOSE AS A FUNCTION OF TIME

		Time (seconds)						
		1	*2*	*4*	*7*	*10*	*15*	*20*
Explosion yield	*Distance (miles)*	*Percentage of initial gamma-radiation dose delivered*						
20 KT	0.5	67	78	88	95	97	100	-----
5 MT	1.5	5	17	43	76	90	98	100

12.47 As shown by the table, there is some possibility of reducing the radiation dose by immediate evasive action. However, from the numbers given above for the attenuation by concrete and earth, it is obvious that a nuclear radiation shield must be very massive if it is to be effective. Normal clothing, for example, will do little to attenuate initial nuclear radiation, although it may provide complete protection from thermal radiation. Another difficulty in connection with obtaining shelter in the open is the scattering of nuclear radiation, so that it may reach a person from many directions and not just along a direct line from the point of explosion.

RESIDUAL NUCLEAR RADIATION

FALLOUT HAZARD

12.48 The principal effects on personnel from residual radiation are similar to those from comparable doses of initial nuclear radiation as described in the preceding section. However, the hazards of exposure to residual radiation are entirely different from exposure to initial radiation and these hazards are described in this section.

12.49 Protection against residual nuclear radiation occupies a position of special significance. Because the early fallout can cover

an area much larger than that over which blast, thermal radiation, and initial nuclear radiation are significant, it is possible for people to become casualties at such distances from the explosion that the immediate effects are negligible or completely absent. As noted earlier, it is not feasible to state the degree of hazard from residual radiation in a reasonably accurate manner because it is so highly dependent upon conditions, especially wind speeds and directions over a considerable height. It is certain, however, that a surface burst in the megaton range will lead to contamination of very large areas by early fallout. This fallout will reach the ground very soon after the explosion at near distances, but at distances of several hundred miles, up to 24 hours may elapse before the fallout starts to arrive.

12.50 The early fallout hazard is of two main kinds: one results from the actual contact of the radioactive material with the skin, causing what are called "beta burns" produced by the action of the beta particles, and the second is due to the continuous exposure of the body to gamma rays, both direct and scattered, from fallout particles. It is with the second of these hazards that the discussion here will be mainly concerned. The protective measures for use against beta burns are chiefly associated with keeping the dust-like particles off the skin. If the fallout dust does get on the skin, it should be immediately washed off with soap and water. The possible hazard from entry of radioactive material into the body by ingestion will be considered later (§ 12.66 *et seq.*).

Induced Radioactivity

12.51 In addition to the radioactive fallout, there may be a residual radiation hazard near ground zero caused by induced activity resulting from the capture of neutrons by various elements in the soil, especially sodium and manganese. The induced-activity hazard may exist on the ground after an air burst when the initial fallout is virtually absent. However, this activity not only decays much more rapidly than does that from fallout, but it extends only a short distance (1 mile or less) from ground zero. Since the destruction in this area would be considerable, the only persons entering it for some time after the explosion should be rescue teams and others performing urgent missions. Such teams would be equipped with instruments to inform them of the radiation hazard.

Protective Measures

12.52 Assuming the population is to remain in the fallout area, and not be evacuated, it is necessary to obtain protection which

attenuates the gamma radiation. The basic principle to be borne in mind is that any massive or thick material will decrease the nuclear radiation level to some extent, whereas lighter construction, e.g., window areas, hollow, thin, or light walls, etc., permits the radiation to penetrate. A layer of concrete 8 inches thick or of earth 12 inches thick will yield an attenuation factor of 10; [2] doubling these thicknesses will increase the factor to 100. Thus, each extra foot of earth between an individual and the fallout will increase the protection factor tenfold. It should be remembered that scattered radiation will come from many directions, and so protection is necessary from all directions, either by the use of a mass of material or by distance.

12.53 Information has been published that describes procedures and standards for evaluating the potential of existing structures as fallout shelters and for modifying such structures to improve their effectiveness in this respect. The recommended procedures and standards may also be utilized in the design of new structures. Furthermore, instructions for building simple and effective fallout shelters are readily available. Basically, a fallout shelter is a structure with massive walls and ceiling. Practical materials of construction are earth, concrete, or solid masonry. Attenuation of the gamma radiation is provided by absorption in these materials and by the distance separating the fallout particles from the people in the shelter.

12.54 Since a shelter may have to be occupied continuously for periods as long as 2 weeks, until the natural decay of the radioactivity outside will allow the people to emerge, stocks of food and other supplies will be required. Where fallout arrives soon after the explosion, the early radiation dose rate will be high. It may then be necessary to wait several days before it is possible to come out of the shelter for more than a limited period without risking a radiation dose of sufficient magnitude to cause serious illness. In the path of the fallout, the early radiation levels will be lower at more distant points from the explosion, and the time necessary to occupy the shelter will be shorter, unless "hot spots" are present (§ 9.55). However, in any area where contamination is at all significant, it will probably be necessary to spend the first day or two after the burst sheltered from the residual gamma radiation. It is during the period immediately following the nuclear explosion, when the radiation level is at its highest, that protection is most important.

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[2] It should be noted that more than twice these thicknesses of concrete (18 inches) and of earth (26 inches) are required to attenuate the initial nuclear radiation to the same extent (§ 12.45) because the energy of the initial gamma rays is greater than in the residual (fallout) radiation.

12.55 A fallout shelter of the kind referred to in §12.53 will provide a protection factor of about 200 from the residual radioactivity; in other words, the dose rate in the shelter will be only ½ percent of that measured outside at a height of 3 feet above the ground. Where a shelter is not available, a similar protection factor from radiation can be obtained in the following manner in a small area of the basement of a two-story house. A sturdy table is placed in a corner adjacent to an unexposed outer wall and covered with 10 to 12 inches of soil, sandbags, solid concrete block, etc., according to what is available. If there are no heavy partitions or walls near the corner of the basement chosen, a layer of sandbags or concrete blocks should be stacked along the walls up to the height of the material on top of the table. Within the area under the table, there will be a protective factor of at least 100 from fallout radiation. The disadvantage of this type of protection is that it is unlikely that stocks of food and water would be available within the shelter, so that it could not be occupied continuously for an extended period, as could the more permanent type outlined previously. In almost any house with a buried basement, having uniformly thick exterior walls, a protection factor of 20 to 40 is possible. The maximum protection can be obtained near the floor and in the corners of the basement adjacent to an unexposed outer wall.

12.56 Before leaving a shelter, either temporarily or permanently, it is highly desirable that the radiation dose rate, both in the immediate area of the shelter and in the surrounding vicinity, be known. Marked variations in fallout patterns have been observed in weapons tests, with unexpected areas (hot spots) of exceptionally high activity. Hence, it is not sufficient to know merely that a nearby location is relatively safe. Communications equipment, e.g., battery-powered radios, and radiation measuring instruments should be in shelters. Otherwise it will not be possible to obtain information on radiation dose rates in the locality and in the immediate vicinity of the shelter, particularly at early times when high radiation levels will prevent radiation monitors from moving safely and freely about the community. As a rough rule-of-thumb, it may be stated that for every sevenfold increase in time, the radiation level will decrease by a factor of 10, provided the fallout is complete. For example, the radiation level at the end of 7 days will have fallen to roughly one-tenth of that at the end of 1 day. At the end of 49 days, it will have decreased by a factor of 100, etc.[3]

12.57 It is appropriate to mention here that whether or not fallout is visible to the eye, its measurement requires the use of suitable

[3] The rule is applicable to any unit of time; thus at 7 hours the residual radiation level will be one-tenth of that at 1 hour, at 14 hours it will be one-tenth of that at 2 hours, and so on, provided the fallout is complete at both times.

instruments sensitive to nuclear radiations. Some, although perhaps not all, of the fallout in the Marshall Islands, after the test explosion of March 1, 1954 (§ 9.100 *et seq.*), could be seen as a white powder or dust. This was due, partly at least, to the light color of the calcium oxide or carbonate of which the particles were mainly composed. It is probable that whenever there is sufficient fallout to constitute a hazard, the dust will be visible. Nevertheless, continuous monitoring with instruments for radioactive contamination would appear to be essential in all areas in the vicinity of the burst.

Radiological Surveys

12.58 As soon after a nuclear explosion as conditions permit, radiological monitoring surveys will have to be initiated for the purpose of developing information on the extent and levels of the contamination. At early times in heavily contaminated areas, where dose rates will be very high, only the most limited amount of monitoring can be accomplished by individuals with hand-carried instruments. In these circumstances, some kind of remote radiation monitoring equipment may be necessary. This will permit the monitor to remain within the shelter while taking readings of the dose rate outside.

12.59 The most rapid method for obtaining radiation levels in a large area is by aerial survey. Because of their long range in air, gamma rays can be detected by sensitive instruments at a height of a few thousand feet. Low-flying airplanes or helicopters, carrying suitable radiation instruments for measuring dose rates, can survey large areas unimpeded by damage on the surface and by impassable streets and roads. Moreover, by making initial flights at an altitude of 1,600 feet or so, the dose rates are only about 1 percent of those on the ground, so that the hazard to the monitor is decreased accordingly.

12.60 The dose rates measured at an altitude must be multipled by an appropriate factor to give the approximate dose rates near the ground. This factor will depend primarily on the height above the ground and nature of the terrain. In the absence of more specific information, the data in Fig. 9.181 may be used to estimate the attenuation factor at a known altitude with reference to that at a height 3 feet above the ground.

12.61 The aerial survey is important because it can be made readily and can provide information which might be impossible to obtain in any other way at the time of interest. Nevertheless, such a survey can serve only as a rough guide and should be made only after all the early fallout is out of the air and on the ground. For points of special

interest, the aerial survey must be supplemented by measurements made on the ground when it is safe to do so. The information obtained from the aerial survey will help, however, in planning the ground survey. In this way, the first appreciation of the broad aspects of the radiological situation will lead to the determination of conditions at critical points, to the establishment of dose-rate contours, and to the location of contaminated hot spots as well as the safest areas.

Radiation Doses and Times in Contaminated Areas

12.62 For the planning of defensive actions in connection with the residual activity from fallout or for carrying out survey operations in an area contaminated by the residues from a nuclear explosion, it is necessary either to make some estimate of the permissible time of stay for a prescribed gamma-radiation dose (in roentgens or rems) or to determine the dose which would be received in a certain period of time. The basic data are presented in the form of graphs in Chapter IX, but the same results may be expressed, in a somewhat more limited form, in tables that are more convenient for some purposes.

12.63 If the radiation dose rate (in roentgens or rems per hour) is known at a certain time at a given location, Table 12.63 may be used to determine the dose rate at any other time at the same location, *assuming that the fallout has descended completely and there has been no change other than that resulting from natural radioactive decay.* The same table can be utilized to determine the time after the explosion at which the dose rate will have attained a specific value. Suppose, for example, that at 5 hours after the explosion the measured dose rate is 6 roentgens per hour; when will it have decreased to 1 roentgen per hour? To obtain the answer, find the line in the left-hand column indicating "5 hours," and follow this horizontally until the value nearest to 6 is reached; this is 5.8, which is lower than the actual dose rate. Now proceed vertically down this column until the indicated value is somewhat less than 1.0; it is seen to be roughly 25 hours.

12.64 To determine the allowable time of stay in a contaminated area before a specified total dose is received, Table 12.64 may be employed if the dose rate at the time of entry is known. Suppose that upon entering a contaminated area at 8 hours after the explosion, the dose rate (R) is found to be 45 roentgens per hour. A competent authority has decided that exposed persons in the area may receive a total dose (D) of 25 roentgens, without endangering themselves, in order to perform an important mission; how long can they stay?

TABLE 12 63

FALLOUT ACTIVITIES AT VARIOUS TIMES AFTER A NUCLEAR EXPLOSION

Time after explosion	Dose rate																				
6 min	16	32	66	95	127	159	318	477	636	795	954	1 272	1 590								
12 min	7	14	28	41	55	69	138	207	276	345	414	552	691	1 380							
18 min	4 3	8 6	17	25	34	43	86	129	172	216	259	344	431	862	1 290						
30 min	2 3	4 5	9 1	13	18	23	45	68	91	114	136	182	227	456	681	908	1,140				
42 min	1 5	3 0	6 0	9 1	12	15	30	46	61	76	91	122	152	304	456	608	760	912	1 220		
1 hr	1 0	2 0	4 0	6 0	8 0	10	20	30	40	50	60	80	100	200	300	400	500	600	800	1 000	
1 hr 30 min	0 6	1 2	2 4	3 7	4 9	6 1	12	18	24	31	37	48	61	122	183	244	305	366	488	610	
2 hr	0 4	0 9	1 8	2 6	3 5	4 4	8 7	13	18	22	26	35	44	87	131	175	219	262	350	437	
3 hr	0 3	0 5	1 1	1 6	2 1	2 7	5 4	8 0	11	13	16	21	27	54	80	107	134	161	214	268	
5 hr		0 3	0 6	0 9	1 2	1 5	2 9	4 4	5 8	7 3	8 7	12	15	29	44	58	73	87	116	145	
7 hr			0 4	0 6	0 8	1 0	1 9	2 9	3 9	4 9	5 8	8	10	19	29	39	49	58	78	97	
10 hr				0 4	0 5	0 6	1 3	1 9	2 5	3 2	3 8	5 1	6 4	13	19	25	32	38	51	64	
15 hr					0 3	0 4	0 8	1 2	1 6	1 9	2 3	3 2	3 9	7 8	12	16	19	23	31	39	
1 day							0 5	0 7	0 9	1 2	1 3	1 8	2 3	4 5	6 8	9 0	12	13	18	23	
1 d 12 hr							0 3	0 4	0 6	0 7	0 9	1 2	1 5	2 9	4 4	5 8	7 3	8 7	12	15	
2 d							-		0 4	0 5	0 6	0 8	1 0	1 9	2 9	3 9	4 9	5 8	7 8	10	
4 d												0 3	0 4	0 8	1 3	1 7	2 1	2 5	3 3	4 2	
1 wk														0 5	0 7	0 9	1 2	1 4	1 8	2 3	
2 wk																0 3	0 4	0 5	0 6	0 8	
4 wk												---							0 3	0 4	

TABLE 12.64

ALLOWABLE STAY TIME IN AREA CONTAMINATED BY FALLOUT FROM A NUCLEAR EXPLOSION

D/R=Allowable dose in roentgens divided by dose rate in roentgens per hour at time of entry.	Time of entry in hours after the explosion																		
	0.1	0.2	0.5	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40
D/R	Duration of exposure (in hours and minutes) required to produce specified values of D/R for various times of entry after the explosion.																		
0.2	1-11	0-25	0-15	0-14	0-13	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12	0-12
0.3	9-40	1-00	0-22	0-22	0-20	0-19	0-19	0-19	0-19	0-18	0-18	0-18	0-18	0-18	0-18	0-18	0-18	0-18	0-18
0.4	312-24	2-22	0-42	0-31	0-27	0-26	0-26	0-25	0-25	0-25	0-25	0-25	0-25	0-24	0-24	0-24	0-24	0-24	0-24
0.5	∞	6-12	1-02	0-42	0-35	0-34	0-32	0-32	0-32	0-31	0-31	0-31	0-31	0-31	0-31	0-30	0-30	0-30	0-30
0.6	------	19-20	1-26	0-54	0-44	0-41	0-39	0-39	0-38	0-38	0-38	0-37	0-37	0-37	0-37	0-37	0-37	0-36	0-36
0.7	------	82-06	2-05	1-08	0-52	0-49	0-47	0-46	0-45	0-45	0-44	0-44	0-44	0-44	0-43	0-43	0-43	0-43	0-42
0.8	------	624-48	2-56	1-23	1-02	0-57	0-54	0-53	0-52	0-51	0-51	0-51	0-50	0-50	0-49	0-49	0-49	0-49	0-49
0.9	------	2, 000-00	4-09	1-42	1-12	1-05	1-02	1-00	0-59	0-58	0-58	0-57	0-57	0-57	0-56	0-55	0-55	0-55	0-55
1.0	------	∞	5-56	2-03	1-23	1-14	1-10	1-08	1-06	1-05	1-05	0-04	1-04	1-03	1-02	1-02	1-02	1-01	1-01
1.25	------	--------	15-30	3-13	1-54	1-38	1-31	1-28	1-25	1-24	1-23	1-22	1-21	1-20	1-19	1-18	1-17	1-17	1-16
1.5	------	--------	48-20	4-57	2-30	2-05	1-54	1-49	1-45	1-43	1-41	1-40	1-39	1-37	1-36	1-34	1-33	1-33	1-32
2.0	------	--------	1, 562-00	11-52	4-06	3-13	2-46	2-35	2-29	2-24	2-20	2-18	2-16	2-13	2-10	2-08	2-06	2-05	2-04
2.5	------	--------	∞	31-00	6-26	4-28	3-48	3-28	3-16	3-08	3-03	2-59	2-55	2-51	2-46	2-45	2-40	2-38	2-36
3.0	------	--------	--------	96-39	9-54	6-09	5-01	4-28	4-10	3-58	3-49	3-43	3-38	3-30	3-24	3-17	3-14	3-11	3-08
4.0	------	--------	--------	3, 124-00	23-43	11-05	8-12	6-57	6-16	5-50	5-33	5-19	5-10	4-58	4-44	4-32	4-26	4-20	4-15
6.0	------	--------	--------	∞	193-19	35-35	19-48	14-43	12-19	10-55	10-02	9-24	8-57	8-19	7-46	7-15	7-01	6-48	6-34
10.0	-- ---	--------	--------	--------	∞	728-49	124-00	59-18	39-34	30-39	25-42	22-35	21-32	17-52	15-41	13-57	13-05	12-24	11-42

The allowable dose (D) is divided by the dose rate (R) at the time of entry to give D/R, i.e., 25/45=0.55. This result falls between two values in the left-hand column of Table 12.64, and the smaller one is taken. Follow the D/R=0.5 line horizontally until the column headed "8 hours" after the detonation is reached. The allowable stay time is seen to be 31 minutes; for D/R=0.6, the corresponding time is 38 minutes, and so the actual permissible stay time would be about 34 minutes. By using both Tables 12.63 and 12.64, a variety of other estimates can be made.

