The Effects of Nuclear Weapons

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Dedicated to Calvin and Hobbes.

Contents

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

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

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Preface

When “The Effects of Atomic Weapons” was published in 1950, the explosive energy yields of the fission bombs available at that time were equivalent to some thousands of tons (i.e., kilotons) of TNT. With the development of thermonuclear (fusion) weapons, having energy yields in the range of millions of tons (i.e., megatons) of TNT, a new presentation, entitled “The Effects of Nuclear Weapons,” was issued in 1957. A completely revised edition was published in 1962 and this was reprinted with a few changes early in 1964. Since the last version of “The Effects of Nuclear Weapons” was prepared, much new information has become available concerning nuclear weapons effects. This has come in part from the series of atmospheric tests, including several at very high altitudes, conducted in the Pacific Ocean area in 1962. In addition, laboratory studies, theoretical calculations, and computer simulations have provided a better understanding of the various effects. Within the limits imposed by security requirements, the new information has been incorporated in the present edition. In particular, attention may be called to a new chapter on the electromagnetic pulse. We should emphasize, as has been done in the earlier editions, that numerical values given in this book are not—and cannot be—exact. They must inevitably include a substantial margin of error. Apart from the difficulties in making measurements of weapons effects, the results are often dependent upon circumstances which could not be predicted in the event of a nuclear attack. Furthermore, two weapons of different design may have the same explosive energy yield, but the effects could be markedly different. Where such possibilities exist, attention is called in the text to the limitations of the data presented; these limitations should not be overlooked. The material is arranged in a manner that should permit the general reader to obtain a good understanding of the various topics without having to cope with the more technical details. Most chapters are thus in two parts: the first part is written at a fairly low technical level whereas the second treats some of the more technical and mathematical aspects. The presentation allows the reader to omit any or all of the latter sections without loss of continuity. The choice of units for expressing numerical data presented us with a dilemma. The exclusive use of international (SI) or metric units would have placed a burden on many readers not familiar with these units, whereas the inclusion of both SI and common units would have complicated many figures, especially those with logarithmic scales. As a compromise, we have retained the older units and added an explanation of the SI system and a table of appropriate conversion factors. Many organizations and individuals contributed in one way or another to this revision of “The Effects of Nuclear Weapons,” and their cooperation is gratefully acknowledged. In particular, we wish to express our appreciation of the help given us by L. J. Deal and W. W. Schroebel of the Energy Research and Development Administration and by Cmdr. H. L. Hoppe of the Department of Defense.

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General Principles of Nuclear Explosions

1.1 Characteristics of nuclear explosions

1.1.1 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 (§ 1.11). 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 (ideally) 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 insofar 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, for the release of a given amount of energy, the mass of a nuclear explosive would be much less than that of a conventional high explosive.

[1] The terms "nuclear" and atomic" may be used interchangeably so far as weapons, explosions, and energy are concerned, but "nuclear" is preferred for the reason given in § 1.11.

Consequently, in the former case, there is a much smaller amount of material available in the weapon itself that is converted into the hot, compressed gases mentioned above. This results in somewhat different mechanisms for the initiation of the blast wave. Third, the temperatures reached in a nuclear explosion are very much higher than in a conventional explosion, and a fairly large proportion of the energy in a nuclear explosion is emitted in the form of light and heat, generally referred to as "thermal radiation." This is capable of causing skin burns and of starting fires at considerable distances. Fourth, 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 people (and other living organisms) 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 certainly cannot be predicted in the event of an attack. Furthermore, two weapons producing the same amount 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.

1.1.2 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,

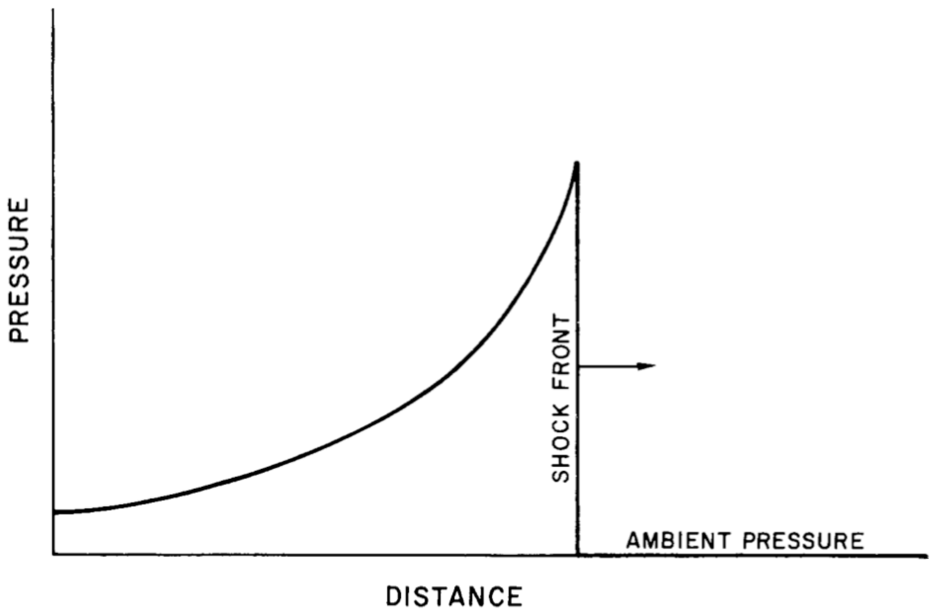

Figure 1.01: Variation of pressure (in excess of ambient) with distance in an ideal shock wave.

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 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 all atoms, whereas the atoms of uranium are the heaviest of those found on earth. Heavier atoms, such as those of plutonium, also important for the release of nuclear energy, have been made artificially (§ 1.14). Frequently, two or more atoms of the same or of different elements join together to form a "molecule."

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.

1.10 Each isotope of a given element is identified by its “mass number,” which is the sum of the numbers of protons and neutrons in the nucleus. For example, the element uranium, as found in nature, consists mainly of two isotopes with mass numbers of 235 and 238; they are consequently referred to as uranium–235 and uranium–238, respectively. The nuclei of both isotopes contain 92 protons—as do the nuclei of all uranium isotopes—but the former have in addition 143 neutrons and the latter 146 neutrons. The general term “nuclide” is used to describe any atomic species distinguished by the composition of its nucleus, i.e., by the number of protons and the number of neutrons. Isotopes of a given element are nuclides having the same number of protons but different numbers of neutrons in their nuclei.

1.11 In a conventional explosion, the energy released 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 sometimes referred to as atomic energy is thus actually 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.

1.12 Many nuclear processes are known, but not all 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 internal 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.

1.13 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" (splitting) and "fusion" (joining together). 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.

1.14 The materials used to produce nuclear explosions by fission are certain isotopes of the elements uranium and plutonium. As noted above, uranium in nature consists mainly of two isotopes, namely, uranium-235 (about 0.7 percent), and uranium-238 (about 99.3 percent). The less abundant of these isotopes, i.e., uranium-235, is the readily fissionable species that is commonly used in nuclear weapons. Another isotope, uranium-233, does not occur naturally, but it is also readily fissionable and it can be made artificially starting with thorium-232. Since only insignificant amounts of the element plutonium are found in nature, the fissionable isotope used in nuclear weapons, plutonium-239, is made artificially from uranium-238.

1.15 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 plutonium releases as much explosive energy as does the explosion of about 8,000 (short) tons of TNT.

1.16 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. Other fusion reactions are described in § 1-69.

1.17 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.

1.18 In certain fusion processes, between nuclei of the hydrogen isotopes, neutrons of high energy are liberated (see § 1.72). These can cause fission in the most abundant isotope (uranium-238) in ordinary uranium as well as in uranium-235 and plutonium239. 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. Such weapons might typically release about equal amounts of explosive energy from fission and from fusion.

1.19 A distinction has sometimes been 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 are both correctly described as nuclear 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.

1.1.3 Energy Yield Of A Nuclear Explosion

1.20 The "yield" of a nuclear weapon is a measure of the amount of explosive energy it can produce. It is the usual practice to state the yield in terms of the quantity of TNT that would generate the same amount of energy when it explodes. 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 were dropped over Japan in 1945 and used in the tests at Bikini in 1946, released very roughly the same quantity of energy as 20,000 tons (or 20 kilotons) of TNT (see, however, § 2.24). Since that time, much more powerful weapons, with energy yields in the megaton range, have been developed.

1.21 From the statement in § 1.15 that the fission of 1 pound of uranium or plutonium will release the same amount of explosive energy as about 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. The material that has not undergone fission remains in the weapon residues after the explosion.

1.1.4 Distribution of Energy In Nuclear Explosions

1.22 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 by a nuclear explosive is millions of times as great as that produced by a chemical explosive. Consequently, the temperatures reached in the former case are very 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.

1.23 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 radiation energy increases rapidly with in creasing 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 is released as thermal radiation. The manner in which this takes place is described later (§ 1.77 *et seq.*).

1.24 The fraction of the explosion energy received at a distance from the burst point in each of the forms depicted in Fig. 1.02 depends on the nature and yield of the weapon and particularly on the environment of the explosion. For a nuclear detonation in the atmosphere below an altitude of about 100,000 feet, from 35 to 45 percent of the explosion energy is received as thermal energy in the visible and infrared portions of the spectrum (see Fig. 1.74). In addition, below an altitude of about 40,000 feet, about 50 percent of the explosive energy is used in the production of air shock. At somewhat higher altitudes, where there is less air with which the energy of the exploding nuclear weapon can interact, the proportion of energy converted into shock is decreased whereas that emitted as thermal radiation is correspondingly increased (§ 1.36).

1.25 The exact distribution of energy between air shock and thermal radiation is related in a complex manner to the explosive energy yield, the burst altitude, and, to some extent, to the weapon design, as will be seen in this and later chapters. However, an approximate rule of thumb for a fission weapon exploded in the air at an altitude of less than about 40,000 feet is that 35 percent of the explosion energy is in the form of thermal radiation and 50 percent produces air shock. Thus, for a burst at moderately low altitudes, the air shock energy from a fission weapon will be about half of that from a conventional high explosive with the same total energy release; in the latter, essentially all of the explosive energy is in the form of air blast. This means that if a 20-kiloton fission weapon, for example, is exploded in the air below 40,000 feet or so, the energy used in the production of blast would be roughly equivalent to that from 10 kilotons of TNT.

1.26 Regardless of the height of burst, approximately 85 percent of the explosive energy of a nuclear fission weapon produces air blast (and shock), thermal radiation, and heat. The remaining 15 percent of the energy is released as various nuclear radiations. Of this, 5 percent constitutes the initial nuclear radiation, defined as that produced within a minute or so of the explosion (§ 2.42). The final 10 percent of the total fission energy represents that of the residual (or delayed) nuclear radiation which is emitted over a period of time. This is largely due 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 (§ 1.18), 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.

1.27 Because 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 § 1.20. 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. This common convention will be adhered to in subsequent chapters. For example, when the yield of a nuclear weapon is quoted or used in equations, figures, etc., it will represent that portion of the energy delivered within a minute or so, and will exclude the contribution of the residual nuclear radiation.

1.28 The initial nuclear radiation consists mainly of "gamma rays," which are electromagnetic radiations of high energy (see § 1.73) 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 at very high intensities which cause a tingling sensation, gamma rays and neutrons can produce harmful effects even at a distance from their source. Consequently, the initial nuclear radiation is an important aspect of nuclear explosions.

1.29 The delayed nuclear radiation arises mainly 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 electrons, i.e., particles carrying a negative electric charge, moving with high speed; they are formed by a change (neutron —» proton + electron) within the nuclei of the radioactive atoms. Beta particles, which are also invisible, are much less penetrating than gamma rays, but like the latter they represent a potential hazard.

1.30 The spontaneous emission of beta particles and gamma rays from radioactive substances, i.e., a radioactive nuclide (or radionuclide), 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 the radionuclide 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.

1.1.5 Types Of Nuclear Explosions

1.31 The immediate phenomena associated with a nuclear explosion, as well as the effects of shock and blast and of 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.

1.32 Provided the nuclear explosion takes place at an altitude where there is still an appreciable atmosphere, e.g., below about 100,000 feet, the weapon residues almost immediately 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 5,700 feet (1.1 mile) across at maximum brilliance. This means that, in this particular case, the explosion must occur at least 2,850 feet above the earth's surface if it is to be called an air burst.

1.33 The quantitative aspects of an air burst will be dependent upon its energy yield, but the general phenomena are much the same in all cases. Nearly all of the shock energy that leaves the fireball appears as air blast, although some is generally also transmitted into the ground. The thermal radiation will travel long distances through the air and may 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. For air bursts of higher energy yields, the corresponding distances will, of course, be greater. The thermal radiation is largely stopped by ordinary opaque materials; hence, buildings and clothing can provide protection.

1.34 The initial nuclear radiation 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 interactions with matter that result in the absorption of energy from gamma rays and from neutrons are quite different, as will be seen in Chapter VIII. Different materials are thus required for the most efficient removal of these radiations; but concrete, especially if it incorporates a heavy element, such as iron or barium, represents a reasonable practical compromise for reducing the intensities of both gamma rays and neutrons. A thickness of about 4 feet of ordinary concrete would probably provide adequate protection from the effects of the initial nuclear radiation for people at a distance of about 1 mile from an air burst of a 1-megaton nuclear weapon. However, at this distance the blast effect would be so great that only specially designed blast-resistant structures would survive.

1.35 In the event of a moderately high (or high) air burst, the fission products remaining after the nuclear explosion will be dispersed in the atmosphere. The residual nuclear radiation 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 things.

1.36 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 converted into blast and shock is less and decreases with increasing altitude. Two factors affect the thermal energy radiated at high altitude. First, since a shock wave does not form so readily in the less dense air, the fireball is able to radiate thermal energy that would, at lower altitudes, have been used in the production of air blast. Second, the less dense air allows energy from the exploding weapon to travel much farther than at lower altitudes. Some of this energy simply warms the air at a distance from the fireball and it does not contribute to the energy that can be radiated within a short time (§ 1.79). In general, the first of these factors is effective between 100,000 and 140,000 feet, and a larger proportion of the explosion energy is released in the form of thermal radiation than at lower altitudes. For explosions above about 140,000 feet, the second factor becomes the more important, and the fraction of the energy that appears as thermal radiation at the time of the explosion becomes smaller.

1.37 The fraction of the explosion energy emitted from a weapon as nuclear radiations is independent of the height of burst. However, the partition of that energy between gamma rays and neutrons received at a distance will vary since a significant fraction of the gamma rays result from interactions of neutrons with nitrogen atoms in the air at low altitudes. Furthermore, the attenuation of the initial nuclear radiation with in creasing 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 range on the earth's surface from a high-altitude detonation than from a moderately high air burst. In both cases the residual radiation from the fission products and other weapon residues will not be significant on the ground (§ 1-35).

1.38 Both the initial and the residual nuclear radiations from high-altitude bursts will interact with the constituents of the atmosphere to expel electrons from the atoms and molecules. Since the electron carries a negative electrical charge, the residual part of the atom (or molecule) 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.” The existence of large numbers of electrons and ions at high altitudes may have seriously degrading effects on the propagation of radio and radar signals (see Chapter X). The free electrons resulting from gamma-ray ionization of the air in a high-altitude explosion may also interact with the earth’s magnetic field to generate strong electromagnetic fields capable of causing damage to unprotected electrical or electronic equipment located in an extensive area below the burst. The phenomenon known as the “electromagnetic pulse” (or EMP) is described in Chapter XI. The EMP can also be produced in surface and low air bursts, but a much smaller area around the detonation point is affected.

1.39 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 radiation 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 generally be less than for an air burst. However, the residual nuclear radiation, i.e., the radiation emitted after the first minute, now becomes of considerable significance, since large quantities of earth or water in the vicinity of the explosion will be contaminated with radioactive fission products.

1.40 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.

1.41 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.

1.2 Scientific Basis Of Nuclear Explosions[2]

1.2.1 Fission Energy

1.42 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,

$$\text{neutron} + \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \rightarrow \text{fission fragments} + 2 \text{ or } 3 \text{ neutrons} + \text{ energy}$$

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 suffering fission, and the energy liberated, increasing at a tremendous rate, as will be seen shortly.

1.43 There are many different ways in which the nuclei of a given fissionable species can split up into two fission fragments (initial fission products), 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 1.43.

1.44 The results in the table may be taken as being approximately applicable to either uranium-233, uranium-235, or plutonium-239. These are the only three known substances, which are reason ably stable so that they can be stored without appreciable decay, that are capable of undergoing fission

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

Table 1.43: Distribution of fission energy

	MeV
Kinetic energy of fission fragments	166 ± 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	$10 \pm$
Total energy per fission	200 ± 6

by neutrons of all energies. Hence, they are the only materials that can by used to sustain a fission chain. Uranium-238, the most abundant isotope in natural uranium (§ 1.14), 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.

1.45 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, which is converted into other forms of energy within the exploding weapon, and also most of the neutron kinetic energy, 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 immediately 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. § 1.43) the results quoted in Table 1.45 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.[3]

1.2.2 Critical Mass For A Fission Chain

1.46 Although two to three neutrons are produced in the fission reaction for every nucleus that undergoes fission, not all of these neutrons are available

[3]The majority of the experimental and theoretical values of the explosive energy released by TNT range from 900 to 1,100 calories per gram. At one time, there was some uncertainty as to whether the term "kiloton" of TNT referred to a short kiloton (2×10^6 pounds), a metric kiloton (2.205×10^6 pounds), or a long kiloton (2.24×10^6 pounds). In order to avoid ambiguity, it was agreed that the term "kiloton" would refer to the release of 10^{12} calories of explosive energy. This is equivalent to 1 short kiloton of TNT if the energy release is $1,102$ calories per gram or to 1 long kiloton if the energy is 984 calories per gram of TNT.

for causing further fissions. Some of the fission neutrons are lost by escape, whereas others are lost in various nonfission reactions. In order to sustain a fission chain reaction, with continuous release of energy, at least one fission neutron must be available to cause further fission for each neutron previously absorbed in fission. 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 especially important to consider the neutrons which escape from the substance undergoing fission.

1.47 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 mass of the fissionable material, at constant density, 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. The same result can also be achieved by having a constant mass but compressing it to a smaller volume (higher density), so that the surface area is decreased.

1.48 The situation may be understood by reference to Fig. 1.48 showing two spherical masses, one larger than the other, of fissionable material of the same density. Fission is 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 arrow head 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. 1.48 that a much greater fraction of the neutrons is lost from the smaller than from the larger mass.

1.49 If the quantity of a fissionable isotope of uranium (or plutonium) is such that the ratio of the surface area to the mass 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. Such a quantity of material is said to be "subcritical." But as the mass of the piece of uranium (or plutonium) is increased (or the volume is decreased by compression) 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 under the existing conditions.

1.50 For a nuclear explosion to take place, the weapon must thus contain

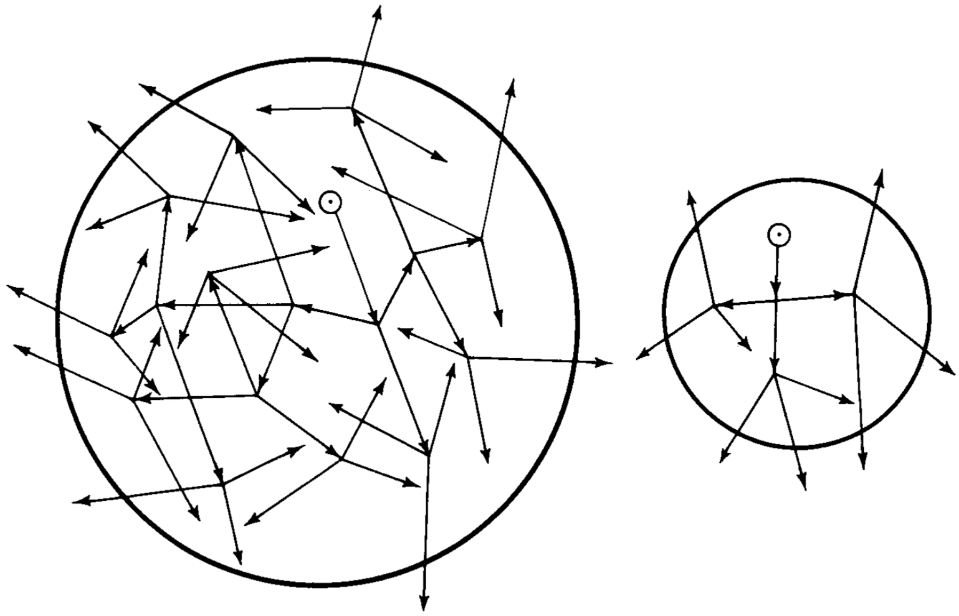

Figure 1.48: Effect of increased mass of fissionable material in reducing the proportion of neutrons lost by escape.

a sufficient amount of a fissionable uranium (or plutonium) isotope for the critical mass to be exceeded. Actually, the critical mass depends, among other things, on the shape of the material, its composition and density (or compression), 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.

1.2.3 Attainment Of Critical Mass For A Weapon

1.51 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 6f 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 subexplosive change in the configuration, such as by melting.

1.52 Two general methods have been described for bringing about a nuclear explosion, that is to say, for quickly converting a subcritical system into a supercritical one. In the first method, two or more pieces of fissionable material, each less than a critical mass, are brought together very rapidly in order to form one piece that exceeds the critical mass (Fig. 1.52). This may be achieved in some kind of gun-barrel device, in which an explosive propellant 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.

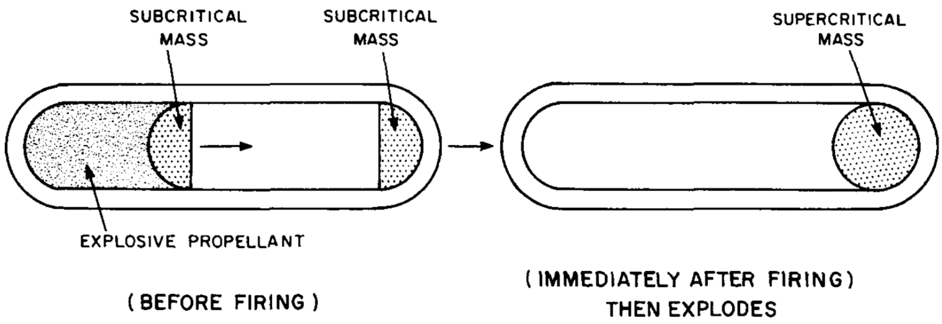

Figure 1.52: Principle of a gun-assembly nuclear device.

1.53 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 as indicated above. The compression may be achieved by means of a spherical arrangement of specially fabricated shapes (lenses) 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 lens system is set off, by means of a detonator on the outside of each lens, an inwardly-directed spherical "implosion" wave is produced. A similar wave can be realized without lenses by detonating a large number of points distributed over a spherical surface. When the implosion wave reaches the sphere of uranium (or plutonium), it causes the latter to be compressed and become supercritical (Fig. 1.53). The introduction of neutrons from a suitable source can then initiate a chain reaction leading to an explosion.

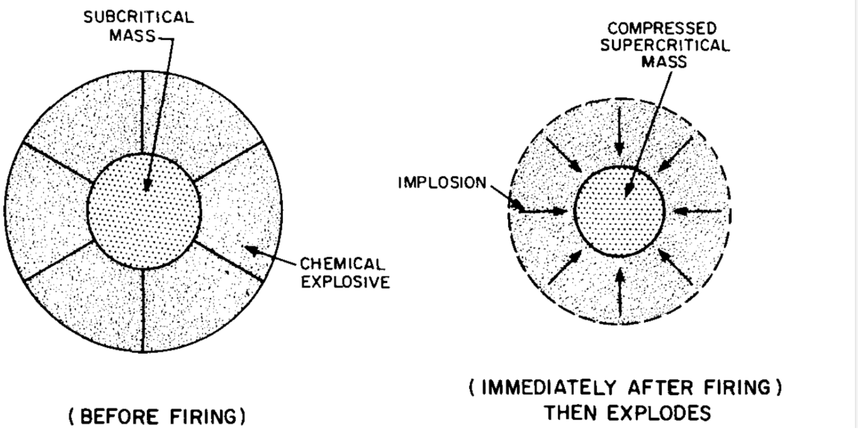

Figure 1.53: Principle of an implosion-type device.

1.2.4 Time Scale Of A Fission Explosion

1.54 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 10^{-8} of a second, i.e., 0.01 microsecond.[6]

1.55 It was mentioned earlier that not all the fission neutrons are available for maintaining the fission chain because some are lost by escape and by removal 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 thus 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;

[6]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.

hence, the increase in the number of neutrons per generation is $N(f-l)$ or $N(f-l-1)$. For convenience, the quantity $f-l-1$, that is, 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 Rate of neutron increase

$$dN/dt = Nx/g.$$

The solution of this equation is

$$N = N_0 e^{xt/g}.$$

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 f, and if this is represented by n, it follows that

$$N = N_0 e^{xn} \tag{1.55.1}$$

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

$$N = N_0 e^{xn}.$$

1.56 If the value of x is known, equation (1.55.1) 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 (1.55.1) may be written as

$$N \approx N_0 e^n \text{ or } N_0 10^{n/2.3}.$$

1.57 According to the data in Table 1.45, it would need $1.45x10^{22}$ 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 (1.56.1) that it would take approximately 51 generations to produce the necessary number of neutrons. Similarly, to release 100 kilotons of energy would require $1.45x10^{25}$ 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. Clearly, most of the fission energy is released in an extremely short time period. The same conclusion is reached for any value of the fission explosion energy.

1.58 In 50 generations or so, i.e., roughly half microsecond, after the initiation of the fission chain, so much energy will have been released—about 10^{11}

calories—that extremely high temperatures will be attained. Consequently, in spite of the restraining effect of the tamper (§ 1.50) 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 mass becomes subcritical and the self-sustaining chain reaction soon ends. An appreciable proportion of the fissionable material remains unchanged and some fissions will continue as a result of neutron capture, but the amount of energy released at this stage is relatively small.

1.59 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.

1.2.5 Fission Products

1.60 Many different, initial fission product nuclei, i.e., fission fragments, are formed when uranium or plutonium nuclei capture neutrons and suffer fission. There are 40 or so different ways in which the nuclei can split up when fission occurs; hence about 80 different fragments are produced. The nature and proportions of the fission fragment nuclei vary to some extent, 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 (§ 1.72), the products are somewhat different, especially in their relative amounts, from those formed from uranium-235 by ordinary fission neutrons.

1.61 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 (§ 1.29). 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.

1.62 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 four stages of radioactivity for each fission fragment before a stable (nonradioactive) nucleus is formed. Because of the large number of different ways in which fission can occur and the several stages of decay involved, the fission product mixture becomes very complex.[8] More than 300 different isotopes of 36 light elements, from zinc to terbium, have been identified among the fission products.

1.63 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 radionuclide (§ 1.30) involved. This is defined as the time required for the radioactivity of a given quantity of a particular nuclide to decrease (or decay) to half of its original value. Each individual radionuclide 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.

1.64 Although every radionuclide 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. 1.64. 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.

1.65 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 § 1.58, remains after the explosion. The fissionable uranium and plutonium isotopes 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.

1.66 Because of their greater mass and charge, alpha particles are much less penetrating than beta particles or gamma rays of the same energy. Thus, very few alpha particles from radioactive sources can travel more than 1 to 3 inches in air before being stopped. It is doubtful that these particles can get through the unbroken skin, and they certainly cannot penetrate

[8] The general term "fission products" is used to describe this complex mixture.

clothing. Consequently, the uranium (or plutonium) present in the weapon residues does not constitute a hazard if the latter are outside the body. However, if plutonium enters the body by ingestion, through skin abrasions, or particularly through inhalation, the effects may be serious.

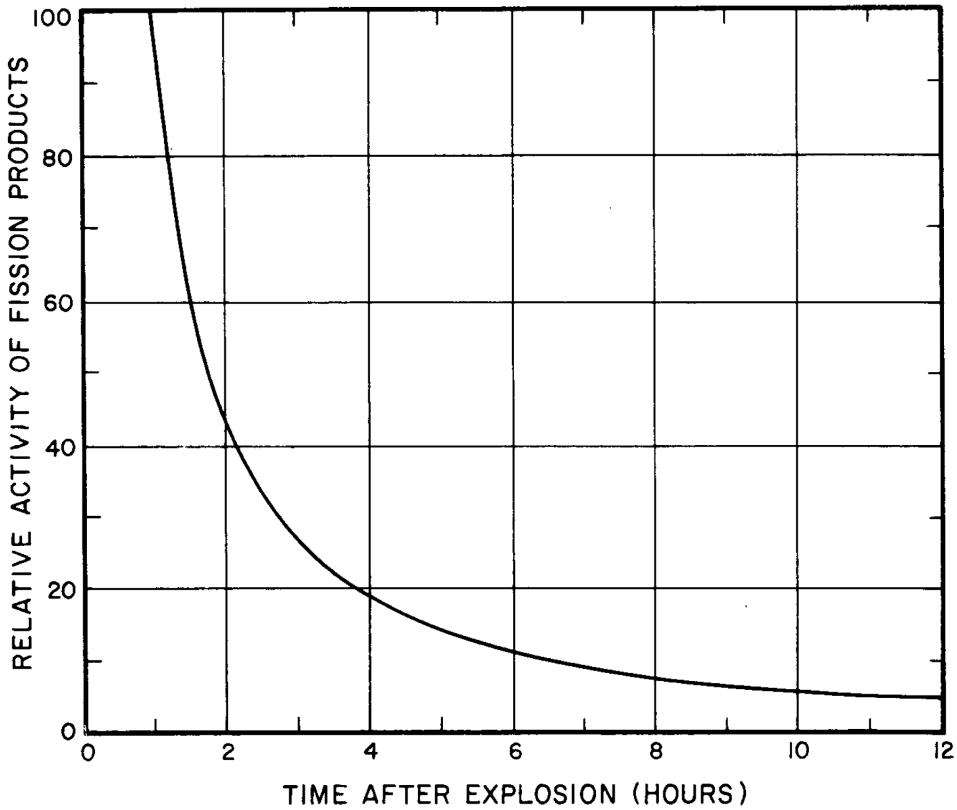

Figure 1.64: Rate of Decay of fission products after a nuclear explosion (activity is taken as 100 at 1 hour after the detonation).

1.2.6 Fusions (Thermonuclear) Reactions

1.67 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 charged-particle accelerators, 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 mass numbers (§ 1.10) of 1, 2, and 3, respectively. These are generally referred to as hydrogen (^{1}H), deuterium (^{2}H or D), and tritium (^{3}H or T). 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 (^{1}H) nuclei (or protons) contain no neutrons; deuterium (D) nuclei contain one neutron, and tritium (T) nuclei contain two neutrons.

1.68 Several different fusion reactions have been observed between 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 to raise the temperature to very high levels. In these circumstances the fusion processes are referred to as "thermonuclear reactions," as mentioned in § 1.17.

1.69 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:

$$\begin{aligned} \mathrm{D} + \mathrm{D} &= {}^{3}\mathrm{He} + n + 3.2\ \mathrm{MeV} \\ \mathrm{D} + \mathrm{D} &= \mathrm{D} + {}^{1}\mathrm{He} + 4.0\ \mathrm{MeV} \\ \mathrm{T} + \mathrm{D} &= {}^{4}\mathrm{He} + n + 17.6\ \mathrm{MeV} \\ \mathrm{T} + \mathrm{T} &= {}^{4}\mathrm{He} + 2n + 11.3\ \mathrm{MeV} \end{aligned}$$

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. The first two of these reactions occur with almost equal probability at the temperatures associated with nuclear explosions (several tens of million degrees Kelvin), whereas the third reaction has a much higher probability and the fourth a much lower probability. Thus, a valid comparison of the energy released in fusion reactions with that produced in fission can be made by noting 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 (§ 1.43). Weight for weight, therefore, the fusion of deuterium nuclei would produce nearly three times as much energy as the fission of uranium or plutonium.

1.70 Another reaction of thermonuclear weapons interest, with tritium as a product, is

$${}^{6}\mathrm{Li} + n \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{T} + 4.8\ \mathrm{MeV}$$

where ^{6}Li represents the lithium-6 isotope, which makes up about 7.4 percent of natural lithium. Other reactions can occur with lithium-6 or the more abundant isotope lithium-7 and various particles produced in the weapon. However, the reaction shown above is of most interest for two reasons: (1) it has a high probability of occurrence and (2) if the lithium is placed in the weapon in the form of the compound lithium deuteride (LiD), the tritium formed in the reaction has a high probability of interacting with the deuterium. Large amounts of energy are thus released by the third reaction in § 1.69, and additional neutrons are produced to react with lithium-6.

1.71 In order to make the nuclear fusion reactions take place at the required rate, temperatures of the order of several tens of 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 lithium deuteride (or a mixture of deuterium and tritium) 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.

1.72 It will be observed that in three of the fusion reactions given in § 1.69, 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 radiation arising from the fission products. On the average, the energy released in the explosion of a thermonuclear weapon originates in roughly equal amounts from fission and fusion processes, although there may be variations in individual cases. In "boosted" fission weapons, thermonuclear neutrons serve to enhance the fission process; energy released in the thermonuclear reaction is then a small fraction of the total energy yield.

1.2.7 Thermal Radiation

1.73 The observed phenomena associated with a nuclear explosion and the effects on people and materials are largely determined 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 wavelength (or very high frequency) gamma rays (§ 1.28) and X rays, through the invisible ultraviolet to the visible region, and then to the infrared and radar and radio waves of relatively long wavelength (and low frequency).