12.65 There are two important reservations which must be kept in mind in using Tables 12.63 and 12.64. First, if there is any change in the situation, either by further contamination or by decontamination in the period between the two times concerned, the results will not be valid. Second, even if the conditions under which the tables are applicable are fulfilled, the estimates should be used for *planning purposes only*, and to provide a guide for any action that may be required. Changes in dose rates and total accumulated doses over a period of time must always be checked by instruments.

Food and Water

12.66 After a nuclear attack, in addition to protection from external residual radiation exposure, it is important that personnel in the fallout area also be protected from internal radiation exposure due to ingestion of radioactive fallout material along with food and water. Food and water are not adversely affected by exposure to the residual radioactivity. The principle of protection to be understood is that fallout material must be removed from food and water prior to consumption to prevent this material from getting inside the body. Relative to that which could be taken into the body by eating and drinking, it appears that the amount of radioactive material taken in by inhalation may be small (see §11.160). Nevertheless, air which contains fallout particles should not be directly inhaled without a protective respiratory device (such as a dust-filter respirator) until it is established by monitoring procedures that the air is free from radioactive contamination.

12.67 The contamination of emergency food and water supplies by residual radiation can be prevented by storing them in dust-tight containers. Although the outside of a container may become contaminated by fallout, most of the radioactive substance can be removed by washing the container before it is opened. The foods or

fluids can then be removed and consumed without significant contamination.

12.68 If emergency food supplies do become contaminated, or if it is necessary to resort to contaminated sources after emergency supplies are exhausted, many types of food can be treated to remove the radioactive material. Fresh fruits and vegetables can be washed or peeled to remove the outer skin or leaves. Food products of the absorbent type cannot be decontaminated in this manner and should be disposed of by burial. Boiling or cooking of the food has no effect in removing the fallout material. Milk, from cows which survive in a heavily contaminated area, may not be safe to drink because of the radioiodine content and this condition may persist for weeks or months.

12.69 Domestic water supplies from underground sources will usually remain free from radioactive contamination. Water supplies from surface sources may become contaminated if watersheds and open reservoirs are in areas of heavy fallout. However, most of the radioactive fallout material would be removed by regular water treatment which includes coagulation, sedimentation, and filtration. If a surface water supply is not treated in this manner, but merely chlorinated, it may be unfit for consumption for several days after an attack. As a result of dilution and natural decay the contamination will decrease with time.

12.70 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 in advance planning to the provision of ion-exchange columns or beds for emergency decontamination use. Home water softeners might serve the same purpose on a small scale. The water contained in a residential hot-water heater would serve as an emergency supply, provided it can be removed without admitting contaminated water. Water may also be distilled to make it safe for drinking purposes. *It should be emphasized that mere boiling of water contaminated with fallout is of absolutely no value in removal of the radioactivity.*

Decontamination

12.71 Decontamination is the process of removing radioactive material from a location where it is a hazard to one in which it can do little or no harm. It is one of the means which are available for reducing the radiation dose that would be received from fallout. Pref-

erably it should be accomplished under the supervision of personnel trained in decontamination procedures. Radiation measuring instruments should be used not only to determine the effectiveness of the decontamination but also to make sure that the contaminated material is disposed of in a safe manner.

12. 72 Because of its particulate nature, fallout will tend to collect on horizontal surfaces, e.g., roofs, streets, tops of vehicles, and the ground. In the preliminary decontamination, therefore, the main effort should be directed toward cleaning such surfaces. The simplest way of achieving this is by water washing, if an adequate supply of water is available. The addition of a commercial wetting agent (detergent) will make the washing more efficient. The radioactive material is thus tranferred to storm sewers where it is less of a hazard. Covering the ground around a building with uncontaminated earth or removing the top layer of the ground to a distance, by means of earth-moving equipment, are methods for reducing the dose rate inside a building. Inasmuch as decontamination of streets, buildings, and other large items requires substantial manpower and resources, the effectiveness of these operations will benefit from sound planning and skilled supervision.

12.73 It is important to note, in connection with removal of contaminated earth for the purpose described above 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 50 feet away, and about 25 percent from distances more than 200 feet away. Thus, complete removal of the contaminated surface from a circle 200 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 greater than one-fourth the initial value.

12.74 It is apparent, therefore, that if 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 cover would be required to decrease the dose rate by a factor of ten.

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12.75 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.

SUMMARY

Planning Protection

12.76 In planning protection against the hazards associated with a nuclear attack, it must be recognized that the amount of protection that will be available to individuals is, in a large degree, directly related to the extent of public knowledge concerning nuclear weapons effects and associated protective measures, and to the steps taken prior to the attack to put these measures into a state of readiness. There are certain actions which can be taken by the unprepared in extreme emergencies, but the protection achieved is minor when compared to that which would be available to those who had made adequate preparations. Moreover, following an attack there are certain procedures that can tend to minimize the remaining hazards and these also will be made more effective by sufficient concern beforehand as to their implementation.

12.77 A massive, reinforced, fireproof shelter structure is required at close distances to protect individuals against the severe immediate effects (blast, thermal, and initial nuclear radiation) of a nuclear explosion. This type of protection is the most comprehensive and requires the greatest amount of preplanning effort and knowledge of the effects hazards. Conventional buildings may also be designed to be blast and fire resistant. Measures to minimize the thermal and fire hazard (§ 12.39 *et seq.*) may also be effected. In those areas where early fallout is expected to be a hazard, shelters may be constructed and provision made for occupying them for considerable lengths of time. Knowledge of warning systems and evacuation procedures will also minimize confusion. Moreover, possession of battery operated communications systems and of radiation monitoring equipment will make it possible to obtain information on the condition of the occupied area following an attack.

12.78 In the event that shelters are not available, certain evasive actions may prove helpful at distances where the immediate effects are least severe. By instantly falling prone and covering exposed portions of the body or getting behind opaque objects, much of the thermal radiation may be avoided, especially in the case of large-yield weapons. Under no circumstances should an individual look in the direction of the fireball. Staying behind thick walls or lying in a deep ditch may help to avoid initial nuclear radiation. All of the above actions will also help to decrease the possible danger from the blast wave. Moreover, persons should avoid areas which have frangible materials, such as window glass, plaster, etc., which may become flying debris by the action of the blast.

12.79 After the immediate effects of the nuclear explosion are over, certain acts are required to minimize the hazards of the early fallout and from the fires which may result from thermal radiation and secondary blast effects. First, if small fires can be quickly extinguished, extensive conflagrations may be prevented. This must be accomplished before the arrival of the fallout or in areas of low radioactivity levels. Some protection from the fallout may be secured in the basements of buildings or in a quickly constructed shelter, such as is described in § 12.55. It is important to keep from coming into physical contact with the fallout particles, and to prevent contamination of food and water sources. Monitoring equipment should be used to determine areas which have safe radiation levels and decontamination efforts can proceed to recover necessary equipment, buildings, and areas.

Conclusion

12.80 Much of the discussion presented in earlier sections of this chapter have been based, for simplicity, on the effects of a single weapon. It must not be overlooked that in a nuclear attack some areas may be subjected to several bursts. The basic principles of protection would remain unchanged, but protective action against *all* the effects of a nuclear explosion—blast, thermal radiation, initial nuclear radiation, and fallout—would become even more important. There is a good possibility that many people would survive a nuclear attack and this possibility would be greatly enhanced by utilizing the principles of protection in preattack preparations and planning, in taking evasive action at the time of an attack, and in determining what should be done in the recovery phase after the attack.

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APPENDIX A

NUCLEAR WEAPONS SAFETY AND ACCIDENT HAZARDS

INTRODUCTION

A.1 Nuclear weapons are designed with great care to explode only when deliberately armed and fired. Nevertheless, there is always a possibility that, as a result of accidental circumstances, an explosion will take place inadvertently. Although all conceivable precautions are taken to prevent them, such accidents might occur in areas where the weapons are assembled and stored, during the course of loading and transportation on the ground, or when actually in the delivery vehicle, e.g., an airplane or a missile.

A.2 In general, nuclear weapons contain varying amounts of high explosive (§ 1.54), in addition to the fissionable material, i.e., the nuclear explosive. The chances that the latter alone will detonate are so remote that they can be ruled out completely. It is the high-explosive component which comprises the main possible hazard, just as it does with conventional weapons. The spontaneous detonation of this material, without external cause, is highly improbable, but an explosion might occur if the weapon were dropped from a height or if it were involved in a fire. Both aircraft and missiles contain fuel or propellant which is combustible and so in an accident to these vehicles a serious fire could develop which might possibly, although by no means certainly, cause the detonation of the high explosive in a nuclear weapon.

A.3 Even if such an explosion did occur, the nuclear component would not necessarily be affected. A nuclear weapon is a complex system and all of its components must function almost perfectly if it is to produce an energy release that even approaches the design value. Any nuclear energy contribution resulting from the accidental detonation of the high-explosive component will, therefore, be either completely absent or very small. During more than 16 years (from 1945 through 1961) of storing, transporting, flying, overhauling, modifying, inspecting, and otherwise working on and with nuclear

weapons, the nuclear part of the weapon has not contributed to the cause or the effect of an accident. Although any accident is to be deplored, the fact that none has been more serious than from a conventional high-explosive weapon of moderate power, is a tribute to the extreme care devoted to the design of nuclear weapons and to the development of safe procedures for handling and transporting them.

A.4 Before discussing the various hazards which might be associated with an accident to a nuclear weapon, mention may be made of the possibility of a nuclear explosion being produced deliberately by sabotage or by the action of a psychotic individual who has access to a weapon. To eliminate or, at least, to minimize the probability of such an occurrence, there are positive physical and procedural measures which prevent deliberate or inadvertent arming, launching, firing, or release of a nuclear weapon. Among the precautions taken mention may be made of the use of launch or release controls which are locked or sealed in the safe position, the employment of two or more separate controls, and procedures requiring the presence of two or more properly informed and authorized persons.

A.5 Since accidents, by their very nature, are completely unpredictable, consideration must be given to all conceivable hazards that might arise in the storage or transportation of nuclear weapons. These hazards may be due to (*a*) fire and detonation of the high explosive, (*b*) fissionable material, i.e., uranium and plutonium, (*c*) tritium, which is radioactive, and (*d*) fission products in the unlikely event that there is an appreciable nuclear yield. These aspects of accidents to nuclear weapons will be considered in turn.

Fire and Detonation

A.6 If a nuclear weapon is exposed to the flames from a gasoline or similar fire, arising from the fuel or propellant of the carrying vehicle, the high explosive will probably ignite and burn. Fires resulting from large quantities of burning high explosives are very difficult to extinguish. At the same time, acrid, suffocating, and toxic gases are produced, and a poisonous residue may remain. If the high explosive is confined, as in an intact weapon, detonation may occur at any time. In addition, high explosives melt at relatively low temperatures; the heat of the fire may thus cause the molten explosive to flow out of the weapon and then resolidify. In this state, the material is extremely sensitive to shock, and may detonate if stepped on.

A.7 In any accident involving a nuclear weapon, such as dropping or exposure to fire, there is a possibility that detonation of the high explosive may occur. However, one of the characteristics of TNT and similar explosives is the unpredictability of their response to a given stimulus. Thus, impact or a fire may or may not cause a detonation. If a detonation does occur, it can range from a very small to a large chemical explosion or it may be a series of small explosions. The breakage of a weapon due to impact or to a small explosion will probably result in scattering of small pieces of high explosive; these may burn and possibly explode.

A.8 Rough handling of high explosives as well as accidents can lead to the formation of powdered explosive. Under these conditions, most explosive materials are more unstable than in bulk form and are more apt to be detonated by shock or change in temperature. Exposure to sunlight also increases the sensitivity of high explosives; at the same time there is a change in color which makes small pieces and powder difficult to distinguish from their surroundings. The danger of an explosion is thereby increased.

A.9 The detonation of high explosives can cause injury to personnel by direct and indirect blast effects, as described in Chapter XI. The greatest danger is probably from flying debris, falling objects, fragments of glass, etc. It is recommended that, in the event of a nuclear weapon becoming involved in a fire, all persons not essential for damage control or recovery operation withdraw to a distance of at least 1,500 feet. This will minimize the injury potential of the blast that would result from the detonation of the high explosive.

A.10 Because of the formation of noxious fumes, etc., as stated above, produced by the burning explosive, and by any vehicle fuel that may be present, only those individuals properly protected with respiratory equipment should be permitted to remain in the downwind path of a fire or potential detonation. Smoke may be tolerated for a short period of time if necessary in the interest of saving lives. When the fire has subsided and a check has been made by instruments that no radiation hazard exists, trained experts may approach the scene of the accident in order to clear the area of scattered pieces of high explosive.

Fissionable Material

A.11 All nuclear weapons contain a certain amount of fissionable material, either uranium or plutonium (or both); these substances are radioactive, emitting alpha particles (§ 9.40). Following an accident

to a nuclear weapon, the fissionable material could, in some circumstances, be spread over a large area. However, because alpha particles cannot penetrate even the dead surface layer of the unbroken skin, the only possible hazard that could arise would be the entry of uranium or plutonium into the body. The danger from plutonium lies in the tendency of this element to concentrate in the bone, where the continuous emission of alpha particles may cause significant injury. Uranium, on the other hand, acts mainly as a chemical poison, and fairly large amounts would have to be absorbed to produce any serious effect. Both uranium and plutonium can be detected as surface contamination by instruments which indicate the presence of alpha particles; the particles from plutonium have the higher energies.

A.12 Plutonium and uranium react readily with oxygen from the air and so they may become dispersed as small particles of oxide if the fissionable material is exposed. This may occur if the nuclear weapon is broken by impact or by the detonation of the high explosive. In the event of a fire, very fine particles of the oxides may be carried in the smoke. In the few instances in which aircraft containing nuclear weapons have burned, the fissionable material melted and was left on the ground as a slag. In this condition, oxides will form on the surface and may become airborne if disturbed, e.g., by the wind, to become an inhalation hazard.

A.13 As is the case with fallout particles (§ 11.156), significant entry of plutonium and uranium oxides into the body can occur through the respiratory tract; even then, the nose and lungs act as effective filters. Because of their small solubility, absorption of the oxides by the gastrointestinal system is very low. Furthermore, pentration of intact skin is impossible and although the material may enter where the skin is broken, it will be localized at the point of access. It may then be cleansed away, even at some later time, without appreciable translocation to the blood stream or other body tissues having occurred.

A.14 The results of observations made at the Nevada Test Site indicate that, at distances greater than 1,500 feet from the incident, the amounts of plutonium that might be received either from a contaminated smoke cloud or in other ways would not exceed the accepted Radioactivity Concentration Guide values (§ 11.100). For undisturbed surfaces, initial concentrations up to 100 micrograms of plutonium per square foot appear to be tolerable; for uranium the tolerance value is somewhat higher. The general conclusion drawn from the tests is that, even though the Radioactivity Concentration Guide for the body burden of plutonium is small (approximately half

a microgram), it is difficult to acquire this amount as a result of a weapon accident outside the exclusion radius given above. The permissible concentration of uranium in the body is larger than for plutonium, and is not likely to be attained in the same circumstances.

Tritium

A.15 Tritium is another radioactive isotope used in weapons which could be hazardous in a confined area. In air tritium becomes an analogue of water, i.e., T_2O or HTO. In an enclosed space where the tritium water vapor can concentrate in the air, it can be easily absorbed through the unbroken skin, the lungs, and the gastrointestinal system, constituting an exposure problem to the entire body. Should it enter the body, tritium water dissolves in the body water and is eliminated at the same rate as ordinary water since it does not tend to concentrate in bone or in any organ as do some of the more hazardous radioactive materials.

A.16 From the point of view of the general public, the possibility of confrontation with a tritium hazard is negligible, for only selected military personnel can gain access to areas of enclosure which contain nuclear weapons. Because the existence of tritium in air can be detected by instruments sensitive to beta particles, monitoring systems are installed wherever necessary. The precautionary procedures employed to protect against the possible hazards from other radioactive materials in weapons provide more than adequate safeguards against tritium. The accepted Radioactivity Concentration Guide for this isotope is 3 millicuries distributed throughout the body. To accumulate such a dose it would be necessary to breathe for an hour air containing a concentration of 21 millicuries per cubic foot.

Fission Products

A.17 Fission products would be produced in an accident with a nuclear weapon only if there were a nuclear (fission) contribution to the energy released in a fire or explosion. The probability that there will be any nuclear yield at all is extremely small, but the possibility must, of course, be kept in mind. In no accident, to date, has there been any fission product release, although in some cases the weapon has become hot enough to cause the fissionable material to melt, as noted earlier.