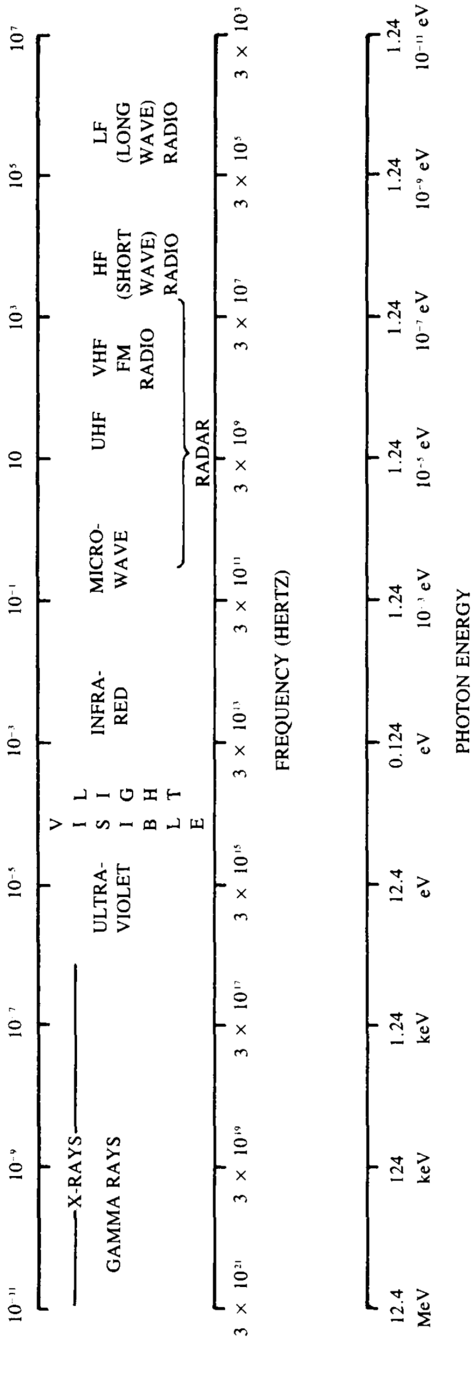

Figure 1.74: Wavelengths, frequencies, and photon energies of electromagnetic radiations.

1.74 The approximate wavelength and frequency regions occupied by the different kinds of electromagnetic radiations are indicated in Fig. 1.74. The wavelength λ in centimeters and the frequency ν in hertz, i.e., in waves (or cycles) per second, are related by $\lambda\nu = c$, where c is the velocity of light, $3.00x10^{10}$ 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

$$E \text{ (ergs)} = h\nu = \frac{hc}{\lambda} = \frac{1.99 \times 10^{-16}}{\lambda \text{ (cm)}} \qquad (1.740.1)$$

where h is a universal constant equal to $6.62x10^{-27}$ erg-second. The energy quantum values for the various electromagnetic radiations are included in Fig. 1.74; 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 (1.74.1) by writing it in the form

$$E \text{ (MeV)} = \frac{1.24 \times 10^{-10}}{\lambda \text{ (cm)}} \qquad (1.740.1)$$

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

1.75 The (thermal) radiation energy density for matter in temperature equilibrium is given by

$$E \text{ (radiation)} = 7.6 \times 7.6 \times 10^{-15} T^4 \text{ ergs/cm}^3,$$

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/cm^3, compared with roughly 10^8 ergs/cm^3 for the material energy, i.e., kinetic energy and internal (electronic, vibrational, and rotational) energy. Hence, as indicated in § 1.23, 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/cm^3, whereas the material energy is in the range of 10^{14} to 10^{15} ergs/cm^3. It has been estimated that in a nuclear explosion some 80 percent of the total energy may be present initially as thermal radiation energy.

1.76 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 spectrum (Fig. 1.74). At the temperatures of a nuclear explosion, however, not only is the radiation energy emitted very rapidly, but most of this energy is in the spectral region with wavelengths shorter than the ultraviolet.

1.77 When a nuclear weapon explodes, temperature equilibrium is rapidly established in the residual material. Within about one microsecond after the explosion, some 70 to 80 percent of the explosion energy, as defined in § 1.27, is emitted as primary thermal radiation, most of which consists of soft X rays.[12] Almost all of the rest of the energy is in the form of kinetic energy of the weapon debris at this time. The interaction of the primary thermal radiation and the debris particles with the surroundings will vary with the altitude of burst and will determine the ultimate partition of energy between the thermal radiation received at a distance and shock.

1.78 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 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 reradiated at a lower temperature from the fireball and the remainder is converted into shock (or blast) energy (see Chapter II). This explains why only about 35 to 45 percent of the fission energy from an air burst is received as thermal radiation energy at a distance, although the primary thermal radiation may constitute as much as 70 to 80 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 wavelengths (lower photon energies), i.e., ultraviolet, visible, and infrared[14] (see Chapter VII).

1.79 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 (and mass) that most of the atoms and molecules 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 reradiated 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. These matters are treated more fully in Chapter II.

[12] X rays are frequently distinguished as "hard" or "soft." The latter have longer wavelengths 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.

[14] 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.

1.3 Bibliography

Omitted

2

Descriptions of Nuclear Explosions

2.1 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, high-altitude, air, surface, underwater, or underground, 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 few weapons with roughly 20 to 30 kilotons of TNT energy in shallow and moderately deep, and 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 altitude will be included. In addition, some of the characteristic phenomena associated with underwater and underground nuclear explosions will be described.

2.2 Description Of Air And Surface Bursts

2.2.1 The Fireball

2.03 As already seen, the fission of uranium (or plutonium) or the fusion of the isotopes of hydrogen 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 (§ 1.78). This leads to the formation of an extremely hot and highly luminous (incandescent) spherical mass of air and gaseous weapon residues which is the fireball referred to in § 1.32; 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 in the atmosphere 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, was 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 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 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 5,700 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.

2.2.2 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 bring 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 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. The circulation entrains more air through the bottom of the toroid, thereby cooling the cloud and dissipating the energy contained in the fireball. As a result, the toroidal motion slows and may stop completely as the cloud rises toward its maximum height.

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 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 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. For 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 residues 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 5 miles in about a minute. The average rate of rise during the first minute or so is nearly 300 miles per hour (440 feet per second). These values should be regarded as rough averages only, and large deviations may be expected in different circumstances (see also Figs. 10.158a, b, c).

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 amount of heat generated the greater will 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 troposphere.[1]

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.

[1]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 (§ 9.128).

2.15 The cloud attains its maximum 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 19,000 feet with the base at about 10,000 feet; the horizontal extent would also be roughly 10,000 feet. For an explosion in the megaton range, however, the horizontal dimensions are greater than the total height (cf. Fig. 2.16).height after about 10 minutes and is then said to be "stabilized." It continues to grow laterally, however, to produce the characteristic mushroom shape (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 land surface or low air bursts, 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 is 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 19,000 feet with the base at about 10,000 feet; the horizontal extent would also be roughly 10,000 feet. For an explosion in the megaton range, however, the horizontal dimensions are greater than the total height (cf. Fig. 2.16).

2.2.3 Characteristics Of A Surface Burst

2.18 Since many of the phenomena and effects of a nuclear explosion occurring on or near the earth's surface are similar to those associated with an air burst, it is convenient before proceeding further to refer to some of the special characteristics of a surface burst. In such a burst, the fireball in its rapid initial growth, abuts (or touches) the surface of the earth (Fig. 2.18a).

Because of the intense heat, some of the rock, soil, and other material in the area is vaporized and taken into the fireball. Additional material is melted, either completely or on its surface, and the strong afterwinds 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 consists 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 When the fireball touches the earth's surface, a crater is formed as a result of the vaporization of dirt and other material and the removal of soil, etc., by the blast wave and winds accompanying the explosion. 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 a water surface, large amounts of water are vaporized and carried up into the radioactive cloud. When the cloud reaches high altitudes the vapor condenses to form water droplets, similar to those in an ordinary atmospheric cloud.

2.2.4 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 the radioactive fission products and other weapon residues,3 but as a general rule the contamination is found mainly in a thin shell near the surface of the particles (§ 9.50). 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 descend to earth. This phenomenon is referred to as "fallout," and the same name is applied to the particles themselves when they reach the ground. 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 radiation referred to in the preceding chapter.

2.24 The extent and nature of the fallout can range between wide extremes. The actual situation is 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 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 (height of burst 1670 feet, yield about 12.5 kilotons) and Nagasaki (height of burst 1640 feet, yield about 22 kilotons) injuries 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. From the 15-megaton thermonuclear device tested at Bikini Atoll on March 1, 1954— the BRAVO shot of Operation CASTLE— the 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 350 miles downwind. The width in the crosswind direction was variable, the maximum being over 60 miles (§ 9.104).

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. Furthermore, variations in the winds, from the time of burst until the particles reach the ground, perhaps several hours later, affect the fallout pattern following a nuclear explosion (see Chapter IX).

2.27 It should be understood that 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 micrometers4 *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 (0.4 inch) in diameter, and even larger close to the burst point.

2.28 Particles in this size range arrive 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 is established within about 24 hours after the burst. This is referred to as “early” fallout, 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” (or “worldwide”) 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 early 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 arises 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.

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 (other than thundershowers) generally originate from atmospheric clouds whose tops are between about 10,000 and 30,000 feet altitude, it is only below this region that scavenging by rain is likely to take place. Another effect that rain may have if it occurs either during or after the deposition of the fallout is to wash radioactive debris over the surface of the ground. This may result in cleansing some areas and reducing their activity while causing hot spots in other (lower) areas.

2.2.5 The Fallout

2.32 At a fraction of a second after a nuclear 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 considered 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 (5,700 feet across), the shock front is some 3 miles farther 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 and the energy of the explosion, the direct and reflected wave fronts merge. This merging phenomenon is called the "Mach effect." The "overpressure," i.e., the pressure in excess of the normal atmospheric value, at the front of the Mach wave is generally about twice as great as that at the direct 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.[2] The overpressure on the ground at the blast wave front at this time is about 20 pounds per square inch, so that the total air pressure is more than double the normal atmospheric pressure.[3]

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 (100 feet) 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

[2]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." The term "surface zero" or "surface ground zero" is also commonly used for ground surface and underground explosions. In some publications, ground (or surface) zero is called the "hypocenter" of the explosion.

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

no detectable Mach effect. (The TRINITY test, conducted on July 16, 1945 near Alamogordo, New Mexico, was the first test of a nuclear (implosion) weapon; the yield was estimated to be about 19 kilotons.)

2.37 Strong transient winds are 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 velocities 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.

2.2.6 Thermal Radiation From An Air Burst

2.38 Immediately after the explosion, the weapon residues emit the primary thermal radiation (§ 1.77). Because of the very high temperature, 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 (secondary) thermal radiation of longer wavelength, consisting of ultraviolet, visible, and infrared rays. Because of certain phenomena occurring in the fireball (see § 2.106 *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. 2.123). 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 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 (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 1megaton 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.

2.2.7 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, consisting 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 20kiloton 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 § 1.69. 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.

2.2.8 The Electromagnetic Pulse

2.46 If a detonation occurs at or near the earth's surface, the EMP phenomenon referred to in § 1.38 produces intense electric and magnetic fields which may extend to distances up to several miles, depending on the weapon yield. The close-in region near the burst point is highly ionized and large electric currents flow in the air and the ground, producing a pulse of electromagnetic radiation. Beyond this close-in region the electromagnetic field strength, as measured on (or near) the ground, drops sharply and then more slowly with increasing distance from the explosion. The intense fields may damage unprotected electrical and electronic equipment at distances exceeding those at which significant air blast damage may occur, especially for weapons of low yield (see Chapter XI).

2.2.9 Other Nuclear Explosion Phenomena

2.47 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 the various radiations on the nitrogen and oxygen of the air.

2.48 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.

2.49 The condensation cloud which was observed in the ABLE Test at Bikini in 1946 is shown in Fig. 2.49. 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 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 farther away, as is apparent in Fig. 2.49, where the disk-like formation on the surface of the water indicates the passage of the shock wave.

2.50 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. 2.50, and then disappeared.

2.51 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.

2.3 Description Of High Altitude Bursts

2.3.1 Introduction

2.52 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. Additional high-altitude nuclear tests were conducted during the FISHBOWL test series in 1962. 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 48 miles. The second, called ORANGE, was exploded at an altitude of 141,000 feet, i.e., nearly 27 miles, on August 12, 1958 (GCT). During the FISHBOWL series, a megaton and three submegaton devices were detonated at high altitudes in the vicinity of Johnston Island. The STARFISH PRIME device, with a yield of 1.4 megatons, was exploded at an altitude of about 248 miles on July 9, 1962 (GCT). The three submegaton devices, CHECKMATE, BLUEGILL TRIPLE PRIME, and KINGFISH, were detonated at altitudes of tens of miles on October 20, 1962, October 26, 1962, and November 1, 1962 (GCT), respectively.

2.53 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 (§ 2.145). The operation consisted of three high-altitude nuclear detonations, each having a yield from 1 to 2 kilotons TNT equivalent. The burst altitudes were from about 125 to 300 miles.

2.3.2 High Altitude Burst Phenomena

2.54 If a burst occurs in the altitude regime of roughly 10 to 50 miles, the explosion energy radiated as X rays will be deposited in the burst region, although over a much larger volume of air than at lower altitudes. In this manner, the ORANGE shot created a large fireball almost spherical in shape. In general, the fireball behavior was in agreement with the expected interactions of the various radiations and kinetic energy of the expanding weapon debris with the ambient air (§ 2.130 *et seq.*).

2.55 The mechanism of fireball formation changes appreciably at still higher burst altitude, since the X rays are able to penetrate to greater distances in the low-density air. Starting at an explosion altitude of about 50 miles, the interaction of the weapon debris energy with the atmosphere becomes the dominant mechanism for producing a fireball. Because the debris is highly ionized (§ 1.38), the earth's magnetic field, i.e., the geomagnetic field, will influence the location and distribution of the late-time fireball from bursts above about 50 miles altitude.

2.56 The TEAK explosion was accompanied by a sharp and bright flash of light which was visible above the horizon from Hawaii, over 700 miles away. Because of the long range of the X rays in the low-density atmosphere in the immediate vicinity of the burst, the fireball grew very rapidly in size. In 0.3 second, its diameter was already 11 miles and it increased to 18 miles in 3.5 seconds. The fireball also 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, arising apparently from electronically excited oxygen atoms produced by a shock wave passing 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 (line-of-sight) visible from Hawaii. 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 The formation and growth of the fireball changes even more drastically as the explosion altitude increases above 65 miles. Because X rays can penetrate the low-density atmosphere to great distances before being absorbed, there is no local fireball. Below about 190 miles (depending on weapon yield), the energy initially appearing as the rapid outward motion of debris particles will still be deposited relatively locally, resulting in a highly heated and ionized region. The geomagnetic field plays an increasingly important role in controlling debris motion as the detonation altitude increases. Above about 200 miles, where the air density is very low, the geomagnetic field is the dominant factor in slowing the expansion of the ionized debris across the field lines. Upward and downward motion along the field lines, however, is not greatly affected (§ 10.64). When the debris is stopped by the atmosphere, at about 75 miles altitude, it may heat and ionize the air sufficiently to cause a visible region which will subsequently rise and expand. Such a phenomenon was observed following the STARFISH PRIME event.

2.59 A special feature of explosions at altitudes between about 20 and 50 miles is the extreme brightness of the fireball. It is visible at distances of several hundred miles and is capable of producing injury to the eyes over large areas (§ 12.79 *et seq.*).

2.60 Additional important effects that result from high-altitude bursts are the widespread ionization and other disturbances of the portion of the upper atmosphere known as the ionosphere. These disturbances affect the propagation of radio and radar waves, sometimes over extended areas (see ChapterX). Following the TEAK event, propagation of high-frequency (HF) radio communications (Table 10.91) was degraded over a region of several thousand miles in diameter for a period lasting from shortly after midnight until sunrise. Some very-high-frequency (VHF) communications circuits in the Pacific area were unable to function for about 30 seconds after the STARFISH PRIME event.

2.61 Detonations above about 19 miles can produce EMP effects (§ 2.46) on the ground over large areas, increasing with the yield of the explosion and the height of burst. For fairly large yields and burst heights, the EMP fields may be significant at nearly all points within the line of sight, i.e., to the horizon, from the burst point. Although these fields are weaker than those in the close-in region surrounding a surface burst, they are of sufficient magnitude to damage some unprotected electrical and electronic equipment. The mechanism of formation and the effects of the EMP are treated in Chapter XI.

2.62 An interesting visible effect of high-altitude nuclear explosions is the creation of an "artificial aurora." Within a second or two after burst time of the TEAK shot a brilliant aurora appeared from the bottom of the fireball and purple streamers were seen to spread toward the north. Less than a second later, 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. 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. Similar auroral effects were observed after the other high-altitude explosions mentioned in § 2.52.

2.4 Description Of Underwater Bursts

2.4.1 Shallow Underwater Explosion Phenomena

2.63 Certain characteristic phenomena are associated with an underwater nuclear explosion, but the details vary 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 July 1946. In this test, a nuclear weapon of approximately 20kilotons yield 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.

2.64 In an underwater nuclear detonation, a fireball is formed, but it is smaller than for 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.

2.65 In the course of its rapid expansion, the hot gas bubble, while still underwater, initiates a shock wave. Intersection of the shock wave with the surface produces an effect which, viewed from above, appears to be a rapidly expanding ring of darkened water. This is often called the "slick" because of its resemblance to an oil slick. Following closely behind the dark region is a white circular patch called the "crack," probably caused by reflection of the water shock wave at the surface.

2.66 Immediately after the appearance of the crack, and prior to the formation of the Wilson cloud (§ 2.48), a mound or column of broken water and spray, called the "spray dome," is thrown up over the point of burst (Fig. 2.66). This dome is caused by the velocity imparted to the water near the surface by the reflection of the shock wave and to the subsequent breakup of the surface layer into drops of spray, The initial upward velocity of the water is proportional to the pressure of the direct shock wave, and so it is greatest directly above the detonation point. Consequently, the water in the center rises more rapidly (and for a longer time) than water farther away. As a result, the sides of the spray dome become steeper as the water rises. The upward motion is terminated by the downward pull of gravity and the resistance of the air. The total time of rise and the maximum height depend upon the energy of the explosion, and upon its depth below the water surface. Additional slick, crack, and spray-dome phenomena may result if the shock wave reflected from the water bottom and compression waves produced by the gas bubble (§ 2.86 *et seq.*) reach the surface with sufficient intensity.

2.67 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. 2.67a). 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. 2.67b.)

2.68 In the shallow underwater (BAKER) burst at Bikini, the spray dome began to form at about 4 milli seconds 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 ecause the upper part was surrounded by the radioactive cloud (Fig. 2.68). 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.

2.69 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 ultimately 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.

2.70 The disturbance created by the underwater burst caused a series of waves to move outward from the center of the explosion across the surface of Bikini lagoon. At 11 seconds after the detonation, the first wave had a maximum height of 94 feet and was about 1.000 feet from surface zero. This moved outward at high speed and was followed by a series of other waves. At 22.000 feet from surface zero, the ninth wave in the series was the highest with a height of 6 feet.

2.71 It has been observed that certain underwater and water 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 the approaching wave makes with the shoreline.

2.4.2 The Visible Base Surge

2.72 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. 2.68). This doughnut-shaped cloud, moving rapidly outward from the column, is called the "base surge." It is essentially a dense cloud of small 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.

2.73 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 $3\frac{1}{2}$ 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. 2.73).

2.74 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. 2.74). 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.

2.75 In the few instances in which base surge formation has been observed over water, the visible configuration has been quite irregular. Nevertheless, to a good approximation, the base surge can be represented as a hollow cylinder with the inner diameter about two-thirds of the outer diameter. The heights of the visible base surge clouds have generally ranged between 1,000 and 2,000 feet.

2.76 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 (§ 2.77) 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.

2.4.3 Radioactive Base Surge

2.77 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 hazard for a distance of several miles, especially in the downwind direction. 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 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.

2.78 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 as several such possibly concentric clouds that approximate a low-lying disc with no hole in the center. The latter shape is more probable for deeper bursts. 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.

2.79 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 is determined by the location of the burst and the depth of the water, and perhaps also by the nature of the bottom material. Although 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.

2.4.4 Thermal And Nuclear Radiations In Underwater Burst

2.80 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 people and as a source of fire are concerned.

2.81 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 radioactive residues present in the column, cloud, and base surge, all three of which are formed within a few seconds of the burst, will contribute to the initial effects.

2.82 However, the water fallout (or rainout) from the cloud and the base surge are also responsible for the residual nuclear radiation, 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.

2.4.5 Deep Underwater Explosion Phenomena

2.83 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. The following discussion is based largely on observations made at the WAHOO shot in 1958, when a nuclear weapon was detonated at a depth of 500 feet in deep water. The generation of large-scale water waves in deep underwater bursts will be considered in Chapter VI.

2.84 The spray dome formed by the WAHOO explosion rose to a height of 900 feet above the surface of the water (Fig. 2.84a). Shortly after the maximum height was attained, the hot gas and steam bubble burst through the dome, throwing out a plume with jets in all directions; the highest jets reached an elevation of 1,700 feet (Fig. 2.84b). There was no airborne radioactive cloud, such as was observed in the shallow underwater BAKER shot. The collapse of the plume created a visible base surge extending out to a distance of over 2% miles downwind and reaching a maximum height of about 1,000 feet (Fig. 2.84c). 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.

2.85 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 while moving in the downwind direction. However, very little radioactivity was found on the surface of the water.

2.86 The hot gas bubble formed by a deep underwater nuclear explosion rises through the water and continues to expand at a decreasing rate until a maximum size is reached. If it is not too near the surface or the bottom at this time, the bubble remains nearly spherical. As a result of the outward momentum of the water surrounding the bubble, the latter actually overexpands; that is to say, when it attains its maximum size its contents are at a pressure well below the ambient water pressure. The higher pressure outside the bubble then causes it to contract, resulting in an increase of the pressure within the bubble and condensation of some of the steam. Since the hydrostatic (water) pressure is larger at the bottom of the bubble than at the top, the bubble does not remain spherical during the contraction phase. The bottom moves upward faster than the top (which may even remain stationary) and reaches the top to form a toroidal bubble as viewed from above. This causes turbulence and mixing of the bubble contents with the surrounding water.

2.87 The momentum of the water set in motion by contraction of the bubble causes it to overcontract, and its internal pressure once more becomes higher than the ambient water pressure. A second compression (shock) wave in the water commences after the bubble reaches its minimum volume. This compression wave has a lower peak overpressure but a longer duration than the initial shock wave in the water. A second cycle of bubble expansion and contraction then begins.

2.88 If the detonation occurs far enough below the surface, as in the WIGWAM test in 1955 at a depth of about 2,000 feet, the bubble continues to pulsate and rise, although after three complete cycles enough steam will have condensed to make additional pulsations unlikely. During the pulsation and up ward motion of the bubble, the water surrounding the bubble acquires considerable upward momentum and eventually breaks through the surface with a high velocity, e.g., 200 miles per hour in the WIGWAM event, thereby creating a large plume. If water surface breakthrough occurs while the bubble pressure is below ambient, a phenomenon called “blowin” occurs. The plume is then likely to resemble a vertical column which may break up into jets that disintegrate into spray as they travel through the air.

2.89 The activity levels of the radioactive base surge will be affected by the phase of the bubble when it breaks through the water surface. Hence, these levels may be expected to vary widely, and although the initial radiation intensities may be very high, their duration is expected to be short.

2.5 Description Of Underground Bursts

2.5.1 Shallow Underground Explosion Phenomena

2.90 For the present purpose, a shallow underground explosion may be regarded as one which produces a substantial crater resulting from the throwout of earth and rock. There is an optimum depth of burst, dependent on the energy yield of the detonation and the nature of the rock medium, which gives a crater of maximum size. The mechanism of the formation of such throwout (or excavation) craters will be considered here. For shallower depths of burst, the behavior approaches that of a surface burst (§ 2.18, 6.03 *et seq.*), whereas for explosions at greater depths the phenomena tend toward those of a deep underground detonation (§ 2.101 *et seq.*).

2.91 When a nuclear weapon is exploded under the ground, a sphere of extremely hot, high-pressure gases, including vaporized weapon residues and rock, is formed. This is the equivalent of the fireball in an air or surface burst. The rapid expansion of the gas bubble initiates a ground shock wave which travels in all directions away from the burst point. When the upwardly directed shock (compression) wave reaches the earth's surface, it is reflected back as a rarefaction (or tension) wave. If the tension exceeds the tensile strength of the surface material, the upper layers of the ground will spall, i.e., split off into more-or-less horizontal layers. Then, as a result of the momentum imparted by the incident shock wave, these layers move upward at a speed which may be about 150 (or more) feet per second.

2.92 When it is reflected back from the surface, the rarefaction wave travels into the ground toward the expanding gas sphere (or cavity) produced by the explosion. If the detonation is not at too great a depth, this wave may reach the top of the cavity while it is still growing. The resistance of the ground to the upward growth of the cavity is thus decreased and the cavity expands rapidly in the upward direction. The expanding gases and vapors can thus supply additional energy to the spalled layers, so that their upward motion is sustained for a time or even increased. This effect is referred to as "gas acceleration."

2.93 The ground surface moving upward first assumes the shape of a dome. As the dome continues to increase in height, cracks form through which the cavity gases vent to the atmosphere. The mound then disintegrates completely and the rock fragments are thrown upward and outward (Fig. 2.93). Subsequently, much of the ejected material collapses and falls back, partly into the newly formed crater and partly onto the surrounding "lip." The material that falls back immediately into the crater is called the "fallback," whereas that descending on the lip is called the "ejecta." The size of the remaining (or "apparent") crater depends on the energy yield of the detonation and on the nature of the excavated medium. In general, for equivalent conditions, the volume of the crater is roughly proportional to the yield of the explosion.

2.94 The relative extents to which spalling and gas acceleration contribute to the formation of a throwout crater depend to large extent on the moisture content of the rock medium. In rock containing a moderately large proportion of water, the cavity pressure is greatly increased by the presence of water vapor. Gas acceleration then plays an important role in crater formation. In dry rock, however, the contribution of gas acceleration to the upward motion of the ground is generally small and may be unobservable.

2.95 As in an underwater burst, part of the energy released by the weapon in a shallow underground explosion appears as an air blast wave. The fraction of the energy imparted to the air in the form of blast depends primarily on the depth of burst for the given total energy yield. The greater the depth of burst, the smaller, in general, will be the proportion of shock energy that escapes into the air. For a sufficiently deep explosion, there is, of course, no blast wave.

2.5.2 Base Surge From Main Cloud

2.96 When the fallback from a shallow underground detonation descends to the ground, it entrains air and fine dust particles which are carried downward. The dust-laden air upon reaching the ground moves outward as a result of its momentum and density, thereby producing a base surge, similar to that observed in shallow underwater explosions. 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 depends upon the depth of burst, the nature of the soil, and the atmospheric conditions, as well as upon the energy yield of the explosion. A dry sandy terrain would be particularly conducive to base surge formation in an underground burst.

2.97 Throwout crater formation is apparently always accompanied by a base surge. If gas acceleration occurs, however, a cloud consisting of particles of various sizes and the hot gases escaping from the explosion cavity generally also forms and rises to a height of thousands of feet. This is usually referred to as the "main cloud," to distinguish it from the base surge cloud. The latter surrounds the base of the main cloud and spreads out initially to a greater distance. The main cloud and base surge formed in the SEDAN test (100 kilotons yield, depth of burial 635 feet in alluvium containing 7 percent of water) are shown in the photograph in Fig. 2.97, taken six minutes after the explosion.

2.98 Both the base surge and the main cloud are contaminated with radioactivity, and the particles present contribute to the fallout. The larger pieces are the first to reach the earth and so they are deposited near the location of the burst. But the smaller particles remain suspended in the air some time and may be carried great distances by the wind before they eventually settle out.

2.5.3 Thermal And Nuclear Radiations in Underground Bursts

2.99 The situations as regards ther mal and nuclear radiations from an un derground burst are quite similar to those described above in connection with an underwater explosion. As a general rule, the thermal radiation is almost completely absorbed by the ground material, so that it does not rep resent a significant hazard. Most of the neutrons and early gamma rays are also removed, although the capture of the neutrons may cause a considerable amount of induced radioactivity in various materials present in the soil (§ 9.35). This will constitute a small part of the residual nuclear radiation, of im portance 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. 2.100 For the reasons given in § 2.82 for an underwater burst, the initial and residual radiations from an under ground burst tend to merge into one another. The distinction which is made in the case of air and surface bursts is consequently less significant in a sub surface explosion.

2.5.4 Deep Underground Explosion Phenomena

2.101 A deep underground explosion is one occurring at such a depth that the effects are essentially fully contained. The surface above the detonation point may be disturbed, e.g., by the formation of a shallow subsidence crater or a mound, and ground tremors may be detected at a distance. There is no significant venting of the weapon residues to the atmosphere, although some of the noncondensable gases present may seep out gradually through the surface. The United States has conducted many deep underground tests, especially since September 1961. Almost all of the explosion energy has been contained in the ground, and, except in the few cases of accidental venting or seepage of a small fraction of the residues, the radioactivity from these explosions has also been confined. The phenomena of deep underground detonations can be described best in terms of four phases having markedly different time scales.

2.102 First, the explosion energy is released in less than one-millionth part of a second, i.e., less than one microsecond (§ 1.54 footnote). As a result, the pressure in the hot gas bubble formed will rise to several million atmospheres and the temperature will reach about a million degrees within a few microseconds. In the second (hydrodynamic) stage, which generally is of a few tenths of a second duration, the high pressure of the hot gases initiates a strong shock wave which breaks away and expands in all directions with a velocity equal to or greater than the speed of sound in the rock medium. During the hydrodynamic phase, the hot gases continue to expand, although more slowly than initially, and form a cavity of substantial size. At the end of this phase the cavity will have attained its maximum diameter and its walls will be lined with molten rock. The shock wave will have reached a distance of some hundreds of feet ahead of the cavity and it will have crushed or fractured much of the rock in the region it has traversed. The shock wave will continue to expand and decrease in strength eventually becoming the "head" (or leading) wave of a train of seismic waves (§ 6.19). During the third stage, the cavity will cool and the molten rock material will collect and solidify at the bottom of the cavity.

2.103 Finally, the gas pressure in the cavity decreases to the point when it can no longer support the overburden. Then, in a matter of seconds to hours, the roof falls in and this is followed by progressive collapse of the overlying rocks. A tall cylinder, commonly referred to as a "chimney," filled with broken rock or rubble is thus formed (Fig. 2.103). If the top of the chimney does not reach the ground surface, an empty space, roughly equivalent to the cavity volume, will remain at the top of the chimney. However, if the collapse of the chimney material should reach the surface, the ground will sink into to the empty space thereby forming a subsidence crater (see Fig. 6.06f). The collapse of the roof and the formation of the chimney represented the fourth (and last) phase of the underground explosion.

2.104 The effects of the RAINIER event of Operation Plumbbob in 1957 will provide an example of the extent to which the surrounding medium may be affected by a deep underground detonation. RAINIER was a 1.7-kiloton nuclear device detonated in a chamber $6 \times 6 \times 7$ feet in size, at a depth of 790 feet below the surface in a compacted volcanic-ash medium referred to geologically as "tuff." During the hydrodynamic stage the chamber expanded to form a spherical cavity 62 feet in radius, which was lined with molten rock about 4 inches thick. The shock from the explosion crushed the surrounding medium to a radius of 130 feet and fractured it to 180 feet. Seismic signals were detected out to distances of several hundred miles and a weak signal was recorded in Alaska. The chimney extended upward for about 400 feet from the burst point. Further information on cavity and chimney dimensions is given in Chapter VI.

2.105 Deep underground nuclear detonations, especially those of high yield, are followed by a number of minor seismic tremors called "aftershocks," the term that is used to describe the secondary tremors that generally occur after the main shock of a large earthquake. In tests made in Nevada and on Amchitka Island in the Aleutians, the aftershocks have not constituted a danger to people or to structures off the test sites. No correlation has been found between underground nuclear detonations and the occurrence of natural earthquakes in the vicinity (§ 6.24 *et seq.*).

2.6 Scientific Aspects Of Nuclear Explosion Phenomena[4]

2.6.1 Introduction

2.106 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

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

detonation that account for the different types of response associated with air, high-altitude, surface, and subsurface bursts, as described earlier in this chapter.

2.107 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 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, thus causing ionization, 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 (ionized) 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 times 10^7 degrees, most of the energy emitted within a microsecond or so is in the soft X-ray region (§ 1.77, see also § 7.75).

2.108 The primary thermal radiation leaving the exploding weapon is absorbed by the atoms and molecules of the surrounding medium. The medium is thus heated and the resulting fireball re-radiates part of its energy as the secondary thermal radiation of longer wavelengths (§ 2.38). The remainder of the energy contributes to the shock wave formed in the surrounding medium. Ultimately, essentially all the thermal radiation (and shock wave energy) is absorbed and appears as heat, although it may be spread over a large volume. In a dense medium such as earth or water, the degradation and absorption occur within a short distance from the explosion, but in air both the shock wave and the thermal radiation may travel considerable distances. The actual behavior depends on the air density, as will be seen later.

2.109 It is apparent that the kinetic energy of the fission fragments, constituting some 85 percent of the total energy released, will distribute itself between thermal radiation, on the one hand, and shock and blast, on the other hand, in proportions determined largely by the nature of the ambient medium. The higher the density of the latter, the greater the extent of the coupling between it and the energy from 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, there is no true fireball and the kinetic energy of the fission fragments is dissipated over a very large volume. In any event, the form and amount in which the thermal radiation is received at a distance from the explosion will depend on the nature of the intervening medium.

2.6.2 Development Of A Fireball In An Air Burst

2.110 As seen above, most of the initial (or primary) thermal radiation from a nuclear explosion is in the soft X-ray region of the spectrum. If the burst occurs in the lower part of the atmosphere where the air density is appreciable, the X rays are absorbed in the immediate vicinity of the burst, and they heat the air to high temperatures. This sphere of hot air is sometimes referred to as the "X-ray fireball." The volume of air involved, resultant air temperatures, and ensuing behavior of this fireball are all determined by the burst conditions. At moderate and low altitudes (below about 100,000 feet), the X rays are aborbed within some yards of the burst point, and the relatively small volume of air involved is heated to a very high temperature.

2.111 The energies (or wavelengths) of the X rays, as determined by the temperature of the weapon debris, cover a wide range (§ 7.73 *et seq.*), and a small proportion of the photons (§ 1.74) have energies considerably in excess of the average. These high-energy photons are not easily absorbed and so they move ahead of the fireball front. As a result of interaction with the atmospheric molecules, the X rays so alter the chemistry and radiation absorption properties of the air that, in the air burst at low and moderate altitudes, a veil of opaque air is generated that obscures the early growth of the fireball. Several microseconds elapse before the fireball front emerges from the opaque X-ray veil.

2.112 The X-ray fireball grows in size as a result of the transfer of radiation from the very hot interior where the explosion has occurred to the cooler exterior. During this "radiative growth" phase, most of the energy transfer in the hot gas takes place in the following manner. First, an atom, molecule, ion, or electron absorbs a photon of radiation and is thereby converted into an excited state. The atom or other particle remains in this state for a short time and then emits a photon, usually of lower energy. The residual energy is retained by the particle either as kinetic energy or as internal energy. The emitted photon moves off in a random direction with the velocity of light, and it may then be absorbed once again to form another excited particle. The latter will then re-emit a photon, and so on. The radiation energy is thus transmitted from one point to another within the gas; at the same time, the average photon energy (and radiation frequency) decreases. The energy lost by the photons serves largely to heat the gas through which the photons travel.

2.113 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 fireball will occur more rapidly than if the mean free path is short. 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 in the hot gas.

2.114 In the radiative growth phase, the photon mean free paths in the hot fireball are of the order of (or longer than) the fireball diameter because at the very high temperatures the photons are not readily absorbed. As a result, the energy distribution and temperature are fairly uniform throughout the volume of hot gas. The fireball at this stage is consequently referred to as the "isothermal sphere." The name is something of a misnomer, since temperature gradients do exist, particularly near the advancing radiation front.

2.115 As the fireball cools, the transfer of energy by radiation and radiative growth become less rapid because of the decreasing mean free path of the photons. When the average temperature of the isothermal sphere has dropped to about 300,000°C, the expansion velocity will have decreased to a value comparable to the local acoustic (sound) velocity. At this point, a shock wave develops at the fireball front and the subsequent growth of the fireball is dominated by the shock and associated hydrodynamic expansion. The phenomenon of shock formation is sometimes called "hydrodynamic separation." For a 20-kiloton burst it occurs at about a tenth of a millisecond after the explosion when the fireball radius is roughly 40 feet.

2.116 At very early times, beginning in less than a microsecond, an "inner" shock wave forms driven by the expanding bomb debris. This shock expands outward within the isothermal sphere at a velocity exceeding the local acoustic velocity. The inner shock overtakes and merges with the outer shock at the fireball front shortly after hydrodynamic separation. The relative importance of the debris shock wave depends on the ratio of the yield to the mass of the exploding device and on the altitude of the explosion (§ 2.136). The debris shock front is a strong source of ultraviolet radiation, and for weapons of small yield-to-mass ratio it may replace the X-ray fireball as the dominant energy source for the radiative growth.

2.117 As the (combined) shock front from a normal air burst 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 luminous shell thus formed constitutes the advancing visible fireball during this "hydrodynamic phase" of fireball growth. The fireball now consists of two concentric regions. The inner (hotter) region is the isothermal sphere of uniform temperature, and it is surrounded by a layer of luminous, shock-heated air at a somewhat lower, but still high, temperature. Because hot (over 8,000°C) air is effectively opaque to visible radiation, the isothermal sphere is not visible through the outer shocked air.

2.118 Some of the phenomena described above are represented schematically in Fig. 2.118; qualitative temperature profiles are shown at the left and pressure profiles at the right of a series of photographs of the fireball at various intervals after the detonation of a 20kiloton 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.

2.119 From the shapes of the curves at the right of Fig. 2.118 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.

2.120 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 15 milliseconds (0.015 second) after the detonation of a 20-kiloton weapon, for example, is referred to as the "breakaway."

2.6.3 Temperature Of The Fireball

2.121 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 Figure 2.121. 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.

2.122 As indicated earlier, the interior temperature of the fireball decreases steadily, but the apparent surface temperature, which influences the emission of thermal radiation, decreases to a minimum and then increases to a maximum before the final steady decline. 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.

2.123 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. 2.123, for a 20-kiloton explosion. But 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.

2.124 Provided the temperature of the air at the shock front is sufficiently high, the isothermal sphere is invisible (§ 2.117). 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 3,000°C (5,400°F) 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 (§ 2.120).

2.125 As a result of this unmasking of the isothermal sphere, the apparent surface temperature (or brightness) of the fireball increases (Fig. 2.123), after passing through the temperature minimum of about 3,000°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 brightness 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; energy is then 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 by the emission of radiation and mixing with air. It is during the second pulse that the major part of the thermal radiation is emitted in an air burst (§ 2.38 *et seq.*). In such a burst, the rate of emission of radiation is greatest when the surface temperature is at the maximum.

2.126 The curves in Figs. 2.121 and 2.123 apply to a 20-kiloton nuclear burst, but similar results are obtained for explosions of other energy yields. The minimum temperature of the radiating surface and the subsequent temperature maximum are essentially independent of the yield of the explosion. But the times at which these temperatures occur for an air burst increase approximately as the 0.4 power of the yield (Chapter VII). The time of breakaway is generally very soon after the thermal minimum is attained.

2.6.4 Size Of The Fireball

2.127 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 the same yield. The relationship between the average radius and the yield is then given approximately by

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

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

$$R \text{ (at breakaway) for air burst } \approx 110W^{0.4} \tag{2.127.1}$$

For a contact surface burst, i.e., in which the exploding weapon is actually on the surface,[5] blast wave energy is reflected back from the surface into the fireball (§ 3.34) and W in equation (2.127.1) should probably be replaced by 2 W, where W is the actual yield. Hence, for a contact surface burst, R (at breakaway) for contact surface burst

$$R \text{ (at breakaway) for contact surface burst } \approx 145W^{0.4} \tag{2.127.2}$$

For surface bursts in the transition range between air bursts and contact bursts, the radius of the fireball at breakaway is somewhere between the

[5]For most purposes, a contact surface burst may be defined as one for which the burst point is not more than $5W^{0.3}$ feet above or below the surface.

values given by equations (2.127.1) and (2.127.2). 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. 2.121).

2.128 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

$$H \text{ (maximum at local fallout)t } \approx 180W^{0.4} \qquad (2.128.1)$$

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. 2.128. For an explosion of 1,000 kilotons, i.e., 1 megaton yield, it can be found from Fig. 2.128 or equation (2.128.1) 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 (2.128.1) there will definitely be no local fallout. The amount, if any, maybe expected, however, to be small enough to be tolerable under emergency conditions.

2.129 Other aspects of fireball size are determined by the conditions under which the fireball rises. If the fireball is small compared with an atmospheric scale height, which is about 4.3 miles at altitudes of interest (§ 10.123), the late fireball rise is caused by buoyant forces similar to those acting on a bubble rising in shallow water. This is called "buoyant" rise. The fireball is then essentially in pressure equilibrium with the surrounding air as it rises. If the initial fireball radius is comparable to or greater than a scale height, the atmospheric pressure on the bottom of (he fireball is much larger than the pressure on the top. This causes a very rapid acceleration of the fireball, referred to as "ballistic" rise. The rise velocity becomes so great compared to the expansion rate that the fireball ascends almost like a solid projectile. "Overshoot" then occurs, in which a parcel of dense air is carried to high altitudes where the ambient air has a lower density. The dense "bubble" will subsequently expand, thereby decreasing its density, and will fall back until it is in a region of comparable density.

2.6.5 High Altitude Bursts

2.130 For nuclear detonations at heights up to about 100,000 feet (19 miles), the distribution of explosion energy between thermal radiation and blast varies only to a small extent with yield and detonation altitude (§ 1.24). But at burst altitudes above 100,000 feet, the distribution begins to change more noticeably with increasing height of burst (see Chapter VII). 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. There is a progressive decline in the blast energy with increasing height of burst above 100,000 feet, but the proportion of the explosion energy received as effective thermal radiation on the ground at first increases only slightly with altitude. Subsequently, as the burst altitude increases, the effective thermal radiation received on the ground decreases and becomes less than at an equal distance from an air burst of the same total yield (§ 7.102).

2.131 For nuclear explosions at altitudes between 100,000 and about 270,000 feet (51 miles) the fireball phenomena are affected by the low density of the air. 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 heat and into radiations of longer wavelength (smaller photon energy). The volume of the atmosphere in which the energy of the radiation is deposited, over a period of a millisecond or so, may extend for several miles, the dimensions increasing with the burst altitude. The interaction of the air molecules with the prompt gamma rays, neutrons, and high-energy component of the X rays produces a strong flash of fluorescence radiation (§ 2.140), but there is less tendency for the X-ray veil to form than in an air burst (§ 2.111).

2.132 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. The outer shock wave (§ 2.116) is slow to form and radiative expansion predominates in the growth of the fireball. The air at the shock front does not become hot enough to be opaque at times sufficiently early to mask the radiation front and the fireball radiates most of its energy very rapidly. There is no apparent temperature minimum as is the case for 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 of fairly short duration. In the absence of the obscuring opaque shock front, the fireball surface is visible throughout the period of radiative growth and the temperature is higher than for a low-altitude fireball. Both of these effects contribute to the increase in the thermal radiation emission.

2.133 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. 2.133. In a low (or moderately low) air burst, the thermal radiation is emitted in two pulses, but in a high-altitude burst there is only a single pulse in which most of the radiation is emitted in a relatively short time. Furthermore, the thermal pulse from a high-altitude explosion is richer in ultraviolet radiation than is the main (second) pulse from an air burst. The reason is that formation of ozone, oxides of nitrogen, and nitrous acid (§ 2.123), which absorb strongly in this spectral region, is decreased.

2.134 For burst altitudes above about 270,000 feet, there is virtually no absorption of the X rays emitted in upward directions. The downward directed X rays are mostly absorbed in a layer of air, called the "X-ray pancake," which becomes incandescent as a result of energy deposition. The so-called pancake is more like the frustum of a cone, pointing upward, with a thickness of roughly 30,000 feet (or more) and a mean altitude of around 270,000 feet; the radius at this altitude is approximately equal to the height of burst minus 270,000 feet. The height and dimensions of the pancake are determined largely by the emission temperature for the primary X rays, which depends on the weapon yield and design, but the values given here are regarded as being reasonable averages. Because of the very large volume and mass of air in the X-ray pancake, the temperatures reached in the layer are much lower than those in the fireballs from bursts in the normal atmosphere. Various excited atoms and ions are formed and the radiations of lower energy (longer wavelength) re-emitted by these species represent the thermal radiation observed at a distance.

2.135 For heights of burst up to about 270,000 feet, the early fireball is approximately spherical, although at the higher altitudes it begins to elongate vertically. The weapon debris and the incandescent air heated by the X rays roughly coincide. Above 270,000 feet, however, the debris tends to be separate from the X-ray pancake. The debris can rise to great altitudes, depending on the explosion yield and the burst height; its behavior and ionization effects are described in detail in Chapter X. The incandescent (X-ray pancake) region, on the other hand, remains at an essentially constant altitude regardless of the height of burst. From this region the thermal radiation is emitted as a single pulse containing a substantially smaller proportion of the total explosion energy but of somewhat longer duration than for detonations below roughly 270,000 feet (see § 7.89 *et seq.*).

2.136 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 by the weapon debris (§ 2.116), at least for bursts up to about 400,000 feet (75 miles) altitude. For example, disturbance of the ionosphere in the vicinity of Hawaii after the TEAK shot (at 252,000 feet altitude) 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 shock wave. Soon after excitation, the excess energy was emitted as visible radiation toward the red end of the spectrum (6,300 and 6,364 A).

2.137 For bursts above about 400,000 feet, the earth's magnetic field plays an increasingly important role in controlling weapon debris motion, and it becomes the dominant factor for explosions above 200 miles or so (Chapter X). At these altitudes, the shock waves are probably magnetohydrodynamic (rather than purely hydrodynamic) in character. The amount of primary thermal radiation produced by these shock waves is quite small.

2.6.6 Air Fluorescence Phenomena

2.138 Various transient fluorescent effects, that is, the emission of visible and ultraviolet radiations for very short periods of time, accompany nuclear explosions in the atmosphere and at high altitudes. These effects arise from electronic excitation (and ionization) of atoms and molecules in the air resulting from interactions with high-energy X rays from the fireball, or with gamma rays, neutrons, beta particles, or other charged particles of sufficient energy. The excess energy of the excited atoms, molecules, and ions is then rapidly emitted as fluorescence radiation.

2.139 In a conventional air burst, i.e., at an altitude below about 100,000 feet, the first brief fluorescence that can be detected, within a microsecond or so of the explosion time, is called the "Teller light." The excited particles are produced initially by the prompt (or instantaneous) gamma rays that accompany the fission process and in the later stages by the interaction of fast neutrons with nuclei in the air (§ 8.53).

2.140 For bursts above 100,000 feet, the gamma rays and neutrons tend to be absorbed, with an emission of fluorescence, in a region at an altitude of about 15 miles (80,000 feet), since at higher altitudes the mean free paths in the low-density air are too long for appreciable local absorption (§ 10.29). The fluorescence is emitted over a relatively long period of time because of time-of-flight delays resulting from the distances traveled by the photons and neutrons before they are absorbed. An appreciable fraction of the high-energy X rays escaping from the explosion region are deposited outside the fireball and also produce fluorescence. The relative importance of the X-ray fluorescence increases with the altitude of the burst point.

2.141 High-energy beta particles associated with bursts at sufficiently high altitudes can also cause air fluorescence. For explosions above about 40 miles, the beta particles emitted by the weapon residues in the downward direction are absorbed in the air roughly at this altitude, their outward spread being restricted by the geomagnetic field lines (§ 10.63 *et seq.*). A region of air fluorescence, called a "beta patch," may then be formed. If the burst is at a sufficiently high altitude, the weapon debris ions can themselves produce fluorescence. A fraction of these ions can be channeled by the geomagnetic field to an altitude of about 70 miles where they are stopped by the atmosphere (§ 10.29) and cause the air to fluoresce. Under suitable conditions, as will be explained below, fluorescence due to beta particles and debris ions can also appear in the atmosphere in the opposite hemisphere of earth to the one in which the nuclear explosion occurred.

2.6.7 Auroral Phenomena

2.142 The auroral phenomena associated with high-altitude explosions (§ 2.62) are caused by the beta particles emitted by the radioactive weapon residues and, to a varying extent, by the debris ions. Interaction of these charged particles with the atmosphere produces excited molecules, atoms, and ions which emit their excess energy in the form of visible radiations characteristic of natural auroras. In this respect, there is a resemblance to the production of the air fluorescence described above. However, auroras are produced by charged particles of lower energy and they persist for a much longer time, namely, several minutes compared with fractions of a second for air fluorescence. Furthermore, the radiations have somewhat different wavelength characteristics since they are emitted, as a general rule, by a different distribution of excited species.

2.143 The geomagnetic field exerts forces on charged particles, i.e., beta particles (electrons) and debris ions, so that these particles are constrained to travel in helical (spiral) paths along the field lines. Since the earth behaves like a magnetic dipole, and has north and south poles, the field lines reach the earth at two points, called "conjugate points," one north of the magnetic equator and the other south of it. Hence, the charged particles spiraling about the geomagnetic field lines will enter the atmosphere in corresponding conjugate regions. It is in these regions that the auroras may be expected to form (Fig. 2.143).

2.144 For the high-altitude tests conducted in 1958 and 1962 in the vicinity of Johnston Island (§ 2.52), the charged particles entered the atmosphere in the northern hemisphere between Johnston Island and the main Hawaiian Islands, whereas the conjugate region in the southern hemisphere region was in the vicinity of the Samoan, Fiji, and Tonga Islands. It is in these areas that auroras were actually observed, in addition to those in the areas of the nuclear explosions.

2.145 Because the beta particles have high velocities, the beta auroras in the remote (southern) hemisphere appeared within a fraction of a second of those in the hemisphere where the burst had occurred. The debris ions, however, travel more slowly and so the debris aurora in the remote hemisphere, if it is formed, appears at a somewhat later time. The beta auroras are generally most intense at an altitude of 30 to 60 miles, whereas the intensity of the debris auroras is greatest in the 60 to 125 miles range. Remote conjugate beta auroras can occur if the detonation is above 25 miles, whereas debris auroras appear only if the detonation altitude is in excess of some 200 miles.

2.6.8 The Argus Effect

2.146 For bursts at sufficiently high altitudes, the debris ions, moving along the earth's magnetic field lines, 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 which spiral about the geomagnetic lines of force. When the particles enter a region where the strength of the earth's magnetic field increases significantly, as it does in the vicinity of the conjugate points, some of the beta particles are turned back (or reflected). Consequently, they may travel back and forth, from one conjugate region to the other, a number of times before they are eventually captured in the atmosphere. (More will be said in Chapter X about the interactions of the geomagnetic field with the charged particles and radiations produced by a nuclear explosion.)

2.147 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. Within a few hours after a high altitude nuclear detonation, the beta particles form a shell completely around the earth. In the ARGUS experiment (§ 2.53), in which the bursts occurred at altitudes of 125 to 300 miles, well defined shells of about 60 miles thickness, with measurable electron densities, were established and remained for several days. This has become known as the "ARGUS effect." Similar phenomena were observed after the STARFISH PRIME (§ 2.52) and other high-altitude nuclear explosions.

2.6.9 Effect On The Ozone Layer

2.148 Ozone (03) is formed in the upper atmosphere, mainly in the stratosphere (see Fig. 9.126) in the altitude range of approximately 50,000 to 100,000 feet (roughly 10 to 20 miles), by the action of solar radiation on molecular oxygen (02). The accumulation of ozone is limited by its decomposition, partly by the absorption of solar ultraviolet radiation in the wavelength range from about 2,100 to 3,000 A and partly by chemical reaction with traces of nitrogen oxides (and other chemical species) present in the atmosphere. The chemical decomposition occurs by way of a complex series of chain reactions whereby small quantities of nitrogen oxides can cause considerable breakdown of the ozone. The equilibrium (or steady-state) concentration of ozone at any time represents a balance between the rates of formation and decomposition; hence, it is significantly dependent on the amount of nitrogen oxides present. Solar radiation is, of course, another determining factor; the normal concentration of ozone varies, consequently, with the latitude, season of the year, time of day, the stage in the solar (sunspot) cycle, and perhaps with other factors not yet defined.

2.149 Although the equilibrium amount in the atmosphere is small, rarely exceeding 10 parts by weight per million parts of air, ozone has an important bearing on life on earth. If it were not for the absorption of much of the solar ultraviolet radiation by the ozone, life as currently known could not exist except possibly in the ocean. A significant reduction in the ozone concentration, e.g., as a result of an increase in the amount of nitrogen oxides, would be expected to cause an increased incidence of skin cancer and to have adverse effects on plant and animal life.

2.150 As seen in § 2.08 and 2.123, nuclear explosions are accompanied by the formation of oxides of nitrogen. An air burst, for example, is estimated to produce about 1032 molecules of nitrogen oxides per megaton TNT equivalent. For nuclear explosions of intermediate and moderately high yield in the air or near the surface, the cloud reaches into the altitude range of 50,000 to 100,000 feet (Fig. 2.16); hence, the nitrogen oxides from such explosions would be expected to enhance mechanisms which tend to decrease the ozone concentration. Routine monitoring of the atmosphere during and following periods of major nuclear testing have shown no significant change in the ozone concentration in the sense of marked, long-lasting perturbations. However, the large natural variations in the ozone layer and uncertainties in the measurements do not allow an unambiguous conclusion to be reached. Theoretical calculations indicate that extensive use of nuclear weapons in warfare could cause a substantial decrease in the atmospheric ozone concentration, accompanied by an increase in adverse biological effects due to ultraviolet radiation. The ozone layer should eventually recover, but this might take up to 25 years.

2.7 Bibliography

omitted

3

Air Blast Phenomena In Air And Surface Bursts

3.1 Characteristics Of The Blast Wave in Air

3.01 Most of the material damage caused by a nuclear explosion at the surface or at a low or moderate altitude in the air is due—directly or indirectly—to the shock (or blast) wave which accompanies the explosion. Many 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 primarily on the energy yield (§ 1.20) 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. 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 stated in Chapter II, the expansion of the intensely hot gases at extremely high pressures in the fireball causes a shock wave to form, 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 (§ 2.120), pressures at the shock front are two or three times as large as the already very high pressures in the interior of the fireball.

3.04 As the blast wave travels in the air away from its source, the overpressure at the front steadily decreases, and

3.1.1 Development Of The Blast Wave

3.1.2 The Dynamic Pressure

3.1.3 Changes In The Blast Wave With Time

3.2 Reflection Of Blast Wave At A Surface

3.2.1 Incident And Reflected Waves

3.2.2 Height Of Burst And Blast Damage

3.2.3 Contact Surface Burst

3.3 Reflection Of Blast Wave At A Surface

3.3.1 Terrain Effects

3.3.2 Meteorological Conditions

3.3.3 Effect Of Altitude

3.3.4 Surface Effects

3.3.5 Ground Shock From Air Blast

3.4 Technical Aspects Of Blast Wave Phenomena

3.4.1 Properties Of The Ideal Blast Wave

3.53 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 mainly 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.

3.54 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 (merged) wave, as stated in § 3.34, 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.

3.55 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

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

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, p, of the air behind the shock front is related to the ambient density, p_0, by

$$\begin{aligned} \frac{p}{\rho_0} &= \frac{2\gamma P_0 + (\gamma + 1)\, p}{2\gamma P_0 + (\gamma - 1)\, p} \\ &= \frac{7 + 6p/P_0}{7 + p/P_0} \end{aligned}$$

The dynamic pressure, q, is defined by

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

so that it is actually the kinetic energy per unit volume of air immediately behind the shock front; this quantity has the same dimensions as pressure.

Introduction of the Rankine-Hugoniot equations for p and u given above leads to the relation

$$\begin{aligned} q &= \frac{p^2}{2\gamma P_0 + (\gamma - 1)p} \\ &= \frac{5}{2} \cdot \frac{p^2}{7P_0 + p} \end{aligned} \tag{3.55.1}$$

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. 3.55.

3.56 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

$$p_r = 2p + (\gamma + 1)q. \tag{3.56.1}$$

Upon using equation (3.55.1) for air, this becomes

$$p_r = 2p\frac{7P_0 + 4p}{7P_0 + p}. \tag{3.56.2}$$

It can be seen from equation (3.56.2) 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 (3.56.1) 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 on a flat surface, is included in Fig. 3.55.

3.57 The equations in § 3.55 give the peak values of the various blast parameters at the shock front. The variation of the overpressure at a given point with time after its arrival at that point has been obtained by numerical integration of the equations of motion and the results are represented in Fig. 3.57. In these curves the "normalized" overpressure, defined by $p(t)/p$, where $p(t)$ is the overpressure at time t after the arrival of the shock front and p is the peak overpressure, is given as a function of the "normalized" time, t/t_p^+, where t_p^+ is the duration of the overpressure positive phase. The parameter indicated on each curve is the peak overpressure to which that curve refers. It is seen, therefore, that the variation of the normalized (and actual) overpressure with time depends on the peak overpressure. Values of t_p^+ for various burst conditions are given in Fig. 3.76.

3.58 Similarly, the variation of the normalized dynamic pressure, $q(t)/q$, with the normalized time, t/t_q^+, where t_q^+ is the duration of the dynamic pressure positive phase, depends on the peak value of the dynamic pressure. This is shown by the curves in Fig. 3.58 for several indicated values of the peak dynamic pressure; values of t_q^+ required for use with this figure will be found in Fig. 3.76. It should be noted that, since the duration of the dynamic pressure positive phase is somewhat longer than that for the overpressure, i.e., t_q^+ is longer than t_p^+. Figs. 3.57 and 3.58 do not have a common time base.

3.59 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 area) may be defined as the total area under the curve for the variation of overpressure with time. The positive phase overpressure impulse (per unit area), I_p^+, may then be represented mathematically by

$$I_p^+ = \int_0^{t_p^+} p(t)dt.$$

where $p(t)$ is obtained from Fig. 3.57 for any overpressure between 3 and 3,000 psi. The positive phase dynamic impulse is defined by a similar expression in which $q(t)$ and t_q^+ replace $p(t)$ and t_p^+, respectively.

3.4.2 Scaling Laws

3.60 In order 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.

3.61 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

$$\frac{D}{D_1} = \left(\frac{W}{W_1}\right)^{1/3} \tag{3.61.1}$$

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 (3.61.1) that

$$D = D_1 \times W^{1/3} \tag{3.61.2}$$

where D_1, refers to the slant range 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 range, D, can be evaluated from equation (3.61.2).

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

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

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

$$d = d_1 \times W^{1/3} \tag{3.61.2}$$

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).[1]

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

$$\frac{t}{t_1} = \frac{d}{d_1} = \left(\frac{W}{W_1}\right)^{1/3}$$

and

$$\frac{I}{I_1} = \frac{d}{d_1} = \left(\frac{W}{W_1}\right)^{1/3}$$

where t_1, represents arrival time or positive phase duration and I_1, is the positive phase 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

[1] The symbol d used for the distance from ground zero, whereas D refers to the slant range, i.e., the distance from the actual burst.

ground zero. If W_1 is taken as 1 kiloton, then the various quantities are related as follows:

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

and

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

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

3.4.3 Altitude Corrections

3.64 The data presented (§ 3.55 *et seq.*) for the characteristic properties of a blast wave are strictly applicable to a homogeneous (or uniform) atmosphere at sea level. At altitudes below about 5,000 feet, the temperatures and pressures in the atmosphere do not change very much from the sea-level values. Consequently, up to this altitude, it is a reasonably good approximation to treat the atmosphere as being homogeneous with sea-level properties. The equations given above may thus be used without correction if the burst and target are both at altitudes up to 5,000 feet. If it is required to determine the air blast parameters at altitudes where the ambient conditions are appreciably different from those at sea level, appropriate correction factors must be applied.

3.65 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

$$p = p_1 \frac{P}{P_0}. \tag{3.65.1}$$

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

$$d = d_1 W^{1/3} \left(\frac{P_0}{P}\right)^{1/3} \tag{3.65.2}$$

A similar expression is applicable to the slant range, D. The arrival time of positive phase duration at this new distance is

$$t = t_1 W^{1/3} \left(\frac{P_0}{P}\right)^{1/3} \left(\frac{T_0}{T}\right)^{1/3}. \tag{3.65.3}$$

The factor $(T_0/T)^{1/2}$ appears in this expression because the speed of sound is proportional to the square root of the absolute temperature. For impulse at altitude, the appropriate relationship is

$$I = I_1 W^{1/3} \left(\frac{p}{P_0}\right)^{1/3} \left(\frac{T_0}{T}\right)^{1/3}. \tag{3.65.4}$$

The foregoing equations are applicable when the target and burst point are at roughly the same altitude. If the altitude difference is less than a few thousand feet, the temperature and pressure at a mean altitude may be used. But if the altitude difference is considerable, a good approximation is to apply the correction at the target altitude (§ 3.46). For bursts above about 40,000 feet, an allowance must be made for changes in the explosion energy partition (§ 3.67.)

3.66 In order to facilitate calculations based on the equations in the preceding paragraph, the following factors have been defined and tabulated (Table 3.66):

$$S_p = \frac{P}{P_0}$$
$$S_d = \left(\frac{P_0}{P}\right)^{1/3} \qquad (3.55.1)$$
$$S_t = \left(\frac{P}{P_0}\right)^{1/3} \left(\frac{T_0}{T}\right)^{1/3}$$

so that

$$p = p_1 S_p \qquad (3.66.1)$$
$$D = D_1 W^{1/3} S_d \text{ and}$$
$$d = d_1 W^{1/3} S_p. \qquad (3.66.1)$$
$$t = t_1 W^{1/3} S_p \qquad (3.66.1)$$
$$I = I_1 W^{1/3} S_p S_t. \qquad (3.66.4)$$

The reference values P_0 and T_0) are for a standard sea-level atmosphere. The atmospheric pressure 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. In a strictly homogeneous atmosphere the altitude scaling factors S_p, S_d, and S_t would all be unity and equations (3.66.1), etc., would reduce to those in § 3.65. Below an altitude of about 5,000 feet the scaling factors do not differ greatly from unity and the approximation of a homogeneous (sea-level) atmosphere is not seriously in error, as mentioned above.

3.67 The correction factors § 3.66 are applicable for burst altitudes up to about 40,000 feet (about 7.6 miles). Nearly all of the energy from nuclear explosions below this altitude is absorbed by air molecules near the burst. Deviations from the scaling laws described in the preceding paragraphs are caused principally by differences in the partitioning of the energy components when the burst occurs above 40,000 feet. At such altitudes, part of the energy that would have contributed to the blast wave at lower altitudes is emitted as thermal radiation.

3.68 To allow for the smaller fraction of the yield that appears as blast energy at higher altitudes, the actual yield is multiplied by a “blast efficiency

Table 3.66: Average Atmospheric Data for Mid-Latitudes

Altitude (feet)	Temperature (degrees Kelvin)	Pressure (psi)	Altitude Scaling Factors			Speed of Sound (ft/sec)
			S_p	S_d	S_t	
0	288	14.70	1.00	1.00	1.00	1,116
1,000	286	14.18	0.96	1.01	1.01	1,113
2,000	284	13.67	0.93	1.02	1.03	1,109
3,000	282	13.17	0.90	1.04	1.04	1,105
4,000	280	12.70	0.86	1.05	1.06	1,101
5,000	278	12.23	0.83	1.06	1.08	1,097
10,000	268	10.11	0.69	1.13	1.16	1,077
15,000	258	8.30	0.56	1.21	1.26	1,057
20,000	249	6.76	0.46	1.30	1.36	1,037
25,000	239	5.46	0.37	1.39	1.48	1,016
30,000	229	4.37	0.30	1.50	1.62	995
35,000	219	3.47	0.24	1.62	1.77	973
40,000	217	2.73	0.19	1.75	1.93	968
45,000	217	2.15	0.15	1.90	2.09	968
50,000	217	1.70	0.11	2.06	2.26	968
55,000	217	1.33	0.090	2.23	2.45	968
60,000	217	1.05	0.071	2.41	2.65	968
65,000	217	0.83	0.056	2.61	2.86	968
70,000	218	0.65	0.044	2.83	3.10	970
75,000	219	0.51	0.035	3.07	3.36	974
80,000	221	0.41	0.028	3.30	3.60	978
85,000	222	0.32	0.022	3.58	3.91	981
90,000	224	0.26	0.017	3.89	4.23	984
95,000	225	0.20	0.014	4.19	4.55	988
100,000	227	0.16	0.011	4.51	4.88	991
110,000	232	0.10	0.0068	5.28	5.67	1,003
120,000	241	0.067	0.0046	6.03	6.40	1,021
130,000	249	0.044	0.0030	6.94	7.28	1,038
140,000	258	0.029	0.0020	7.97	8.27	1,056
150,000	266	0.020	0.0014	9.02	9.27	1,073

factor" to obtain an effective blast yield. There is no simple way to formulate the blast efficiency factor as a function of altitude since, at high altitudes, overpressure varies with distance in such a manner that the effective blast yield is different at different distances. It is possible, however, to specify upper and lower limits on the blast efficiency factor, as shown in Table

3.68 for several altitudes. By using this factor, together with the ambient pressure P and the absolute temperature T at the observation point (or target) in the equations in § 3.65 (or § 3.66), an estimate can be made of the upper and lower limits of the blast parameters. An example of such an estimate will be given later.

Table 3.68: Blast Efficiency Factors For High-Altitude Bursts

Burst Altitude (feet)	Blast Efficiency Factor Upper Limit	Lower Limit
40,000	1.0	0.9
60,000	1.0	0.8
90,000	0.9	0.6
120,000	0.7	0.4
150,000	0.4	0.2

3.4.4 Standard Curves And Calculations Of Blast Wave Properties

3.69 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.

3.70 From the curves given below the values of the blast wave properties can be determined for a free air burst or as observed at the surface for an air burst at a particular height or for a contact surface burst (zero height). The peak overpressures, dynamic pressures, and positive phase duration times obtained in this manner are the basic data to be used in determining the blast loading and response of a target to a nuclear explosion under specified conditions. The procedures for evaluating the blast damage to be expected are discussed in Chapters IV and V.

3.71 The standard curves give the blast wave properties for a 1-kiloton TNT equivalent explosion in a sea-level atmosphere. By means of these curves and the scaling laws already presented, the corresponding properties can be calculated for an explosion of W-kilotons energy yield. Examples of the use of the curves are given on the pages facing the figures. It should be borne in mind that the data have been computed for nearly ideal conditions and that significant deviations may occur in practice.

3.72 The variation of peak overpressure with distance from a 1-kiloton TNT equivalent free air burst, i.e., a burst in a homogeneous atmosphere where no boundaries or surfaces are present, for a standard sea-level atmosphere is shown in Fig. 3.72. This curve, together with the scaling laws and altitude corrections described above, may be used to predict incident overpressures from air bursts for those cases in which the blast wave arrives at the target without having been reflected from any surface. Other blast wave characteristics may be obtained from the Rankine-Hugoniot equations (§ 3.55 *et seq.*).

3.73 The curves in Fig. 3.73a (high-pressure range), Fig. 3.73b (intermediate pressure range), and Fig. 3.73c (low-pressure range) show the variation with distance from ground zero of the peak overpressure at points near the ground surface for a 1-kiloton air burst as a function of the height of burst. The corresponding data for other explosion energy yields may be obtained by use of the scaling laws. The curves are applicable to a standard sea-level atmosphere and to nearly ideal surface conditions. Deviations from these conditions will affect the results, as explained in previous sections (cf. § 3.35 *et seq.*, also § 3.79 *et seq.*). It is seen from the figures, especially for overpressures of 30 pounds per square inch or less, that the curves show a pronounced "knee." Consequently, for any specified overpressure, there is a burst height that will result in a maximum surface distance from ground zero to which that overpressure extends. This is called the "optimum" height of burst for the given overpressure.