A.18 If there should be any nuclear yield, the hazard would be mainly due to the beta particles and gamma rays emitted by the radio-

active fission products. The effects would be similar to those arising from the residual nuclear radiation, as described in Chapter IX, but scaled down to the actual fission yield in the accident. In addition, neutrons released in the fission process may be captured by materials close to the explosion and so produce induced activity (§ 9.31), consisting of either beta particles alone or in conjunction with gamma rays. Both beta and gamma radiation are easily detected with the proper instruments, so that survey of an accident area will readily indicate if a fission energy release has occurred. If it has, then proper precautions must be taken in cleaning up the area. Incidentally, if the beta-gamma survey meter shows the presence of contamination, it may be taken for granted, without further test, that fissionable material (uranium or plutonium) is also present. As a general rule, it is expected that the radiation dose from fission products and induced activity delivered at a distance of 1,500 feet from the scene of the accident will be negligible.

Protective Measures

A.19 The Department of Defense and the Atomic Energy Commission have several hundred teams of men, in various parts of the United States, who are trained to deal with accidents involving nuclear weapons. Since such an accident may occur anywhere, for example, as the result of the crash of an airplane carrying a weapon, it is imperative that fire, police, civil defense, public health authorities, and other emergency services should take appropriate action. If it appears at all practicable, the first step should be to rescue and assist injured personnel. Next, the nearest military installation or AEC office should be notified of the accident, so that a special team may be dispatched to the scene. At the same time advice may be obtained concerning further action. Meanwhile, the area surrounding the accident should be cleared of all non-essential personnel to a distance of at least 1,500 feet.

A.20 If there is a fire and it is apparent that the weapon is not burning or engulfed in flames, an attempt should be made to extinguish the fire with water, in the normal manner, from the upwind side only. If the water seems to accelerate the burning, then it must be stopped. The weapon should be kept cool by means of a water spray, since it is expected that the high explosive will not detonate if its temperature is maintained below 300° F. In cases where the weapon is not in the fire, the foam used for extinguishing fuel fires can be spread over the weapon to protect it from radiated heat from flames. The breaking

down of a foam blanket on fuel with water streams must be avoided.

A.21 If the weapon is engulfed in flames or it is believed that the high explosive is burning, no attempt should be made to put out the fire. All personnel should then evacuate the area of 1,500 feet radius around the site of the accident because of the danger of detonation occurring. It may be mentioned that burning high explosive may sometimes be detected by jets of white flame coming out of the weapon ("torching"), but this is not always observed. Consequently, if the flames, such as those produced by burning fuel, appear to be growing in intensity and extending toward or actually enveloping the weapon, all personnel should be removed from the scene.

A.22 The area downwind from the accident should be kept clear in order to avoid the toxic, and possibly radioactive, smoke from a burning weapon. If exposure to dense smoke is necessary for any length of time, dust-filtering masks and goggles, or special breathing apparatus, should be used. But the lack of such equipment should not hold up rescue efforts which require a short stay in the smoke area. Personnel who have been exposed to smoke must be monitored for radioactivity and, if necessary, decontaminated by members of the special team trained for the work. In fact, such action is advisable for all personnel who may have been contaminated in any way. They should be prevented from wandering about, since this would spread the radioactivity and make it more difficult to clear up.

A.23 If the special team has not arrived by the time the fire has subsided or been extinguished, no attempt should be made to clean up the scene of the accident. It may be highly radioactive and could represent a serious radiation hazard. For the same reason, the area of the accident should be roped off so as to prevent access by anyone, other than members of the survey teams. After they have made a careful examination of the area, they will either undertake its decontamination or will advise on what should be done in the interests of safety and security.

APPENDIX B

ANNOUNCED NUCLEAR DETONATIONS

This appendix contains information concerning all announced nuclear detonations carried out by the United States, the U.S.S.R., the United Kingdom, and the Republic of France prior to January 1964.

The dates and times given in the list of U.S. shots are Greenwich Civil Time (GCT). The heights of burst are heights above the surface; the heights of the cloud and tropopause refer to mean sea level (MSL). The abbreviations T, KT, and MT are used to express the explosion yields in tons, kilotons (1,000 tons), and megatons (1,000,000 tons) TNT equivalent, respectively. The term "nominal" implies a yield of approximately 20 kilotons TNT equivalent.

The approximate latitudes and longitudes of the various test sites are as follows:

UNITED STATES	
Nevada Test Site, U.S.A.	37° N. 116° W.
Eniwetok Proving Grounds, Pacific:	
Eniwetok	11° N. 162° E.
Bikini	11° N. 165° E.
Johnston Island, Pacific	17° N. 169° W.
Christmas Island, Pacific	2° N. 157° W.
UNITED KINGDOM	
Monte Bello Islands, Australia	20° S. 115° E.
Woomera, Australia	31° S. 137° E.
Maralinga Proving Ground, Australia	30° S. 131° E.
Christmas Island, Pacific	2° N. 157° W.
Nevada Test Site, U.S.A.	37° N. 116° W.
U.S.S.R.	
Arctic Test Site	75° N. 55° E. (Novaya Zemlya).
Siberian Test Site	52° N. 78° E.
U.S.S.R.	Denotes the explosion was in Soviet territory, but the test site was not identified.
REPUBLIC OF FRANCE	
Reggan, Algeria	27° N. 0°.
In Ekker, Algeria	24° N. 5° E.

ANNOUNCED UNITED STATES NUCLEAR DETONATIONS

Name	Date (GCT)	Time (GCT)	Location of Shot	Height of Burst (Feet)	Type of Burst	Mean Sea Level (Feet)			Yield	Remarks
						Cloud Top	Cloud Base	Tropo-pause		
TRINITY:										
Trinity	16/7/45	1230	Alamogordo, N.M.	100	Tower	35,000			19 KT	First test of an A-bomb.
WORLD WAR II	5/8/45	2315	Hiroshima, Japan	~1,850	Air				Nominal	First combat use.
	9/8/45	0158	Nagasaki, Japan	~1,850	Air				Nominal	Second combat use.
CROSSROADS:										
Able	30/6/46	2201	Bikini	520	Air	35,000			Nominal	
Baker	24/7/46	2135	Bikini	−90	UW	8,000			Nominal	
SANDSTONE:										
X-ray	14/4/48	1817	Eniwetok	200	Tower	56,000	25,000	56,000	37 KT	
Yoke	30/4/48	1809	Eniwetok	200	Tower	55,000	35,000	54,000	49 KT	
Zebra	14/5/48	1804	Eniwetok	200	Tower	28,000	20,000	54,000	18 KT	
RANGER:										
Able	27/1/51	1345	Nevada	1,060	Air	17,000		33,000	1 KT	
Baker	28/1/51	1352	Nevada	1,080	Air	35,000		32,000	8 KT	
Easy	1/2/51	1347	Nevada	1,080	Air	12,000		35,000	1 KT	
Baker-2	2/2/51	1349	Nevada	1,100	Air	36,000		38,000	8 KT	
Fox	6/2/51	1347	Nevada	1,435	Air	42,000		40,000	22 KT	
GREENHOUSE:										
Dog	7/4/51	1834	Eniwetok	300	Tower			55,000		
Easy	20/4/51	1827	Eniwetok	300	Tower	40,000	30,000	54,000	47 KT	
George	8/5/51	2130	Eniwetok	200	Tower			55,000		
Item	24/5/51	1817	Eniwetok	200	Tower			55,000		
BUSTER-JANGLE:										
Able	22/10/51	1400	Nevada	100	Tower	8,000	6,700		<0.1 KT	
Baker	28/10/51	1520	Nevada	1,118	Air	29,000	23,000	39,000	3.5 KT	
Charlie	30/10/51	1500	Nevada	1,132	Air	40,000	32,000	38,000	14 KT	
Dog	1/11/51	1530	Nevada	1,417	Air	40,000	27,000	38,000	21 KT	
Easy	5/11/51	1630	Nevada	1,314	Air	45,000	31,000	35,000	31 KT	
Sugar	19/11/51	1700	Nevada	4	Surface	16,000	11,000		1.2 KT	
Uncle	29/11/51	2000	Nevada	−17	UG	11,000			1.2 KT	

TUMBLER-SNAPPER:										
Able	1/4/52	1700	Nevada	793	Air	16,000		42,000	1 KT	
Baker	15/4/52	1730	Nevada	1,050	Air	16,000	10,000	38,000	1 KT	
Charlie	22/4/52	1730	Nevada	3,447	Air	42,000	31,000	38,000	31 KT	
Dog	1/5/52	1630	Nevada	1,040	Air	42,000	28,000	38,000	19 KT	
Easy	7/5/52	1215	Nevada	300	Tower	34,000		41,000	12 KT	
Fox	25/5/52	1200	Nevada	300	Tower	41,000		37,000	11 KT	
George	1/6/52	1155	Nevada	300	Tower	37,000		37,000	15 KT	
How	5/6/52	1155	Nevada	300	Tower	41,000		40,000	14 KT	
IVY:										
Mike	31/10/52	1915	Eniwetok		Surface	~100,000		56,000	10.4 MT	Experimental thermonuclear device.
King	15/11/52	2330	Eniwetok	1,480	Air	~70,000		55,000	High yield	
UPSHOT-KNOTHOLE:										
Annie	17/3/53	1320	Nevada	300	Tower	41,000	28,000	36,000	16 KT	
Nancy	24/3/53	1310	Nevada	300	Tower	42,000	26,000	40,000	24 KT	
Ruth	31/3/53	1300	Nevada	300	Tower	14,000	11,000	36,000	0.2 KT	
Dixie	6/4/53	1530	Nevada	6,020	Air	43,000	33,000	36,000	11 KT	
Ray	11/4/53	1245	Nevada	100	Tower	13,000	8,000	38,000	0.2 KT	
Badger	18/4/53	1235	Nevada	300	Tower	35,000	23,000	39,000	23 KT	
Simon	25/4/53	1230	Nevada	300	Tower	45,000	31,000	38,000	43 KT	
Encore	8/5/53	1530	Nevada	2,425	Air	41,000	29,000	39,000	27 KT	
Harry	19/5/53	1205	Nevada	300	Tower	43,000	27,000	42,000	32 KT	
Grable	25/5/53	1530	Nevada	524	Gun	38,000	23,000	38,000	15 KT	Fired from 280 mm gun.
Climax	4/6/53	1115	Nevada	1,334	Air	43,000	35,000	39,000	61 KT	
CASTLE:										
Bravo	28/2/54	1845	Bikini		Surface	114,000	55,000	55,000	15 MT	Experimental thermonuclear device.
Romeo	26/3/54	1830	Bikini		Barge			55,000		
Koon	6/4/54	1820	Bikini		Surface			53,000	~100 KT	
Union	25/4/54	1810	Bikini		Barge			57,000		
Yankee	4/5/54	1810	Bikini		Barge			55,000		
Nectar	13/5/54	1820	Eniwetok		Barge			56,000		
TEAPOT:										
Wasp	18/2/55	2000	Nevada	762	Air	22,000	15,000		1 KT	
Moth	22/2/55	1345	Nevada	300	Tower	25,000	16,000		2 KT	
Tesla	1/3/55	1330	Nevada	300	Tower	30,000	18,000	38,000	7 KT	
Turk	7/3/55	1320	Nevada	500	Tower	44,000	36,000	40,000	43 KT	
Hornet	12/3/55	1320	Nevada	300	Tower	35,000	27,000	38,000	4 KT	
Bee	22/3/55	1305	Nevada	500	Tower	40,000	29,000	37,000	8 KT	
Ess	23/3/55	2030	Nevada	−67	UG	12,000		39,000	1 KT	

ANNOUNCED UNITED STATES NUCLEAR DETONATIONS—Continued

Name	Date (GCT)	Time (GCT)	Location of Shot	Height of Burst (Feet)	Type of Burst	Mean Sea Level (Feet)			Yield	Remarks
						Cloud Top	Cloud Base	Tropopause		
TEAPOT—Continued										
Apple-1	29/3/55	1255	Nevada	500	Tower	32,000	22,000	39,000	14 KT	
Wasp Prime	29/3/55	1800	Nevada	740	Air	32,000		40,000	3 KT	
HA	6/4/55	1800	Nevada	36,620 (MSL)	Air	55,000		31,000	3 KT	
Post	9/4/55	1230	Nevada	300	Tower	16,000	13,000		2 KT	
Met	15/4/55	1915	Nevada	400	Tower	40,000	31,000	37,000	22 KT	
Apple-2	5/5/55	1210	Nevada	500	Tower	43,000	34,000	41,000	29 KT	
Zucchini	15/5/55	1200	Nevada	500	Tower	35,000	25,000	44,000	28 KT	
WIGWAM:										
Wigwam	14/5/55	2000	29° N. 126° W	−2,000	UW				30 KT	
REDWING:										
Lacrosse	4/5/56	1825	Eniwetok		Surface			53,000		Kiloton range.
Cherokee	20/5/56	1751	Bikini	4,320	Air			53,000		Several megatons. First air drop by U.S. of a thermonuclear weapon.
Zuni	27/5/56	1756	Bikini		Surface			51,000		
Erie	30/5/56	1815	Eniwetok	300	Tower			54,000		
Seminole	6/6/56	0055	Eniwetok		Surface			52,000		
Flathead	11/6/56	1826	Bikini		Barge			50,000		
Blackfoot	11/6/56	1826	Eniwetok	200	Tower			52,000		
Osage	16/6/56	0114	Eniwetok	680	Air			52,000		
Dakota	25/6/56	1806	Bikini		Barge			54,000		
Apache	8/7/56	1806	Eniwetok		Barge			52,000		
Navajo	10/7/56	1756	Bikini		Barge			50,000		
Tewa	20/7/56	1748	Bikini		Barge			52,000		
Huron	21/7/56	1816	Eniwetok		Barge			51,000		

PLUMBBOB:									
Boltzmann	28/5/57	1155	Nevada	500	Tower	33,000	23,000	41,000	12 KT
Franklin	2/6/57	1155	Nevada	300	Tower	17,000	14,000		140 T
Lassen	5/6/57	1145	Nevada	500	Balloon	7,000		43,000	0.5 T
Wilson	18/6/57	1145	Nevada	500	Balloon	35,000	25,000	40,000	10 KT
Priscilla	24/6/57	1330	Nevada	700	Balloon	43,000	24,000	49,000	37 KT
Hood	5/7/57	1140	Nevada	1,500	Balloon	48,000	35,000	53,000	74 KT
Diablo	15/7/57	1130	Nevada	500	Tower	32,000	20,000	43,000	17 KT
John	19/7/57	1400	Nevada	20,000	Rocket	44,000		48,000	~2 KT
Kepler	24/7/57	1150	Nevada	500	Tower	28,000	20,000	34,000	10 KT
Owens	25/7/57	1330	Nevada	500	Balloon	35,000	20,000	49,000	9.7 KT
Stokes	7/8/57	1225	Nevada	1,500	Balloon	37,000	27,000	47,000	19 KT
Shasta	18/8/57	1200	Nevada	500	Tower	32,000	16,000	50,000	17 KT
Doppler	23/8/57	1230	Nevada	1,500	Balloon	38,000	23,000	43,000	11 KT
Franklin Prime	30/8/57	1240	Nevada	750	Balloon	32,000	21,000	32,000	4.7 KT
Smoky	31/8/57	1230	Nevada	700	Tower	38,000		35,000	44 KT
Galileo	2/9/57	1240	Nevada	500	Tower	37,000	17,000	39,000	11 KT
Wheeler	6/9/57	1245	Nevada	500	Balloon	17,000	14,000	50,000	197 T
Laplace	8/9/57	1300	Nevada	750	Balloon	20,000	14,000	44,000	1 KT
Fizeau	14/9/57	1645	Nevada	500	Tower	40,000	27,000	43,000	11 KT
Newton	16/9/57	1250	Nevada	1,500	Balloon	32,000	19,000	52,000	12 KT
Rainier	19/9/57	1700	Nevada	−790	UG				1.7 KT
Whitney	23/9/57	1230	Nevada	500	Tower	30,000	18,000	53,000	19 KT
Charleston	28/9/57	1300	Nevada	1,500	Balloon	32,000	20,000	45,000	12 KT
Morgan	7/10/57	1300	Nevada	500	Balloon	40,000	26,000	37,000	8 KT
HARDTACK PHASE I:									
Yucca	28/4/58	0240	12° 37′ N., 163° 01′ E.	86,000	Balloon			53,000	
Cactus	5/5/58	1815	Eniwetok		Surface			51,000	
Fir	11/5/58	1750	Bikini		Barge			54,000	
Butternut	11/5/58	1815	Eniwetok		Barge			53,000	
Koa	12/5/58	1830	Eniwetok		Surface			57,000	
Wahoo	16/5/58	0130	Eniwetok	−500	UW			59,000	
Holly	20/5/58	1830	Eniwetok		Barge			52,000	
Nutmeg	21/5/58	2120	Bikini		Barge			54,000	
Yellowwood	26/5/58	0200	Eniwetok		Barge			55,000	
Magnolia	26/5/58	1800	Eniwetok		Barge			54,000	
Tobacco	30/5/58	0215	Eniwetok		Barge			55,000	
Sycamore	31/5/58	0300	Bikini		Barge			55,000	

There was no tunnel venting.

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ANNOUNCED UNITED STATES NUCLEAR DETONATIONS—Continued

Name	Date (GCT)	Time (GCT)	Location of Shot	Height of Burst (Feet)	Type of Burst	Mean Sea Level (Feet)			Yield	Remarks
						Cloud Top	Cloud Base	Tropopause		
HARDTACK PHASE I—Continued										
Rose	2/6/58	1845	Eniwetok		Barge			57,000		
Umbrella	8/6/58	2315	Eniwetok	−150	UW			54,000		
Maple	10/6/58	1730	Bikini		Barge			53,000		
Aspen	14/6/58	1730	Bikini		Barge			52,000		
Walnut	14/6/58	1830	Eniwetok		Barge			54,000		
Linden	18/6/58	0300	Eniwetok		Barge			54,000		
Redwood	27/6/58	1730	Bikini		Barge			52,000		
Elder	27/6/58	1830	Eniwetok		Barge			52,000		
Oak	28/6/58	1930	Eniwetok		Barge			50,000		
Hickory	29/6/58	0000	Bikini		Barge			51,000		
Sequoia	1/7/58	1830	Eniwetok		Barge			52,000		
Cedar	2/7/58	1730	Bikini		Barge			51,000		
Dogwood	5/7/58	1830	Eniwetok		Barge			52,000		
Poplar	12/7/58	0330	Bikini		Barge			55,000		
Juniper	22/7/58	0420	Bikini		Barge			51,000		
Oliver	22/7/58	2030	Eniwetok		Barge			48,000		
Pine	26/7/58	2030	Eniwetok		Barge			52,000		
Teak	1/8/58	1050	Johnston Island	252,000	Rocket					Megaton range.
Orange	12/8/58	1030	Johnston Island	141,000	Rocket					Megaton range.
HARDTACK PHASE II:										
Eddy	19/9/58	1400	Nevada	500	Balloon	11,000	7,500	48,000	83 T	
Mora	29/9/58	1405	Nevada	1,500	Balloon	18,500	10,000	40,000	2 KT	
Tamalpais	8/10/58	2200	Nevada	−330	UG	Low diffuse cloud			72 T	Slight venting.
Quay	10/10/58	1430	Nevada	100	Tower	10,000	7,500		79 T	
Lea	13/10/58	1320	Nevada	1,500	Balloon	17,000	12,000		1.4 KT	
Hamilton	15/10/58	1600	Nevada	50	Tower	6,000	4,500		1.2 T	
Logan	16/10/58	0600	Nevada	−830	UG				5 KT	No venting.
Dona Ana	16/10/58	1420	Nevada	450	Balloon	11,000	6,500	49,000	37 T	

Rio Arriba	18/10/58	1425	Nevada	72.5	Tower	13,500	11,000		90 T	
Socorro	22/10/58	1330	Nevada	1,450	Balloon	26,000	20,000		6 KT	
Wrangell	22/10/58	1650	Nevada	1,500	Balloon	10,000	7,000		115 T	
Rushmore	22/10/58	2340	Nevada	500	Balloon	11,500		42,000	188 T	
Sanford	26/10/58	1020	Nevada	1,500	Balloon	26,000	12,500		4.9 KT	
De Baca	26/10/58	1600	Nevada	1,500	Balloon	17,500	10,000		2.2 KT	
Evans	29/10/58	0000	Nevada	−848	UG				55 T	Venting.
Humboldt	29/10/58	1445	Nevada	25	Tower	7,500	6,000		7.8 T	
Santa Fe	30/10/58	0300	Nevada	1,500	Balloon	18,000	13,000	39,000	1.3 KT	
Blanca	30/10/58	1500	Nevada	−835	UG	7,700			19 KT	Slight venting.
ARGUS:										
Argus I	27/8/58		South Atlantic (38° S. 12° W.)	~300 miles	Rocket				1-2 KT	
Argus II	30/8/58		South Atlantic (50° S. 8° W.)	~300 miles	Rocket				1-2 KT	
Argus III	6/9/58		South Atlantic (50° S. 10° W.)	~300 miles	Rocket				1-2 KT	

ANNOUNCED U.S. NUCLEAR DETONATIONS, 1961–63

NEVADA SERIES

Name	Date (GCT)	Time (GCT)	Depth [1] (feet)	Type	Medium	Depression [2] (Diam. & Depth, feet)	Yield [3] (KT)	Remarks
Antler	15/ 9/61	1700	1,319	Underground	Tuff	None	2.4	Tunnel.
Shrew	16/ 9/61	1945	322	Underground	Alluvium	None	Low	
Chena	10/10/61	1800	838	Underground	Tuff	None	Low	Tunnel.
Mink	29/10/61	1830	630	Underground	Alluvium	None	Low	
Fisher	3/12/61	2304	1,193	Underground	Alluvium	600; 14	13.5	
Mad	13/12/61	1800	594	Underground	Alluvium	None	0.43	
Ringtail	17/12/61	1635	1,191	Underground	Alluvium	778; 2.17	Low	
Feather	22/12/61	1630	812	Underground	Tuff	None	Low	Tunnel.
Stoat	9/ 1/62	1630	992	Underground	Alluvium	602; 7.1	4.5	
Agouti	18/ 1/62	1800	856	Underground	Alluvium	604; 40	5.9	
Dormouse	30/ 1/62	1800	1,191	Underground	Alluvium	547; 14.4	Low	
Stillwater	8/ 2/62	1800	625	Underground	Alluvium	406; 39	2.7	
Armadillo	9/ 2/62	1800	786	Underground	Alluvium	590; 29	6.6	
Hardhat	15/ 2/62	1800	943	Underground	Granite	None	5.9	
Chinchilla	19/ 2/62	1630	492	Underground	Alluvium	302; 27	1.8	
Codsaw	19/ 2/62	1750	696	Underground	Tuff	230; 11	Low	
Cimarron	23/ 2/62	1800	1,000	Underground	Alluvium	484; 34	11.2	
Platypus	24/ 2/62	1630	190	Underground	Alluvium	None	Low	
Danny Boy	5/ 3/62	1815	110	See remarks	Basalt		0.42	Cratering test; crater diam. 265 ft, depth 84 ft.
Ermine	6/ 3/62	1630	240	Underground	Alluvium	None	Low	
Brazos	8/ 3/62	1800	841	Uhderground	Alluvium	466; 31	7.6	
Hognose	15/ 3/62	1630	789	Underground	Alluvium	478; 65	Low	
Hoosic	28/ 3/62	1800	614	Underground	Tuff	294; 20	3	
Chinchilla II	31/ 3/62	1800	448	Underground	Alluvium	235; 11	Low	
Dormouse II	5/ 4/62	1800	856	Underground	Alluvium	538; 96	10	
Passaic	6/ 4/62	1800	764	Underground	Tuff	512; 63	Low	
Hudson	12/ 4/62	1800	480	Underground	Tuff	None	Low	
Platte	14/ 4/62	1800	560	Underground	Tuff	None	1.7	Tunnel.
Dead	21/ 4/62	1840	634	Underground	Tuff	256; 11	Low	

Black	27/ 4/62	1800	714	Underground	Tuff	408; 55	Low	
Paca	7/ 5/62	1933	848	Underground	Alluvium	484; 60	Low	
Aardvark	12/ 5/62	1900	1,424	Underground	Tuff	924; 72	38	
Eel	19/ 5/62	1500	714	Underground	Tuff	234; 11	Low	
White	25/ 5/62	1500	635	Underground	Tuff	490; 50	Low	
Raccoon	1/ 6/62	1700	539	Underground	Alluvium	314; 24	Low	
Packrat	6/ 6/62	1700	860	Underground	Alluvium	598; 44	Low	
Des Moines	13/ 6/62	2200	610	Underground	Tuff	None	Low	Tunnel.
Daman I	21/ 6/62	1700	854	Underground	Alluvium	556; 96	Low	
Haymaker	27/ 6/62	1800	1,340	Underground	Alluvium	974; 107	56	
Marshmallow	28/ 6/62	1700	900	Underground	Tuff	None	Low	Tunnel.
Sacramento	30/ 6/62	2130	500	Underground	Alluvium	356; 41	Low	
Little Feller II	7/ 7/62	1900	----------	Surface		None	Low	Slightly above ground.
Johnny Boy	11/ 7/62	1645	2	Surface	Alluvium		0.5	Slightly below ground.
Merrimac	13/ 7/62	1600	1,356	Underground	Alluvium	662; 50	Low	
Small Boy	14/ 7/62	1830	----------	Surface		None	Low	Slightly above ground.
Little Feller I	17/ 7/62	1700	----------	Surface		None	Low	Slightly above ground. Troop participation.
Wichita	27/ 7/62	2100	493	Underground	Alluvium	390; 36	Low	
York	24/ 8/62	1500	744	Underground	Tuff	500; 80	Low	
Bobac	24/ 8/62	1700	675	Underground	Alluvium	425; 45	Low	
Hyrax	14/ 9/62	1710	720	Underground	Alluvium	474; 100	Low	
Peba	20/ 9/62	1700	793	Underground	Alluvium	400; 80	Low	
Allegheny	29/ 9/62	1700	692	Underground	Tuff	100; 10	Low	
Mississippi	5/10/62	1700	1,620	Underground	Tuff	425; 125	Intermediate	
Roanoke	12/10/62	1500	510	Underground	Tuff	80; 5	Low	
Bandicoot	19/10/62	1800	800	Underground	Alluvium	300; 100	Low	
Santee	27/10/62	1500	1,050	Underground	Alluvium	400; 20	Low	
Madison	12/12/62	1725	1,160	Underground	Tuff	None	Low	Tunnel.
Numbat	12/12/62	1745	775	Underground	Alluvium	500; 60	Low	
Casselman	8/ 2/63	1600	1,000	Underground	Alluvium	450; 75	Intermediate or less.	
Acushi	8/ 2/63	1830	856	Underground	Alluvium	300; 50	Intermediate or less.	
Carmel	21/ 2/63	1947	536	Underground	Alluvium	None	Low	
Gerbil	29/ 3/63	1549	925	Underground	Alluvium	555; 48	Low	
Ferret Prime	5/ 4/63	1752	792	Underground	Alluvium	400; 100	Low	
Stones	22/ 5/63	1540	1,289	Underground	Alluvium	850; 90	Intermediate	
Yuba	5/ 6/63	1700	796	Underground	Tuff	None	Low	
Hutia	6/ 6/63	1400	442	Underground	Alluvium	300; 20	Low	

ANNOUNCED U.S. NUCLEAR DETONATIONS, 1961–63—Continued

NEVADA SERIES—Continued

Name	Date (GCT)	Time (GCT)	Depth [1] (feet)	Type	Medium	Depression [2] (Diam. & Depth, feet)	Yield [3] (KT)	Remarks
Mataco	14/ 6/63	1410	642	Underground	Alluvium	300; 50	Low	
Kennebec	25/ 6/63	2300	740	Underground	Alluvium	200; 30	Low	
Pekan	12/ 8/63	2345	997	Underground	Alluvium	550; 60	Low	
Satsop	15/ 8/63	1300	738	Underground	Alluvium	300; 40	Low	
[4]	20/ 8/63							
Kohocton	23/ 8/63	1320	852	Underground	Alluvium	None	Low	
Antanum	13/ 9/63	1353	740	Underground	Alluvium	None	Low	
Bilby	13/ 9/63	1700	2,413	Underground	Tuff	1800; 80	~200	
Grunion	11/10/63	1400	856	Underground	Alluvium	550; 90	Low	
Clearwater	16/10/63	1700	1,798	Underground	Tuff	None	Intermediate	
Anchovy	14/11/63	1600	853	Underground	Alluvium	600; 65	Low	
Mustang	15/11/63	1500	544	Underground	Alluvium	125; 15	Low	
Greys	22/11/63	1730	988	Underground	Alluvium	470; 42	Low	
Sardine	4/12/63	1638	855	Underground	Alluvium	550; 50	Low	
Eagle	12/12/63	1602	541	Underground	Alluvium	440; 60	Low	

[1] Depth is distance to nearest point at the earth's surface.

[2] Depression is subsidence of earth into underground cavity, as distinguished from crater formed by throw-out of earth.

[3] Low yield means less than 20 kilotons; intermediate means 20 to 999 kilotons inclusive; low megaton means one to several megatons.

[4] For purposes of totaling announced detonations, add 23 undeground U.S. weapons-related tests at the Nevada Test Site as having been conducted between September 15, 1961, and August 20, 1963. No other data on the 23 tests are available for public use.

VELA UNIFORM SEISMIC DETONATION

Name	Date	Depth	Medium	Yield	Location	Remarks
Shoal	10/26/63	1,205	Granite	About 12 KT	Near Fallon, Nev.	Nuclear test detection-research experiment.

PACIFIC SERIES

Name	Date (GCT)	Time (GCT)	Location	Height	Type of burst	Yield [1]	Remarks
Adobe	25/ 4/62	1546	Christmas Island area		Air	Intermediate	
Aztec	27/ 4/62	1602	Christmas Island area		Air	Intermediate	
Arkansas	2/ 5/62	1802	Christmas Island area		Air	Low megaton	
Questa	4/ 5/62	1905	Christmas Island area		Air	Intermediate	
Frigate Bird	6/ 5/62	2330	Christmas Island area		Air		Warhead in missile launched from Polaris submarine.
Yukon	8/ 5/62	1801	Christmas Island area		Air	Intermediate	
Mesilla	9/ 5/62	1701	Christmas Island area		Air	Intermediate	
Muskegon	11/ 5/62	1537	Christmas Island area		Air	Intermediate	
Swordfish	11/ 5/62	2002	Eastern Pacific		UW	Low	Antisubmarine rocket (ASROC) system proof test.
Encino	12/ 5/62	1703	Christmas Island area		Air	Intermediate	
Swanee	14/ 5/62	1522	Christmas Island area		Air	Intermediate	
Chetco	19/ 5/62	1537	Christmas Island area		Air	Intermediate	
Tanana	25/ 5/62	1609	Christmas Island area		Air	Low	
Nambe	27/ 5/62	1703	Christmas Island area		Air	Intermediate	
Alma	8/ 6/62	1703	Christmas Island area		Air	Intermediate	
Truckee	9/ 6/62	1537	Christmas Island area		Air	Intermediate	
Yeso	10/ 6/62	1601	Christmas Island area		Air	Low megaton	
Harlem	12/ 6/62	1537	Christmas Island area		Air	Intermediate	
Rinconada	15/ 6/62	1601	Christmas Island area		Air	Intermediate	
Dulce	17/ 6/62	1601	Christmas Island area		Air	Intermediate	
Petit	19/ 6/62	1501	Christmas Island area		Air	Low	
Otowi	22/ 6/62	1601	Christmas Island area		Air	Intermediate	

PACIFIC SERIES—Continued

Name	Date (GCT)	Time (GCT)	Location	Height	Type of burst	Yield	Remarks
Bighorn	27/ 6/62	1519	Christmas Island area		Air	Megaton range	
Bluestone	30/ 6/62	1521	Christmas Island area		Air	Low megaton	
Starfish Prime	9/ 7/62	0900	Johnston Island area	400 km	High altitude	1.4 megatons	
Sunset	10/ 7/62	1633	Christmas Island area		Air	Intermediate	
Pamlico	11/ 7/62	1537	Christmas Island area		Air	Low megaton	
Androscoggin	2/10/62	1618	Johnston Island area		Air	Intermediate	
Bumping	6/10/62	1603	Johnston Island area		Air	Low	
Chama	18/10/62	1601	Johnston Island area		Air	Low megaton	
Checkmate	20/10/62	0830	Johnston Island area	Tens of km	High altitude	Low	
Bluegill Triple Prime	26/10/62	1000	Johnston Island area	Tens of km	High altitude	Submegaton	
Calamity	27/10/62	1546	Johnston Island area		Air	Intermediate	
Housatonic	30/10/62	1602	Johnston Island area		Air	Megaton range	
Kingfish	1/11/62	1210	Johnston Island area	Tens of km	High altitude	Submegaton	
Tightrope	4/11/62	0730	Johnston Island area	Tens of km	High altitude	Low	

PLOWSHARE NUCLEAR DETONATIONS[1]

Name	Date (GCT)	Time (GCT)	Depth (ft)	Medium	Yield	Location	Remarks
Gnome	10/12/61	1900	1,184	Salt	3.1 KT	Near Carlsbad, N. Mex.	Multiple-purpose experiment; formed hemispheric cavity, 160–170 ft diameter, 60–80 ft high.
Sedan	6/7/62	1700	635	Alluvium	100 KT	Nevada Test Site	Excavation experiment; formed crater about 1,280 ft diameter, 320 ft max depth; displaced about 6.5 million cu yd or 10.4 million tons of earth.
Anacostia	27/11/62	1800	750	Tuff	Low	Nevada Test Site	Plowshare Device Development Test.
Kaweah	21/ 2/63	1947	750	Alluvium	Low	Nevada Test Site	Plowshare Device Development Test.
Tornillo	11/10/63	2100	500	Alluvium	Low	Nevada Test Site	Plowshare Device Development Test.

[1] For the development of peaceful uses of nuclear explosives.

SAFETY EXPERIMENTS

Since 1955, the U.S. Atomic Energy Commission has conducted a number of safety experiments at the Nevada Test Site to determine the safety of nuclear weapons in case of accident. The following list includes those experiments which resulted in a measurable nuclear yield.