3.74 The variation of peak overpressure with distance from ground zero for an air burst at any given height can be readily derived from the curves in Figs. 3.73a, b, and c. A horizontal line is drawn at the desired height of burst and then the ground distances for specific values of the peak overpressure can be read off. These curves differ from the one in Fig. 3.72 for a free air burst because they include the effect of reflection of the blast wave at the earth's surface. A curve for peak overpressure versus distance from ground zero for a contact surface burst can be obtained by taking the height of burst in Figs. 3.73a, b, and c to be zero.

3.75 The curves in Fig. 3.75 indicate the variation 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. Since height-of-burst charts indicate conditions after the blast wave has been reflected from the surface, the curves do not represent the dynamic pressure of the incident wave. At ground zero the wind in the incident blast wave is stopped by the ground surface, and all of the incident dynamic pressure is transformed to static overpressure. Thus, the height-of-burst curves show that the dynamic pressure is zero at ground zero. At other locations, reflection of the incident blast wave produces winds that at the surface must blow parallel to the surface. The dynamic pressures associated with these winds produce horizontal forces. It is this horizontal component of the dynamic pressure that is given in Fig. 3.75.

3.76 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. 3.76; 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.

3.77 The curves in Figs. 3.77a 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 nearly ideal surface.

3.78 The peak overpressures in Figs. 3.74a, b, and c, which allow for reflection at the ground surface, are considered to be the side-on overpressures (§ 4.06 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 $p_r(a)$ depends on the side-on pressure p and the angle, α, between blast wave front and the struck surface (Fig. 3.78a). The values of the ratio $p_r(a)/p$ as a function of angle of incidence for various indicated side-on pressures are given in Fig. 3.78b. It is seen that for normal incidence, i.e., when $\alpha = 0°$, the ratio $p_r(a)/p$ is approximately 2 at low overpressures and increases with the overpressure (§ 3.56). The curves in Fig. 3.78b 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. 4.07).

3.4.5 The Precursor

3.79 The foregoing results have referred to blast wave conditions near the surfaces that are ideal or nearly ideal (§ 3.47), so that the Rankine-Hugoniot equations are applicable. When the surface is nonideal, there may be mechanical or thermal effects (or both) on the blast wave. Some of the phenomena associated with mechanical effects were mentioned in § 3.48. As a consequence of thermal nonideal behavior, the overpressure and dynamic pressure patterns can be distorted. Severe thermal effects are associated with the formation of a precursor (§ 3.49) which produces significant changes in the parameters of the blast wave.

3.80 When a nuclear weapon is detonated over a thermally nonideal (heat absorbing) surface, radiation from the fireball produces a hot layer of air, referred to as a "thermal layer," near the surface. This layer, which often includes smoke, dust, and other particulate matter, forms before the arrival of the blast wave from an air burst. It is thus referred to as the preshock thermal layer. Interaction of the blast wave with the hot air layer may affect the reflection process to a considerable extent. For appropriate combinations of explosion energy yield, burst height, and heat-absorbing surfaces, an auxiliary (or secondary) blast wave, the precursor, will form and will move ahead of the main incident wave for some distance. It is called precursor because it precedes the main blast wave.

3.81 After the precursor forms, the main shock front usually no longer extends to the ground; if it does, the lower portion is so weakened and distorted that it is not easily recognized. Between the ground and the bottom edge of the main shock wave is a gap, probably not sharply defined, through which the energy that feeds the precursor may flow. Ahead of the main shock front, the blast energy in the precursor is free not only to follow the rapidly moving shock front in the thermal layer, but also to propagate upward into the undisturbed air ahead of the main shock front. This diverging flow pattern within the precursor tends to weaken it, while the energy which is continually fed into the precursor from the main blast wave tends to strengthen the precursor shock front. The foregoing description of what happens within a precursor explains some of the characteristics shown in Fig. 3.81. Only that portion of the precursor shock front that is in the preshock thermal layer travels faster than the main shock front; the energy diverging upward, out of this layer, causes the upper portion to lose some of its forward speed. The interaction of the precursor and the main shock front indicates that the main shock is continually overtaking this upward-traveling energy. Dust, which may billow to heights of more than 100 feet, shows the upward flow of air in the precursor.

3.82 Considerable modification of the usual blast wave characteristics may occur within the precursor region. The overpressure wave form shows a rounded leading edge and a slow rise to its peak amplitude. In highly disturbed waveforms, the pressure jump at the leading edge may be completely absent. (An example of a measured overpressure waveform in the precursor region is given in Fig. 4.67a.) Dynamic pressure waveforms often have high-frequency oscillations that indicate severe turbulence. Peak amplitudes of the precursor waveforms show that the overpressure has a lower peak value and the dynamic pressure a higher peak value than over a surface that did not permit a precursor to form. The higher peak value of the dynamic pressure is primarily attributable to the increased density of the moving medium as a result of the dust loading in the air. Furthermore, the normal Rankine-Hugoniot relations at the shock front no longer apply.

3.83 Examples of surfaces which are considered thermally nearly ideal (unlikely to produce significant precursor effects) and thermally nonideal (expected to produce a precursor for suitable combinations of burst height and ground distance) are given in Table 3.83. Under many conditions, e.g., for scaled heights of burst in excess of 800 feet or at large ground distances (where the peak overpressure is less than about 6 psi), precursors are not expected to occur regardless of yield and type of surface. Thermal effects on the blast wave are also expected to be small for contact surface bursts; consequently, it is believed that in many situations, especially in urban areas, nearly ideal blast wave conditions would prevail.

3.84 For this reason, the curves for various air blast parameters presented earlier, which apply to nearly ideal surface conditions, are considered to be most representative for general use. It should be noted, however, that blast phenomena and damage observed in the precursor region for low air bursts at the Nevada Test Site may have resulted from nonideal behavior of the surface. Under such conditions, the overpressure waveform may be irregular and may show a slow rise to a peak value somewhat less than that expected for nearly ideal conditions (§ 3.82). 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 (3.56.2).

3.85 Similarly, the dynamic pressure waveform will probably be irregular (§ 3.82), but the peak value may be several times that computed from the peak overpressure by the Rankine-Hugoniot relations. Damage to and displacement of targets which are affected by dynamic pressure may thus be considerably greater in the nonideal precursor region for a given value of peak overpressure than under nearly ideal conditions.

3.5 Bibliography

omitted

4

Air Blast Loading

4.1 Interaction Of Blast Wave With Structures

4.1.1 Introduction

4.01 The phenomena associated with the blast wave in air from a nuclear explosion have been treated in the preceding chapter. The behavior of an object or structure exposed to such a wave may be considered under two main headings. The first, called the "loading," i.e., the forces which result from the action of the blast pressure, is the subject of this chapter. The second, the "response" or distortion of the structure due to the particular loading, is treated in the next chapter.

4.02 For an air burst, the direction of propagation of the incident blast wave will be toward 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 buildup on the horizontal surfaces. Consequently, in addition to the horizontal loading, as in the Mach region (§ 3.24 et seq.), 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.

4.03 The discussion of air blast loading for above ground structures in the Mach region in the sections that follow emphasizes the situation where the reflecting surface is nearly ideal (§ 3.47) and the blast wave behaves normally, in accordance with theoretical considerations. A brief description of blast wave loading in the precursor region (§ 3.79 et seq.) is also given. 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. It is important to remember, however, 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.

4.04 Details of the interaction of a blast wave with any structure are quite complicated, particularly if the geometry of the structure is complex. However, it is frequently possible to consider equivalent simplified geometries, and blast loadings of several such geometries are discussed later in this chapter.

4.1.2 Diffraction Loading

4.05 When the front of an air blast wave strikes the face of a structure, 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 structure (§ 3.78). The pressure increase is due to the conversion of the kinetic energy of the air behind the shock front into internal energy as the rapidly moving air behind the shock front is decelerated at the face of the structure. The reflected shock front propagates back into the air in all directions. The high pressure region expands outward towards the surrounding regions of lower pressure.

4.06 As the wave front moves forward, the reflected overpressure on the face of the structure 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 sides and the roof. The front face, however, is still subjected to wind pressure, although the back face is shielded from it.

4.07 The developments described above are illustrated in a simplified form in Figs. 4.07a, b, c, d, e;[2] this shows, in plan, successive stages of a structure without openings which is being struck by an air blast wave moving in a horizontal direction. In Fig. 4.07a the wave front is seen approaching the structure with the direction of motion perpendicular to the face of the structure exposed to the blast. In Fig. 4.07b the wave has just reached the front face, producing a high reflected overpressure. In Fig. 4.07c the blast wave has proceeded about halfway along the structure and in Fig. 4.07d the wave front has just passed the rear 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

[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.

the wave front has passed completely, as in Fig. 4.07e, approximately equal air pressures are exerted on the sides and top 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 characteristics of the blast loading would be similar to that just described (Figs. 4.07f, g, h, and i).

4.08 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, as in Figs. 4.07b, c, and d or g and h. 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 response will depend upon the size, shape, and weight of the structure and how firmly it is attached to the ground. Other characteristics of the structure are also important in determining the response, as will be seen later.

4.09 When the blast wave has engulfed the structure (Fig. 4.07e or 4.07i), the pressure differential is small, and the loading is due almost entirely to the drag pressure3 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 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.

4.10 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 persist for a longer time (§ 4.13). For thin structures, e.g., telegraph or utility poles and smokestacks, the diffraction period is so short that the corresponding loading is negligible.

4.11 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, the squeezing (crushing) action, due to the pressure being higher outside than inside after the diffraction stage, will not occur.

4.1.3 Drag (Dynamic Pressure) Loading

4.12 During the whole of the overpressure positive phase (and for a short time thereafter) a structure will be subjected to the dynamic pressure (or drag) loading caused by the transient winds behind the blast wave front. Under nonideal (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.

4.13 Except at high blast overpressures, the dynamic pressures at the face of a structure are much less than the peak overpressures due to the blast wave and its reflection (Table 3.07). However, the drag loading on a structure persists for a longer period of time, compared to the diffraction loading. For example, the duration of the positive phase of the dynamic pressure on the ground at a slant range of 1 mile from a 1-megaton nuclear explosion in the air is almost 3 seconds. 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.

4.14 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 longer duration of the positive phase of the blast wave from weapons of high energy yield, such devices cause more damage to drag-sensitive structures (§ 4.18) than might be expected from the peak overpressures alone. 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 longer duration of the positive phase of the blast wave from weapons of high energy yield, such devices cause more damage to drag-sensitive structures (§ 4.18) than might be expected from the peak overpressures alone.

4.1.4 Structural Characteristics and Air Blast Loading

4.15 In analyzing the response to blast loading, as will be done more fully in Chapter V, 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. Although 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.

4.16 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 such as dwelling houses.

4.17 Because, even with large structures, the diffraction loading will generally be operative for a fraction of a second only, the duration of the blast wave positive phase, which is usually much longer, will not be significant. In other words, the length of the blast wave positive phase will not materially affect 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 blast 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 blast overpressure (§ 3.78).

4.18 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 pressure (or drag force) 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.

4.19 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. Furthermore, the drag coefficient can be either positive or negative, according to circumstances (§ 4.29).

4.20 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.

4.21 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 on the duration of the positive phase of the blast wave as well as on 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 (see § 5.48 et seq.).

4.2 Interaction Of Objects With Air Blast[3]

4.2.1 Development Of Blast Loading

4.22 The usual procedure for predicting blast damage is by an analysis, supported by such laboratory and full-scale observations as may be available. The analysis is done in two stages: first the air blast loading on the particular structure is determined; and second, an evaluation is made of the response of the structure to this loading. The first stage of the analysis for a number of idealized targets of simple shape is discussed in the following sections. The second stage is treated in Chapter V.

4.23 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 HI, 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

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

experimental 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 (dynamic pressures less than about 40 pounds per square inch), and (2) the object being loaded is in the region of Mach reflection.

4.24 To obtain a general idea of the blast loading process, a simple object, namely, a cube with one side facing toward the explosion, will be selected as an example. It will be postulated, further, that the cube is rigidly attached to the ground surface and remains motionless when subjected to the loading. The blast wave (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 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. 4.24).

4.25 When the blast wave strikes the front of the cube, reflection occurs producing reflected pressures which may be from two to eight times as great as the incident overpressure (§ 3.56). The blast wave then bends (or diffracts) around the cube exerting pressures on the sides and top of the object, and finally on its back 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 it 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.

4.26 The pressures on the sides and top of the cube build up to the incident overpressure when the blast front arrives at the points in question. This is followed by a short period of low pressure caused by a vortex formed at the front edge during the diffraction process and which travels along or near the surface behind the wave front (Fig. 4.26). 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 in § 4.43, the drag pressure here has a negative value.

4.27 When the blast wave reaches the rear of the cube, it diffracts around the edges, and travels down the back surface (Fig. 4.27). The pressure takes a certain time ("rise time") to reach a Figure 4.24. Blast wave approaching cube 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 (§ 4.44). 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 back face.

4.28 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.

4.29 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 is the drag coefficient. The value of C_d depends on the orientation of the particular face to the blast wave front and may be positive or negative. The drag pressures (or loading) may thus be correspondingly 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 (§ 3.57 et seq.).

4.30 The foregoing discussion has referred to the loading on the various surfaces in a general manner. For a particular point on a surface, the loading depends also on the distance from the point to the 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.

4.2.2 Effect Of Size On Loading Development

4.31 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, i.e., 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.

4.32 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 positive phase duration of the incident blast wave, the diffraction loading impulse per unit area (§ 3.59) is greater for long objects than for short ones.

4.33 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 dynamic pressure. It is the latter, and not the size of the object, which determines the application time (and impulse per unit area) of the drag loading.

4.34 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 dynamic pressure 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.

4.2.3 Effect Of Shape On Loading Development

4.35 The description given above for the interaction of a blast wave with a cube may be generalized to apply to the loading on a structure 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 structure. For a curved structure, e.g., a sphere or a cylinder (or part of a sphere or cylinder), 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 structure and the location of the point in question on the front surface.

4.36 The drag coefficient, i.e., the ratio of the drag pressure to the dynamic pressure (§ 4.29), varies with the shape of the structure. 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 at various points on the surfaces. The time of buildup (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 structure.

4.37 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.

4.2.4 Blast Loading–Time Curves

4.38 The procedures whereby curves showing the air blast loading as a function of time may be derived are given below. The methods presented are for the following five relatively simple shapes: (1) closed box-like structure; (2) partially open box-like structure; (3) open frame structure; (4) cylindrical structure; and (5) semicircular arched structure. These methods can be altered somewhat for objects having similar characteristics. For very irregularly shaped structures, however, the procedures described may provide no more than a rough estimate of the blast loading to be expected.

4.39 As a general rule, the loading analysis of a diffraction-type structure is extended only until the positive phase overpressure falls to zero at the surface under consideration. Although the dynamic pressure persists after this time, the value is so small that the drag force can be neglected. However, for drag-type structures, the analysis is continued until the dynamic pressure is zero. During the negative overpressure phase, both overpressure and dynamic pressure are too small to have any significant effect on structures (§ 3.11 et seq.).

4.40 The blast wave characteristics which need to be known for the loading analysis and their symbols are summarized in Table 4.40. 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.

4.41 A closed box-like structure may be represented simply by a parallelepiped, as in Fig. 4.41, having a length L, height H, and breadth B. Structures with a flat roof and walls of approximately the same blast resistance as the frame will fall into this category. 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. The pressures on the interior of the structure then remain near the 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 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).

4.42 *(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 (Fig. 4.42). 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, for peak overpressures being considered (50 pounds per square inch or less), 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, and U is the blast front (shock) velocity. 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. The average 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_p^+. The pressure-time curve for the front face can thus be determined, as in Fig. 4.42.

4.43 *(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 times $t = L/U$. 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 is approximately -0.4 for the blast pressure range under consideration (§ 4.23). The loading increases from zero at $t = 0$ to the value p_a at the time L/U, as shown in Fig. 4.43. Subsequently, the average pressure at any time t is given by

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

where t lies between L/U and $t_p^+ + L/2U$, as seen in Fig. 4.43. The overpressure and dynamic pressure, respectively, are the values at the time $t - L/2U$. Hence, the overpressure on the sides and top becomes zero at time $t_p^+ + L/2U$.

4.44 *(c) Average Loading on Back Face.*—The shock front arrives at the back face at time L/U, but it requires an additional time, $4S/U$, for the average pressure to build up to the value p_b (Fig. 4.44), where p_b is given approximately by

$$p_b = p\left(\frac{L + 4S}{2U}\right) + C_d q\left(\frac{L + 4S}{2U}\right).$$

Here, as before, S equal to H or $B/2$ whichever is the smaller. The drag coefficient on the back face is about $^{-}0.3$ for the postulated blast pressure range. The average pressure at any time t after the attainment of p_b 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 $t_p^+ + L/U$, as seen in Fig. 4.44.

4.45 *(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. 4.45. The left-hand diagram gives the individual front and back loading curves, as derived from Figs. 4.42 and 4.44, 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.

4.2.5 Partially Open Box–Like Structures

4.46 A partially open box-like 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.

4.47 *(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.

4.48 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 in side and the outside pressures with time are as represented in Fig. 4.48.

4.49 *(b) Average Loading on Sides and Top.*– The outside pressures are obtained as for a closed structure (§ 4.43), 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. 4.49.

4.50 *(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. 4.50).

4.51 *(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.

4.2.6 Open Frame Structure

4.52 A structure in which small separate elements are exposed to a blast wave, e.g., a truss bridge, may be regarded as an open frame structure. Steel-frame office buildings with a majority of the wall area of glass, and industrial buildings with asbestos, light steel, or aluminum panels quickly become open frame structures after the initial impact of the blast wave.

4.53 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.

4.54 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 faces where the majority of the elements are located, as shown below in Fig. 4.56.

4.55 The major portion of the loading on an open frame structure consists of the drag 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 multiplied 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

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

where C_d is 1.0 and $\sum A_i$ is the sum of the projected areas of all the members.

$$F(\text{frame}) = q(t) A,$$

where $A = \sum A_i$

4.56 The loading (force) versus time for a frame of length L, having major areas in the planes of the front and rear faces, is shown in Fig. 4.56. The symbols A_{fw} and A_{bw} represent the areas of the front and back faces, respectively, which transmit loads before failure, and I_{fw} and A_{bw} are the overpressure loading impulses on front and back members, respectively. Although drag loading commences immediately after the blast wave strikes the front face, i.e., at $t = 0$, the back face is not fully loaded until the wave has traveled the distance L, i.e., at time $t = L/U$. The average drag loading, q_a, on the entire structure at this time is considered to be that which would occur at the distance $L/2$ from the front of the structure, so that

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

and the average force on the frame, F_a (frame), is

$$F_a(\text{frame}) = q \left(\frac{L}{2U} \right) A,$$

where C_d is 1.0, as above. After this time, the average drag force on the frame at any time t is given by

$$F_a(\text{frame}) \text{ at time } t = q \left(t - \frac{L}{2U} \right) A,$$

where t lies between L/U and $t_q^+ + L/2U$, as seen in Fig. 4.56.

4.2.7 Cylindrical Structures

4.57 The following treatment is applicable to structures with a circular cross section, such as telephone poles and smokestacks, for which the diameters are small compared to the lengths. The discussion presented here provides methods for determining average pressures on projected areas of cylindrical structures with the direction of propagation of the blast perpendicular to the axis of the cylinder. A more detailed method for determining the pressure time curves for points on cylinders is provided in the discussion of the loading on arched structures in § 4.62 et seq. The general situation for a blast wave approaching a cylindrical structure is represented in section in Fig. 4.57.

4.58 *(a) Average Loading on Front Surface.–* When an ideal blast wave impinges on a flat surface of a structure, the pressure rises instantaneously to the reflected value and then it soon drops to the stagnation pressure (§ 4.25). On the curved surface of a cylinder the interaction of the blast wave with the front face is much more complex in detail. However, in terms of the average pressure, the load appears as a force that increases with time from zero when the blast front arrives to a maximum when the blast wave has propagated one radius. This occurs at a time $D/2U$, where D is the diameter of the cylinder. For the blast pressure range being considered, the maximum average pressure reaches a value of about $2p$ as depicted in Fig. 4.58. The load on the front surface then decays in an approximately linear manner to the value it would have at about time $t = 2D/U$. Subsequently, the average pressure decreases as shown. The drag coefficient for the front surface of the cylinder is 0.8.

4.59 *(b) Average Loading on the Sides.–* Loading of the sides commences immediately after the blast wave strikes the front surface but, as with the closed box discussed in § 4.41 et seq., the sides are not fully loaded until the wave has traveled the distance D, i.e., at time $t = D/U$. The average pressure on the sides at this time is indicated by p_{s1} given approximately by

$$p_{s1} = p\left(\frac{D}{U}\right),$$

Complex vortex formation then causes the average pressure to drop to a minimum, p_{s2}, at the time $t = 3D/2U$; the value of p_{s2} is about half the maximum overpressure at this time, i.e.,

$$p_{s2} \approx \frac{1}{2}p\left(\frac{3D}{2U}\right),$$

The average pressure on the side then rises until time $9D/2U$ and subsequently decays as shown in Fig. 4.59. The drag coefficient for the side face is 0.9.

4.60 *(c) Average Loading on Back Surface.–* The blast wave begins to affect the back surface of the cylinder at time $D/2U$ and the average pressure gradually builds up to p_{b1} (Fig. 4.60) at a time of about $4D/U$. The value of p_{b1} is given by

$$p_{b1} \approx \frac{1}{2}p\left(\frac{4D}{U}\right),$$

The average pressure on the side then rises until time $9D/2U$ and subsequently decays as shown in Fig. 4.59. The drag coefficient for the side face is 0.9.

4.60 *(c) Average Loading on Back Surface.*– The blast wave begins to affect the back surface of the cylinder at time $D/2U$ and the average pressure gradually builds up to p_{bl} (Fig. 4.60) at a time of about $4D/U$. The value of p_{bl} is given by

$$p_{b1} = \frac{1}{2} p \left(\frac{4D}{U} \right),$$

The average pressure continues to rise until it reaches a maximum, p_{b2}, at a time of about $20D/U$, where

$$p_{b1} = p \left(\frac{20D}{U} \right) + C_d q \frac{20D}{U},$$

The average pressure at any time t after the maximum is represented by

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

where t lies between $20D/U$ and $t_p^+ + D/2U$. The drag coefficient for the back surface is ¯0.2.

4.61 The preceding discussion has been concerned with average values of the loads on the various surfaces of a cylinder, whereas the actual pressures vary continuously from point to point. Consequently, the net horizontal loading cannot be determined accurately by the simple process of subtracting the back loading from the front loading. A rough approximation of the net load may be obtained by procedures similar to those described for a closed box-like structure (§ 4.45), but a better approximation is given by the method referred to in § 4.65 et seq.

4.2.8 Arched Structures

4.62 The following treatment is applicable to arched structures, such as ground huts, and, as a rough approximation, to dome shaped or spherical structures. The discussion presented here is for a semicylindrical structure with the direction of propagation of the blast perpendicular to the axis of the cylinder. The results can be applied to a cylindrical structure, such as discussed above, since it consists of two such semicylinders with identical loadings on each half. Whereas the preceding treatment referred to the average loads on the various faces of the cylinder (§ 4.57 et seq.), the present discussion describes the loads at each point. The general situation is depicted in Fig. 4.62; 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.

4.63 When an ideal blast wave impinges on a curved surface, vortex formation occurs just after reflection, so that there may be a temporary sharp pressure drop before the stagnation pressure is reached. A generalized representation of the variation of the pressure with time at any point, z, is shown in Fig. 4.63. 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 is the rise time. Vortex formation causes the pressure to drop to p_2, and this is followed by an increase to p_3, the stagnation pressure; subsequently, the pressure, which is equal to $p(t)+C_dq(t)$, where C_d is the appropriate drag coefficient, decays in the normal manner.

4.64 The dependence of the pressures p_1 and p_2 and the drag coefficient C_d on the angle α is represented in Fig. 4.64; the pressure values are expressed as the ratios to p_r, where p_r is the ideal reflected pressure for a flat surface. When a 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 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. 4.64, 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 a on the back half, i.e., for an α between 90° and 180°. The times t_2 and t_3 are independent of the angle α.

4.65 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.

4.66 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 $p_rA(2H/U)$, 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 net drag coefficient for a single cylinder is about 0.4 in the blast pressure range of interest (§ 4.23). Hence, in addition to the initial impulse, the remainder of the net horizontal loading may be represented by the force $0.4q(t)A$, as seen in Fig. 4.66, 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 (§ 4.55) with C_d equal to 0.2.

4.2.9 Nonideal Blast Wave Loading

4.67 The preceding discussions have dealt with loading caused by blast waves reflected from nearly ideal ground surfaces (§ 3.47). In practice, however, the wave form will not always be ideal. In particular, if a precursor wave is formed (§ 3.79 et seq.), the loadings may depart radically from those described above. Although it is beyond the scope of the present treatment to provide a detailed discussion of nonideal loading, one qualitative example is given here. Figure 4.67a shows a nonideal incident air blast (shock) wave and Figs. 4.67b, c, and d give the loading patterns on the front, top, and back, respectively, of a rectangular block as observed at a nuclear weapon test. Comparison of Figs. 4.67b, c, and d with the corresponding Figs. 4.42, 4.43, and 4.44 indicates the departures from ideal loadings that may be encountered in certain circumstances. The net loading on this structure was significantly less than it would have been under ideal conditions, but this would not necessarily always be the case.

4.3 Bibliography

omitted

5

Structural Damage From Air Blast

5.1 Introduction

5.1.1 General Observations

5.01 The two preceding chapters have dealt with general principles of air blast and the loads on structures produced by the action of the air blast wave. In the present chapter, the actual damage to buildings of various types, bridges, utilities, and vehicles caused by nuclear explosions will be considered. In addition, criteria of damage to various targets will be discussed and quantitative relationships will be given between the damage and the distances over which such damage may be expected from nuclear weapons of different yields.

5.02 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.

5.03 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.

5.04 An examination of the areas in Japan affected by nuclear explosions

(§ 2.24) 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 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 enormous numbers of flying missiles consisting of bricks (and other masonry), glass, pieces of wood and metal, etc. These caused considerable amounts of secondary damage to structures and utilities, and numerous casualties 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. 5.06).

5.07 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 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.

5.05 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 by 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 (Chapter VII).

5.06 A highly important consequence of the tremendous power of the nuclear explosions 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 secondary damage to structures and utilities, and numerous casualties 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. 5.06).

5.07 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 on experimental structures exposed to air blast at nuclear weapons tests in Nevada.

5.2 Factors Affecting Response

5.2.1 Strength And Mass

5.08 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 (§ 5.14) of the component materials and members.

5.09 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.

5.10 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.

5.11 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.

5.2.2 Structural Design

5.12 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 (sideways) 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.

5.13 Of existing structures, those intended to be earthquake resistant and 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.

5.2.3 Ductility

5.14 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.

5.15 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" (or internal force) 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 load; that is to say, some deformation is permanent, but there is no failure. Only when the stress reaches the "ultimate strength" does failure occur.

5.16 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.

5.17 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 is quite large for some steels.

5.18 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.

5.3 Commercial And Administrative Structures

5.3.1 Introduction

5.19 In this and several subsequent sections, the actual damage to various types of structures caused by the air blast from nuclear explosions will be described. First, commercial, administrative, and similar buildings will be considered. These buildings are of substantial construction and include banks, offices, hospitals, hotels, and large apartment houses. Essentially all the empirical information concerning the effects of air blast on such multistory structures has been obtained from 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. As is to be expected from the preceding discussion, buildings of the first two types are more blast resistant than those of the third type; however, even light to moderate damage (see Table 5.139a) to frame supported buildings can result in casualties to people in these buildings.

5.3.2 Multistory, Reinforced-Concrete Frame Buildings

5.20 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 640 feet from ground zero in Hiroshima, is seen in Fig. 5.20a. 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. 5.20b at about the same distance from ground zero. This suffered more severely than the one of a seismic design.

5.21 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.

5.22 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. 5.22a) 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 ground zero, especially in the region of Mach reflection, the consequences of horizontal loading were apparent (Fig. 5.22b).

5.23 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 (Fig. 5.23). 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 $3\frac{3}{4}$ miles and in a few instances out to 8 miles.

5.24 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.

5.3.3 Multistory, Steel Frame Buildings

5.25 There was apparently only one steel-frame structure having more than two stories in the Japanese cities exposed to nuclear explosions. This was a five-story structure in Nagasaki at a distance of 4,500 feet (0.85 mile) from ground zero (Fig. 5.25). 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.

5.26 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. 5.26. The heavy walls of the structure transmitted their loads to the steel frame, the columns of which collapsed. Weakening of unprotected steel by fire could have contributed significantly to the damage to steel-frame structures (§ 5.31).

5.3.4 Building With Load Bearing Walls

5.27 Small structures with light load-bearing walls offered little resistance to the nuclear blast and, in general, collapsed completely. Large buildings of the same type, but with cross walls and of somewhat heavier construction, were more resistant but failed at distances up to 6,300 feet (1.2 miles) from ground zero. Cracks were observed at the junctions of cross walls and side-walls 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.

5.3.5 Japanese Experience

5.28 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.

5.29 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 (Fig. 5.29). 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, complete collapse. Roof trusses were buckled by compression resulting from lateral blast loading on the side of the building facing the explosion.

5.30 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.

5.31 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.

5.32 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, possibly because the strength of concrete is decreased to a lesser extent by fire than is that of steel.

5.33 Damage to machine tools 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.

5.34 Smokestacks, especially those of reinforced concrete, proved to have considerable blast resistance (Fig. 5.34a). 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. 5.34b. Steel smokestacks 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.

5.3.6 Nevada Tests

5.35 A considerable amount of information on the blast response of structures of several different kinds was obtained in the studies made at the Nevada Test Site in 1953 and 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.

5.36 Three types of metal buildings of standard construction, such as are used for various commercial and industrial purposes, were exposed at peak overpressures of 3.1 and 1.3 pounds per square inch. The main objectives of the tests, made in 1955, were to determine the blast pressures at which such 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.

5.3.7 Steel Frame With Aluminum Panels

5.37 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. 5.37a). 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. 5.37b).

5.38 At a peak overpressure of 1.3 pounds per square inch the main steel frame suffered only slight distortion. The aluminum roofing and siding were not blown off, although the panels were disengaged from the bolt fasteners on the front face of the steel columns and girts (horizontal connecting members). 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.

5.39 As presently designed, structures of this type may be regarded as being repairable, provided they are not exposed to blast pressures exceeding 1 pound per square inch. Increased blast resistance would probably result from improvement in the design of girts and purlins (horizontal members supporting rafters), in particular. Better fastening between sill and wall footing and increased resistance to transverse loading would also be beneficial.

5.3.8 Self-Framing With Steel Panels

5.40 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. 5.40a). The one subjected to 3.1 pounds per square inch peak overpressure (and a dynamic pressure of 0.2 pound per square inch) was completely demolished (Fig. 5.40b). 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.

5.41 Although damage at 1.3 pounds per square inch peak overpressure was much less, it was still considerable in parts of the structure. 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.

5.42 It appears that the steel panel type of structure is repairable if exposed to overpressures of not more than about $\frac{3}{4}$ 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.

5.3.9 Self-Framing With Corrugated Steel Panels

5.43 The third type of industrial building was a completely frameless structure made of strong, deeply-corrugated 43-inch wide panels of 16-gauge 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. 5.43).

5.3.10 Positive Phase Duration Tests

5.44 At a peak overpressure of 3.1 and a dynamic pressure of 0.2 pound 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 from the elements for its contents. 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. 5.44).

5.45 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.

5.46 Another building of this type, exposed to 1.3 pounds per square inch peak 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 where necessary and some minor repairs would have rendered the building completely serviceable.

5.47 The corrugated steel, frameless structure proved to be the most blast-resistant of those tested. It is believed that, provided the overpressure 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.

5.3.11 Positive Phase Duration Tests

5.48 Tests were carried out at Nevada in 1955 and at Eniwetok Atoll in the Pacific in 1956 to investigate the effect of the 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. 5.48a). 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. 5.48b).

5.49 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 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 (horizontal member of the roof truss) and column connections. The girts on the windward side were severely damaged and all of the siding was completely blown off (Fig. 5.49).

5.50 The second building, with the stronger siding, was exposed in Nevada to a peak 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. 5.50). 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.

5.51 Structures of the same type were subjected to similar pressures in the blast wave from a megaton range explosion at Eniwetok; namely, a peak 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 semidrag 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. 5.51a 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 overpressure value, if the duration of the positive phase of the blast wave is increased (cf. § 4.13).

5.4 Residential Structures

5.4.1 Japanese Experience

5.52 There were many woodframed residential structures with adobe walls in the Japanese cities which were subjected to nuclear attack, but such a large proportion were destroyed by fire that very little detailed information concerning blast damage was obtained. It appeared that, although the quality of the workmanship in framing was usually high, little attention was paid to good engineering principles. On the whole, therefore, the construction was not well adapted to resist wracking action (distortion). For example, mortise and tenon joints were weak points in the structure and connections were in general poor. Timbers were often dapped (cut into) more than was necessary or slices put in improper locations, resulting in an overall weakening (Fig. 5.52).

5.53 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.

5.4.2 Nevada Tests

5.54 The main objectives of the tests made in Nevada in 1953 and 1955 (§ 5.35) 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 would 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 deals primarily with blast effects.

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

5.55 In the 1953 test, two essentially identical houses, of a type common in the United States, were placed at different locations. They were of typical wood-frame construction, with two stories, basement, and brick chimney (Fig. 5.55). 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.

5.56 One of the two houses was located in the region of Mach reflection where the peak incident 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.

5.57 Some indication of the blast damage suffered by this dwelling can be obtained from Fig. 5.57. 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.

5.58 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.

5.59 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. 5.59). People 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.

5.60 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.