Name	Date (GCT)	Time (GCT)	Location of Shot	Height of Burst (Feet)	Type of Burst	Mean Sea Level (Feet)			Yield	Remarks
						Cloud Top	Cloud Base	Tropopause		
1956	18/1/56	2130	Nevada		Surface					
PLUMBBOB:										
Pascal A	26/7/57	0800	Nevada		UG	6,000				Slight nuclear yield.
Coulomb B	6/9/57	2005	Nevada		Surface	18,000		50,000	0.3 KT	
1957:										
Pascal C	6/12/57	2015	Nevada		Vertical shaft					Slight yield.
Coulomb C	9/12/57	2000	Nevada		Surface				0.5 KT	
HARDTACK PHASE II:										
Otero	12/9/58	2000	Nevada	—480	UG	9,000			38 T	
Bernalillo	17/9/58	1930	Nevada	—456	UG	7,500	5,500		15T	
Luna	21/9/58	1900	Nevada	—484	UG	Low diffuse cloud			1.5 T	
Valencia	26/9/58	2000	Nevada	—484	UG	5,500			2 T	
Mars	28/9/58	0000	Nevada		UG	Low diffuse cloud			13 T	Shot vented through tunnel.
Hidalgo	5/10/58	1410	Nevada	377	Balloon	12,000	8,000		77 T	
Colfax	5/10/58	1615	Nevada	—350	UG	5,500	4,500		5.5 T	
Neptune	14/10/58	1800	Nevada	—98.5	UG	11,000			115 T	Shot vented.
Vesta	17/10/58	2300	Nevada		Surface	10,000			24 T	
Catron	24/10/58	1500	Nevada	72 5	Tower	8,500	5,000		21 T	
Juno	24/10/58	1601	Nevada		Surface	5,500			1.7 T	
Ceres	26/10/58	0400	Nevada	25	Tower	6,000			0.7 T	
Chavez	27/10/58	1430	Nevada	52.5	Tower	6,500			0.6 T	
Titania	30/10/58	2034	Nevada	25	Tower	6,000			0.2 T	

UNITED KINGDOM NUCLEAR DETONATIONS

Name	Date	Type of Burst	Yield	Location	Remarks
HURRICANE	3/10/52	Ship	Kiloton range	Monte Bello Islands	
TOTEM	14/10/53	Tower	Kiloton range	Woomera	Test held at Emu Field, 300 miles NW of Woomera.
	26/10/53	Tower	Kiloton range	Woomera	Test held at Emu Field, 300 miles NW of Woomera.
MOSAIC	16/5/56	Tower	Kiloton range	Monte Bello Islands	
	19/6/56	Tower	Kiloton range	Monte Bello Islands	
BUFFALO	27/9/56	Tower	Kiloton range	Maralinga	
	4/10/56	Surface	Low yield	Maralinga	
	11/10/56	Air	Low yield	Maralinga	First air drop
	22/10/56	Tower	Kiloton range	Maralinga	
GRAPPLE	15/5/57	Air	Megaton range	Christmas Island area	
	31/5/57	Air	Megtaon range	Christmas Island area	
	19/6/57	Air	Megaton range	Christmas Island area	
ANTLER	14/9/57	Tower	Low yield	Maralinga	
	25/9/57	Tower	Kiloton range	Maralinga	
	9/10/57	Balloon	Kiloton range	Maralinga	
GRAPPLE	8/11/57	Air	Megaton range	Christmas Island area	
GRAPPLE—1958 SERIES	28/4/58	Air	Megaton range	Christmas Island area	
	22/8/58	Balloon	Kiloton range	Christmas Island area	
	2/9/58	Air	Megaton range	Christmas Island area	
	11/9/58	Air	Megaton range	Christmas Island area	
	23/9/58	Balloon	Kiloton range	Christmas Island area	

JOINT UNITED KINGDOM-UNITED STATES NUCLEAR DETONATIONS

Date	Type of Burst	Yield	Location	Remarks
1/3/62	Underground	Low	Nevada Test Site	Announced by AEC as a joint United States-United Kingdom test of a British nuclear device.
7/12/62	Underground	Low	Nevada Test Site	Announced by AEC as a joint United States-United Kingdom test of a British nuclear device.

REPUBLIC OF FRANCE NUCLEAR DETONATIONS

Date	Type of Burst	Yield	Location	Remarks
13/2/60	Tower	60–70 KT	Reggan	Tower was 350 feet high; first test of a nuclear device by France.
1/4/60	Surface	Small	Reggan	
27/12/60	Tower	Small	Reggan	
25/4/61	Tower	Small	Reggan	
1/5/62	Underground	Medium	In Ekker	

U.S.S.R. NUCLEAR DETONATIONS

Date	Type of Burst	Yield	Location	Remarks
29/8/49	Atmospheric		USSR	First Russian nuclear detonation.
3/10/51*	Atmospheric		USSR	Statement by White House.
22/10/51*	Atmospheric		USSR	Statement by White House.
12/8/53	Atmospheric	Thermonuclear	USSR	Part of a series.
23/8/53	Atmospheric	Fission	USSR	Part of a series; energy release equivalent to type detonated at Nevada Test Site.
26/10/54*	Atmospheric		USSR	Statement by AEC; part of a series which began in mid-September and continued at intervals to the announcement date.
4/8/55*	Atmospheric		USSR	Statement by AEC; part of a series detonated in the preceding few days.
24/9/55*	Atmospheric		USSR	Statement by AEC; part of a series recently detonated.
10/11/55*	Atmospheric		USSR	Statement by AEC; part of a series recently detonated.
23/11/55*	Atmospheric	Megaton range	USSR	Statement by AEC; part of a series.
21/3/56*	Atmospheric		USSR	Statement by AEC; part of a series detonated in preceding few days.
2/4/56*	Atmospheric		USSR	Statement by AEC; part of a series detonated in preceding few days.
24/8/56	Atmospheric	Less than megaton	Siberia	Part of a series.
30/8/56	Atmospheric	Large	Siberia	Part of a series.
2/9/56	Atmospheric		USSR	Part of a series.
10/9/56	Atmospheric		USSR	Part of a series; announced by Soviet Union.
17/11/56	Atmospheric	Large	USSR	Part of a series.
19/1/57	Atmospheric		USSR	Part of a series.
8/3/57	Atmospheric		USSR	Part of a series.
3/4/57	Atmospheric		USSR	Part of a series.
6/4/57	Atmospheric		USSR	Part of a series.
10/4/57	Atmospheric	Large	USSR	Part of a series.
12/4/57	Atmospheric		USSR	Part of a series.
16/4/57	Atmospheric	Large	Siberia	Part of a series; largest tested so far in this series.
22/8/57	Atmospheric	Substantial	Siberia	
9/9/57*	Atmospheric	Moderate	Siberia	Statement by AEC; detonated within the preceding 2 days.
24/9/57	Atmospheric	Megaton range	Arctic	
6/10/57	Atmospheric	Thermonuclear	USSR	Announced by Soviet Union as a hydrogen device; AEC said it was of substantial size.
10/10/57	Atmospheric	Small	Arctic	

28/12/57	Atmospheric		Siberia	
23/2/58	Atmospheric	Megaton range	Arctic	
27/2/58	Atmospheric	Megaton range	Arctic	
27/2/58	Atmospheric	Large	Arctic	
14/3/58	Atmospheric	Below megaton range	Arctic	
14/3/58	Atmospheric	Below megaton range	Arctic	
15/3/58	Atmospheric	Below megaton range	Arctic	
20/3/58	Atmospheric	Small	Arctic	
21/3/58	Atmospheric		Siberia	This detonation was in a larger range than the test the day before.
22/3/58	Atmospheric	Medium	Arctic	
30/9/58	Atmospheric	Moderate to high	Arctic	
30/9/58	Atmospheric	Moderate to high	Arctic	
2/10/58	Atmospheric	Moderate	Arctic	
2/10/58	Atmospheric	Moderate	Arctic	
5/10/58	Atmospheric		Arctic	Smaller yield than the four immediately preceding detonations.
10/10/58	Atmospheric	Relatively large**	Arctic	
12/10/58	Atmospheric	Large**	Arctic	
15/10/58	Atmospheric	Large**	Arctic	
18/10/58	Atmospheric	Large**	Arctic	
19/10/58	Atmospheric	Small	Arctic	
20/10/58	Atmospheric	Large**	Arctic	
22/10/58	Atmospheric	Large**	Arctic	
24/10/58	Atmospheric	Large**	Arctic	
25/10/58	Atmospheric	Relatively large	Arctic	
1/11/58	Atmospheric	Relatively low	Siberia	
3/11/58	Atmospheric	Relatively low	Siberia	
1/9/61	Atmospheric	Intermediate range	Semipalatinsk	Announced by White House.
4/9/61	Atmospheric	Low kiloton range	Semipalatinsk	Announced by AEC.
5/9/61	Atmospheric	Low to intermediate range.	Semipalatinsk	Announced by AEC.
6/9/61	Atmospheric	Low to intermediate range.	East of Stalingrad	Announced by AEC.
10/9/61	Atmospheric	Order of several megatons.	Novaya Zemlya	Announced by AEC.
10/9/61	Atmospheric	Low to intermediate kiloton range.	Novaya Zemlya	Announced by AEC.
12/9/61	Atmospheric	Order of several megatons.	Novaya Zemlya	Announced by AEC.
13/9/61	Atmospheric	Low to intermediate range.	Semipalatinsk	Announced by AEC.
13/9/61	Atmospheric	Low to intermediate range.	Novaya Zemlya	Announced by AEC.
14/9/61	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
16/9/61	Atmospheric	Order of a megaton	Novaya Zemlya	Announced by AEC.
17/9/61	Atmospheric	Intermediate	Semipalatinsk	Announced by AEC.
18/9/61	Atmospheric	Order of a megaton	Novaya Zemlya	Announced by AEC.
20/9/61	Atmospheric	Order of a megaton	Novaya Zemlya	Announced by AEC.
22/9/61	Atmospheric	Order of a megaton	Novaya Zemlya	Announced by AEC.
2/10/61	Atmospheric	Order of a megaton	Novaya Zemlya	Announced by AEC.
4/10/61	Atmospheric	Order of several megatons.	Novaya Zemlya	Announced by AEC.
6/10/61	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
8/10/61	Atmospheric	Low yield range	Novaya Zemlya	Announced by AEC.

12/10/61	Atmospheric	Low to intermediate range.	Semipalatinsk	Announced by AEC.
20/10/61	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
23/10/61	Atmospheric	About 25 megatons	Novaya Zemlya	Announced by AEC.
23/10/61	Underwater	Low yield range	South of Novaya Zemlya.	Announced by AEC.
25/10/61	Atmospheric	Intermediate to high; probably less than a megaton.	Novaya Zemlya	Announced by AEC.
27/10/61	Atmospheric	Low to intermediate range.	Novaya Zemlya	Announced by AEC.
30/10/61	Atmospheric	58 megatons	Novaya Zemlya	Announced by AEC; detonated in vicinity of 12,000 feet.
31/10/61	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
31/10/61	Atmospheric	Intermediate to high yield range; probably below a megaton.	Novaya Zemlya	Announced by AEC.
2/11/61	Atmospheric	Low to intermediate range.	Novaya Zemlya	Announced by AEC.
2/11/61	Atmospheric	Low to intermediate range.	Novaya Zemlya	Announced by AEC.
4/11/61	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC. On Dec. 9, 1961, the AEC stated in a preliminary analysis of the recent Soviet nuclear test series that the Soviets had conducted approximately 50 atmospheric tests.
2/2/62	Underground	Well above the threshhold of underground detectability, even by a single national system.	Semipalatinsk	Announced by AEC as "apparently conducted."
5/8/62	Atmospheric	30 megatons	Novaya Zemlya	Announced by AEC. On Aug. 6, 1962, the Atomic Energy Commission stated that tests in the low kiloton range had been conducted a few days prior to the nuclear detonation of Aug. 5.
7/8/62	Atmospheric	Low kiloton range	Central Siberia	Announced by AEC.
10/8/62	Atmospheric	Less than one megaton	Novaya Zemlya	Announced by AEC.
20/8/62	Atmospheric	Order of several megatons.	Novaya Zemlya	Announced by AEC.
22/8/62	Atmospheric	Low megaton range	Novaya Zemlya	Announced by AEC.
25/8/62	Atmospheric	Order of several megatons.	Novaya Zemlya	Announced by AEC.
25/8/62	Atmospheric	Low	Semipalatinsk	Announced by AEC.
27/8/62	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
2/9/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
8/9/62	Atmospheric	Megaton range	Novaya Zemlya	AEC announcement said this was tenth specific test in current series, but all detected tests are not specifically announced, and a number of additional tests had been conducted.
15/9/62	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
16/9/62	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
18/9/62	Atmospheric	A few megatons	Novaya Zemlya	Announced by AEC.
19/9/62	Atmospheric	Multimegaton	Novaya Zemlya	Announced by AEC as second largest atmospheric test in current series, and fourth multimegaton test in past 5 days.
21/9/62	Atmospheric	A few megatons	Novaya Zemlya	Announced by AEC.
25/9/62	Atmospheric	Multimegaton	Novaya Zemlya	Announced by AEC as second largest in current series.
27/9/62	Atmospheric	Less than 30 megatons	Novaya Zemlya	Announced by AEC.
7/10/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.

14/10/62	Atmospheric	Low yield range	Semipalatinsk	Announced by AEC.
22/10/62	High altitude	A few hundred kilotons.	Central Asia	Announced by AEC.
22/10/62	Atmospheric	Several megatons	Novaya Zemlya	Announced by AEC.
27/10/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
28/10/62	High altitude	Intermediate range	Central Asia	Announced by AEC as similar to test conducted on Oct. 22.
28/10/62	Atmospheric	Low	Semipalatinsk	Announced by AEC.
29/10/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
30/10/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
1/11/62	High altitude	Intermediate range	Central Asia	Announced by AEC.
1/11/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
3/11/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
3/11/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
4/11/62	Atmospheric	Intermediate	Semipalatinsk	Announced by AEC.
17/11/62	Atmospheric	Low	Semipalatinsk	Announced by AEC.
18/12/62	Atmospheric	Intermediate	Novaya Zemlya	Announced by AEC.
18/12/62	Atmospheric	Intermediate	Novaya Zemlya	Announced by AEC.
20/12/62	Atmospheric	Low	Novaya Zemlya	Announced by AEC.
22/12/62	Atmospheric	Intermediate range	Novaya Zemlya	Announced by AEC.
23/12/62	Atmospheric	See remarks	Novaya Zemlya	Dec. 26 AEC announcement said a number of atmospheric tests held Dec. 23–25.
24/12/62	Atmospheric	About 20 megatons	Novaya Zemlya	Largest about 20 MT, others low to a few megatons.
25/12/62	Atmospheric	See remarks	Novaya Zemlya	

*Date of announcement, not necessarily shot date.

**October 24, 1958, AEC announced that these test detonations had been of high yield, i.e., a yield in the probable megaton range.

APPENDIX C

THE DETECTION OF NUCLEAR EXPLOSIONS

INTRODUCTION

C.1 From the standpoint of detection, the environments in which nuclear explosions are possible can be divided into three categories, namely (1) subsurface, i.e., underground and underwater, (2) surface to lower atmosphere, and (3) space. In the category of subsurface bursts the major techniques for which significant scientific data are available are based on measurements of seismic (earth motion) and hydroacoustic (underwater sound) effects. The seismic method is also applicable to bursts at the surface or in the lower atmosphere, and in addition there are procedures involving detection of radioactive debris, acoustic (sound) phenomena, and the electromagnetic pulse (or radio signal).

C.2 For the detection of explosions in space, both ground-based and satellite-based techniques have been proposed. Among the possible ground-based methods are observations of direct visible light and of fluorescence of the air and detection of the electromagnetic pulse. The disturbance of the ionosphere by the radiations from a nuclear explosion can generally be observed in various ways on the earth's surface, e.g., backscattering of radar signals, absorption of cosmic "noise", phase shift of very-low-frequency radio waves, and the use of ionosondes to determine the heights of ionized layers in the atmosphere. Interaction between the residues from a nuclear explosion at high altitude and the earth's magnetic field may produce changes in the electric current and magnetic field as measured on the surface which could be employed as a means of detection. In addition, measurements of sunlight scattered by the weapon debris might provide a method of identification of the elements present.

C.3 Satellite-based detection techniques would involve, in general, direct measurement of radiations produced at the time of (or immediately after) the explosion, namely, thermal X-rays, gamma rays, and neutrons. Beta particles (electrons) which are trapped by the earth's magnetic field could also be detected by instruments located on a satellite. Except for the latter technique, none of these satellite-based

detection procedures has been tested in connection with a nuclear explosion at high altitude or in space. Furthermore, it should be mentioned that there is only limited information concerning natural events which would produce signals similar to, and would thus tend to mask, those from a nuclear explosion. It is evident, therefore, that much remains to be done in the development of reliable techniques for the detection of nuclear detonations, especially those requiring satellite-based instrumentation.

C.4 In the subsequent paragraphs, the various procedures which could possibly be used for the detection of nuclear explosions are outlined and discussed. The order of the treatment is based mainly upon convenience of presentation and not especially on the environment of the detonation. It should be noted that few of the methods are sufficiently developed to be immediately applicable for detection purposes. Most of the others are based on observed nuclear explosion effects, but their value has not yet been determined. Moreover, little is known of the extent to which natural phenomena would interfere because of the similarity of the signals produced. Extensive experimental studies are therefore required to investigate the efficacy of the procedures described and to design instruments for their application.