5.61 Principal damage to the first floor system consisted of broken joists. 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 (2×6 inches with 16-inch spacing).

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

5.4.4 Two-Story, Wood-Frame House: 1955 Test

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

5.64 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. 5.64). But the superstructure was so badly damaged that it could not have been occupied without expensive repair which would not have been economically advisable.

5.65 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. 5.65).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.

5.4.5 Two-Story, Brick-Wall-Bearing House: 1955 Test

5.66 For comparison with the tests on the two-story, wood-frame structures made in Nevada 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 peak overpressure, respectively, in the 1955 tests (Fig. 5.66). 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.

5.67 At an incident peak overpressure of 5 pounds per square inch, the brick-wall house was damaged beyond repair (Fig. 5.67). The side and back walls failed outward. The front wall failed initially inward, but its subsequent behavior was obscured by dust. The final location of the debris from the front wall is therefore uncertain, but very little 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.

5.68 Farther from the explosion, where the peak 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. 5.68).

5.4.6 One-Story, Wood-Frame (Rambler Type) House: 1955 Test

5.69 A pair of the so-called "rambler" type, single-story, wood frame houses were erected at the Nevada Test Site on concrete slabs pouredin place at grade. They were of conventional design except that each container a shelter, above ground, consisting of the bathroom walls, floor, and ceiling of reinforced concrete with blast door and shutter (Fig. 5.69).

5.70 When exposed to an incident peak 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 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. 5.70).

5.71 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 seen 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 beam and distortion of the frame. In addition, the porch roof was lifted 6 inches off its supports.

5.4.7 One-Story, Precast Concrete House: 1955 Test

5.72 Another residential type of construction tested in Nevada in 1955 was a single-story house made of precast, lightweight (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. 5.72).

5.73 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. 5.73).

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

5.75 At a peak overpressure of 1.7 pounds per square inch, the precast concrete-slab house suffered relatively minor damage. 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, i.e., where the sash projected into the concrete.

5.4.8 One-Story, Reinforced-Masonry House: 1955 Test

5.76 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. 5.76).

5.77 At a peak overpressure of about 5 pounds per square inch, windows were destroyed and doors blown in the demolished. The steel window sash was distorted, but nearly all remained in place. The house suffered only minor structural damage and could have been made habitable at relatively small cost (Fig. 5.77).

5.78 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. 5.77) 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.

5.79 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.

5.4.9 Trailer-Coach Mobile Homes: 1955 Test

5.80 Sixteen trailer-coaches of various makes, intended for use as mobile homes, were subjected to blast in the 1955 test in Nevada. Nine were located where the peak blast overpressure was 1.7 pounds per square inch, and the other seven where the peak 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.

5.81 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.

5.82 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.

5.83 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 tom 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.

5.84 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.

5.5 Transportation

5.5.1 Light Land Transportation

5.85 In Japan, trolley-car equipment was heavily damaged by both blast and fire, although the poles were frequently left standing. Buses and automobiles generally were rendered inoperable by blast and fire as well as by damage caused by flying debris. However, the damage decreased rapidly with distance. An American made automobile was badly damaged and burned at

3,000 feet (0.57 mile) from ground zero, but a similar vehicle at 6,000 feet (1.14 miles) suffered only minor damage.

5.86 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. In most cases, however, 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 (§ 3.79 et seq.). Hence, the damage radii cannot be determined from overpressure alone. 5.87 Some illustrations of the effects of a nuclear explosion on motorized vehicles are shown in Figs. 5.87a and b. 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. But 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.

5.88 During the 1955 tests in Nevada, studies 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 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 a peak 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, for vehicles in general, overpressure is not usually the sole or even the primary damage mechanism.

5.89 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 peak 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. 5.89). 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. 5.89, was a 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.

5.90 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 peak overpressure of 1 pound per square inch, were largely unharmed.

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

5.5.2 Aircraft

5.92 Railroad equipment suffered blast damage in Japan and also in 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 from a kiloton-range weapon, 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 would be more severe (Fig. 5.92a). At a peak overpressure of 6 pounds per square inch the body of an empty wooden boxcar, weighing about 20 tons, was lifted off the trucks, i.e., the wheels, axles, etc., carrying the body, and landed about 6 feet away. The trucks themselves were 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. 5.92b). 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 peak overpressure, a loaded boxcar of the same type was overturned, and at 9 pounds per square inch it was completely demolished.

5.93 A Diesel locomotive weighing 46 tons was exposed to a peak 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 railroad track at this point.

5.5.3 Aircraft

5.94 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 10 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.

5.95 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. 5.95a.

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 5.95b shows damage to an aircraft oriented with its tail toward the burst and exposed to 2.4 pounds per square inch peak overpressure. Skin was dished in on the vertical stabilizer, horizontal stabilizers, wing surface above the flaps, and outboard wing sections. Vertical stabilizer bulkheads and the fuselage frame near the cockpit were buckled.

5.5.4 Shipping

5.96 Damage to ships from an air or surface burst is due primarily to the air blast, since little pressure is transmitted through the water. At closer ranges, air blast can cause hull rupture resulting in flooding and sinking. Such rupture appears likely to begin near the waterline on the side facing the burst. Since the main hull generally is stronger than the superstructure, structures and equipment exposed above the waterline may be damaged at ranges well beyond that at which hull rupture might occur. Masts, spars, radar antennas, stacks, electrical equipment, and other light objects are especially sensitive to air blast. Damage to masts and stacks is apparent in Fig. 5.96; the ship was approximately 0.47 mile from surface zero at the ABLE test (about 20-kiloton air burst) at Bikini in 1946. Air blast may also roll and possibly capsize the ship; this effect would be most pronounced for the air blast wave from a large weapon striking the ship broadside.

5.97 Blast pressures penetrating through openings of ventilation systems and stack-uptake systems can cause damage to interior equipment and compartments, and also to boilers. Damage to the latter may result in immobilization of the ship. The distortion of weather bulkheads may render useless interior equipment mounted on or near them. Similarly, the suddenly applied blast loading induces rapid motion of the structures which may cause shock damage to interior equipment. Equipment in the superstructure is most susceptible to this type of damage, although shock motions may be felt throughout the ship.

5.6 Utilities

5.6.1 Electrical Distribution Systems

5.98 Because of the extensive damage caused by the nuclear explosions to the cities in Japan, the electrical distribution systems suffered severely. Utility poles were destroyed by blast or fire, and overhead lines were heavily damaged at distances up to 9,000 feet (1.7 miles) from ground zero (Fig. 5.98). Underground electrical circuits were, however, little affected. Switchgear and transformers were not damaged so much directly by blast as by secondary effects, such as collapse of the structure in which they were located or by debris. Motors and generators were damaged by fire.

5.99 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 expected to suffer little or no damage; (2) to study the extent and character of the damage that might be sustained in a nuclear attack; and (3) to determine the nature of the repairs that would be needed to restore electrical service in those areas where homes and factories would survive sufficiently to permit their use after some repair. With these objectives in mind, two identical power systems were erected; one to be subjected to a 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.

5.100 Each power system consisted of a high-voltage (69-kV) transmission line on steel towers connected to a conventional, outdoor transformer substation. From this proceeded typical overhead distribution lines on 15 wood poles; the latter were each 45 feet long and were set 6 feet in the ground. Service drops from the overhead lines supplied electricity to equipment placed in some of the houses used in the tests described earlier. 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 power transformer represented equipment of the kind that might supply electricity to large industrial plants.

5.101 At a peak 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.

5.102 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. 5.102a). 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. 5.102b). 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 and positive phase duration, so that the overpressure is not the important criterion of damage.

5.103 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 were 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.

5.104 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. 5.104). Other damage was believed to be caused by missiles.

5.105 Several distributor transformers had fallen from the poles and secondary wires and service drops were down (Fig. 5.105). Nevertheless the transformers, pot heads, arresters, cutouts, primary conductors of both aluminum and copper, and the aerial cables were unharmed. Although the pole line would have required some rebuilding, the general damage was such that it could have been repaired within a day or so with materials normally carried in

5.6.2 Gas, Water, And Sewerage System

5.106 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. 5.106a 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.

5.107 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.

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

5.6.3 Natural And Manufactured Gas Installations

5.109 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.

5.110 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. No domestic or ordinary industrial structures at the surface would have survived the higher of these pressures.

5.111 The second type of installation consisted of typical service lines of steel, copper, and plastic materials connected to 20-foot lengths of 6-inch steel main. Each service pipe rose out of the ground at the side of a house, and was joined to a pressure regulator and meter. The pipe then entered the wall of the house about 2 feet above floor level. The copper and plastic services terminated inside the wall, so that they would be subject to strain if the house moved on its foundation. The steel service 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 several houses. Duplicate installations were located at peak overpressures of 5 and 1.7 pounds per square inch, respectively.

5.112 Neither of the underground installations was greatly affected by the blast. At the 30 pounds per square inch peak overpressure location a $1\frac{1}{2}$-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.

5.113 At the peak overpressure of 1.7 pounds per square inch, where the houses did not suffer severe damage, (§ 5.59), 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 peak overpressure, which was demolished beyond repair (§ 5.57), 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.

5.114 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 (§ 5.67), 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.

5.6.4 Liquid Petroleum (LP) Gas Installations

5.115 Various LP-gas installations have been exposed to air blast from nuclear tests in Nevada to determine the effects of 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.

5.116 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 peak overpressures of 5 and 1.7 pounds per square inch. Others were located where the peak 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.

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

5.118 The dual-cylinder installation, exposed to 25 pounds per square inch peak 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 peak overpressure the components, although often separated, could generally be salvaged and used again. The cylinder installations at 5 pounds per square inch peak 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 neither 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.

5.119 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 peak 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. 5.73).

5.120 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 peak 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. 5.120). 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.

5.121 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 would not be affected under such conditions that the house remains habitable.

5.7 Miscellaneous Targets

5.7.1 Communication Equipment

5.122 The importance of having communications equipment in operating condition after a nuclear attack is evident and so a variety of such equipment has been tested in Nevada. Among the items exposed to air blast 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.

5.123 At the higher overpressure region, where typical houses were damaged beyond repair, the communications equipment proved to be very resistant to blast. This equipment is drag sensitive and so the peak overpressure does not determine the extent of damage. Standard broadcast and television receivers, and mobile radio base stations were found to be in working condition, even though they were covered with 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.

5.124 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. 5.124)'. This represented the only serious damage to any of the equipment tested.

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

5.126 Some 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 (§ 5.104), 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.

5.7.2 Bridges

5.127 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. 5.127a and b). One bridge, only 270 feet from ground zero, i.e., about 2,100 feet from the burst point, 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.

5.7.3 Heavy-Duty Machine Tools

5.128 The vulnerability of heavy duty machine tools and their components to air blast from a nuclear explosion was studied at the Nevada Test Site to supplement the information from Nagasaki (§ 5.33). 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. 5.128). The purpose of this wall was to simulate the exterior wall of the average industrial plant and to provide debris and missiles.

5.129 Of the four machines, the three lighter ones were moved from their foundations and damaged quite badly (Fig. 5.129a). The fourth, weighing 12,000 pounds, which was considered as the only one to be actually of the heavy-duty type, survived (Fig. 5.129b). From the observations it was concluded that a properly anchored machine tool of the true heavy-duty type would be able to withstand peak overpressures of 10 pounds per square inch or more without substantial damage.

5.130 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.

5.131 Behind the two-story brick house in the peak overpressure region of 5 pounds per square inch (§ 5.67), a 200-ton capacity hydraulic press weighing some 49,000 pounds was erected. 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 was 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 debris falling from the house.

5.132 At the 3-pounds per square inch peak overpressure location, there were two light, industrial buildings of standard type. In each of these was placed a vertical milling machine weighing about 3,000 pounds, a 50 gallon capacity, stainless-steel, pressure vessel weighing roughly 4,100 pounds, and a steel steam oven approximately 2Vi feet wide, 5 feet high, and 9 feet long. Both buildings suffered extensively from blast, 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.

5.133 The damage sustained by machine tools in the Nevada tests was probably less than that suffered in Japan at the same blast pressures (§ 5.33). Certain destructive factors, present in the latter case, were absent in the 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.

5.134 The remainder of this chapter is concerned with descriptions of air-blast damage criteria for various types of targets and with the development of damage-distance relationships for predicting the distances at which damage may be expected from nuclear explosions of different energy yields. The nature of any target complex, such as a city, is such, however, that exact predictions are not possible. Nevertheless, by application of proper judgment to the available information, results of practical value can be obtained. The conclusions given here are considered to be applicable to average situations that might be encountered in an actual target complex.

5.135 Damage to structures and objects is generally classified in three categories: severe, moderate, and light. In several of the cases discussed below, the specific nature of each type of damage is described, but the following broad definitions are a useful guide.

5.8 Analysis Of Damage From Air Blast

5.8.1 Introduction

5.134 The remainder of this chapter is concerned with descriptions of airblast damage criteria for various types of targets and with the development of damage-distance relationships for predicting the distances at which damage may be expected from nuclear explosions of different energy yields. The nature of any target complex, such as a city, is such, however, that exact predictions are not possible. Nevertheless, by application of proper judgment to the available information, results of practical value can be obtained. The conclusions given here are considered to be applicable to average situations that might be encountered in an actual target complex.

5.135 Damage to structures and objects is generally classified in three categories: severe, moderate, and light. In several of the cases discussed

below, the specific nature of each type of damage is described, but the following broad definitions are a useful guide.

> *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.
>
> *Light 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. Minor repairs are sufficient to permit use of the structure or object for its intended purpose.

5.136 For a number of types of targets, the distances out to which different degrees of damage may be expected from nuclear explosions of various yields have been represented by diagrams, such as Figs. 5.140 and 5.146. These are based on observations made in Japan and at various nuclear tests, on experiments conducted in shock tubes in laboratories and with high-explosives in field tests, and on theoretical analyses of the loading and response of structures (see Chapter IV). As a result of these studies, it is possible to make reasonably accurate predictions of the response of interior as well as exterior wall panels and complete structures to the air-blast wave. These predictions, however, must take into account constructional details of each individual structure. Moreover, observations made during laboratory tests have indicated a large scatter in failure loadings as a result of statistical variations among wall and material properties. The data in Figs. 5.140 and 5.146 are intended, however, to provide only gross estimates for the categories of structures given in Tables 5.139a and b. The response of a particular structure may thus deviate from that shown for its class in the figures.

5.137 For structures that are damaged primarily by diffraction loading (§ 4.03), the peak overpressure is the important factor in determining the response to blast. In some instances, where detailed analyses have not been performed, peak overpressures are given for various kinds of damage. Approximate damage-distance relationships can then be derived by using peak overpressure-distance curves and scaling laws from Chapter III. For equal scaled heights of burst, as defined in § 3.62, the range for a specified damage to a diffraction-sensitive structure 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, for a given scaled burst height.

5.138 Where the response depends mainly on drag (or wind) loading, the peak overpressure is no longer a useful criterion of damage. The response of a drag-sensitive structure is determined by the length of the blast wave positive phase as well as by the peak dynamic pressure (§4.12 et seq.). 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 pressure 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.

5.8.2 Above-Ground Buildings And Bridges

5.139 The detailed nature of the damage in the severe, moderate, and light categories to above-ground structures of various types are given in Tables 5.139a and b. For convenience, the information is divided into two groups. Table 5.139a is concerned with structures of the type that are primarily affected by the blast wave during the diffraction phase, whereas the structures in Table 5.139b are drag sensitive.

5.140 The ranges for severe and moderate damage to the structures in Tables 5.139a and b are presented in Fig. 5.140, based on actual observations and theoretical analysis. The numbers (1 to 21) in the figure identify the target types as given in the first column of the tables. The data refer to air bursts with the height of burst chosen so as to maximize the radius of damage for the particular target being considered and is not necessarily the same for different targets. For a surface burst, the respective ranges are to be multiplied by three fourths. An example illustrating the use of the diagram is given. The various above-ground structures in Fig. 5.140 are identified (Items 1 through 21) and the different types of damage are described in Tables 5.139a and b. The "fan" from each point indicates the range of yields for which the diagram may be used. For a surface burst multiply the damage distances obtained from the diagram by three fourths.

The results are estimated to be accurate within ±20 percent for the average target conditions specified in § 5.141.

Example

Given: Wood-frame building (Type 5). A 1 MT weapon is burst (a) at optimum height, (b) at the surface. Find: The distances from ground zero to which severe and moderate damage extend.

Solution: (a) From the point 5 (at the right) draw a straight line to 1 MT (1000 KT) on the severe damage scale and another to 1 MT (1000 KT) on the moderate damage scale. The intersections of these lines with the distance scale give the required solutions for the optimum burst height; thus,

Distance for severe damage = 29.000 feet. *Answer.*
Distance for moderate damage = 33.000 feet. *Answer.*

(b) For a surface burst the respective distances are three-fourths those obtained above; hence.

Distance for severe damage = 22.000 feet. *Answer.*
Distance for moderate damage = 25.000 feet. *Answer.*

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

5.8.3 Structural Elements

5.8.4 Drag-Sensitive Targets

Transportation Equipment Communication and Power Lines Forests

5.8.5 Parked Aircraft

5.151 Aircraft are relatively vulnerable to air blast effects associated with nuclear detonations. The forces developed by peak 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.

5.152 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 (§ 5.94). 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.

5.153 The various damage categories for parked transport airplanes, light liaison airplanes, and helicopters are outlined in Table 5.153 together with the approximate peak overpressures at which the damage may be expected to occur. The aircraft are considered to be parked in the open at random orientation with respect to the point of burst. The data in the table 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.

5.154 Aircraft with 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).

5.8.6 POL Storage Tanks

5.155 The chief cause of failure of POL (petroleum, oil, lubricant) storage tanks exposed to the blast wave appears to be 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. Furthermore, 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. Peak overpressures required for severe damage to POL tanks of diameter D may be obtained from Figs. 5.155a and b. Figure 5.155a is applicable to nuclear explosions with energy yields from 1 to 500 kilotons and Fig. 5.155b to yields over 500 kilotons. For yields less than 1 kiloton, the peak overpressure for severe damage may be taken to be 1 pound per square inch.

5.8.7 Lightweight, Earth Covered and Buried Structures

5.156 Air blast is the controlling factor for damage to lightweight 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 be determined by the degree of protection from nuclear radiation required at the design overpressure or dynamic pressure (see Chapter VIII).

5.157 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.

5.158 For lightweight, shallow buried underground structures the top of the earth cover is at least flush with the original grade but the depth of cover is not more than 6 percent of the span. Such structures are not sufficiently deep for the ratio of the depth of burial to the span to be large enough to obtain the benefits described in § 5.161. The soil provides little attenuation of the air blast pressure applied to the top surface of a shallow buried underground structure. Observations made at full-scale nuclear tests indicate that there is apparently no increase in pressure on the structure as a result of ground shock reflection at the interface between the earth and the top of the structure.

5.159 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. 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.

5.160 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 5.160 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.

5.161 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 attenuation with depth of the pressure induced by air blast, and from the arching of the load from more deformable areas to less deformable ones. Limited experience at nuclear tests suggests that the arching action of the soil effectively reduces the loading on flexible structures.

5.9 Bibliography

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6

Radio and Radar Effects

6.1 Introduction

6.1.1 Radio Blackout

10.01 The transmission of electromagnetic waves with wavelengths of 1 millimeter or more, which are used for radio communications and for radar, is often dependent upon the electrical properties, i.e., the ionization (§ 8.17), of the atmosphere. The radiations from the fireball of a nuclear explosion and from the radioactive debris can produce marked changes in the atmospheric ionization. The explosion can, therefore, disturb the propagation of the electromagnetic waves mentioned above. Apart from the energy yield of the explosion, the effects are dependent on the altitudes of the burst and of the debris and on the wavelength (or frequency) of the electromagnetic waves. In certain circumstances, e.g., short-wave (high-frequency) communications after the explosion of a nuclear weapon at an altitude above about 40 miles, the electromagnetic signals may be completely disrupted, i.e., "blacked out," for several hours.

10.02 In this chapter, the normal ionization of the atmosphere will be described and this will be followed by a discussion of the disturbances produced by nuclear bursts at various altitudes. Consideration will then be given to the effects of these disturbances on the propagation of electromagnetic waves in different frequency ranges. Apart from the effects that can be ascribed directly to changes in ionization, radio communications and radar signals can be degraded in other ways, e.g., by noise, distortion, changes in direction, etc. These disturbances, which cannot be treated in a quantitative manner, will be discussed briefly.

6.1.2 Electromagnetic Pulse

10.03 Another consequence of a nuclear explosion that may cause temporary interference with radio and radar signals is an electrical (or electromagnetic) pulse of short duration emitted from the region of the burst. The most serious potential effects of this pulse are damage to electrical and electronic equipment, rather than to the propagation of electromagnetic waves. Hence, the electromagnetic pulse will be considered separately in Chapter XI.

6.1.3 Effect of Ionization on Electromagnetic Waves

10.04 Ionization, that is, the formation of ion pairs consisting of separated electrons and positive ions, can be produced, either directly or indirectly, by the gamma rays and neutrons of the prompt nuclear radiation, by the beta particles and gamma rays of the residual nuclear radiation, by the X rays and the ultraviolet light present in the primary thermal radiation, and by positive ions in the weapon debris. 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.

10.05 When an electromagnetic wave[1] interacts with free electrons, some of the energy of the wave is transferred to the electrons as energy of vibration. If the electrons do not lose this energy as the result of collisions with other particles (atoms, molecules, or ions) in the air, they will reradiate electromagnetic energy of the same frequency, but with a slight time delay. Thus, the energy is restored to the wave without loss, but with a change in phase (§ 10.82 *et seq.*). If, however, the air density is appreciable, e.g., more than about one ten-thousandth (10^{-4}) of the sea-level value, as it is below about 40 miles altitude, collisions of electrons with neutral particles will take place at a significant rate. Even above 40 miles, collisions between electrons and ions are significant if the electron density is abnormally high. In such collisions, most of the excess (coherent) energy of the electron is transformed into kinetic energy of random motion and cannot be reradiated. The result is that energy is absorbed from the wave and the electromagnetic signal is attenuated.

10.06 Other conditions being the same, more energy is absorbed from an electromagnetic wave by an ionized gas as the wavelength of the signal is increased, i.e., as its frequency decreases. This may be regarded as being due

[1] As used in this chapter, the term "electromagnetic wave" refers to radiations of wavelength of 1millimeter or more, such as are used in radio and radar, and not to the entire spectrum described in § 1.74 *et seq.*

to the longer time interval, as the frequency is decreased, between successive alternations (or reversals) of the oscillating electromagnetic field (§ 1.73). When the accelerating influence of the wave is applied for a longer time, a given electron will attain a higher vibrational velocity during each cycle of the wave, and will dissipate a greater amount of energy upon collision.

10.07 Positive and negative ions can also absorb energy from an electromagnetic wave. Because of their larger mass, however, the ions attain much lower velocities than electrons and so they are less effective in absorbing energy. Thus, the effects of ions may ordinarily be neglected. However, for some situations in the denser (low-altitude) portion of the atmosphere, where ions can persist for an appreciable time, or for frequencies low enough for the ions to have time to acquire significant velocity before reversal of the electromagnetic field, the effect of ions may be important.

10.08 A radio or radar wave traveling upward from the ground begins to be bent (refracted) when an increase of electron density is encountered. Increased electron density causes the wave path to bend away from the region of higher electron density toward the region of lower density (§ 10.85). As the electromagnetic wave penetrates farther into a region where the electron density increases toward a peak value, more and more bending occurs. For certain combinations of the angle of incidence (angle between propagation direction and the vertical), the electron density, and the frequency, the wave may actually be refracted back toward the earth (Fig. 10.08). This process is commonly referred to as "reflection," although it is not the same as true reflection, in which there would be no penetration of the ionized layer of air. True (or specular) reflection, as from a mirror, does occur to some extent especially with electromagnetic waves of the lowest radio frequencies.

6.1.4 Ionization in the Normal Atmosphere

10.09 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 30 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. 9.126). The ionosphere consists of three, more-or-less distinct, layers, called the D-, E-, and F-regions. Multiple layers, which sometimes occur in the E- and F-regions, may be disregarded for the present purpose. Typical variations of electron density with altitude and with time of day are illustrated in Fig. 10.09. The approximate altitudes of the three main regions of the ionosphere are given in Table 10.09.

10.10 Although the D-, E-, and F-regions always exist in the daytime and the E- and F-regions at night, the details of the dependence of the electron density on altitude, especially in the F-region, vary with the season, with the geographic latitude, with the solar (sunspot) activity, and with

Table 10.09: Approximate altitudes of regions in the ionosphere

Region	Approximate Altitude (miles)
D	30 – 55
E	55 – 95
F	Above 95

other factors. The curves in Fig. 10.09 are applicable to summer, at middle latitudes, around the time of maximum sunspot activity. The effects of the variable factors mentioned above are fairly well known, so that the corresponding changes in the electron density-altitude curve can be predicted reasonably accurately.

10.11 In addition to these systematic variations in the electron density, there are temporary changes arising from special circumstances, such as solar flares and magnetic storms. Solar flares can cause a ten-fold increase in the electron density in the D-region, but that in the F-region generally increases by no more than a factor of two. Magnetic storms, on the other hand, produce most of their effect in the F-region. In some latitudes, the maximum electron density in the ionosphere during a magnetic storm may decrease to some 6 to 10 percent of its normal value.

10.12 Apart from these major changes in electron density, the causes of which are known, there are other variations that are not well understood. Sometimes an irregular and rapidly varying increase in the electron density is observed in the E-region. Apparently one or more layers of high electron density are formed and they extend over distances of several hundred miles. This is referred to as the "sporadic-E" phenomenon. A somewhat similar effect, called "spread-F," in which there are rapid changes of electron density in space and time, occurs in the F-region. The areas affected by spread-F are generally much smaller than those associated with sporadic-E.

6.1.5 Characteristics of the Ionosphere

10.13 The composition of the atmosphere, especially at the higher altitudes, varies with the time of day and with the degree of solar activity; however, a general description that is applicable to daytime conditions and mean sunspot activity is sufficient for the present purpose. Near the earth's surface, the principal constituents of the atmosphere are molecular nitrogen (N_2) and molecular oxygen (O_2). These diatomic gases continue to be the dominant ones up to an altitude of approximately 75 miles. At about 55 miles, ultraviolet radiation from the sun begins to dissociate the oxygen molecules into two atoms of oxygen (O). The extent of dissociation increases with altitude, so that above 120 miles or so, oxygen atoms are the dominant species in the low-pressure atmosphere. This condition persists up to an altitude of some 600 miles. Ozone (O_3) and nitric oxide (NO) are formed in the lower atmosphere by the action of solar radiations on the oxygen and nitrogen. Although the amounts of ozone and nitric oxide are quite small, they are important because each absorbs radiation and enters into chemical reactions in a characteristic manner.

10.14 The electrons (and positive ions) in the normal ionosphere are produced by the interactions of solar radiations of short wavelength with the various molecular and atomic species present in the atmosphere. In the D-region, the ions are almost exclusively NO^*, and these ions are also the most important in the E-region; in the latter region, however, there are, in addition, about one-third as many O_2^+ ions. Atomic oxygen ions, O^+, begin to appear in the upper parts of the E-region, and their proportion increases with altitude. In the F-region, the proportion of NO^+ and O_2^+ ions decreases, where as that of O^+ increases steadily. Above an altitude of about 120 miles (up to 600 miles), O^+ ions are dominant.

10.15 The actual electron density at any altitude depends on the rate of formation of electrons as a result of ionization and their rate of removal, either by recombination with positive ions or by attachment to neutral particles (molecules or atoms). Recombination tends to be the more important removal process at high altitudes (low atmospheric pressure), whereas attachment to neutral particles predominates at lower altitudes, where molecular nitrogen and oxygen are the main components of the atmosphere.

10.16 At altitudes below about 30 miles, i.e., below the D-region, where the air is relatively dense, the probability of interaction between free electrons and neutral molecules is large. The few electrons that are produced by short wavelength solar radiation that penetrates so low into the atmosphere are thus rapidly removed by attachment.The density of free electrons in the atmosphere below about 30 miles is consequently so small that it can be neglected.

10.17 In the altitude range from roughly 30 to 55 miles (D-region of the ionosphere), the density of neutral particles is relatively low, between about 10^{-3} and 10^{-5} of the sea-level density. Because of this low density, the rate of attachment is not large and electrons 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 between about 10^2 and 10^3 electrons per cubic centimeter (electrons/cm^3) in the daytime. At night, when electrons are no longer being generated by solar radiations, the free electrons in the D-region 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 collisions to cause considerable attenuation of electromagnetic waves, in the manner described in § 10.05.

10.18 In the E-region of the ionosphere (55 to 95 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 daytime electron density is about 10^3 to 10^5 electrons/cm^3, 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 in the E-region. If sporadic-E conditions exist, radio signals are reflected (§ 10.08) in an erratic manner.

10.19 The F-region extends upward from an altitude of about 95 miles. Here the neutral-particle density is so low that free electrons have extremely long lifetimes. At about 190 miles, the peak electron density in the daytime is approximately 10^6 electrons/cm^3, decreasing to about 10^5 electrons/cm^3 at night. During the day there are various layers of ionization in the F-region, which tend to merge and lose their identity at night. The altitude of peak ionization may also shift at night. Other factors causing changes in the F-region were referred to earlier (§ 10.12). Attenuation of electromagnetic signals in the F-region is small, despite the high electron density, because of the very low electron-neutral collision frequency; however, reflection effects (§ 10.08) make the region important.

10.20 Normally, the low electron densities in the D-region are sufficient to reflect back to earth only those electromagnetic waves with frequencies below about 1 million hertz, ,i.e., 1 megahertz (§ 1.74), provided the angle of incidence is small. At larger angles, the limiting frequency for reflection by the normal D-region is increasingly less than 1 megahertz. Waves of higher frequency pass through the D-region, with some refraction (bending) and attenuation, and penetrate into the E-region or into the F-region if the frequencies are high enough. Reflection may then occur in the E- or F-region, where the electron densities are higher than in the D-region. For a given angle of incidence, the electron density required for reflection increases with the frequency of the electromagnetic wave. The smaller the angle of incidence, i.e., the more nearly vertical the direction of propagation, the higher the frequency that will be reflected by a given electron density.

6.2 Ionization Produced by Nuclear Explosions

6.2.1 Introduction

10.21 Up to three-fourths of the energy yield of a nuclear explosion may be expended in ionizing the atmosphere. The resulting changes are characteristic of the given weapon and of the burst and debris altitudes. The ionization effects caused by the nuclear and thermal radiations from a low-altitude nuclear explosion are much more intense within a limited volume of space, i.e., in and near the fireball, than the changes produced naturally, e.g., by solar flares. Nuclear explosions at high altitudes may affect a considerable portion of the ionosphere in ways somewhat similar to changes in solar activity; however, the mechanisms and details of the interactions with the atmosphere are quite different. Because of the complexities of these interactions, descriptions of "typical" changes to be expected from a nuclear explosion are often not applicable or even very meaningful. A careful analysis of each situation, with the conditions stated fairly explicitly, is usually necessary.

10.22 Atmospheric ionization and disturbances to the propagation of electromagnetic signals caused by a nuclear explosion can be described in terms of four spatial regions: (1) the hot fireball, (2) the atmosphere surrounding the fireball, (3) the D-region, and (4) the high- altitude region which includes the normal E- and F-regions of the ionosphere.

10.23 Fireballs from explosions at low altitude are relatively small (roughly, a 1-megaton explosion at sea level produces a fireball of about 0.6 mile diameter at 1 second). The air inside the fireball is at a temperature of many thousands of degrees. Electron density and collision frequency are high, and the absorption of electromagnetic waves is so large that the fireball is considered to be opaque. At intermediate burst altitudes (up to about 50 or 60 miles), the early fireball is larger in size, but it is still defined as a hot, ionized mass of air which is opaque to radio and radar signals for many seconds With increasing altitude the characteristics of the region of energy absorption change. At burst altitudes above about 190 miles, the atmosphere is very thin and the energy from the nuclear explosion can spread over very large distances.

10.24 When the burst point is below the D-region, the atmosphere around the fireball is ionized in varying around the fireball is ionized in varying degrees by the initial thermal and nuclear radiations and by the delayed gamma rays and beta particles from the radioactive debris. The chemistry of the atmosphere may be modified significantly, thus making predictions of electron persistence difficult (and greatly complicating the problem of analyzing multiple-burst situations). For near-surface explosions, the density of the air prevents radiation from escaping very far from the fireball, and the ionization is both localized and short-lived due to very rapid attachment of free electrons to neutral particles. As the detonation altitude is increased the radiation can escape to greater distances, and the electron density will reach values at which electromagnetic signal propagation can be affected.

10.25 When prompt of delayed radiation from the explosion can reach the D-region, the electron density of that region is enhanced. Most of the widespread and persistent absorption of electromagnetic waves then takes place in and near the D-region of the normal ionosphere. For electromagnetic waves in the radio and radar frequency ranges, circumstances are such that the maximum attenuation usually occurs within a layer 10 miles deep centered at an altitude of about 40 miles (§10.128). Hence, most of the subsequent discussion pertaining to D-region ionization will be in terms of the free electron density at an altitude of 40 miles.

10.26 In the E- and F-regions of the ionosphere, the frequency of electron-neutral particle collisions is low, and refraction rather than absorption is generally the predominant effect. When the burst or debris altitude is high enough for prompt or delayed radiation to reach the E- and F-regions, the electron density of those regions may be increased. On the other hand, nuclear explosions sometimes cause a decrease of electron density in the E- and F-regions, largely due to traveling hydrodynamic and hydromagnetic disturbances[2] and to changes in air chemistry (§10.71 *et seq.*).

10.27 Increased ionization in the D-region may occur not only in the vicinity of the nuclear explosion, but also at its magnetic conjugate in the earth's opposite hemisphere (§2.143). Charged particles, especially beta particles (electrons), resulting from the explosion will spiral along the earth's magnetic field lines. Upon reaching the conjugate region, the beta particles will cause ionization similar to that produced near the burst point.