C.5 The capability estimates, discussed below, of various techniques for detecting clandestine nuclear explosions can only be interpreted when taken in the context of a definitely specified worldwide detection system. The effectiveness of any system for the detection of clandestine nuclear explosions will depend upon the number of stations installed in the area of concern, the number of investigations permitted in those local areas from which unidentified underground signals originated, and the proper and prompt integration of data collected by the various techniques.

GROUND-BASED TECHNIQUES

Detection of Airborne Radioactive Debris

C.6 The most positive indication that a nuclear explosion has occurred is provided by the identification of radioactive debris. Residues from nuclear explosions within the troposphere, i.e., from the earth's surface to altitudes of 25,000 to 55,000 feet (see § 9.147), can be collected by suitable filters carried by aircraft or located on the ground. The time taken for the residual cloud to spread in the troposphere depends upon the height of burst, the energy yield, and the meteorological conditions. The best time for collecting aerial

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samples is prior to 20 days after the event. Subsequent to 30 days from detonation time and when the yield of the explosion is of a low order of magnitude, radioactive decay and diffusion will have reduced the gross activity to a point where it may not differ significantly from that of the background.

C.7 Nuclear explosions which deposit debris in the stratosphere above the maximum attainable altitudes of sampling aircraft may readily escape detection by this means. Although the debris from such explosions may ultimately fall out to accessible altitudes, the length of time required is such that diffusion and radioactive decay are likely to reduce the specific activity to background levels. It has been suggested that rockets might be used to collect samples at high altitudes, but it is not known if this procedure is feasible.

C.8 For those nuclear explosions from which radioactive debris can be collected, it is possible with present radiochemical techniques to detect and identify fission products in a clean sample containing the residue from as few as 10^8 fissions, i.e., less than 1 part in 10^{15} of the products from a 1-kiloton fission yield explosion. If the sample contains the remains from 10^{10} fissions and is not mixed to any considerable extent with residues from previous detonations, it is possible to determine its age, within 5 to 10 percent. Hence, the time at which the nuclear explosion occurred can be estimated with fair accuracy.

C.9 Samples from the troposphere for radiochemical examination can be obtained by drawing large volumes of air through filters at stations on the ground. Dry fallout particles are also collected on large exposed surfaces which are subsequently washed down with water to collect any deposit that may have formed. Since much of the radioactive debris in the troposphere is brought down with rain (§ 9.151), samples of rainfall are useful for determining whether a nuclear explosion has occurred. Provided there have been no disturbing meteorological conditions, such as rainout or stagnant meteorological systems which could limit the weapon residues from spreading in the atmosphere, it is estimated that a 1-kiloton fission explosion in the troposphere could be detected if clean samples can be obtained on the ground prior to 20 days after the detonation at distances not greater than 1,300 to 2,000 miles from the detonation. Explosions of the order of tens of kilotons (or even larger) in the stratosphere, however, may never produce detectable radioactive debris at altitudes at which collection is presently possible with aircraft.

C.10 In addition to the collection of radioactive debris at ground stations, suitable filters can be carried by aircraft. When there are other indications, e.g., by the detection methods described in §§ C.13, C.14, C.30 *et seq.*, that a nuclear detonation may have occurred in the

atmosphere, aircraft can collect adequate samples for analysis at distances up to 2,000 to 3,000 miles from a nuclear explosion within 5 to 6 days after it has taken place. If the general location of the radioactive cloud is known, samples taken by aircraft 2 to 5 days after the event can be used to estimate the time of the explosion. It is generally not possible to establish the location of the burst since the back-tracking of a radioactive cloud from the pick up point involves meteorological uncertainties of large magnitude.

C.11 Shallow subsurface bursts, at such depths that contaminated earth or water is thrown up into the air, may also be detected by radiochemical analysis of debris samples. However, the method is less sensitive, for detonations of the same energy yield, than it is for explosions in the troposphere because much of the radioactivity in a subsurface burst remains locally in the ground or water. Furthermore, the airborne debris is subject to rainout and excessive diffusion in the low-level winds.

C.12 It may be noted that all nuclear explosions will produce radioactive debris consisting mainly of fission products. Thermonuclear weapons may owe about 50 percent of their energy, on the average, to fission, although in especially designed "clean" weapons (§ 9.44) the contribution of fission can be reduced to a few percent of the total energy. Thermonuclear reactions as such may possibly be detected by an increase in the carbon-14 content of the atmosphere (§ 9.34) and perhaps also by the presence of abnormal amounts of tritium. The detection of the radioactive products from a purely thermonuclear device would be much more difficult than the debris from a fission explosion.

Light Scattering by Airborne Debris

C.13 The airborne debris from a nuclear explosion is initially ionized (§ 10.40) and if the detonation occurs in near space, up to a few thousand miles altitude, some of the ions will be trapped by the earth's magnetic field. Such debris deposited in the upper atmosphere may perhaps be detected by measurement of the wave lengths in scattered sunlight that are characteristic of the elements present. It has been predicted theoretically that nuclear weapons debris in near space may be identifiable by this method. It is not possible, however, to state with confidence the energy yields of the explosions which may be detected nor to establish the range at which measurable effects might be observed.

Acoustic Waves

C.14 The blast wave produced by an explosion in air degenerates into an ordinary sound (or acoustic) wave which propagates outward to considerable distances. In a homogeneous atmosphere, the amplitude of the air pressure wave scales approximately as the cube root of the yield and inversely as the distance from the burst point. However, the observed amplitude is strongly affected by the state of the atmosphere, so that it may be larger or smaller, by a factor of as much as five or more, than that predicted by this simplified scaling.

C.15 With existing microbarographs of special design, which are sensitive to pressure changes of the order of 0.1 dyne per square centimeter, i.e., about 10^{-7} of normal atmospheric pressure, it should be possible to detect a 1-kiloton explosion in the atmosphere, over the backbround disturbances, at several hundreds of miles away. For a given detonation, the actual distance will depend on the meteorological conditions along the path and the background noise at the recording site. When the upper winds are mainly in one direction, a 1-kiloton explosion in the atmosphere at altitudes up to 100,000 feet and possibly as much as 150,000 feet should then be detectable, with good (60 to 90 percent) probability, under average noise conditions, at a station selected for its satisfactory acoustic properties, at distances out to 1,300 to 2,000 miles downwind and about 300 miles in the upwind direction. When the upper winds are erratic and the average wind velocity is small, such as is frequently the case during spring and fall, it should be possible to detect with good probability a 1-kiloton explosion in the air, under average noise conditions at a properly selected site, as far away as 800 miles in any direction.

C.16 By a process of direction finding and triangulation, based on observations from at least three suitably located stations surrounding the explosion, taking into account diurnal and seasonal meteorological conditions, an approximate indication may be obtained of the region in which the burst has occurred. If the stations are 1,000 miles apart, the location can probably be estimated within 60 miles, but the accuracy would be better if the stations were closer together.

C.17 Acoustic waves which resemble the signals from nuclear (and chemical) explosions may be produced by natural events, primarily volcanic and meteoric explosions. Such events would, of course, add to the difficulty of detecting nuclear explosions by the acoustic method.

C.18 Although deep underwater explosions transmit very little sound to the air, they may produce hydroacoustic (or underwater sound) waves which are very easily detected by hydrophones at great

distances if the explosion is conducted near the axis of an underwater sound channel in open oceans. Thus, it appears that even a fractional kiloton detonation underwater in the open sea could be detected in this manner as far as 6,000 miles away provided no obstructing sea mounts, island, etc., were present. However, explosions as relatively large as 1 kiloton might be missed if they were conducted under circumstances which were unfavorable to detection. In some cases, the effects of an explosion and those of a submarine disturbance may be similar. The incidence of the latter may not be great but it is not well-known. If the location of an underwater nuclear detonation is suspected from the detection of hydroacoustic waves, it might possibly be confirmed by radiochemical analysis of a sample of water taken from the ocean in the vicinity of the explosion provided the debris comes to the surface and can be located. Debris from very deep underwater nuclear explosions may never reach the surface.

Seismic Waves

C.19 Nuclear explosions occurring underground or underwater produce seismic waves, that is, waves similar to those caused by earthquakes. These waves propagate to considerable distances and can be detected by means of sensitive seismographs when the wave amplitudes exceed the continual background "noise" due to microseisms, which are small tremors caused by coastal storms, strong winds, heavy machinery, etc. The problem, however, is to distinguish between the signals produced by a subsurface explosion and those from earthquakes. In the completely contained underground RAINIER shot, described in § 2.94 *et seq.*, a nuclear device having an energy yield of 1.7 kilotons was detonated in water-filled tuff and the seismic signal was equivalent to that from an earthquake of magnitude approximately 4.06 on the Gutenberg-Richter scale. It has been estimated that roughly 10 thousand shallow-focus earthquakes of this magnitude and larger, and even more of lower magnitude, occur annually all over the world (see Fig. C.29).

C.20 If definite indications of an underground event are obtained by the clear recording of a sufficient number of signals at several stations surrounding the source, then it should be possible to determine the locality of the disturbance within an area of roughly 80 square miles. If the signals recorded do not satisfy the foregoing conditions, the area of localization will be much greater. On the basis of a number of seismic signals, a natural earthquake can often be identified as such, but seismic signals alone cannot identify an

underground nuclear explosion. Only the collection of radioactive weapons debris constitutes positive identification of nuclear explosions.

C.21 One method which may help to discriminate between the signals from an underground detonation and an earthquake is based on the expectation that in an underground (or underwater) explosion the earth initially moves outward and produces a compressional wave in all directions, whereas in most earthquakes the motion is outward (compressional wave) in some directions and inward (rarefactional wave) in others. If this is the case, a group of seismograph stations located around a subsurface explosion should all record what is called a "positive first motion"; that is to say, the very first signal received should correspond to an outward displacement due to the compression of the earth. Most earthquakes, on the other hand, should give positive first motions in some directions and negative first motions in other directions.

C.22 There is always a possibility that microseisms or other extraneous earth disturbances will interfere with the positive first motion of the signal from a nuclear explosion. The first observed motion may then appear to be negative and the effect could be attributed to an earthquake. It is generally accepted that the first motion due to the P-waves (or longitudinal waves) from an explosion of the RAINIER type may be reliable at distances up to 450 miles, provided the peak seismic signal is at least 10 times as great as the background noise. At distances between roughly 450 and 700 miles, it is necessary for the signal to be about 20 times the noise if the real first motion is to be observed. Obviously, where the background noise is high, explosions of low energy yield would be difficult to detect in this manner. These conclusions refer to the "near zone" of detection extending to a distance of about 700 miles. There is also a "shadow zone" between about 700 and 1,500 miles where the initial wave is anomalously small, and a "far zone", starting at about 1,500 miles from the disturbance, within which strong seismic signals are received from waves which have followed a different path through the earth. Signals in the far zone are also subject to the difficulty of distinguishing the first motion in the presence of the microseismic background.

C.23 During the HARDTACK II (1958) series of underground explosions, LOGAN (5 kilotons) and BLANCA (19 kilotons) produced a number of seismograms in each of the three zones which exhibited apparent rarefaction first motion. Only those seismographs within a few hundred miles of these two events showed consistently clear compressional first motions. On the basis of the response of all the

seismograph stations surrounding BLANCA and LOGAN, these two underground nuclear explosions could both have been identified incorrectly as earthquakes if the mere existence of rarefactional first motions were taken as a definitive criterion.

C.24 The strength of the signal produced by a given underground burst depends on the nature of the medium in which it takes place. This is due to differences in the extent of mechanical energy transfer (or coupling) between the explosion and the surrounding soil or rock. Tests have been made of the seismic effects of ordinary high explosives in a salt medium using TNT charges up to 1 ton. Although the extrapolations from these small HE explosions into the nuclear kiloton range indicated that salt would have a decoupling factor of 2.5 compared to tuff for a tamped explosion, the underground nuclear detonation (GNOME) of about 3–4 kilotons conducted on December 10, 1961, in a salt bed near Carlsbad, New Mexico, revealed that in the kiloton range, salt has a coupling (rather than decoupling) factor of about 2.5 compared to tuff for tamped nuclear explosions.

C.25 A decrease in seismic coupling can be achieved by exploding the nuclear weapon in a large hole. The estimated diameters of spherical holes necessary to produce different degrees of decoupling for various explosion yields are summarized in the accompanying table, which applies to holes at a depth of about 3,000 feet. The size required would be reduced at greater depths and increased at lesser depths. The decoupling effects are estimated with respect to fully tamped shots in tuff. For example, it is estimated that a 100-kiloton explosion in a hole 250 feet in diameter in salt will give roughly the same signal on a distant seismograph as a 3.3-kiloton tamped shot in Nevada tuff. If the same device were detonated in a hole 770 feet in diameter its apparent yield would be reduced to 0.33 kiloton.

ESTIMATES OF SEISMIC DECOUPLING OF NUCLEAR EXPLOSIONS

Energy Yield (kilotons)	*Diameter of hole to decouple by 300 in salt compared to fully tamped in tuff.* (feet)*	*Diameter of hole to decouple by 30 in salt compared to fully tamped in tuff.* (feet)*
10	360	115
20	450	145
50	610	195
100	770	250
300	1100	360

*Calculated for depth of about 3,000 feet.

C.26 The theoretical estimates above have been experimentally confirmed to some extent by scaled chemical explosions in salt cavities. It has also been estimated that by the addition of heat absorbers within the cavity it may be possible to increase the overall decoupling effect to a factor of 1000.

C.27 Efforts are being made to improve the seismic method for detecting subsurface explosions. One approach is to develop seismographs which respond only to particular wave frequencies, thus making the background noise less significant. It is possible that instruments which are sensitive to very long waves, i.e., at the low frequencies of 0.01 to 0.1 cycle per second, may prove useful in this respect because microseisms at these frequencies are thought to be relatively small.[1] Another possibility is to employ arrays of detectors which partially cancel the microseismic noise. A third approach is to design detectors capable of operation in deep wells several thousand feet below the earth's surface. Since it is expected that much of the background noise is confined to regions near the surface, such instruments may be able to detect much weaker signals than can be distinguished from the background on the surface itself. It is estimated that an improvement in signal-to-noise ratio by a factor of 100 to 1,000 would be necessary in order to detect the muffled seismic waves from a fully decoupled shot.

C.28 In order to distinguish between an underground explosion and an earthquake, the possible use of the first motion criterion as a means of identifying earthquakes is being investigated. In the meantime, there appears to be only one reliable earthquake indicator, i.e., determination of the "depth of focus." This requires measurement of the time interval between the arrival of the direct and surface reflected P-wave and is presently applicable with confidence only to earthquakes which occur at depths greater than 30 to 50 miles. A large number of shallow-focus earthquakes occur each year for which no precise depth can be obtained and hence for which there is as yet no known method of general applicability for identification.

C.29 An indication of the nature of the problem can be obtained from Fig. C.29. This shows the approximate average number of shallow earthquakes occurring in a year with magnitudes which are equivalent to and larger than the indicated yields of underground nuclear bursts, with RAINIER coupling, i.e., a tamped shot in a medium like Nevada tuff. The broken lines in the figure represent the estimated range of uncertainty in the data. It is seen that there are

[1] Microseisms peak at about 0.2 cycle per second; detection appears to be better at either lower or higher frequencies.

roughly 18,000 shallow earthquakes per annum which are equivalent to underground explosions of 1 kiloton or more, and some 3,000 equivalent to 10-kiloton and larger bursts, assuming the same coupling as in the RAINIER shot.

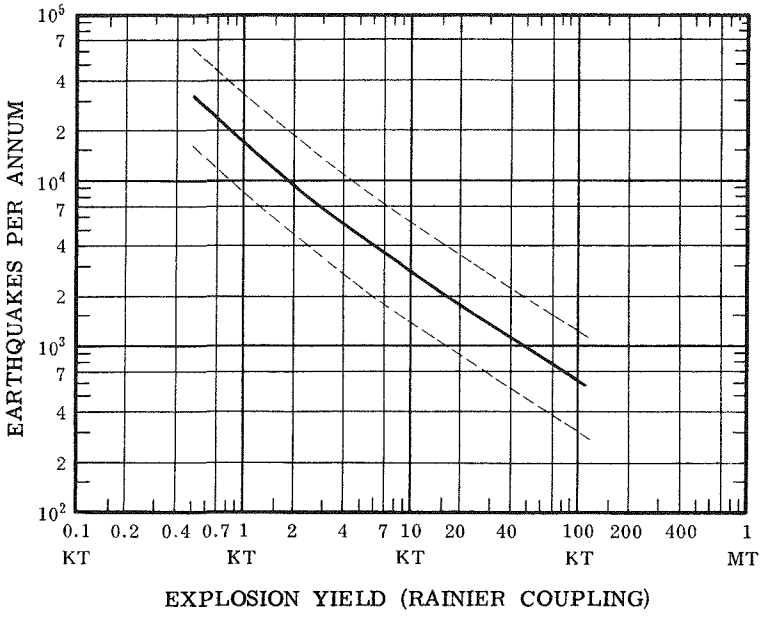

Figure C.29. Number of shallow earthquakes per annum with magnitudes equivalent to or larger than underground explosions of various yields, assuming RAINIER coupling. (The broken lines represent the range of uncertainty of the data.)