6.2.2 Energy Deposition

10.28 A detailed analysis of energy deposition, the starting point for examining the effects of nuclear explosions on the propagation of radio and radar signals, is very complicated. The fundamental principles, however, are well known and relatively simple. Consider ionizing radiation entering the earth's atmosphere from a nuclear explosion at high altitude or, as it normally does, from the sun. As it travels downward, the radiation at first encounters air of such low density that very few interactions occur with atmospheric atoms and molecules. Hence, very little ionization is produced. As the air density increases with decreasing altitude, interactions of the atoms and molecules with the radiation take place at rapidly increasing rates and energy is removed from the radiation.

10.29 The concept of "stopping altitude" provides a useful approximate model for treating of ionizing radiation and the atmosphere in which the density changes with altitude. The stopping altitude for a given type of radiation is the level in the atmosphere to which that radiation coming from above will penetrate before losing so much of its energy that it produces little further ionization. The radiation is then said to have been "stopped." Most of the energy will actually be deposited within a few miles of the stopping altitude. Only a small proportion of the energy is absorbed at the higher altitudes where the air has a lower density and is relatively transparent to the radiation, and little energy remains to be given up at lower altitudes.

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[2] A hydrodynamic disturbance of the atmosphere is a direct result of the shock wave. The air is ionized and so its motion is affected by the earth's magnetic field. The combination of hydrodynamic and magnetic effects leads to hydromagnetic (or magnetohydrodynamic) disturbances.

Different types of radiation deposit their energy in the atmosphere in different ways and thus have different stopping altitudes. Table 10.29 shows approximate stopping altitudes for various ionizing out puts from a typical nuclear explosion. The altitude quoted for debris ions refers to ionization that results from the random (thermal) motion of these ions. The debris mass can, however, be carried to greater heights by the rising fireball and cause ionization by the emission of delayed radiations.

Table 10.29: APPROXIMATE STOPPING ALTITUDES FOR PRINCIPAL WEAPON OUTPUTS CAUSING IONIZATION

Weapon Output	Stopping Altitude (miles)
Prompt Radiation	
X rays	35 to 55
Neutrons and gamma rays	15
Debris ions	70
Delayed Radiation	
Gamma rays	15
Beta rays	35

10.30 For detonations below 15 miles altitude, the minimum stopping altitude in Table 10.29, the air is essentially opaque to all ionizing radiations. The radiation will penetrate only a fairly short distance into the atmosphere before most of its energy is absorbed in causing ionization (or is transformed into other kinds of energy). As the altitude of the explosion increases to 15 miles and above, the radiation can escape to increasingly greater distances. Once the stopping altitude for a given ionizing radiation is reached, the atmosphere above the burst is relatively transparent to that radiation, which can then travel upward and outward to great distances.

10.31 Below the stopping altitude, in a region of uniform density, the nominal penetration distance of ionizing radiation of a particular kind and energy is inversely proportional to the air density. (The penetration distance is often expressed in terms of the mean free path, as described in §2.113.) For a particular radiation of a single energy traveling through an undisturbed region of constant density, the penetration distance (or mean free path) can be calculated relatively easily. For a radiation spectrum covering a range of energies and for complex paths along which the air density changes, the computations are more laborious. For a disturbed atmosphere, calculations of the penetration distance are difficult and not very reliable.

6.2.3 Location of the Resultant Ionization

10.32 The region of maximum energy deposition is the location where ion-pair production is the greatest, but it is not always the location of the maximum density of free electrons. At altitudes below about 30 miles, i.e., at relatively high air densities, removal processes are so rapid that the average lifetime of a free electron is a fraction of a second. An extremely high ion-pair production rate is then required to sustain even a few free electrons per cubic centimeter. But in the D-region (starting at about 30 miles altitude) removal processes are not so rapid and higher electron densities are possible. For the delayed gamma rays, for example, the stopping altitude, i.e., the region of maximum energy deposition and ion-pair production rate, is 15 miles; how ever, the resultant electron density tends to a maximum at a higher altitude in the D-region.

10.33 To understand the ionization resulting from nuclear explosions, it is helpful to examine four detonation altitude regimes separately; they are; (1) below 10 miles, (2) between 10 and 40 miles, (3) between 40 and 65 miles, and (4) above 65 miles. Different mechanisms associated with various burst heights will be considered, but it should be understood that these altitude regimes 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, and one type of mechanism gradually supersedes another and becomes dominant. The four spatial regions where there may be significant effects (§10.22) also shift in importance as the altitudes of the detonation and of the radioactive debris change.

6.2.4 Detonation Below 10 Miles in Altitude

10.34 For nuclear explosions at altitudes below 10 miles (and somewhat higher), most of the energy is deposited in the atmosphere in the immediate vicinity of the detonation, resulting in the formation of the fireball and the air blast wave, as described in Chapter II. The electron density within the fireball, initially at least equal to the particle density (about 10^{19} cm^3), will remain above about 10^8 electrons/cm^3 for times up to 3 and 4 minutes, depending on the nature of the weapon. For about 10 seconds the fireball temperature will be high enough (above 2,500° Kelvin) to cause significant ionization of the air by the thermal radiation (§10.04). After this period, beta radiation from the radioactive debris within the fireball may sustain the ionization level for up to 3 or 4 minutes. Thus, the fireball region will be sufficiently ionized to absorb electromagnetic signals for a period of at least 10 seconds and possible for as long as 3 or 4 minutes; however, the spatial extent of the ionization will be small.

10.35 After a few seconds, as the hot fireball rises upward buoyantly (§2.129), it will take the form of a torus. The torus, having lost its luminous qualities, will coalesce into a flattened cloud shape. The transition from a fireball or torus to a debris cloud is indefinite, but at late enough times—after a few minutes—the fireball as such will cease to exist, and only a cloud of radioactive debris will remain. This cloud will reach a final stabilization altitude in about 5 minutes. It will then be spread by whatever winds prevail at that altitude range. Typically, the average spreading velocity is about 35 feet per second.

10.36 The atmosphere surrounding the fireball will be ionized by prompt neutrons and by prompt gamma radiation, but the free electrons thus formed will persist less than a second. The air will also be ionized by the delayed radiation emitted continuously from the radioactive debris within the fireball. Close to the fireball, the continuous emission from the adjacent gamma-ray source will result in a high electron density in spite of the fairly rapid removal of electrons by attachment of air particles at the low altitudes under consideration. Thus, for detonations below10 miles, there will be a region surrounding the fireball which will absorb electromagnetic waves appreciably for tens of seconds. This effect will be negligible for most radiofrequency systems, but it may be significant for radars with highly directional beams that pass fairly near (in addition to those passing through) the fireball.

10.37 In the atmosphere around the region referred to above, the electron density will be much lower because the gamma rays are somewhat attentuated by the air, and the electrons that are formed are removed rapidly by attachment. Hence, the number of free electrons is not expected to be as large, neither will they be as widely distributed, as in the region around the fireball for bursts at higher altitudes (§10.43 *et seq.*). Refraction of radar signals (§10.118) and clutter (§10.120) may then be more significant than absorption. These effects are also important if the signals pass through or near the stem or cloud of a burst that is sufficiently low for debris from the surface to be carried aloft.

10.38 The D-region is not affected to any great extent by prompt radiation from nuclear explosions below 10 miles, since the burst is below the stopping altitude for X rays, neutrons, and gamma rays (Table 10.29). Ionization in the D-region may be increased, however, by delayed radiation, if the radioactive debris is carried upward by the rising fireball above 15 miles, the stopping altitude for gamma radiation. There may be additional ionization due to beta particles if the debris rises as high as 35 miles, but this is expected only for weapons of large yield (see Fig. 10.158c).

10.38 Ionization in the E- and F-regions is not changed significantly by radiation from a nuclear explosion below 10 miles, except possibly by the rising debris from a high-yield burst (cf. §10.41). However, perturbations in the refractive properties of the F-region have been noted following explosions in this altitude regime. Traveling disturbances (§10.26) that move outward in the E- and lower F-regions appear to result from the initial blast wave.

6.2.5 Detonations at 10 to 40 Miles Altitude

10.40 If the explosion occurs in the altitude regime of roughly 10 to 40 miles, thermal energy radiated as X rays will be deposited in the vicinity of the burst, as at lower altitudes, with subsequent reradiation to form the familiar fireball. Ionization by debris ions or by beta particles within the fireball may sustain the electron density after the temperature has fallen to the 2,500° Kelvin required for significant thermal ionization by air. The fireball region will be ionized to high levels—more than 107 electrons per cubic centimeter—for a period of at least 30 seconds and possibly for longer than 3 minutes. The spatial extent of the ionization will be larger than for detonations at the lower altitude considered previously.

10.41 The fireball will be spherical in shape initially, with the transition from sphere to torus occurring later than for bursts at lower altitudes. Further more, the debris, most of which is carried upward by the hot, rising fireball, may reach considerably greater heights. Multimegaton weapons detonated near the upper limit of the 10 to 40 miles altitude regime will begin to exhibit the effects of an initial ballistic impulse, caused by pressure gradients across the large vertical diameter of the fireball (§2.129). As the fireball and debris rise into thinner air, they continue to expand. The ballistically rising fireball can reach altitudes far above the detonation point. Because of the rapid upward motion of the fireball and the decrease in atmospheric density with altitude, the density of the fireball may be greater than that of the surrounding atmosphere. Overshoot then occurs, and after reaching maximum altitude, the fireball descends until it encounters air of density comparable to its own.

10.42 When the cloud of debris stabilizes in altitude, its horizontal spread will be influenced by diffusion and by the prevailing winds. A spreading velocity of 165 feet per second is a reasonable estimate for debris at altitudes between about 50 and 125 miles; the spread is, however, more complex than is implied by such an assumption of a uniform expansion.

10.43 For bursts in the 10 to 40 miles altitude regime, the X rays are largely confined within the fireball, especially at the lower altitudes. Even though the prompt gamma rays carry only a small proportion of the explosion energy (§10.138), they will cause ionization in the surrounding air for a very short time. However, the main source of prompt ionization in the surrounding air (and also in the D-region for detonations above 15 miles) appears to be the fast neutrons. There are three important interaction processes of such neutrons with atomic nuclei in the atmosphere which can lead to ionization; they are absorption, inelastic scattering, and elastic scattering (see Chapter VIII). The amount of absorption is small for fast neutrons and the inelastic scattering gamma rays are spread over a large volume, so that the resulting electron density is low. Most of the neutron-induced (prompt) ionization arises from elastic scattering of the neutrons. The nuclei that recoil from the scattering process have sufficient energy to produce ionization by interaction with atmospheric atoms and molecules.

10.44 The persistent ionization in the air is caused mainly, however, by delayed gamma radiation. Most of the beta particles from the radioactive debris are absorbed within the fireball, but the gamma rays can travel great distances when the debris is above their stopping altitude (15 miles). The size of the ionized region surrounding the fireball can then be quite large. Calculation of the electron densities is fairly complicated since it depends on the attenuation of the gamma rays by the atmosphere and the electron loss mechanisms which change with altitude.

10.45 Ionization in the D-region from delayed gamma rays and beta particles will be much more important for detonations in the 10 to 40 miles altitude regime than for those below 10 miles. If the debris attains an altitude above 15 miles, the delayed gamma rays can reach the D-region and produce ionization there. When the debris is below 35 miles, the stopping altitude for beta particles, the energy of these particles is deposited close to or within the debris cloud. The ionization is thus restricted to this region.

10.46 For the beta particles to cause ionization in the D-region, the debris must be above 35 miles. Because of their electric charge, the spread of the beta particles is largely prevented by the earth's magnetic (geomagnetic) field. The area over which the beta particles produce ionization in the D-region is thus essentially the same as the area of the debris when its initial expansion has ceased.

10.47 If the debris rises above 40 miles, the beta particles will travel back and forth along the geomagnetic field lines. They will then cause ionization in the local D-region and also in the magnetic conjugate region in the opposite hemisphere of the earth (Fig. 10.47). If the radioactive debris is uniformly distributed over a horizontal plane, the electron density in the D-region due to the beta particles will be about the same in both hemispheres. In practice, atmospheric winds and turbulence and geomagnetic anomalies cause the distribution of the debris to be nonuniform, but a uniform distribution is generally assumed for estimating electron densities resulting from nuclear explosions.

10.48 Unlike the beta particles, the gamma rays are not affected by the geomagnetic field and they can therefore spread in all directions. If the debris rises above 40 miles, the delayed gammas can produce ionization over a large area in the D-region. The ionization is not restricted by the tube of magnetic field lines containing the debris, as is that from the beta particles. The D-region ionization caused by the delayed gamma rays is thus more extensive in area although usually less intense than that due to the beta particles.

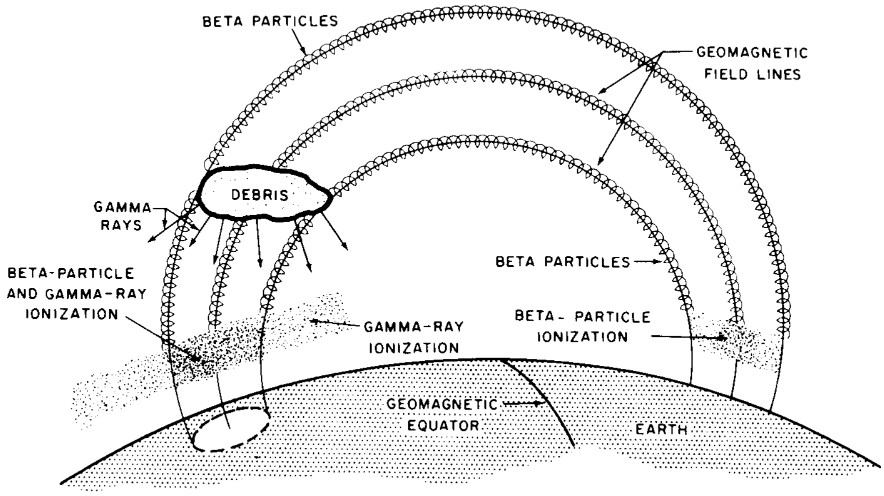

Figure 10.47: Location of beta and gamma ionization regions when the debris from an explosion in the northern hemisphere is above 40 miles altitude.

10.49 Since the beta particles are largely prevented from spreading by the geomagnetic field, the ionization they produce (in the D-region) is not greatly affected by the altitude to which the radioactive debris rises, provided it is above 40 miles. For the accompanying gamma radiation, however, the intensity, and hence the associated ionization, decreases the higher the altitude of the debris above the D-region. The areal extent increases at the same time.Gamma-ray ionization in the magnetic conjugate region will be much smaller and will arise from such debris ions as have traveled along the geomagnetic field lines and reached the vicinity of the D-region in the other terrestrial hemisphere (§§2.141, 10.64).

10.50 There are two other sources of ionization in the conjugate region, namely, Compton electrons and neutrons. Gamma rays lose part of their energy in the atmosphere by Compton scattering (§8.89). If the Compton electrons are formed above about 40miles, they will either deposit their energy (and cause ionization) locally in the D-region or be guided by the geomagnetic field to the conjugate region. Since delayed gamma rays are spread over a fairly large volume when the radioactive debris is above about 15 miles, Compton electrons can produce widespread ionization. The space affected is larger than that in which beta particles cause ionization in both conjugate regions.Although the ionization from Compton electrons in the magnetic conjugate region is not large, the effects on the propagation of electromagnetic waves, especially those of lower frequencies, can be important.

10.51 Many of the neutrons produced in a nuclear explosion above 15 miles will travel upward, escaping to high altitudes. Since neutrons are not affected by the geomagnetic field, they spread over a large region. A free neutron disintegrates spontaneously, with a half-life of about 12 minutes, into a proton and an electron (beta particle). The latter will be trapped by the geomagnetic field lines and will produce ionization in the D-region after following a field line into the atmosphere, either in the vicinity of the explosion or at the magnetic conjugate. The ionization levels produced by neutrons in this manner are low, but they have been detected at distances of several thousand miles from the burst point. From the times at which the effects were observed, they could have been caused only by neutrons.

10.52 Thermal X rays begin to escape from the fireball for detonations in the upper portion of the 10 to 40 miles altitude regime and can cause appreciable ionization in the E-region above the burst point. Ionization in the E- and F-regions will be perturbed by traveling disturbances to a greater extent from detonations in this altitude regime than from explosions of similar yield below 10 miles. A high-yield detonation near 40 miles altitude may produce a region of severe electron density depletion (§10.71 *et seq.*). Fireballs rising above 65 miles and beta particles escaping from fission debris above 40 miles also increase the electron density in the E- and F-regions.

6.2.6 Detonations at 40 to 65 Miles Altitude

10.53 X rays ionize a region of considerable extent around a detonation in the 40 to 65 miles regime. The mechanism of fireball formation changes appreciably in this range (§2.130 *et seq.*), since at 65 miles the X-ray stopping altitude has been exceeded, and the radiations can spread very widely. Starting at about 50 miles altitude, the interaction of the expanding weapon debris with the atmosphere becomes the dominant mechanism producing a fireball. Above about 50 miles, the geomagnetic field will influence the location and distribution of the late time fireball, as will be seen shortly. The 40 to 65 miles altitude regime is also a transitional one for deionization mechanisms in the fireball, and for the dynamic motion of the rising fireball.

10.54 Above about 40 miles, the temperature of the fireball is no longer the governing factor in ionization. The electron density changes only in accordance with the increase in volume of the fireball, thus causing a wider distribution of the free electrons in space. Recombination of electrons with positive atomic ions, produced by the high temperatures in the fireball, is the main removal process. This is, however, much slower than the recombination with molecular ions which predominates in the normal D- and E-regions. Electron densities greater than 10^8 electrons/cm^3 can then persist for tens of seconds, resulting in significant attenuation and refraction of electromagnetic waves. The persistence depends on how rapidly the fireball volume increases and on the detailed chemistry of the fireball gases.

10.55 For explosions of high and moderately high yields at altitudes near the upper limit of the regime under consideration, the fireball may rise to heights of hundreds of miles (see Figs. 10.158b and c). At these heights, the fireball and debris regions will be affected by the geomagnetic field lines (§10.63 *et seq.*). For smaller yields, the fireball generally rises buoyantly and smoothly to a nominal stabilization altitude, with no overshoot (Fig. 10.158a). A spreading velocity of 165 feet per second is frequently used to make rough estimates of debris motion for stabilization altitudes between 50 and 125 miles. If more than a rough estimate is required, upper-altitude wind information must be used to calculate the spreading velocity.

10.56 The region identified for lower altitude bursts as that around the fireball now merges into the D-, and E-, and F-regions. Hence, it will not be discussed separately here or in the next section which is concerned with detonations above 65 miles altitude.

10.57 The D-region is more widely influenced by prompt radiation from detonations above 40 miles than from detonations below that altitude, since both X rays and neutrons have longer penetration distances at the higher altitudes. For detonations above 40 miles, X rays produce essentially all the prompt ionization in the D-region. As indicated in §10.43, fast neutrons are apparently the main source of prompt ionization in this region for detonations at somewhat lower altitudes.

10.58 Continuing ionization of the D-region by delayed gamma rays and beta particles is of major importance when the burst altitude is between 40 and 65 miles. The situation is similar to that described in §10.47 for the case in which the debris rises to a height of more than 40 miles. The beta-particle ionization is restricted to areas, in the D-regions of both hemispheres of the earth, which are each roughly equal to the area of the debris. The delayed gamma rays spread in all directions, however, and the ionization in the D-region near the burst point is consequently more extensive in area but is less intense than that due to the beta particles. The upward motion of the debris can allow the gamma rays to irradiate areas of the D-region several hundred miles in radius. It is apparent that the electron densities resulting from such widespread irradiation will generally be low.

10.59 Compton electrons from delayed gamma rays and beta particles formed by the spontaneous disintegration of neutrons can cause widespread, although relatively weak, ionization in the D-region near the burst point and also at its magnetic conjugate. The general effects are similar to those described in §§10.50 and 10.51 for nuclear detonations at lower altitude.

10.60 Detonations above 40 miles, and particularly those above 50 or 55 miles, will irradiate the E-region extensively with X rays. Consequently, there will be prompt ionization, with the usual fairly long E-region recovery time, in addition to that caused by the continuing radiations from the radioactive debris. Ionization effects in the E-region, similar to sporadic-E (§10.12), have been noted following detonations above 40 miles.

10.61 Strong F-region disturbances, involving an initial increase followed by a decrease in electron density, were observed over an area of more than a thousand miles in radius for many hours after the TEAK megaton-range burst at about 48 miles altitude (§2.52). The proposed explanation for these disturbances is given in §10.71 *et seq.*There also appeared to be an effect similar to spread-F (§10.12) which ended at sunrise, and some tilting of the normal ionospheric stratification which altered the path of reflected radio signals. Similar but less severe effects were noted after subsequent high-altitude explosions.

6.2.7 Detonations Above 65 Miles

10.62 The mechanisms of fireball formation and growth continue to change as the detonation altitude increases above 65 miles. At these altitudes, X rays travel great distances in the very low-density atmosphere and do not produce a normal fireball. Below about 190 miles, depending on the weapon yield, the energy initially appearing as the high outward velocity of debris particles will still be deposited within a fairly short distance. This results in the formation of a heated and ionized region. The apparent size of this so-called "fireball" region may depend on the manner in which it is viewed. The optical (or radiating) fireball may not coincide with the radar fireball, i.e., the region affecting radar signals, and the fireball boundary may not be well defined. Because of the large dimensions, times of the order of a few seconds may be required before the initial motion of the debris is reduced significantly.

10.63 The geomagnetic field plays an increasingly important role in controlling debris motion as the detonation altitude increases. Above about 300 miles, where the density of the atmosphere is very low, the geomagnetic field is the dominant factor slowing the outward expansion of the weapon debris. This debris is initially highly ionized and is consequently a good electrical conductor. As it expands, it pushes the geomagnetic field out ahead of it, and the magnetic pressure caused by the deformation of the field can slow down and stop the debris expansion. The debris may expand hundreds of miles radially before being stopped by the magnetic pressure. The problem of the expansion of ionized debris against a magnetic field is quite complex. Instabilities in the interface between the expanding debris and the geomagnetic field can cause jetting of debris across field lines, and some debris can escape to great distances.

10.64 Debris initially directed downward will be stopped by the denser air below the burst point at an altitude of about 70 miles, whereas upward-directed debris travels for long distances. If, in being stopped by the atmosphere, the downward-directed debris heats and ionizes the air, that heated region will subsequently rise and expand. Some upward-directed, ionized debris will follow geomagnetic field lines and will reach the conjugate region in the other hemisphere of the earth.

10.65 The geomagnetic field will also play an important role in determining the continued growth and location of the ionized region once it has formed. Expansion along the field lines can continue after expansion across the field has stopped. Arcs (or tubes) of charged particles, mainly beta particles, may be formed, extending from one hemisphere to the other. Ionization will then occur in the upper atmosphere in each conjugate region. This may happen even for detonations below 65 miles if the fireball is still highly ionized after it reaches altitudes of a few hundred miles.

10.66 Within the fireball, the rapidly moving debris ions cause ionization of the air; each such ion can ionize many air molecules and atoms before losing its kinetic energy. Because of the reduced air density above 65 miles, the initial ionization within the fireball is less than for detonations at lower altitudes. However, if expansion is largely along the geomagnetic field lines, decrease in electron density due to volume expansion may be relatively slow. Dimensions across the geomagnetic field are typically a few hundred miles after a few minutes.

10.67 As stated in §10.54, electron recombination with positive atomic ions will proceed slowly, and electron densities in the fireball high enough to produce attenuation of radar signals may last up to a few minutes. Electron densities sufficient to affect electromagnetic signals of lower frequency may persist much longer. The formation, location, and extent of the ionized regions are dependent both on weapon characteristics and atmospheric composition and are difficult to predict.

10.68 Apart from the ionization within the fireball region due to the kinetic energy of the debris ions, the radioactive debris causes ionization (in the D-region), after the initial expansion has ceased. This ionization results from the emission of beta particles and delayed gamma rays. Hence, the location of the debris after the initial expansion is important.

10.69 Neutrons and X rays traveling downward from a burst above about 65 miles altitude will irradiate large areas of the D-region. Some widespread ionization of low intensity will also be caused by the decay of neutrons in the earth's magnetic field, as described in §10.51.

10.70 The debris that is initially directed upward or jets across the field lines 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 along the field lines and drifting eastward in longitude around the earth, will spread within a few hours to form a shell of high-energy beta particles, i.e., electrons, completely around the earth (§2.147).

6.2.8 Indirect Effects of High–Altitude Explosions

10.71 The electron density in the E- and F-regions of the ionosphere may be changed by effects associated with a nuclear explosion other than direct ionization. The most important of these effects are hydrodynamic (shock) and hydromagnetic disturbances (see §10.26 footnote) and changes in air chemistry. As the shock wave from the detonation propagates through the atmosphere, the air in a given region experiences first a compression phase and then a suction phase (§3.04). During the compression phase, the density of the air, and hence of the electrons present, increases because of the decrease in volume. However, the combined effect of heating by compression and of expansion of the air during the suction phase may be a decrease in the electron density below the normal value.

10.72 The TEAK high-altitude shot produced a shock wave which propagated for several hundred miles from the burst point. As the shock passed a particular location, the electron densities in the E- and F-regions first increased and then decreased well below normal until local sunrise (§10.61). Changes in the chemistry of the atmosphere may have been partly responsible for the decrease in electron density.

10.73 As the shock wave slows down, it eventually becomes an acoustic (or sound) wave, often called a gravity acoustic wave because it is propagated in a medium (the atmosphere) whose density variation is determined by gravity. Acoustic waves travel thousands of miles from the burst point and can cause perturbations in the E- and F-regions at great distances. These perturbations are evidently hydromagnetic in nature, since the electron densities, which are difficult to calculate, are apparently dependent on the direction of propagation of the acoustic waves relative to the local geomagnetic field lines.

10.74 As well as causing ionization, X rays from a nuclear explosion, like gamma rays, can produce excited states (§8.23) of atoms and molecules of the air in the E- and F-regions. These excited neutral particles can undergo chemical reactions which affect electron densities. If the detonation altitude is above about 200 miles, the resulting changes can be widespread and may last for several hours. The moderate decrease in electron density in the F-region, observed out to more than 600 miles from the burst point after the STARFISH PRIME event (1.4 megatons at 250 miles altitude), has been attributed to changes in air chemistry caused by X rays.

6.3 Effects on Radio and Radar Signals

6.3.1 Signal Degradation

10.75 Nuclear explosions can degrade, i.e., attenuate, distort, or interfere with, signals from radar, communication, navigation, and other systems employing electromagnetic waves propagated through the atmosphere. In general, systems that depend on the normal ionosphere for propagation by reflection or scattering, as will be described in due course, can be affected over large areas for periods ranging from minutes to hours following a single burst at high altitude. Electromagnetic waves that pass through the ionosphere, but do not rely on it for propagation, e.g., satellite communication and some radar systems, can also be affected, but usually only over localized regions and for periods of seconds to minutes. Systems which use waves that propagate below the ionosphere, along lines-of-sight between ground stations or between ground stations and aircraft, will not, in general, experience signal degradation.

10.76 The signal strength required for acceptable systems performance is usually given in terms of a signal-to-noise ratio. The term "noise" refers to random signals that may originate within the receiver itself or may arise from external sources, usually thunderstorms and other electrical disturbances in the atmosphere. Nuclear explosions can also generate noise. When the signal-to-noise ratio falls below a minimum acceptable level, system degradation occurs in the form of increased error rate, e.g., symbol or word errors for communications systems and false or missed targets for radars. As the result of a nuclear explosion, the signal-to-noise ratio may be decreased by attenuation of the signal strength or by increase in noise (or by both).

10.77 Detailed analysis of system performance requires consideration of many factors. These include the following: the geographic and geomagnetic locations of the burst point and of the propagation paths; time variations of the electromagnetic transmission properties along these paths, i.e., propagation channel characteristics; the effect of these characteristics on the desired signal, on noise generated within the receiver, and on undesired signals reaching the receiver; the signal processing used; the system mission; and criteria of system performance.

6.3.2 Signal Attenuation

10.78 Absorption of energy from the electromagnetic waves is the major source of signal attenuation following the detonation of a nuclear weapon. In general, the absorption produced by a certain electron density is related inversely to the square of the wave frequency (§10.130); hence, absorption is more important for low- than for high frequency systems that use the ionosphere for long-range transmission. The extent of absorption depends strongly on the location of the transmission path relative to the burst point and to the time after the burst. Shortly after the explosion, absorption may be so intense that there is a blackout and communication is impossible. This will be followed by a period of reduced system performance before fairly normal conditions are restored. The duration of the blackout, particularly for systems operating below about 30 megahertz, is generally long in comparison with that of reduced performance. Absorption may also affect received noise levels if the noise reaches the receiver via the ionosphere.

10.79 When the electron densities are decreased by the effects of a nuclear explosion, signal attenuation, especially in the frequency range between 3 and 30 megahertz, can result from loss of reflection (due to refraction) from the E- and F-region. Signals which would normally reach the receiver by reflection from the ionosphere may then be only weakly refracted so that they continue into space.

6.3.3 Noise

10.80 Two noise sources from a nuclear detonation are thermal radiation from the fireball and synchrotron radiation from beta particles traveling along the geomagnetic field lines. The fireball may remain at temperatures above 1,000° Kelvin for a few hundred seconds and may produce considerable noise if the antenna is pointed at the fireball. Thermal noise generally will be significant only for systems with low (internal) receiver noise. The actual noise received will depend on the properties of the fireball, e.g., whether or not it is absorbing at the frequency of interest, the amount of attenuation outside the fireball, and the directivity of the receiving antenna.

10.81 Beta particles spiraling along the geomagnetic field lines radiate electromagnetic energy in the form of what is known as "synchrotron radiation." This covers a range of frequencies, but is much more intense at low than at high frequencies. Synchrotron radiation picked up by an antenna will produce noise in the receiver. However, the noise level is relatively weak and is not significant except for very sensitive, low-frequency systems with the antenna beam at right angles to the geomagnetic field lines.

6.3.4 Phase Effects

10.82 In free space, the phase velocity of an electromagnetic wave, i.e., the rate of propagation of a plane of constant phase, is equal to the velocity of light in a vacuum. In an ionized medium, however, the phase velocity exceeds the velocity of light by an amount which depends on the frequency of the wave and the electron density of the medium. If an electromagnetic signal traverses a region that has become ionized by a nuclear detonation, it will consequently suffer phase changes. A communication system that uses phase information will thus be affected. Furthermore, because the phase velocity varies with the wave frequency, a signal consisting of waves of several frequencies, as is commonly the case, will be distorted because the phase relationships between the waves will be changed.

10.83 If the propagation path passes through regions of varying electron densities, that is to say, if the electron densities encountered by the signal vary with time, a frequency shift (Doppler shift) occurs. For wide-band communications systems there may then be interference between adjacent channels. As a result, the effective (or useful) bandwidth would be decreased.

10.84 Although the phase velocity of electromagnetic waves is greater in an ionized medium than in free space, the group velocity, i.e., the velocity with which the signal energy is transmitted, is less than the velocity of light. The group velocity is also dependent on the wave frequency and the electron density of the medium. A signal passing through an ionized region thus suffers frequency-dependent time delays as compared with propagation through free space. This will cause various errors in radar systems, as will be seen in §10.119.

6.3.5 Refraction and Scattering Effects

10.85 The phase change of an electromagnetic wave in an ionized medium is related to the refractive index of the wave in this medium (§10.125). The index of refraction in free space is unity, but in an ionized region it is less than unity by an amount that increases with the electron density, for waves of a given frequency. As a result, the direction of propagation of an electromagnetic wave is changed in passing from free space, i.e., the nonionized (or very weakly ionized) atmosphere, into a region of significant ionization. This is the basis of the refraction (or bending) of electromagnetic waves by an ionized medium described in §10.08. The wave is always bent away from the region of lower refractive index (higher electron density) toward that of higher refractive index (lower electron density).

10.86 If an electromagnetic wave is propagated through a region of increasing electron density, i.e., of decreasing refractive index, the continued refraction may cause the wave to return to the region of low electron density from which it originally came. The wave is then said to be reflected. By increasing the electron density in the ionosphere, a nuclear detonation will change the reflection altitude of electromagnetic waves coming from the earth. Thus, systems that rely on reflection from the ionosphere for long-range communications can be adversely affected by the detonation. Even if reflected signals are not normally used, unwanted reflected signals may cause interference with the desired direct signals.

10.87 When an electromagnetic wave encounters patches (or blobs) of irregular ionization, successive refractions may lead to more-or-less random changes in the direction of propagation. This is referred to as "scattering." The term "forward scattering" is used when the propagation after scattering is in the same general direction as before scattering. If the electromagnetic wave is scattered toward the location from which it came, the effect is described as "backscattering."

10.88 Reflection and scattering of electromagnetic waves from ionized regions produced by a nuclear explosion can result in abnormal propagation paths between transmitter and receiver of a radio system. Multipath interference, which occurs when a desired signal reaches the receiver after traversing two or more separate paths, produces fading and signal distortion. Interfering signals, due to anomalous propagation from other radio transmitters, can increase noise levels to such an extent that the desired signal might be masked. In radar systems, changes in the propagation direction due to refraction can cause angular errors. Moreover, if a radar signal is scattered back to the receiver, it can mask desired target returns or, depending on the characteristics of the scattering medium, it may generate a false target (§10.120 *et seq.*).

6.3.6 Radio Communication Systems

10.89 The general category of radio systems of interest includes those in which electromagnetic waves are reflected or scattered from the troposphere (§9.126) or the ionosphere. Such systems are used primarily for long-distance communications; however, other uses, e.g., over-the-horizon radars, also fall in this category.

10.90 Detailed analysis of communications systems, even for the normal atmosphere, is difficult and depends largely on the use of empirical data. Measurements made during nuclear tests have shown that both degradation and enhancement of signals can occur. The limited information available, however, has been obtained in tests for weapon yields and detonation altitudes which were not necessarily those that would maximize the effects on communications systems.