Electromagnetic (Radio) Signal

C.30 The electromagnetic pulse, with frequencies lying mainly in the range of 10 to 15 kilocycles, which results from the asymmetric emission of gamma rays accompanying a nuclear explosion, as described in §10.03 *et seq.*, has been proposed as a means for detecting such explosions. Provided there is no high background noise level in the vicinity of the receiving station, it should be possible to detect the radio signal from a 1-kiloton explosion as far as 3,000 miles away. The procedure is expected to be applicable to air bursts at altitudes up to about 600 miles. By means of radio directional equipment, the azimuthal angle of the signal source could be determined with an

accuracy of 2°; this corresponds to an uncertainty of about 30 miles in a distance of 1,000 miles. The time of receipt of the radio signal is within a small fraction of a second of the instant of the explosion.

C. 31 The great drawback to the radio detection method is that lightning flashes produce signals, i.e., static (or atmospherics), in about the same frequency range as the pulse signal from a nuclear explosion. Close to the point of burst the characteristics of the electromagnetic signal are different from those caused by lightning, but at distances over 600 miles away they are essentially indistinguishable with equipment at present available. Techniques are under development which may perhaps provide automatic exclusion of much of the static from lightning, but currently it is not possible to distinguish the signals from nuclear explosions from those produced by lightning flashes. Until this problem is solved the radio detection method will have an unacceptably high "false-alarm" rate.

Visible Light and Fluorescence

C.32 The visible light from a nuclear explosion offers a means of detection. Although the method is impractical for ordinary air bursts and is useless for subsurface detonations, it may be applicable to explosions at great distances from the earth because of the long range over which the light can be seen. It is estimated that detection should be possible at the earth's surface of a megaton-order shielded [2] or unshielded explosion at an altitude of 200,000 miles in the daytime and a factor of 10 or more greater at night. Cloud cover over the observation point will, of course, render the method useless, but this difficulty could be partially overcome if there are several stations at widely separated locations.

C.33 When the thermal X-rays from a high-altitude nuclear explosion, even one well above the atmosphere, first interact with the low-density air they cause excitation of neutral and ionized nitrogen molecules. As seen in §2.120, the excess energy is rapidly re-emitted as a bright pulse of (visible) fluorescence radiation. This radiation is restricted to a few very narrow characteristic wavelength bands, and it has been possible to devise an effective detection system using a wide-angle lens and a narrow band filter in the appropriate spectral region. Detection is feasible under bright daylight conditions, but is somewhat better at night; thus, a 1-megaton unshielded explosion

[2] A shielded explosion is one in which the nuclear device is surrounded by a thin sheet of lead or other material to reduce the amount of radiation emitted. Such a shield would be particularly effective for thermal X-rays (C.42).

might be detected at a distance of several million miles away at night. It has been confirmed that lightning flashes produce no disturbing signals in the detection system, although auroras may possibly do so. It remains to be determined whether or not either of these techniques possesses adequate long range and a sufficiently low false-alarm rate to be useful in a space detection system.

Backscatter Radar

C.34 High-altitude nuclear explosions can produce changes in the electron density of the ionosphere which may persist for some time and cause interference with radio communications and radar systems (Chapter X). These changes in the ionosphere can be detected by the backscattering of radar signals, at frequencies of 10 to 30 megacycles, from the ionized regions produced by nuclear explosions. An unshielded explosion, with a 1-megaton yield, at an altitude of 10,000 miles may be detected in this manner. The main difficulty with this detection procedure is the occurrence of natural phenomena which produce disturbances of the ionosphere similar to those from a nuclear explosion in space. Further study is required to determine the false-alarm rate and to understand better the character of the backscatter signal from a nuclear test in space.

Cosmic Noise Absorption

C.35 The ionization produced in the ionosphere by thermal X-rays (and other radiations) from a high-altitude nuclear explosion will affect the absorption characteristics of this region of the atmosphere. Radio noise coming from great distances in space must pass through the ionosphere on its way to the receiver, called a "riometer." Analysis of the effect of the ionization expected from a nuclear explosion in space indicates that in a time of the order of 1 second or less there should occur a measurable change in strength of the received cosmic noise. Changes in intensity due to natural causes, however, are observed to take place in roughly 30 seconds. Research is underway to determine whether or not intensity changes with shorter time periods do exist in nature. If false-alarm rates prove to be acceptable, the riometer technique is estimated to have a range of roughly 10,000 miles for a 1-megaton unshielded nuclear explosion. Since the ionization is largely produced by the X-rays from the nuclear device, the effectiveness of the method could be drastically decreased by a light-weight shield between the weapon and the earth. Another

drawback is that radio emission from the sun sometimes becomes so intense that the riometer may become saturated and during these periods it may be expected to be completely inoperable.

Very-Low-Frequency (VLF) Anomaly

C.36 The VLF phase anomaly technique is another among those sensitive to changes produced by irradiation of the atmosphere with thermal X-rays from a nuclear explosion in space. Consequently, it is not useful for shielded nuclear explosions. It is based upon the fact that the ionospheric disturbance from the nuclear explosion causes slight changes in the propagation time of the waves from a very-low-frequency transmitter to a distant receiver, thus producing a measurable phase shift in the received signal (§10.52). Investigations have revealed no phase shifts from natural sources which are as rapid as those expected from nuclear explosions is space. The possible range of the phase anomaly method is estimated roughly as several million miles from a 1-megaton unshielded explosion.

Ionosonde Measurements

C.37 The "ionosonde" is an instrument which is basically a vertical incidence radar for determining the height of the ionized layers of the atmosphere. As already seen, a nuclear explosion is accompanied by anomalous ionization which may produce detectable changes in ionization levels. It is probable that the ionosonde method may possess a range capability of the order of 10,000 miles for a 1-megaton unshielded explosion.

Disturbance of Magnetic and Electric Fields

C.38 A nuclear explosion within the earth's magnetic field is expected to produce magnetohydrodynamic waves in this field with a resulting perturbation of the earth currents and magnetic field measured on the surface. For example, both types of disturbance were recorded from the Argus high-altitude tests (§ 2.54). Further investigation of these effects is required, however, to obtain a better understanding of the phenomena and to ascertain the frequency of disturbances from natural causes that resemble those expected from nuclear explosions. There is some theoretical foundation for the suggestion that the ionizing radiations from a nuclear explosion at great distances,

even beyond the sensible magnetic field of the earth, may produce measurable effects near the earth's surface. Here again, additional study and experimental tests are required to establish the validity of the magnetic and electric field techniques.

MEASUREMENT OF DIRECT RADIATIONS BY SATELLITE-BASED INSTRUMENTS

Introduction

C.39 In principle, it should be possible to detect a nuclear explosion by means of the direct radiations emitted, namely, thermal X-rays, gamma rays, neutrons, and beta particles. But since these radiations are either absorbed or degraded in energy in their passage through air and are affected by electric and magnetic fields, they must originate and be detected outside the atmosphere and beyond the earth's radiation belts (§ C.40). The necessary equipment would, therefore, have to be installed in a number of satellites in space and the information telemetered to earth by means of radio signals. Observations of the direct radiations may thus be suitable for detecting nuclear detonations occurring above the atmosphere out to great distances—possibly hundreds of millions of miles—in space.

C.40 The question of the orbits of earth satellites to be used for detection purposes is complicated by the existence of the radiation (Van Allen) belts which surround the earth. Observations made from the minimum radius of the inner belt to the maximum radius of the outer one, i.e., at distances about 1,000 to 40,000 miles from the earth, would be useless because of interference. Hence, the altitude of the satellite orbits would have to lie outside this region, as also would the burst point.

Thermal X-Rays

C.41 More than 50 percent of the total energy of a nuclear detonation in free space appears as thermal X-rays (§ 1.72). These radiations can probably be detected at greater distances than gamma rays, neutrons, or beta particles, depending on shielding and background conditions. In order to minimize the false-alarm rate, several detectors could be arranged in a group. The detection of a possible nuclear explosion would be that signals, with the proper time characteristics, would be received simultaneously by a predetermined number of the instruments.

C.42 Provided the satellite is outside the earth's radiation belts, the maximum theoretical range of the X-ray technique is expected to be about 1 billion (10^9) miles from a 1-megaton unshielded burst. However, the X-ray detection procedure is particularly sensitive to the interposition of a suitable shield around the detonating weapon; this would reduce the amount of energy appearing as thermal X-rays, because of a decrease in both the temperature and the fraction of the radiation which escapes. As a result, the range of detection would be decreased by as much as a factor of 250, reducing the estimated range to 4 million miles. Improvements of the detecting instruments may provide a partial compensation for the effect of shielding.

Gamma Rays

C.43 The gamma rays, both prompt (or instantaneous) and delayed, should also be detectable at great distances from a nuclear explosion. For the prompt radiation, emitted within less than a microsecond, an arrangement of scintillation detectors would be required to give signals in coincidence within a time interval of a few hundred-millionths of a second, i.e., a few shakes (§ 1.42). As this coincidence might be due to a local cosmic-ray shower, it would be necessary that a number of Geiger counters, distributed throughout the satellite, should show no coincidence. These counters would respond to the cosmic-ray shower but would not, in general, be sensitive enough to react to the gamma rays at a long distance from a nuclear detonation. The effective range of the detection method for prompt gamma rays is about 20 million miles for an unshielded 1-megaton shot.

C.44 Since the delayed gamma rays are emitted by the weapon debris after the explosion, they are not easily shielded. Consequently, the detection of these radiations, within 1 second of the detonation, should prove useful for ranges up to 2 million miles from a 1-megaton explosion, regardless of whether it were shielded or not. An arrangement of scintillation detectors, discriminating against gamma rays of higher energy than those emitted by fission products, would be required.

Neutrons

C.45 The detection of neutrons, although less sensitive than that of the radiations considered above, is believed to be least susceptible to false alarms from background effects. The instruments would

consist of, for example, a boron trifluoride counter or lithium iodide scintillator surrounded by a moderator for slowing down the fission or thermonuclear neutrons. The prompt neutrons could be used to indicate the occurrence of an unshielded 1-megaton burst out to a million miles or to a shorter distance if the weapon is shielded. Delayed fission neutrons are not affected by shielding the exploding device, but the range of detection is only about 100,000 miles for 1 megaton.

Beta Particles

C.46 A procedure of somewhat limited scope is based on the detection of beta particles, i.e., electrons emitted by fission products, trapped by the earth's magnetic field as a result of the so-called Argus effect (§ 10.44). Simple electron counters can be used to detect a higher than normal density produced by any nuclear explosion greater than 1 kiloton occurring between 70° N and 70° S magnetic latitudes and at altitudes up to 30,000 miles. Outside this limited region, the sensitivity of the method decreases rapidly with distance. It is, of course, unaffected by shielding of the exploding weapons.

Summary

C.47 A considerable uncertainty in connection with satellite-based detection techniques is the lack of adequate knowledge of the background level on a microsecond time scale of pulses of radiation in space which could produce false alarms. Actual trials of prototype detection packages launched into orbit are required to measure false-alarm rates and to determine the operational characteristics of the equipment, in order to ascertain the capability of satellite-based detection techniques.

C.48 Provided the many outstanding problems can be solved, the estimated ranges of the various methods proposed for detecting nuclear explosions in space are summarized in the accompanying table. The distances given are for a 1-megaton detonation, for both unshielded and shielded situations. Except for the trapped-electron technique, for which the detection range is believed to be independent of the explosion, the ranges for 1 to 10 kiloton detonations would be roughly one-hundredth to one-tenth of the respective distances in the table.

ESTIMATED DETECTION RANGES FOR 1-MEGATON DETONATIONS IN SPACE *

GROUND-BASED TECHNIQUES

Method	*Range in Miles*	
	Unshielded	*Shielded***
Direct visible light (daytime)	200, 000 [a]	>200, 000 [a]
Direct visible light (nighttime)	>2, 000, 000 [a]	>2, 000, 000 [a]
Fluorescence	6, 000, 000 [b]	60, 000–600, 000 [b]
Backscatter Radar	~10, 000	~1, 000
Cosmic Noise Absorption	~10, 000	~1, 000
Ionosonde Method	~10, 000	~1, 000
Electromagnetic Pulse	>1, 000	>1, 000
VLF Phase Anomaly	6, 000, 000	60, 000–600, 000
Electric and Magnetic Fields	~10, 000	~10, 000

SATELLITE-BASED TECHNIQUES

Methoa	*Range in Miles*	
	Unshielded	*Shielded***
Thermal X-rays	1, 000, 000, 000	4, 000, 000
Prompt gamma rays	2, 000, 000	2, 000, 000
Delayed gamma rays	2, 000, 000	2, 000, 000
Prompt neutrons	1, 000, 000	1, 000, 000
Delayed neutrons	100, 000	100, 000
Trapped electrons	30, 000	30, 000

[a] These estimates apply only if the line of sight is not obscured by cloud cover.

[b] Fluorescence is less affected by cloud cover than is visible light.

*Except for the trapped-electron method, the estimated ranges for 1 to 10-kiloton detonations are roughly one-hundredth to one-tenth those for 1 megaton.

**For the definition of a shielded explosion, see § C.32, footnote.

GLOSSARY

A-BOMB: An abbreviation for atomic bomb.

ABSORBED DOSE: The amount of energy imparted by nuclear (or ionizing) radiation to unit mass of absorbing material. The unit is the rad. See *Dose, Rad.*

ABSORPTION: As applied to gamma (or X-) radiation it is strictly the process (or processes) resulting in the transfer of energy by the radiation to an absorbing material through which it passes. In this sense, absorption involves only the photoelectric effect and pair production. However, the term is frequently used interchangebly with attenuation, which includes the Compton effect; absorption then includes both the removal and scattering of photons. See *Attenuation, Compton effect, Pair production, Photoelectric effect, Scattering.*

ABSORPTION COEFFICIENT: A number characterizing the ability of a given material to absorb (or attenuate) 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.

ACTIVATION DETECTOR: A material used to determine neutron flux or density by virtue of the radioactivity induced in it as a result of neutron capture. See *Neutron flux, Threshold detector.*

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 fireball does not touch the earth's surface when the luminosity is a maximum (in the second pulse).

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.*

ANGSTROM: A unit of length, represented by A, equal to 10^{-8} centimeter. It is commonly used to express the wave lengths of electromagnetic radiations in the visible, ultraviolet, and X-ray regions.

ARCHING: In the case of a buried structure, it is the tendency for the soil particles to lock together in the form of an arch, with the result that part of the stress is transmitted around the structure instead of through it.

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: See *Radioactive cloud.*

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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 the common isotope of carbon (carbon 12) is taken to be exactly 12; 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.

ATTENUATION: Decrease in intensity of a signal, beam, or wave as a result of absorption of energy and of scattering out of the path of a detector, but not including the reduction due to geometric spreading, i.e., the inverse square of distance effect. See *Absorption, Inverse square law.*

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: See *Fireball.*

BASE SURGE: A cloud which rolls outward from the bottom of the column produced by a subsurface explosion. For underwater bursts the visible surge is, in effect, a cloud of liquid (water) droplets with the property of flowing almost as if it were a homogeneous fluid. After the water evaporates, an invisible base surge of small radioactive particles may persist. 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 direct fission products emit (negative) beta particles. Physically, the beta particle is identical with an electron moving at high velocity. See *Electron, Fission products, Radioactivity.*

BIOLOGICAL HALF-TIME: 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.

BLACK BODY: An ideal body which would absorb all (and reflect none) of the radiation falling upon it. The spectral energy distribution of a black body is described by Planck's equation; the total rate of emission of radiant energy is proportional to the fourth power of the absolute temperature (Stefan-Boltzmann law).

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 loading, 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 pulse of air in which the pressure increases sharply at the front, accompanied by winds, propagated continuously from an explosion. See *Shock wave.*

BOMB DEBRIS: See *Weapon debris.*

BREAKAWAY: The onset of a condition in which the shock front (in the air) moves away from the exterior of the expanding fireball produced by the explosion of a nuclear (or atomic) weapon. See *Fireball, Shock front.*

BREMSSTRAHLUNG: Literally "braking radiation." Radiations covering a range of wave lengths (and energies) in the X-ray region resulting from the electrical interaction of fast (high-energy) electrons with atomic nuclei. Bremsstrahlung are produced by the interaction of beta particles with matter. See *X-rays.*

BURST: Explosion or detonation. See *Air burst, High-altitude 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.

CLEAN WEAPON: One in which measures have been taken to reduce the amount of residual radioactivity relative to a "normal" weapon of the same energy yield.

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. See *Radioactive cloud.*

CLOUD PHENOMENA: See *Base surge, Cloud column, Fallout, Fireball, Radioactive cloud.*

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.

COMPTON EFFECT: The scattering of photons (of gamma or X-rays) by the orbital electrons of atoms. In a collision between a (primary) photon and an electron, some of the energy of the photon is transferred to the electron which is generally ejected from the atom. Another (secondary) photon, with less energy, then moves off in a new direction at an angle to the direction of motion of the primary photon. See *Scattering.*

COMPTON ELECTRON: An electron of increased energy ejected from an atom as the result of a Compton interaction with a photon. See *Compton effect.*

CONDENSATION CLOUD: A mist or fog of minute water droplets which temporarily surrounds the fireball 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.*

CONTAINED UNDERGROUND BURST: An underground detonation at such a depth that none of the radioactive residues escape through the surface of the ground. See *Crater.*

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 weapon debris have become incorporated with particles of dirt, etc. Contamination can also arise from the radioactivity induced in certain substances by the action of neutrons from a nuclear explosion. See *Decontamination, Fallout, Induced radioactivity, Weapon debris.*

CRATER: The pit, depression, or cavity formed in the surface of the earth by an explosion. The *apparent crater* is the depression which is seen after the burst; it is smaller than the *true crater*, i.e., the cavity actually formed by the explosion, because it is covered with a layer of loose earth, rock, etc. In a deep underground burst when there is no rupture of the surface, the resulting cavity is called a *camouflet.*

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 3.700×10^{10} nuclear disintegrations occur per second. The *gamma curie* is sometimes defined correspondingly as the quantity of material in which this number of gamma-ray photons are emitted per second.

DAMAGE CRITERIA: Standards or measures used in estimating specific levels of damage.

DEBRIS: See *Weapon debris.*

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.

DELAYED FALLOUT: See *Fallout.*

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. Deuterium is extracted from water which always contains 1 atom of deuterium to about 6,500 atoms of ordinary (light) hydrogen. 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.

DIRTY WEAPON: One which produces a larger amount of radioactive residues than a "normal" weapon of the same yield. See *Salted weapon.*

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 or which he would receive per unit of time. It is usually expressed as roentgens, rads, or rems 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. See *Survey Meter.*

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 and dose rates. 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 the drag 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 behind the shock front as it impinges on the object or structure.

EARLY FALLOUT: See *Fallout.*

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.*

ELECTROMAGNETIC RADIATION: A traveling wave motion resulting from oscillating magnetic and electric fields. Familiar electromagnetic radiations range from X-rays (and gamma rays) of short wavelength, through the ultraviolet, visible, and infrared regions, to radar and radio waves of relatively long wavelength. All electromagnetic radiations travel in a vacuum with the velocity of light. See *Photon.*

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.*

ELECTRON VOLT (EV): The energy imparted to an electron when it is moved through a potential difference of 1 volt. It is equivalent to 1.6×10^{-12} erg.

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 (EPG): 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 fallback to the earth's surface of particles contaminated with radioactive material from the radioactive cloud. The term is also applied in a collective sense to the contaminated particulate matter itself. The *early* (or *local*) *fallout* is defined, somewhat arbitrarily, as those particles which reach the earth within 24 hours after a nuclear explosion. The *delayed* (or *world-wide*) *fallout* consists of the smaller particles which ascend into the upper troposphere and into the stratosphere and are carried by winds to all parts of the earth. The delayed fallout is brought to earth, mainly by rain and snow, over extended periods ranging from months to years.

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: The luminous sphere of hot gases which forms a few millionths of a second after a nuclear (or atomic) explosion as the result of the absorption by the surrounding medium of the thermal X-rays emitted by the extremely hot (several tens of millions degrees) weapon residues. The exterior of the fireball in air is initially sharply defined by the luminous shock front and later by the limits of the hot gases themselves (radiation front). See *Breakaway.*

FIRE STORM: Stationary mass fire, generally in built-up urban areas, generating strong, inrushing winds from all sides; the winds 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 FRACTION: The fraction (or percentage) of the total yield of a nuclear weapon which is due to fission. For thermonuclear weapons the average value of the fission fraction is about 50 percent.

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 36 elements.

FLASH BURN: A burn caused by excessive exposure (of bare skin) to thermal radiation. See *Thermal radiation.*

FRACTIONATION: Any one of several processes, apart from radioactive decay, which results in change in the composition of the radioactive weapon debris. As a result of fractionation, the delayed fallout generally contains relatively more of strontium-90 and cesium-137, which have gaseous precursors, than does the early fallout from a surface burst.

FREE AIR OVERPRESSURE (OR FREE FIELD OVERPRESSURE): 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. See *Electromagnetic radiation, X-rays.*

GENETIC EFFECT: The effect (of nuclear radiation, in particular) of producing changes (mutations) in the hereditary components (genes) in the germ cells present in the reproductive organs (gonads). A mutant gene causes changes in the next generation which may or may not be apparent.

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 *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. See *Biological half-time.*

HALF-RESIDENCE TIME: As applied to delayed fallout, it is the time required for the amount of weapon debris deposited in a particular part of the atmosphere, e.g., stratosphere or troposphere, to decrease to half of its initial value.

HALF-VALUE 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.

HIGH-ALTITUDE BURST: This is defined, somewhat arbitrarily, as a detonation at an altitude over 100,000 feet. Above this level the distribution of the energy of the explosion between blast and thermal radiation changes appreciably with increasing altitude due to changes in the fireball phenomena.

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 (PER UNIT AREA): 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.

INFRARED: Electromagnetic radiations of wavelength between the longest visible red (7,000 Angstroms or 7×10^{-4} millimeter) and about 1 millimeter. See *Electromagnetic radiation.*

INITIAL NUCLEAR RADIATION: Nuclear radiation (esssentially neutrons and gamma rays) emitted from the fireball 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 part of the radiations (fission products, etc., in the radioactive cloud) to attain such a height that only insignificant amounts reach the earth's surface. See *Residual nuclear radiation.*

INTEGRATED NEUTRON FLUX: The product of neutron flux and time, expressed in units of neutrons per square centimeter. It is a measure of neutron exposure dose. See *Dose, Neutron flux.*

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.

INVERSE SQUARE LAW: The law which states that when radiation (thermal or nuclear) from a point source is emitted uniformly in all directions, the amount received per unit area at any given distance from the source, assuming no absorption, is inversely proportional to the square of that distance.

IONIZATION: The separation of a normally electrically neutral atom or molecule into electrically charged components. The term is also employed to describe the degree or extent to which this separation occurs. In the sense used in this book, ionization refers especially to the removal of an electron (negative charge) from the atom or molecule, either directly or indirectly, leaving a positively charged ion. The separated electron and ion are referred to as an *ion pair*. See *Ionizing radiation*.

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.

IONOSPHERE: The region of the atmosphere, extending from roughly 40 to 250 miles altitude, in which there is appreciable ionization. The presence of charged particles in this region profoundly affects the propagation of long-wavelength electromagnetic radiations (radio and radar waves).

ION PAIR: See *Ionization*.

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. Furthermore, uranium-235 is fissionable by neutrons of all energies, but uranium-238 will undergo fission only with neutrons of high energy. See *Nucleus*.

KILO-ELECTRON VOLT (or KEV): An amount of energy equal to 1,000 electron volts. See *Electron Volt*.

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 4.2×10^{19} ergs. See *Megaton energy, TNT equivalent*.

LINEAR ABSORPTION COEFFICIENT: See *Absorption coefficient*.

LIP HEIGHT: The height above the original surface to which earth is piled around the crater formed by an explosion. See *Crater*.

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. See *Diffracting Loading, Drag Loading*.

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.*

MEGACURIE: One million curies. See *Curie.*

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 4.2×10^{22} ergs. See *TNT equivalent.*

MEV (OR MILLION ELECTRON VOLT): A unit of energy commonly used in nuclear physics. It is equivalent to 1.6×10^{-6} erg. Approximately 200 Mev of energy are produced for every nucleus that undergoes fission. See *Electron volt.*

MICROCURIE: A one-millionth part of a curie. See *Curie.*

MICRON: A one-millionth part of a meter, i.e., 10^{-6} meter or 10^{-4} centimeter; it is roughly four one-hundred-thousandths (4×10^{-5}) of an inch.

MICROSECOND: A one-millionth part of a second.

MILLION ELECTRON VOLT: See *Mev.*

MILLIREM: A one-thousandth part of a rem. See *Rem.*

MILLIROENTGEN: A one-thousandth part of a roentgen. See *Roentgen.*

MILLISECOND: A one-thousandth part of a second.

MIRROR POINT: A point at which a charged particle, moving (in a spiral path) along the lines of a magnetic field, is reflected back as it enters a stronger magnetic field region. The actual location of the mirror point depends on the direction and energy of motion of the charged particle and the ratio of the magnetic field strengths. As a result, only those particles satisfying the requirements of the existing situation are reflected.

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 (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.

NEUTRON FLUX: The product of the neutron density (number per cubic centimeter) and the neutron velocity; the flux is expressed as neutrons per square centimeter per second. It is numerically equal to the total number of neutrons passing, in all directions, through a sphere of 1 square centimeter cross sectional area per second.

NEVADA TEST SITE (NTS): 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 of 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, X-rays.*

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. Information concerning the announced nuclear tests made by the United States, the United Kingdom, the U.S.S.R., and France is summarized in Appendix B.

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.*

PAIR PRODUCTION: The process whereby a gamma-ray (or X-ray) photon, with energy in excess of 1.02 Mev. in passing near the nucleus of an atom is converted into a positive electron and a negative electron. As a result, the photon ceases to exist. See *Photon.*

PHOTOELECTRIC EFFECT: The process whereby a gamma-ray (or X-ray) photon, with energy somewhat greater than that of the binding energy of an electron in an atom, transfers all its energy to the electron which is consequently removed from the atom. Since it has lost all its energy, the photon ceases to exist. See *Photon.*

PHOTON: A unit or "particle" of electromagnetic radiation, possessing a quantum of energy which is characteristic of the particular radiation. If ν is the frequency of the radiation in cycles per second and λ is the wave length in centimeters, the energy quantum of the photon in ergs is $h\nu$ or $hc\lambda$, where h is Planck's constant, 6.62×10^{-27} erg-second and c is the velocity of light (3.00×10^{10} centimeters per second). For gamma rays, the photon energy is usually expressed in million electron volt (Mev) units, i.e., $1.24\times10^{-10}/\lambda$ where λ is in centimeters or $1.24\times10^{-2}/\lambda$ if λ is in Angstroms.

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.*

PLASTIC ZONE: The region beyond the rupture zone associated with crater formation in which there is no visible rupture but in which the soil is permanently deformed and compressed to a high density. See *Crater, Rupture zone.*

PLUME: See *Column.*

POSITIVE PHASE: See *Shock wave.*

PRECURSOR: An air pressure wave which moves ahead of the main blast wave for some distance as a result of a nuclear (or atomic) explosion of appropriate yield and low burst height over a heat-absorbing (or dusty) surface. The pressure at the precusror front increases more gradually than in a true (or ideal) shock wave, so that the behavior in the precursor region is said to be nonideal. See *Blast wave, Shock front, 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.*

QUANTUM: See *Photon.*

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.

RADIANT EXPOSURE: The total amount of thermal radiation energy received per unit area of exposed surface; it is usually expressed in calories per square centimeter.

RADIATION: See *Nuclear radiation, Thermal radiation.*

RADIATION INJURY (OR SYNDROME) See *Syndrome (Radiation).*

RADIATION PROTECTION GUIDE: The total amount of ionizing radiation dose over certain periods of time which may be permitted to persons whose occupation involves exposure to such radiation. It is equivalent to what was formerly called the Maximum Permissible Exposure (or MPE).

RADIOACTIVE (OR ATOMIC) CLOUD: An all-inclusive term for the mixture of hot gases, smoke, dust, and other particulate matter from the weapon itself and from the environment, which is carried aloft in conjunction with the rising fireball produced by the detonation of a nuclear (or atomic) weapon.

RADIOACTIVITY CONCENTRATION GUIDE (RCG): The amount of any specified radioisotope that is acceptable in air and water for continuous consumption. It is equivalent to what was formerly called the Maximum Permissible Concentration (or MPC).

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 isstope of a different (daughter) 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 now being replaced by the rad; the name rep is derived from the initial letters of the term "roentgen equivalent physical." Basically, the rep was 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 about 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 (34 electron volts) for the energy lost by an electron in producing a posi-

tive-negative ion pair in air, it is estimated that 1 roentgen of gamma (or X-) radiation, would result in the absorption of about 87 ergs of energy per gram of air.

RUPTURE ZONE: The region immediately adjacent to the crater boundary in which the stresses produced by the explosion have exceeded the ultimate strength of the medium. It is characterized by the appearance of numerous radial cracks of various sizes. See *Crater, Plastic zone.*

SALTED WEAPON: A nuclear weapon which has, in addition to its normal components, certain elements or isotopes which capture neutrons at the time of the explosion and produce radioactive products over and above the usual radioactive weapon debris.

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 recieved at such a point from many directions instead of only from the direction of the source.

SCAVENGING: The selective removal of material from the radioactive cloud from a nuclear explosion by inert substances, such as earth or water, introduced into the fireball. The term is also applied to the process of removal of fallout particles from the atmosphere by rain or snow.

SHEAR (WIND): Unless the term "velocity shear" is used, wind shear refers to differences in direction (directional shear) of the wind at different altitudes. It is commonly expressed in degrees per thousand feet (kilofoot).

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 resembles 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 positive phase for the dynamic pressure is somewhat longer than for overpressure, due

to the momentum of the moving air behind the shock front. 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 *Dynamic pressure, Overpressure.*

SKYSHINE: Radiation, particularly gamma rays from a nuclear explosion, reaching a target from many directions as a result of scattering by the oxygen and nitrogen in the intervening atmosphere.

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.*

STRATOSPHERE: A relatively stable layer of the atmosphere between the tropopause and a height of about 30 miles in which the temperature changes very little (in polar and temperate zones) or increases (in the tropics) with increasing altitudes. In the stratosphere clouds of water never form and there is practically no convection. See *Tropopause, Troposphere.*

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 weapon is detonated actually on the surface (or within $5W^{0.3}$ feet, where W is the explosion yield in kilotons, above or below 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 injury,* 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.

TENTH-VALUE THICKNESS: The thickness of a given material which will decrease the amount (or dose) of gamma radiation to one-tenth of the amount incident upon it. Two tenth-value thicknesses will reduce the dose received by a factor of 10×10, i.e., 100, and so on. The tenth-value thickness of a given material depends on the gamma-ray energy, but for radiation of a particular energy it is roughly inversely proportional to the density of the material.

TESTS: See *Nuclear tests.*

THERMAL ENERGY: The energy emitted from the fireball 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 *Radiant exposure, Thermal radiation, Transmittance.*

THERMAL ENERGY YIELD (OR THERMAL YIELD): The part of the total energy yield of the nuclear (or atomic) explosion which is received as thermal energy usually within a minute or less. In an air burst, the thermal energy is, on the average, about one-third of the total energy of the explosion. For a high-altitude burst, roughly one-fourth of the total yield is received as thermal energy at a distance within about a minute. The thermal energy may be expressed in calories, ergs, or in terms of the TNT equivalent.

THERMAL RADIATION: Electromagnetic radiation emitted (in two pulses from an air burst) from the fireball as a consequence of its very high temperature; it consists essentially of ultraviolet, visible, and infrared radiations. In the early stages (first pulse of an air burst), 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. From a high-altitude burst, the thermal radiation is emitted in a single short pulse.

THERMAL X-RAYS: The electromagnetic radiation, mainly in the soft (low-energy) X-ray region, emitted by the extremely hot weapon debris in virtue of its extremely high temperature; it is also referred to as the *primary thermal radiation.* It is the absorption of this radiation by the ambient medium, accompanied by an increase in temperature, which results in the formation of the fireball which then emits thermal radiation. See *Weapon debris, X-rays.*

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 number 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 weight 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.

TROPOPAUSE: The imaginary boundary layer dividing the stratosphere from the lower part of the atmosphere, the troposhere. The tropopause normally occurs at an altitude of about 25,000 to 45,000 feet in polar and temperate zones, and at 55,000 feet in the tropics.

TROPOSPHERE: The region of the atmosphere immediately above the earth's surface and up to the tropopause in which the temperature falls fairly regularly with increasing altitude, clouds form, convection is active, and mixing is continuous and more or less complete.

TRUE SURFACE BURST: See *Surface burst.*

$2W$ 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., $2W$, burst in free air, i.e., away from any reflecting surface.

ULTRAVIOLET: Electromagnetic radiation of wave length between the shortest visible violet (about 3,850 Angstroms) and soft X-rays (about 100 Angstroms).

UNDERGROUND BURST: The explosion of a nuclear (or atomic) weapon with its center more than $5W^{0.3}$ feet, where W is the explosion yield in kilotons, beneath the surface of the ground. See also *Contained underground burst.*

UNDERWATER BURST: The explosion of a nuclear (or atomic) weapon with its center beneath the surface of the water.

VENTING: The escape through the surface to the atmosphere of the gases and other residues formed in a subsurface explosion.

VISIBILITY RANGE (OR VISIBILITY): The horizontal distance (in kilometers or 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 170 miles (280 kilometers) for an exceptionally clear atmosphere to 0.6 mile or less (1.0 kilometer or less) for dense haze or fog.

WEAPON, ATOMIC (OR NUCLEAR): See *Nuclear weapon.*

WEAPON DEBRIS: The highly radioactive material, consisting of fission products, various products of neutron capture, and uranium and plutonium that have escaped fission, remaining after the explosion.

WEAPON RESIDUE: The extremely hot, compressed gaseous residues formed at the instant of the explosion of a nuclear weapon. The temperature is several tens of million degrees (Kelvin) and the pressure is many millions of atmospheres.

WILSON CLOUD CHAMBER: See *Condensation cloud.*

WORLD-WIDE FALLOUT: See *Fallout.*

X-RAYS: Electromagnetic radiations of high energy having wave lengths shorter than those in the ultraviolet region, i.e., less than 10^{-6} cm or 100 Angstroms. As generally produced by X-ray machines, they are bremsstrahlung resulting from the interaction of electrons of 1 kilo-electron volt or more energy with a metallic target. See *Bremsstrahlung, Gamma rays, Electromagnetic radiation.*

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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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