10.91 It is convenient to discuss radio system effects in accordance with the conventional division of the radiofrequency spectrum into decades of frequency ranges. These ranges, with associated frequencies and wavelengths, are given in Table 10.91. Radar systems, which normally employ the frequency range of VHP or higher, are treated separately in §10.114 *et seq.*

Table 10.91: RADIOFREQUENCY SPECTRUM

Name of Range		Frequency Range[3]	Wavelength Range
Very Low Frequency	VLF	3–30 kHz	10^7–10^6 cm
Low Frequency	VLF	30–300 kHz	10^6–10^5 cm
Medium Frequency	VLF	300–3,000 kHz	10^5–10^4 cm
High Frequency	VLF	3–30 MHz	10^4–10^3 cm
Very High Frequency	VLF	30–300 MHz	10^3–10^2 cm
Ultra High Frequency	VLF	300–3,000 MHz	10^2–10 cm
Super High Frequency	VLF	3–30 GHz	10–1 cm
Extremely Frequency	VLF	30–300 GHz	10–1 mm

6.3.7 Very–Low–Frequency Range (3 to 30 kHz)

10.92 The frequencies in the VLF band are low enough for fewer than 100 free electrons/cm^3 to cause reflection of the signal (§10.20). The bottom of the ionosphere thus effectively acts as a sharp boundary which is not penetrated, and the electromagnetic radiation is confined between the earth and the ionosphere by repeated reflections. The resulting "sky wave," as it is called, may be regarded as traveling along a duct (or guide) whose boundaries are the earth and that level in the atmosphere at which the electron density is about 100 electrons per cubic centimeter. There is also a "ground wave" whereby the signal is transmitted along the surface of the earth and tends to follow its curvature. Global VLF broadcast communications and maritime and aerial navigation systems use the long propagation distances that are possible because ground wave attenuation is relatively low and the sky wave is reflected at the bottom of the ionosphere with little absorption.

10.93 The major effect of nuclear detonations is to cause ionization i.e., an increase in electron density, which may lower the ionospheric reflection altitude. Theoretical analyses and experimental data indicate that the major consequences are phase anomalies and changes in signal strength and in the noise from distant thunderstorms. These effects are expected to persist longer in the daytime than at night because of the slower decay of the electron density, assuming the same weapon yield and burst altitude.

10.94 Phase changes may be large and rapid, e.g., 1,000 degrees or so within a millisecond, and they are followed by a slow recovery of a few degrees per second. Such phase changes may be significant for navigation, synchronous communications, and phase modulation systems. VLF systems operating over short, medium, or long distances can be affected by the phase changes that result from the ionization produced by a nuclear explosion.

10.95 On paths of medium length, where both ground and sky waves are received, the change in phase of the sky wave may result in mutual interference of the two signals. There will then be a reduction in the strength of the processed signal. Over relatively short transmission paths, when only the ground wave is normally used, the change in reflection altitude may cause the sky wave to be received. This may enhance or interfere with the ground wave, according to circumstances. For long-distance VLF communications, when only the sky wave is important, a nuclear explosion can cause large phase changes even at a distance. Thus, after the TEAK and ORANGE high-altitude shots (§2.52), the 18.6-kilohertz signal transmitted from the Naval Radio Station at Seattle, Washington, to Cambridge, Massachusetts, suffered an abrupt phase shift. The entire path was at least 3,000 miles from the burst points.

10.96 Distant thunderstorms produce some atmospheric noise in the VLF band, the noise level depending on the ionospheric reflection height. Hence, a change in this height can affect the signal-to-noise ratio. The system degradation or improvement following a nuclear detonation will depend on the relative geographic locations of the signal source, the noise source, the ionization produced, and the propagation path. Reduction of the signal-to-noise ratio appears to be significant primarily for long transmission paths with ionospheric reflection. A single high-altitude explosion or multiple explosions which produce ionization affecting appreciable portions of a propagation path will result in maximum degradation.

6.3.8 Low–Frequency Range (30 to 300 kHz)

10.97 As the electromagnetic wave frequency is increased above 30 kilohertz, the normal ionosphere behaves much less as a sharp boundary. The wave penetrates several miles before being reflected back toward the earth. The altitude to which the wave penetrates and the attenuation normally experienced depend strongly on the magnitude and the rate of vertical change, i.e., the gradient, of electron density at the bottom of the ionosphere. Reflection extends the useful range of propagation, particularly at night when ionization in the lower D-region is normally absent. Attenuation of the sky wave increases in the daytime, especially for the higher frequencies because of their greater penetration. Although ground waves are commonly used for LF transmissions, sky waves often provide acceptable signals a few thousand miles from the transmitting station.

10.98 Ionization from nuclear explosions will generally not degrade the performance of LF systems which normally depend only on the ground wave unless the change in reflection altitude causes the sky wave to be received. As with VLF, this may enhance or interfere with the ground wave according to the circumstances; however, reception of the sky wave is less likely for LF than for VLF. Systems which rely on skywave propagation may experience attenuation lasting from a few minutes to several hours. For a given yield and burst height, the duration of the disturbance may be expected to be greatest in the daytime. The most severe attenuation appears to occur for long paths, when ionization produced by the detonation affects appreciable portions of the propagation path. Furthermore, large phase shifts can occur.

6.3.9 Medium–Frequency Range (300kHz to 3 MHz)

10.99 Normal propagation in the MF band is characterized by large attenuation of sky waves in the daytime, limiting communication at such times to ground waves. Increase of ionization in the D-region from high-altitude nuclear explosions will cause further attenuation of MF sky waves, and propagation may be limited to the ground wave during both day and night. In regions near the burst (or its magnetic conjugate) the sky wave may be blacked out for hours. Since atmospheric noise propagated by the ionosphere is a principal source of interference, absorption in the D-region may improve ground-wave reception for some paths. However, the limiting signal-to-noise ratio is determined primarily by local thunderstorm activity. Reduction of noise from distant thunderstorms will thus not improve marginal reception.

6.3.10 High–Frequency Range(3 to 30 MHz)

10.100 The HF band is used extensively for long-range communications; the frequencies are high enough to permit transmission of information at a rapid rate and yet are sufficiently low to be reflected by the ionosphere. The signals are propagated from the transmitter to a receiver by successive reflections from the E- or F-region and the surface of the earth. Electromagnetic waves, with frequencies toward the lower end of the HF range are normally reflected from the E-region of the ionosphere after suffering some attenuation by absorption in the D-region. Reflection at the upper end of the range requires higher electron densities and occurs from the F-region (§10.135).

10.101 If a nuclear explosion increases the electron density in the D-region above its usual maximum value of about 10^3 electrons/cm^3, signal attenuation by absorption will be increased. Furthermore, the increase in electron density may lower the reflection altitude and thus change the propagation path of the signal. Communications (and other) systems using the HF range can thus be seriously degraded. Disturbances resulting from an increase in the D-region electron density will persist longer in the daytime than at night, but decreases in the E- and F-regions may reverse the situation (§10.105).

10.102 Both prompt and delayed radiations from a nuclear burst can produce sufficient ionization to cause blackout of HF signals, lasting from a few seconds to several hours. The recovery time depends, among other things, on the weapon yield and the detonation altitude. The period during which the system is degraded is greater for lower than for higher frequencies, because a higher electron density is required in the latter case, and it increases with the number of times the propagation path traverses the region of enhanced ionization.

10.103 The effect of prompt radiation is greatest for high-altitude explosions. Thus, a megaton burst at a height of 200 miles in the daytime would be expected to disrupt HF systems out to a distance of about 1,500 miles from the burst point. Recovery would require from a few hundred to a few thousand seconds, depending on the explosion yield, the signal frequency, and the number of traversals of the D-region made by the electromagnetic wave in its successive reflections from transmitter to receiver.

10.104 The signal degradation due to delayed radiations also varies with the explosion yield and altitude. For weapons detonated at low altitudes, in which the radioactive residues do not rise above 15 miles, the effects on HF systems will generally be small, except for propagation paths close to the burst point. If the debris reaches an altitude above 15 miles but below about 35 to 40 miles, the D-region above the debris will be ionized by delayed gamma rays and possibly by beta particles (§10.46). Should the debris rise above 40 miles, the beta particles will cause ionization both in the burst region and in the magnetic conjugate region. In the low-altitude detonation of weapons of large yield, the debris may rise above 15 miles and significant attenuation of HF signals can occur for propagation paths within several hundred miles of the burst point. For high-altitude detonation of such weapons, blackout may persist for many hours over regions thousands of miles in diameter. Even kiloton-yield detonations at very high altitudes may cause daytime blackout of HF systems over considerable areas for periods of minutes to tens of minutes.

10.105 Nuclear explosions may also affect HF communications by a decrease in the electron density in the E- and F-regions which changes their reflection characteristics. Following the TEAK shot (in the D-region), the maximum usable frequency for long-distance communication was reduced over an area some thousands of miles in radius for a period lasting from shortly after midnight until sunrise (cf. §10.72). Such severe changes in the reflection properties of the ionosphere were not noted, however, during the FISHBOWL high-altitude test series (§2.52). Nevertheless, electron depletion in the E- and F-regions is expected to be a significant degradation factor following large-yield detonations above about 65 miles during the nighttime. Restoration of the normal electron density following a daytime explosion of the same type should occur more rapidly.

10.106 For three events at the highest altitudes in the FISHBOWL series, a number of new propagation modes were noted; in some cases the use of exceptionally high frequencies, well into the VHF range, became possible. When such modes were in existence, in addition to the normal modes, considerable multipath propagation was experienced. The usefulness of the new modes depends markedly on the relative geometry of the transmitter and receiver, and on the reflection mechanism.

10.107 It is important to mention that, although HF communications can be degraded seriously by a nuclear explosion at high altitude, radio systems operating in this band may still be able to perform substantial portions of their mission in some circumstances. It is by no means certain, for example, that HF systems will be blacked out completely if the transmission path is at some distance from the burst point.

6.3.11 Very–High–Frequency (30 to 300 MHz)

10.108 Signals in the VHF range penetrate the normal ionosphere and escape from the earth. Consequently, 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 in a forward direction by patches of unusually intense ionization. Forward propagation ionospheric scatter (FPIS) systems are inefficient, since only a minute fraction of the energy of the transmitter reaches the receiver, but they make additional portions of the electromagnetic spectrum available for fairly reliable communication between ground stations at distances up to 1,500 miles apart.

10.109 Normally, VHF signals scatter from ionization irregularities caused by meteor trails or by turbulence in the upper part of the D-region. Since scattering from meteor trails occurs at altitudes of about 60 miles or more, the propagation path must traverse the region of maximum absorption (around 40 miles altitude) caused by delayed gamma and beta radiations from a nuclear burst. Meteor-scatter circuits normally operate with fairly small signal margins, and so absorption effects can be important.

10.110 Signals in FPIS systems scattered from irregularities in electron density caused by turbulence may be enhanced by the increased ionization from a nuclear explosion. However, absorption will reduce the signal return from normal scatter heights to negligible magnitudes for only a short period of time. New propagation modes, produced by reflection from increased ionization in the F-region or by fireball ionization, can cause a multipath condition which will reduce the effective circuit bandwidth. Following the KINGFISH event (submegaton yield in the E-region), the Midway-to-Kauai ionospheric-scatter circuit in the Pacific was required to operate on a reduced bandwidth for 21 minutes. Pacific FPIS systems also experienced about 30 seconds of blackout following the STARFISH PRIME test (§10.74).

10.111 Line-of-sight propagation traversing the D-region, e.g., satellite communications, can be degraded by absorption due to an increase in electron density arising from delayed radiation. The degradation may last for tens of minutes over regions of hundreds of miles in radius. Attenuation and signal distortion caused by fireball regions above about 60 miles may also affect communication systems operating in the VHF band.

6.3.12 Ultra–High–Frequency Range (300 mHz to 3 GHz)

10.112 In the UHF band (and the upper part of the VHF band), forward scattering by neutral molecules and small particles in the troposphere (below about 12 miles) is used to extend propagation beyond the line of sight. Weapons detonated above the troposphere are not expected to affect tropospheric propagation paths. Bursts at lower altitude may cause degradation for a few seconds if the fireball rises through the propagation path. Significant multipath propagation due to increased ionospheric ionization appears unlikely.

10.113 Line-of-sight propagation through the ionosphere, such as is used by UHF satellite links, can be degraded if the propagation path passes through or near the fireball. Ionization by delayed radiation, especially beta particles, can produce absorption lasting a few minutes over regions of from tens of miles to a few hundred miles in radius. If the ground-to-satellite propagation path moves rapidly, the degradation period will depend primarily on the relative geometry of the path and the disturbed region. Wide-band satellite signals can be degraded by signal distortion.

6.3.13 Radar System Effects (VHF and Above)

10.114 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 typically is 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, the travel time of the signal, and its speed of propagation, 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. There is little effect of ionization on signals of these frequencies provided both the radar and the target are below the ionosphere.

10.115 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 undersirable, 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 can be attenuated to a much greater degree before the radar loses its ability to acquire or track.

10.116 A large amount of attenuation by absorption occurs when the propagation path traverses a fireball. The attenuation is determined by the properties of the fireball and these are strongly dependent on altitude. In general, it can be said that fireballs will be opaque to radar signals operating at frequencies of 10 gigahertz (104 megahertz) and below, for periods of tens of seconds to a few minutes.

10.117 The ionized atmosphere surrounding the fireball will absorb radar frequencies below a few gigahertz, i.e., a few thousand megahertz, when the fireball is above about 10 miles. A smaller region adjacent to the fireball will have the same effect for detonations at lower altitudes (§10.36). The degree and areal extent of the absorption can be calculated with reasonable reliability but lengthy computations are required.

10.118 Although absorption is generally the main source of degradation of radar systems, there are a number of other mechanisms which may be important in some cases. For example, the signal path may be bent by refraction when the electromagnetic wave traverses a medium in which the electron density changes along the path length. As a result, directional errors can occur. This effect may be significant if the signal passes close to the fireball, but outside the region in which absorption predominates, where the electron gradients are large, or if the signal traverses the E-region where the electron density is high and the rate of collision with other particles is low (§10.137).

10.119 The velocity of propagation of the radar signal that is detected is equal to the group velocity of the electromagnetic wave described in §10.84; this determines the travel time of the signal from the transmitter to the target and back. Changes in the group velocity as a result of propagation through an ionized medium will change the signal travel time and will introduce an error in estimating the range of the target. Since the change in the group velocity varies with the wave frequency, radar systems using wide bandwidths will have different travel times over the range of frequencies present in the signal. The return signals will then arrive at different times, leading to what is called "dispersion." The phenomenon is characteristic of transmission through a highly ionized medium and causes substantial range errors.

10.120 The fireball and the charged particles in the tube enclosed by the geomagnetic field lines (§10.65) may reflect or scatter radar waves, thus producing spurious signals which may be confused with target return signals. This effect, known as "clutter," may occur by reflection from rapidly changing gradients of electron density or as backscatter from irregular patches of ionization or from particulate matter thrown into the air when a fireball touches the surface. Clutter returns may be so intense as to affect radars in the same way that terrain features sometimes cause difficulties by reflecting energy back to the receiver thereby masking weak targets.

10.121 If part of the energy of the radar pulses returning from a target experiences forward scattering through small angles, the signals reaching the receiver will fluctuate both in phase and amplitude. The resulting effect is referred to as "scintillation." The phase fluctuations are equivalent to fluctuations in the angle of arrival of the signals, so that the apparent position of the target will appear to move somewhat randomly. The amplitude fluctuations make target identification difficult for the signal processing system.

6.3.14 Summary of Nuclear Detonation Effects

10.122 The general effects of nuclear detonations on the various radio frequency ranges used in radio and radar systems are summarized in Table

10.122.

Table 10.122: Effects of Nuclear Detonations on Radio and Radar Systems

Freq. Band	Spatial Extent Degradation Mechanism	Duration of Effects[a]	Comments
VLF	Phase changes, amplitude changes	Hundreds to thousands of miles; minutes to hours	Ground wave not affected, lowering of sky wave reflection height causes rapid phase change with slow recovery. Significant amplitude degradation of sky wave modes possible
LF	Absorption of sky waves, defocusing	Hundreds to thousands of miles; minutes to hours	Ground wave not affected, effects sensitive to relative geometry of burst and propagation path
MF	Absorption of sky waves, defocusing	Hundreds to thousands of miles; minutes to hours	Ground wave not affected
HF	Absorption of sky waves, loss of support for F-region reflection, multipath	Hundreds to thousands of miles, burst region and conjugate; minutes to hours interference	Daytime absorption larger than nighttime, F-region disturbances may result in new modes, multipath interference
VHF	Absorption, multipath interference, or false targets resulting from resolved multipath radar signals	Few miles to hundreds of miles; minutes to tens of minutes	Fireball and D-region absorption, FPIS circuits may experience attenuation or multipath interference
UHF	Absorption	Few miles to tens of miles; seconds to few minutes	Only important for line-of-sight propagation through highly ionized regions

[a] The magnitudes of spatial extent and duration are sensitive functions of detonation altitude and weapon yield.

Technical Aspects of Radar Effects[4]

6.3.15 Density of the Atmosphere and Altitude

10.123 The decrease in density of the atmosphere with increasing altitude can be represented approximately by the equation

$$\rho(h) \approx \rho_0 e^{-h/H_\rho} \text{ g cm}^3 \qquad (10.123.1)$$

where $\rho(h)$ and ρ_0 are the densities, in g/cm^3 at height h and at sea level, respectively, and H_ρ is called the scale height; h and H_ρ must be expressed in the same units of length, e.g., miles. Because both temperature and composition of the air change with altitude, the scale height is not actually a constant. However, below about 60 miles, use of a constant density scale height of 4.3 miles in equation (10.123.1) gives a fairly good representation of the change in atmospheric density with altitude. For higher altitudes the density scale height increases, i.e., the density varies more slowly with altitude, but since altitudes below 60 miles are of primary interest for the present purpose, the simple exponential relationships with constant scale height will be employed.

10.124 By setting H_ρ in equation (10.123.1) equal to 4.3 miles, the result is

$$\rho(h) \approx \rho_0 e^{-h/4.3} \qquad (10.124.1)$$

and this expression, with h in miles, will be used later. If the base of the exponent is changed from e to 10, where $e \approx 10^{-2.3}$, then

$$\rho(h) \approx \rho_0 10^{-h/4.3\times 2.3} \approx \rho_0 10^{-h/10} \qquad (10.124.1)$$

It follows, therefore, that in the altitude range of interest, the density of the atmosphere decreases approximately by a factor of 10 for every 10 miles increase in altitude. Thus, at an altitude of 40 miles the air density is about 10^{-4} and at 60 miles roughly 10^{-6} of the sea-level density.

6.3.16 Attenuation and Refraction of Electromagnetic Waves

10.125 The propagation of electromagnetic waves of a given frequency through a medium can be described in terms of a "complex" index of refraction, consisting of a real part and an imaginary part. The real part is a phase factor which determines the phase shift and ordinary index of refraction, i.e., the ratio of the phase velocity of the electromagnetic waves in a vacuum to that in the given medium. The imaginary part, on the other hand, is related to the attenuation of the waves by absorption in the medium. From the equations of motion of electromagnetic waves, it is possible to derive expressions for the index of refraction and for the attenuation

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

in an ionized medium. Appropriate forms of these expressions are given and discussed below, with special reference to the effects of nuclear explosions on the ionization of the atmosphere.

10.126 Attenuation of electromagnetic (and other) signals is commonly stated in terms of decibels; thus,

$$\text{Attenuation in decibels } = 10 \log \frac{P_{in}}{P_{out}}$$

where P_{in} is the signal power (or strength) before attenuation and P_{out} is that after attenuation. An attenuation of 10 decibels implies that the signal strength has been reduced to 10 decibels to 10^{-2}, 30 decibels to 10^{-3}, and so on, of the original strength. A decrease of 20 to 40 decibels, depending on the original signal power and the noise level, will generally result in serious degradation of communications. As a rough guide, it may be taken that an attenuation of 30 decibels will reduce substantially the effectiveness of a radio or radar system.

10.127 From the theory of the propagation of electromagnetic waves through an ionized medium, it is found that the signal attenuation, a, in decibels per mile of travel path, is given by

$$a = 7.4 \times 10^4 \frac{N_e \nu}{\omega^2 + \nu^2} \text{ decibels per mile} \qquad (10.127.1)$$

where N_e 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, molecules, or atoms, and ω is the (angular) frequency of the wave (in radians per second). It follows from equation (10.127.1) 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 electron collision frequency.

10.128 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. Theoretical studies show that the attenuation of radio and radar signals caused by nuclear explosions occurs mainly within a 10-mile range centered about an altitude of 40 miles. Hence, by confining attention to the situation in the neighborhood of a 40 mile altitude, it is possible to avoid complexities and yet present a reasonably accurate picture of the effects of the burst on electromagnetic signals.

10.129 There are two exceptions to the foregoing generalizations: (1) attenuation within or close to the fireball or debris regions, and (2) nighttime attenuation by ionization resulting from prompt radiation. In the former case, the altitude of the region of maximum attenuation is governed by the altitude and size of the fireball or debris region. In the second case, the altitude of peak attenuation is about 55 miles, but since the electron density due to delayed radiation is dominant at night after only a few seconds, the prompt ionization can be ignored. The present treatment will, therefore, be mainly concerned with the 10-mile range of the atmosphere centered at an altitude of 40 miles.

10.130 For electromagnetic wave frequencies greater than about 10 megahertz, ν^2 at an altitude of 40 miles may be neglected in comparison with to ω^2 in the denominater of equation (10.127.1); this equation then reduces to

$$a = 7.4 \times 10^4 \frac{N_e \nu}{\omega^2} \text{ decibels per mile} \tag{10.130.1}$$

so that the attenuation (in decibels) is approximately proportional to the electron collision frequency. At 40 miles altitude, the latter is roughly 2×10^7 per second. Upon inserting this value for ν in equation (10.130.1) and converting the wave frequency from radians per second to megahertz, the result is

$$a \approx 3 \times 10^{-2} \frac{N_e}{f^2} \text{ decibels per mile} \tag{10.127.1}$$

where f is the wave frequency in megahertz, i.e., $10^{-6}\omega/2\pi$. If the signal beam has an angle of incidence i, referred to the vertical, and the ionized region is 10 miles thick, the total attenuation. A, is

$$A \approx \frac{N_e}{f^2} \sec i \text{ decibels,} \tag{10.130.2}$$

for frequencies greater than about 10 megahertz.

10.131 The collision frequency used above is for electron collisions with neutral particles, since these predominate at 40 miles altitude. For electron densities greater than about 10^{-9} electrons/cm^3, collisions of electrons with ions can be important, particularly within a fireball at or above 60 miles altitude, where the neutral particle density is low and electron-neutral collision frequencies are small. But for attenuation of electromagnetic signals in the D-region at some distance from the fireball, equation (10.130.2) is applicable.

10.132 For operational HF circuits, the value of $\sec i$ is about 5 under normal conditions. It follows then from equation (10.130.2) that, for a frequency of 10 megahertz, a 10-mile thick layer with an electron density of about 1.5×10^3 electrons/cm^3 at 40 miles altitude will produce 30 decibels of signal attenuation. For a frequency of 30 megahertz, the same attenuation will result from an electron density of about 1.4×10^4 electrons/cm^3. These electron densities may be taken as indicative of the values required to degrade HF systems. Since radars usually operate at frequencies greater than 30 megahertz and $\sec i$ generally will be less than 5, densities exceeding 10^5

electrons/cm^3 are necessary to cause serious attenuation when the signals pass through the D-region of the ionosphere.

10.133 Consideration will now be given to the phase aspects of the propagation of electromagnetic waves through an ionized medium. Provided the electron collision frequency, ν, is small in comparison with the wave frequency, ω, as has been assumed above, the ordinary (real) index of refraction, n, is given by

$$n = \left(1 - \frac{4\pi N_e e^2}{m\omega^2}\right)^{1/2} = \left(1 - \frac{10^{-12} N_e e^2}{\pi m f^2}\right)^{1/2}, \qquad (10.133.1)$$

where e is the charge (4.8×10^{-10} electrostatic unit) and m is the mass ($9,1 \times 10^{-28}$ gram) of the electron, and f is the wave frequency in megahertz. Upon inserting the numerical values for e and m, it is found that

$$n = \left(1 - \frac{0.8 N_e}{10^4 f^2}\right)^{1/2}.$$

Since electron densities are not known very accurately, this result may be approximated to

$$n \approx \left(1 - \frac{N_e}{10^4 f^2}\right)^{1/2}. \qquad (10.133.2)$$

10.134 an electromagnetic wave crosses a plane interface where the index of refraction changes sharply from 1 to n, a beam will be bent by an amount given by the familiar Snell's law, i.e.,

$$\frac{\sin i}{\sin r} = n,$$

where i is the angle of incidence and r the angle of refraction. If the index of refraction is such that $n = \sin i$, then $\sin r = 1$, i.e., r = 90°, and critical reflection occurs; the refraction is so large that the signal is unable to penetrate the medium. The condition for critical reflection by an ionized medium is obtained by setting n in equation (10.133.2) equal to $\sin i$; the result obtained is

$$f \approx 10^{-2}\sqrt{N_e}\sec i \text{ for critical reflection} \qquad (10.134.1)$$

For reflection of an electromagnetic signal encountering a given ionized medium, with electron density N_e, the frequency must be less than that expressed by equation (10.134.1). Alternatively, for reflection of a single of specified frequency f, the electron density of the ionized medium must be greater than that given by this equation.[5]

[5] The quantity $10^{-2}\sqrt{N_e}$ megahertz or, more exactly, $\left(4\pi N_e e^2/m\right)^{1/2}$ radians per second, is called the "critical frequency" or "plasma frequency" of an ionized medium, i.e., a plasma. It is the frequency for which the index of refraction of the given medium is zero. It is also the lowest frequency of an electromagnetic wave that can penetrate into the medium, and then only for normal incidence, i.e., for $i = 0$.

10.135 As in § 10.132, sec i may be taken to be about 5 for an operational HF system. Hence, for a signal of 5 megahertz, at the lower end of the band, to be reflected, the electron density must exceed 10^4 electrons/cm^3. For a frequency of 30 megahertz, the minimum density for reflection is 3.6×10^5. These densities are normally attained in the E- and F-regions of the ionosphere, respectively. A change in the electron density arising from the effects of a nuclear explosion can alter the altitude at which an electromagnetic wave is reflected and can consequently affect communications systems, as seen earlier in this chapter.

10.136 Equation (10.134.1) is applicable only when a nonionized medium is separated from an ionized one Within the fireball itself, however, by a sharp boundary at which the change in refractive index, from 1 to n, occurs over a distance small in comparison to a wavelength at the propagating frequency. This condition does not exist either in the normal ionosphere or after it has been disturbed by a nuclear detonation. The refractive index does not change sharply and there is a gradual bending of the transmitted wave. In such situations, both the electron density and its gradient determine the phase (refraction) effects.

10.137 When the quantity N_e/f^2 is sufficiently large, electromagnetic waves can be both attenuated and refracted by the ionized medium. The effect that predominates depends on the ratio of the electron density gradient to the electron collision frequency. If this ratio is large, then the wave will be refracted, but if it is small the main effect will be attenuation. In most circumstances associated with a nuclear explosion, attenuation around 40 miles altitude predominates. At altitudes above about 60 miles, however, where the collision frequency is small and the electron density gradient moderately large, refraction may be important. Also, near the fireball but outside the absorbing region, refraction of electromagnetic waves up to high frequencies, such as radar signals, is possible (§ 10.37). Although the collision frequency is large, the high electron density gradient is here the dominant factor. Within the fireball itself, however, electromagnetic waves are always strongly absorbed.

6.3.17 Electron Production by Prompt Radiations

10.138 Consider a nuclear explosion of W kilotons yield and let k be the fraction of the yield radiated at a particular energy, i.e., as monochromatic radiation. For a point source of such radiation, assuming negligible scattering and no reradiation, the energy deposited (or absorbed) per unit volume of air, E_D, at an "observation" point at a slant distance D from the explosion is

$$E_D = \frac{kW}{4\pi D^2}\rho\mu_m e^{-\mu_m M}, \qquad (10.138.1)$$

where ρ is the air density at the observation altitude, μ_m is the mass (energy) absorption coefficient in air of the given radiation,[6] and M is the penetration mass, i.e., the mass of air per unit area between the radiation source and the observation point. This equation may be used for all forms of prompt radiation, using the appropriate value of given in Table 10.138. The fraction of the energy radiated as prompt gamma rays is small and its contribution to the electron density is generally less than the for other radiations. If the energy deposited in the air is reradiated or if the source photons or neutrons are scattered and follow a random path before depositing all their energy, equation (10.138.1) must be modified (§ 10.142).

Table 10.138: FRACTION OF EXPLOSION ENERGY AS PROMPT RADIATIONS

Radiation	k
X rays	0.7
Gamma rays	0.003
Neutrons	0.01

10.139 According to Table1.45, 1 kiloton TNT equivalent of energy is equal to 2.6×10^{25} million electron volts. Furthermore, about 3×10^4 ions pairs, i.e., 3×10^4 electrons, are produced for each million electron volts of energy absorbed in air (about 34 electron volts are required to produce an ion pair). Consequently, about 8×10^{29} electrons are produced for each kiloton of energy deposited in the air. Hence, the number of free electrons per unit volume, N_e, is obtained from equation (10.138.1), with W in kilotons, as

$$N_e = 2.4 \times 10^{18} \frac{kW}{D^2} \rho \mu_m e^{-\mu_m M} \text{ cm}^{-3}, \qquad (10.139.1)$$

with ρ in grams per cubic centimeter, μ_m in square centimeters per gram, M in grams per square centimeter, and D in miles.

10.140 An expression for M may be obtained in the following manner. Let H_0 (Fig. 10.140) be the altitude of the explosion point and H that of the observation point which is at a distance D from the burst. Then if D' represents any position between the explosion and the observation point, and h is the corresponding altitude, the value of M in appropriate units is given by

$$M = \int_0^D \rho(D')dD' = \frac{D}{H - H_0} \int_{H_0}^{H} \rho(h)dh$$

[6] The mass absorption coefficient is similar to the mass attenuation coefficient defined in § 8.100, except that it involves the energy absorption coefficient, referred to in the footnote to equation (8.95.1).

where, in deriving the second form, the curvature of the earth has been neglected. If $\rho(h)$ is now represented by equation (10.124.1), it is found that

$$M = 6.8 \times 10^5 \frac{D}{H - H_0} \rho_0 \left(e^{-H_0/4.3 - e^{H/4.3}} \right) \text{ g cm}^{-2}, \qquad (10.140.1)$$

where D, H, and H_0 are in miles and ρ_0 in grams per cubic centimeter; the factor 6.8×10^5, which is the density scale height in centimeters (slightly less than 4.3 miles), is introduced to obtain the required units (g/cm^2) for M.

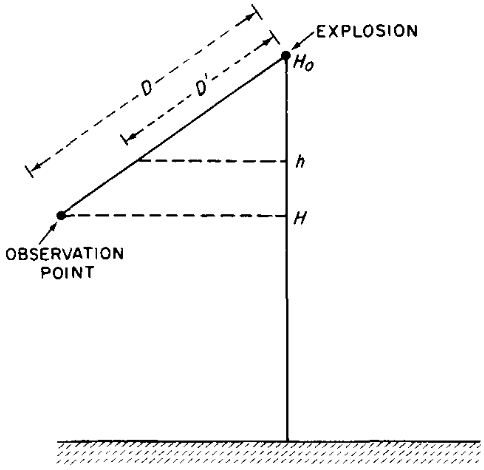

Figure 10.140: Quantities used in defining the penetration mass (M).

10.141 In general, the energy radiated from a nuclear explosion as gamma rays and X rays is not monochromatic but covers a range of photon energies. Hence, integration over the energy spectrum is necessary. For the range in which most of the gamma-ray energy is radiated, the mass absorption coefficient of air, μ_m, can be considered to be constant. But this is not the case for X-ray photons (of lower energy) for which the mass absorption coefficient is approximately inversely proportional to the cube of the energy. Furthermore, the situation is complicated as a result of energy changes that occur when the photons are scattered. For neutrons, the highest electron densities arise from elastic scattering (§ 10.43) and the necessity for summing over multiple scattering angles makes the calculations difficult, especially in an (inhomogeneous) atmosphere of changing density.

10.142 Allowance for the effects of scattering and of the energy spectrum of the radiation can be made approximately by modifying equation (10.139.1) to take the form

$$N_e \approx 2.4 \times 10^{18} \frac{kW}{D^2} \rho F(M) \text{ g cm}^{-2}, \qquad (10.142.1)$$

where $F(M)$ is an effective mass absorption coefficient which is a function of the penetration mass, M. Values of $F(M)/\kappa$, where κ is a normalization factor that permits $F(M)$ for various radiations to be plotted on a single diagram, are given in Fig. 10.142. The values of κ used are shown in the insert.

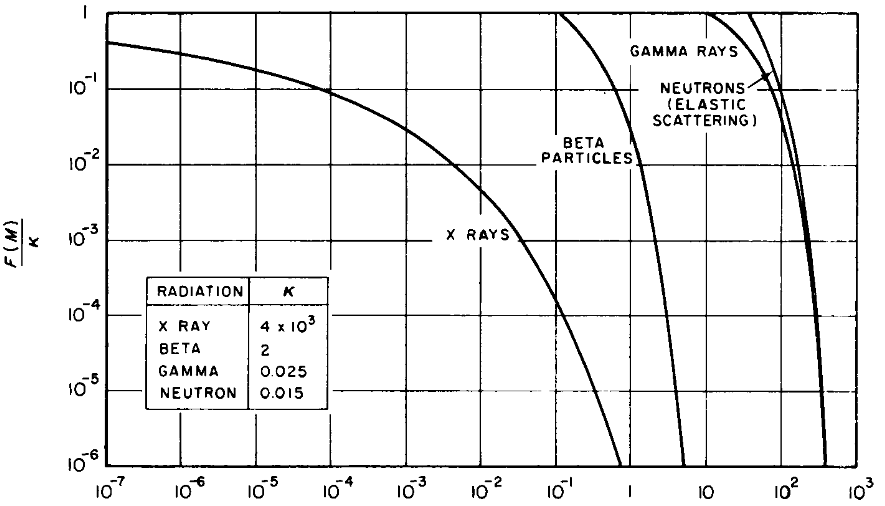

Figure 10.142: Values of $F(M)$ for various radiation sources.

10.143 The electron densities produced by the total prompt radiation (neutrons and X rays) are obtained by summing the contributions of the individual radiations as given by the appropriate forms of equation (10.142.1). In this manner, the curves in Fig. 10.143 for electron densities at a height of 40 miles as a function of horizontal distance[7] were derived for a 1-megaton explosion at various altitudes. Since the electron density is proportional to the energy yield, W, of the weapon, the results for other yields can be readily obtained from Fig. 10.143. In computing M for this figure, the effects of a curved earth and a variable density scale height were included. The calculations show that below about 40 miles, ionization due to neutrons predominates, but for nuclear detonations at higher altitudes the X rays produce essentially all the additional electrons from prompt ionization in the D-region.

10.144 It is seen from Fig. 10.143 that at low burst altitudes, up to about 20 miles, the ionization from prompt radiation is relatively small except at short distances. At higher burst altitudes, not only does the electron density (at 40 miles altitude) for a given horizontal distance increase, but the range for a given electron density, especially above 10^5 electrons/cm^3, increases

[7]The term "horizontal distance," as used here and later, refers to the distance parallel to the earth's surface.

markedly. These densities are sufficient to cause blackout of HF systems that use the sky wave for long-distance propagation. However, it will be seen (§ 10.152) that the blackout would be of relatively short duration.

6.3.18 Rate of Disappearance of Free Electrons Produced by Prompt Radiation

10.145 Free electrons are removed either by attachment to neutral particles (usually molecular, oxygen in the D–region) or by recombination with positive ions. The electron loss by recombination is proportional to the number densities of electrons, N_e, and of positive ions, N_+, so that

$$\frac{dN_e}{dt} = -\alpha N_+ N_e \qquad (10.145.1)$$

where α_d is the recombination coefficient. Below an altitude of about 60 miles, α_d is approximately 2×10^7 cm^{3}sec^{-1}.

10.146 Electron loss by attachment to molecular oxygen is proportional to the square of the atmospheric density and the number density of electrons; thus,

$$\frac{dN_e}{dt} = -\beta \rho^2 N_e \qquad (10.146.1)$$

where β is an attachment coefficient approximately equal to 4×10^{13} cm^{6}g^{-2}sec^{-1}. The quantity $\beta\rho^2$ is often called the attachment rate coefficient, K; it decreases from 6×10^7 sec^{-1} at sea level to about 2×10^{-3} sec^{-1} at 55 miles altitude.

10.147 After electrons are attached to molecules to form negative ions, they may become detached by solar radiation or by collisional processes. The rate of free electron production by detachment is proportional to the number density of negative ions, N_-, and the detachment source strength, i.e.,

$$\frac{dN_e}{dt} = SN_e \qquad (10.147.1)$$

where S, the detachment rate coefficient, is related to the detachment source strength. In the daytime, S is approximately 0.4 sec^{-1} above about 35 miles altitude. Below about 35 miles the value of S is uncertain but apparently it is lower by several orders of magnitude. At night, detachment is negligible at altitudes less than about 50 miles.

10.148 Negative ions formed by attachment of electrons to molecular oxygen can also react with positive ions to form neutral molecules. Since the negative and positive ion densities affect the electron density, the ion loss by recombination must be considered. The rate of positive ion loss by recombination with negative ions is proportional to the number densities of both ions; thus,

$$\frac{dN_+}{dt} = \alpha_1 N_- N_+ \qquad (10.148.1)$$

where α_1 usually known as the mutual neutralization coefficient, is equal to about 3×10^{-8} cm^3 sec^{-1} above 30 miles. Below 30 miles, α_1, is approximately proportional to the atmospheric density and is 4×10^{-6} cm^{3}sec^{-1} at sea level.

6.3.19 Electron Densities from Prompt Radiations

10.149 The differential equations describing the time history of electron and ion densities do not have a closed form solution. However, a number of approximations are available, and numerical solutions have been obtained with the aid of computers for particular cases. An approximate solution, which gives reasonable results for many conditions, is the so-called "equal-alpha" approximation. When α_d is taken equal to α_1 the electron density, $N_e(t)$, as a function of time following a pulse of prompt radiation, can be represented by

$$N_e(t) = \frac{N_e(0)}{1 + \alpha N_e(0)t} \frac{S + Ke^{-(K+S)}t}{S + K} \tag{10.149.1}$$

where $N_e(0)$ is the initial electron density, given by equation (10.142.1), α is an effective recombination coefficient, and t is the time after the burst.

10.150 Approximate values of α, S, and K in centimeter-gram-second units are given in Table 10.150 for an altitude of 40 miles in the daytime and 55 miles at night. These are the altitudes, for day and night, respectively, at which maximum attenuation of electromagnetic signals is to be expected (§ 10.129). Upon inserting the appropriate values into equation (10.149.1), the time history of electron density at the altitude of maximum attenuation is found to be

$$\text{at 40 miles } N_e(t) \approx \frac{1}{3} \frac{N_e(0)}{1 + 10^{-7} N_e(0)t} \text{cm}^{-3} \text{ daytime} \tag{10.150.1}$$

for times more than a few seconds after the burst in the daytime, and

$$\text{at 55 miles } N_e(t) \approx \frac{N_e(0)}{1 + 2 \times 10^{-7} N_e(0)t} \text{cm}^{-3} \text{ nighttime} \tag{10.150.2}$$

for nighttime conditions.

10.151 Calculations of the decay of electron densities from ionization produced by prompt radiations from a nuclear detonation have been made with a computer using numerical solutions that do not involve the equal-alpha approximation. The results for daytime conditions at a height of 40 miles are shown in Fig. 10.151; they are reasonably consistent with equation (10.150.1) provided the electron density is appreciably larger than the normal value in the ionosphere. Natural ionization sources must be considered when the electron density resulting from prompt radiation has decayed to values comparable to those normally existing at an altitude of 40 miles.

Table 10.150: APPROXIMATE VALUES OF α, S, and K IN CGS UNITS

Coefficient	40 miles (daytime)	55 miles (nighttime)
α	10^{-7}	2×10^{-7}
S	0.4	2×10^{-2}
K	0.8	2×10^{-3}

10.151-interlude The curves in Fig. 10.143 show the initial electron densities at 40 miles altitude produced by the prompt radiation from a 1-megaton explosion as a function of distance, for various burst altitudes. Scaling. For any specified combination of burst height and distance, the initial electron density at 40 miles altitude is directly proportional to the yield in megatons, i.e.,

$$N_e(W) = W N_e(1 \text{ MT}),$$

where N^e (1 MT) is the value of the initial electron density at 40 miles altitude and the desired distance from a 1 MT explosion at the desired altitude, and Ne(W) is the corresponding initial electron density for W MT.

Example:

Given: A 1 MT explosion in the daytime at an altitude of 30 miles.

Find: The one-way attenuation of a 100-MHz radar system that would result from D-region ionization at 30 seconds after the burst; the radar beam makes an angle of 80 degrees ($\sec i \sim 6$) with the vertical and intersects the 40 mile altitude layer at a horizontal distance of 125 miles from the burst.

Solution: From Fig. 10.143, the initial electron density at a horizontal distance of 125 miles from a 1 MT explosion at an altitude of 30 miles is about 5×10^6 electrons/cm^3. From Fig. 10.151, this initial value will have decayed to about 10^5 electrons/cm^{3}by 30 seconds after the burst. By use of equation (10.130.2), the attenuation is

$$A \approx 0.4 \frac{N_e}{f^2} \sec i = 0.4 \frac{10^5}{10^4} = 24 \text{ decibels.} \quad \textit{Answer.}$$

Note: The attenuation determined above is due only to prompt radiation. The effect of delayed radiation should also be investigated to estimate the overall effect on the system (§10.154 *et seq.*). □

10.152 There are two aspects of Fig. 10.151 that are of special interest. First, it is seen that when the initial electron density, $N_e(0)$, is greater than 10^7 electrons/cm^3, the electron density, $N_e(t)$, at any time more than about 1 second after the burst (in daytime) is independent of the initial

Table 10.150: APPROXIMATE VALUES OF α, S, and K IN CGS UNITS

Coefficient	40 miles (daytime)	55 miles (nighttime)
α	10^{-7}	2×10^{-7}
S	0.4	2×10^{-2}
K	0.8	2×10^{-3}

value. This condition is referred to as a "saturated atmosphere." It is to be expected from equation (10.150.1), since when $N_e(0)$ is more than 10^7 and t is at least a few seconds, the quantity $10^{-7}N_e(0)t$ in the denominator of the equation is greater than unity. Hence, the latter can be neglected and equation (10.150.1) reduces to

$$N_e(t) \approx \frac{1}{3 \times 10^{-7}t}\ \mathrm{cm}^{-3},$$

so that the electron density at time t is independent of the initial value.

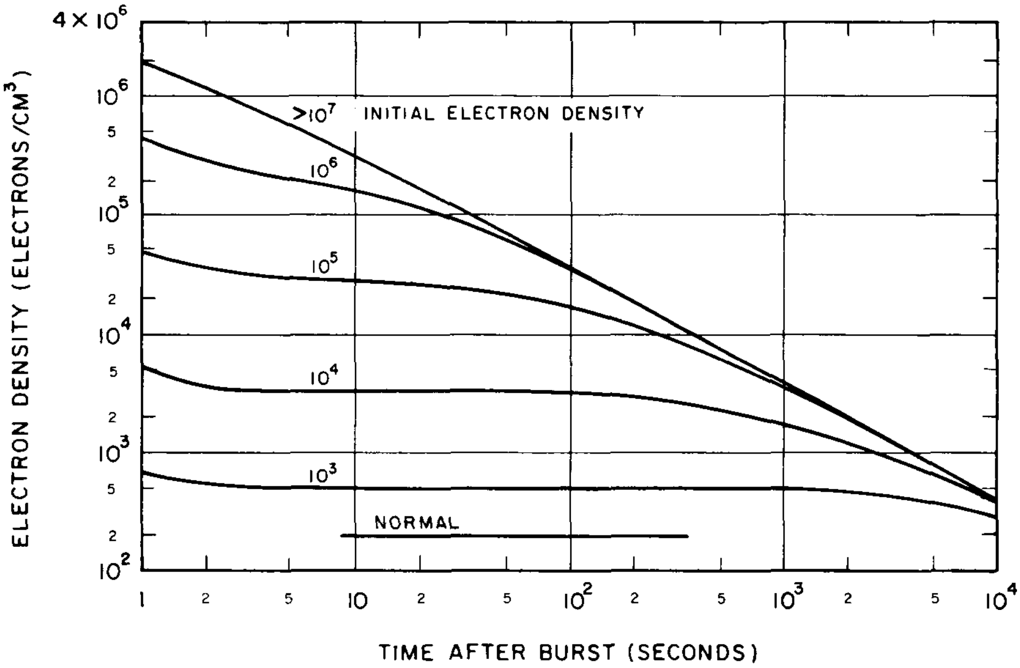

Figure 10.151: Decay of ionization from prompt radiation at 40 miles altitude in the daytime.

10.15X The curves in Fig. 10.151 show the electron density from prompt radiation at 40 miles altitude in the daytime as a function of time after burst, for various values of the initial electron density. These curves together with those in Fig. 10.143 can be used to estimate the electron density at 40 miles altitude in the daytime for various combinations of explosion yields and burst altitudes.

Example:

Given: A 1 MT explosion in the daytime at an altitude of 30 miles.

Find: The one-way attenuation of a 100-MHz radar system that would result from D-region ionization at 30 seconds after the burst; the radar beam makes an angle of 80 degrees (sec $i \approx 6$) with the vertical and intersects the 40 mile altitude layer at a horizontal distance of 125 miles from the burst.

Solution:: From Fig. 10.143, the initial electron density at a horizontal distance of 125 miles from a 1 MT explosion at an altitude of 30 miles is about 5×10^6 electrons/cm^3. From Fig. 10.151, this initial value will have decayed to about 5×10^6 electrons/cm^3 by 30 seconds after the burst. By use of equation (10.130.2), the attenuation is

$$A \approx 0.4 \frac{N_e}{f^2} \text{ sec } i = 0.4 \frac{10^5}{10^4} \, 6 = 24 \text{ decibels. } \textit{Answer.}$$

Note: The attenuation determined above is due only to prompt radiation. The effect of delayed radiation should also be investigated to estimate the overall effect on the system (§ 10.154 *et seq.*) so that the electron density at time t is independent of the initial value. □

10.153 The other matter of interest is that, regardless of the initial value, the electron density in the daytime will have decreased to 10^3 electrons/cm^3 within an hour (or so). This fact is apparent from Fig. 10.151 can be derived from equation (10.150.1). It follows, therefore, that significant degradation of HF or radar systems as the result of ionization by prompt radiation will not persist for more than an hour or so in daytime. At night, decay is faster, as is apparent from equation (10.150.2), and effects on electromagnetic waves of prompt radiations can usually be neglected. As will be seen later, the effects of the delayed radiation may persist for longer times.

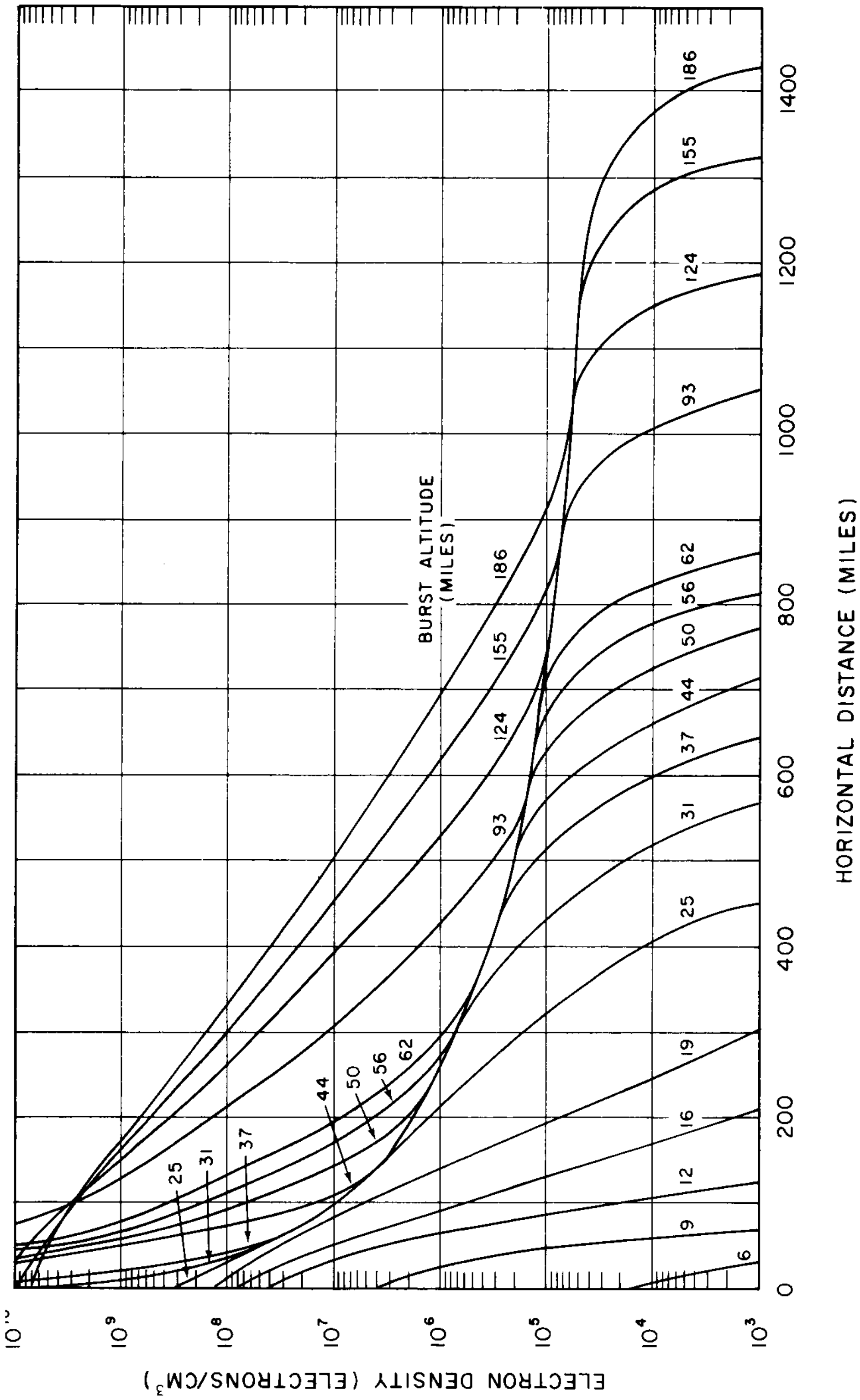

Figure 10.143: Initial electron density at 40-miles altitude produced by prompt radiation from a 1-megaton explosion, as a function of distance (miles), for various burst altitudes.

6.3.20 Rate of Electron Production by Delayed Radiations

10.154 The rate of energy emission as delayed (beta and gamma) radiation from the radioactive residues of a nuclear explosion, consisting mainly of fission products but including activity induced by neutrons in the weapon material (§ 9.32),is represented by

$$I_t = I_1(1+t)^{-1.2} \qquad (10.154.1)$$

where I_t is the rate of energy emission at t seconds after the detonation and I_1 is the value after 1 second.[8] The total beta and gamma energy emitted is obtained (approximately) by integrating between zero time and infinity; thus,

$$\text{Total energy } = \int_0^\infty I_1(1+t)^{-1.2}dt = 5I_1.$$

The fraction of the delayed radiation energy emitted per second at time t is then

$$\frac{I_1(1+t)^{-1.2}}{5I_1} = 0.2(1+t)^{-1.2}.$$

10.155 About 7 percent of the fission explosion energy is radiated as delayed beta particles and gamma rays, with approximately half carried by each kind of explosion. Hence, for an explosion of W_F kilotons fission yield, roughly $0.007(1+t)^{-1.2}W_F$ kilotons of energy per second are radiated by beta particles and the same amount by gamma rays.

10.156 The rate of production of ion pairs (and hence of electrons) by delayed gamma rays can be estimated from an expression similar to that used to determine the electron density arising from the prompt radiation. Thus, if kW in equation (10.142.1) is replaced by $0.007(1+t)^{-1.2}W_F$, the result, assuming a point source for gamma rays (cf. § 10.138), is

$$q_\gamma(t) = 1.7\times 10^{16}\frac{W_F}{D^2(1+t)^{-1.2}}\rho(H)F(M)\ \text{cm}^{-3}\ \text{sec}^{-1} \qquad (10.156.1)$$

where $q_\gamma(t)$ cm^{-3} sec^{-1} is the electron production rate at time t seconds after the nuclear detonation, as observed at a slant distance D miles at an altitude of H miles (see Fig. 10.140). The function $F(M)$ can be obtained from Fig. 10.142 with M defined by an equation similar to equations (10.140.1), except that the detonation altitude H_0 is replaced by the debris altitude H_D.

10.157 The radial motion of the beta particles is largely prevented by the geomagnetic field lines. The area of the D-region at an altitude of 40 miles where the beta ionization occurs is then approximately the same as the area of the debris (Fig. 10.47). If the latter rises above 40 miles, roughly half of the energy is deposited in the local D-region and half at the magnetic

[8] For times that are long in comparison with 1 second, equation (10.154.1) reduces to the same form as (9.147.1).

conjugate. The total area over which the beta-particle energy is deposited is thus twice the debris area. If the debris is assumed to be uniformly distributed over an area A, which may be taken to be πR^2, where R is the debris radius, the electron production rate from ionization due to beta particles in each D-region is then

$$I_\beta(t) = 2.1 \times 10^{17} \frac{W_F}{2A(1+t)^{1.2}\sin\varphi} \rho(H)F(M) \text{ cm}^{-3} \text{ sec}^{-1} \qquad (10.157.1)$$

where φ is the local magnetic dip angle and A is in square miles. The change in the numerical factor (by 4π) arises from the replacement of the area $4\pi D^2$ in equation (10.156.1) by $2A$ in equation (10.157.1) and $\sin\varphi$ is required because of the motion of the beta particles along the field lines. The function $F(M)$ is evaluated from Fig. 10.142 for

$$M = \frac{1}{\sin\phi}\int_H^{H_D} \rho(h)dh \approx \frac{6.8 \times 10^5 \rho_0}{\sin\phi}\left(e^{H/4.3} - e^{-H_D/4.3}\right), \text{ g cm}^{-2} \qquad (10.157.2)$$

where H_D is the debris altitude in miles; in this expression the curvature of the earth is neglected.

10.158 In order to use equations (10.156.1) and (10.157.1) it is necessary to know the altitude, H_D, and radius, R, of the weapon debris. Determination of these quantities requires an understanding of the processes taking place as the debris cloud rises and spreads horizontally. The actual processes are very complex, but a simple model which parallels the gross features of the debris motion has been developed. The debris height and radius, as they change with time, for various burst altitudes as obtained from this model are shown in Figs. 10.158a, b, and c, for energy yields of 10 and 100 kilotons and 1 megaton, respectively. For interpolation between these yields, $W^{1/3}$ scaling may be used, at least for the first few minutes after the explosion. The extreme left-hand end of each curve indicates the altitude of the explosion and the initial size of the fireball. It should be noted that when using Figs. 10.158a, b, and c that W is the total energy yield of the explosion. For thermonuclear weapons, the fission yield W_F in equations (10.156.1) and (10.157.1) is generally taken to be half of the total yield.

10.158-interlude

The curves in Figs 10.159a and b show the electron densities at 40 miles altitude due to beta particles (for debris above 40 miles) and delayed gamma rays (for debris above 15 miles), respectively. Only the attenuation resulting from the highest electron density, which may arise from prompt radiations (Figs. 10.143 and 10.151), delayed gamma radiation, or beta particles, need be considered. The densities, and hence the attenuations, cannot be addded directly. Figures 10.158a through c may be used to estimate the position and size of the debris for use with Figs. 10.159a and b. The curves of Fig. 10.159a (for beta particles) are for a magnetic dip angle of 60°, but they

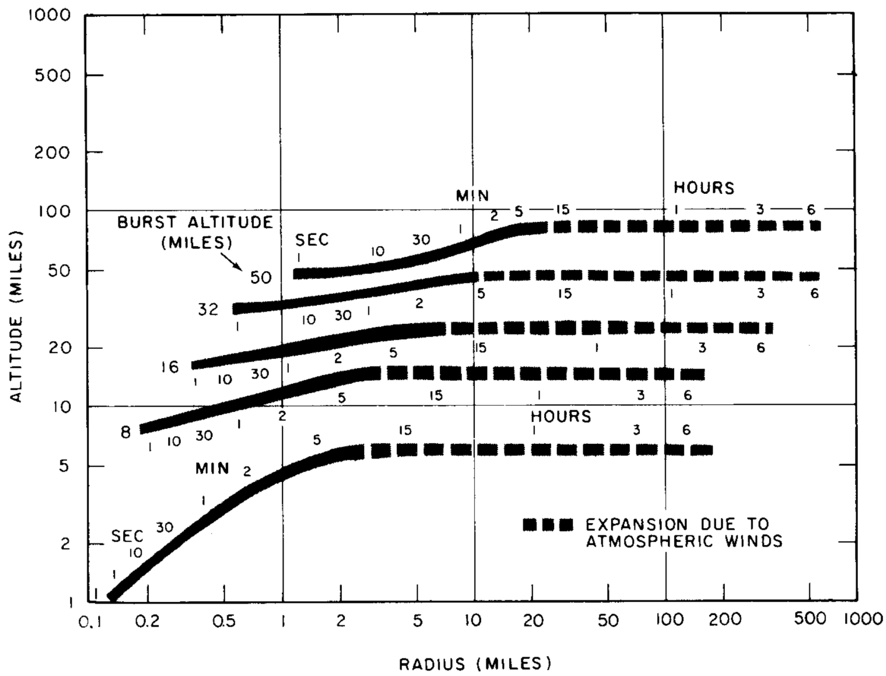

Figure 10.158a: Fireball/debris altitude and horizontal radius for 10-kiloton explosions at various altitudes.

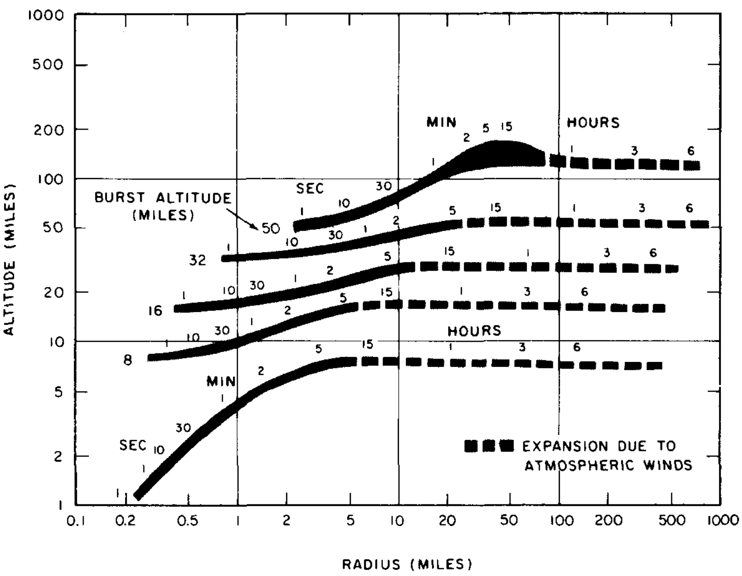

Figure 10.158b: Fireball/debris altitude and horizontal radius for 100-kiloton explosions at various altitudes.

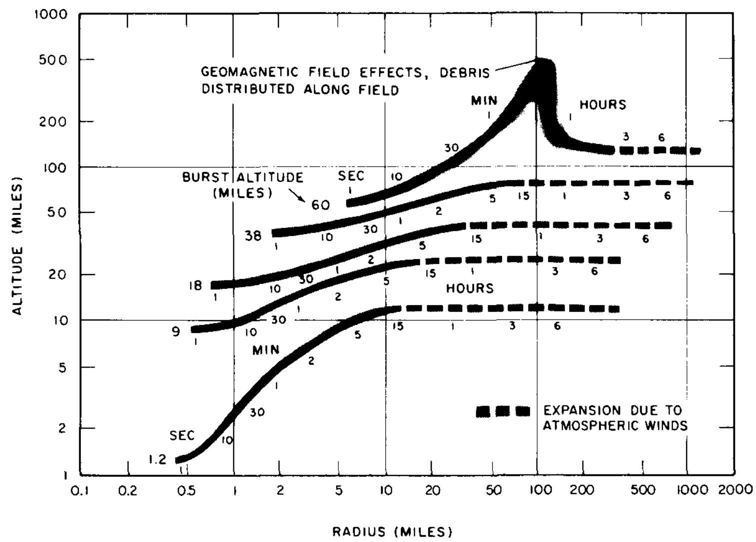

Figure 10.158c: Fireball/debris altitude and horizontal radius for 1-megaton explosions at various altitudes.

provide reasonable estimates for dip angles between about 45° and 75°. The possible effect of the earth's curvature on Fig. 10.159b (gamma rays) is obtained from Fig. 10.162.

Example :

Given: A 1 MT explosion during the night at an altitude of 25 miles and a location in the northern hemisphere where the magnetic dip angle is 60°.

Find: The electron density in the D-region at a horizontal distance of 250 miles north of the burst point (*a*) 5 minutes after the explosion, and (*b*) 2 hours after the explosion.

Solution: Since it is nighttime, any prompt ionization will have died away by the times of interest and can be neglected (§ 10.153).

(*a*) Interpolation of Fig. 10.158c suggests that by 5 minutes the debris will have reached an altitude (H_d) of about 60 miles, with a horizontal radius of about 30 miles. Since the beta particles follow the geomagnetic field lines, the ionization they cause at an altitude of 40 miles (H) will be centered about a point that is displaced a distance d horizontally from the center of the debris, where d is given (approximately) by

$$d \approx (H_d - H) \tan \varphi = (60 - 40) \tan 60° = 35 \text{ miles.}$$

The radial extent of the ionized region will be approximately equal to the debris radius (30 miles). Thus, at 5 minutes after the explosion beta ionization will not affect a point that is located at a horizontal distance of 250 miles from the burst. Hence, at this time only the ionization caused by delayed gamma rays need be considered. The distance D from the debris to the point of interest is about 250 miles and the time is 300 seconds. Since the total yield is 1 MT, the fission yield, W_F may be taken to be 500 kilotons; hence,

$$\frac{W_F}{D^2(1+t)^{1.2}} = \frac{500}{(250)^2(301)^{1.2}} \approx 8 \times 10^{-6}.$$

The debris altitude (60 miles) and the horizontal distance (250 miles) are such that the conditions are in Region 1 of Fig. 10.162, so that Fig. 10.159b is applicable. The electron density due to delayed gamma rays is then found to be 10^3 electrons/cm^3. *Answer.*

(b) At 2 hours after the explosion, the debris will still be at an altitude of about 60 miles, but interpolation of Fig. 10.158c suggests that it will have spread to a radius of about 250 miles. Since the center of the beta ionization will be displaced about 35 miles farther north, the point of interest will be contained within the beta ionized region.[9] At that time, i.e., t = 7200 sec,

$$\frac{W_F}{A(1+t)^{1.2}} = \frac{500}{\pi(250)^2(7201)^{1.2}} \approx 6 \times 10^{-8}.$$

The electron density due to beta particles is found from Fig. 10.159a to be about 2×10^3 electrons/cm^3. The electron density from the delayed gamma rays was estimated above to be 10^3 electrons/cm^3 at 5 minutes after the explosion, and so it will be much less at 2 hours. Hence, the ionization due to the gamma rays can be neglected. *Answer.* □

6.3.21 Electron Densities from Delayed Radiations

10.159 The actual electron density, $N_e(t)$, arising from the delayed radiations at a particular location and time can be calculated by assuming that, soon after the detonation, a transient steady state exists at any instant. The value of $N_e(t)$ is then obtained by equating $q_\beta(t)$ or $q_\gamma(t)$ at any time t to the rate of loss of electrons by various recombination and attachment processes. The curves in Figs. 10.159a and b, for delayed beta particles and gamma rays, respectively, were obtained in this general manner for an altitude of 40 miles, where maximum attenuation of electromagnetic signals due to ionization from delayed radiations occurs both during day and night. In computing the curves, an accurate treatment for the energy spectra of the radiations was used to evaluate the rate of formation of electrons; removal rates were calculated along the lines indicated in § 10.145 *et seq.*, with detailed consideration of all important loss mechanisms. The values shown in Fig. 10.159a were computed for a magnetic dip angle of 60°; however,

[9] It is assumed that the debris expands uniformly about a stationary center once it has ceased to rise. Motion of the debris caused by atmospheric winds introduces many uncertainties in the prediction of ionization at times more than a few minutes after the burst.

they provide reasonable estimates for dip angles between about 45° and 75°, i.e., for mid-latitudes.

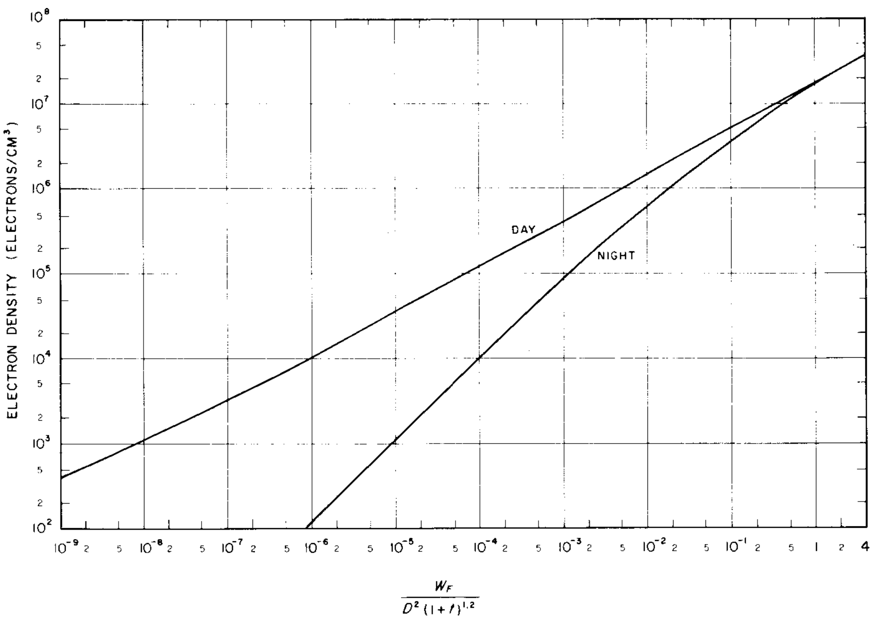

Figure 10.159a: Electron density at 40-mile altitude due to beta particles (for debris above 40 miles).

10.160 The curves in Fig. 10.159a for the electron density resulting from ionization by delayed beta particles are based on the assumption that the debris has risen above 40 miles. The particle energy is then equally distributed be tween the local D-region and the one at the magnetic conjugate. The electron densities given in the figure are those to be expected at the 40-mile altitude in each region. If the debris is below 35 miles, the delayed beta particles cause essentially no ionization in the D-region (§ 10.45); at altitudes of 35 through 40 miles, the ionization in this region is intense, but the electron densities are difficult to calculate. Because beta particles follow the geomagnetic field lines, the ionization they produce at any altitude is not affected by the earth's curvature. Gamma rays, on the other hand, travel in straight lines and may be so affected (§ 10.162).

10.161 The stopping altitude for the delayed gamma rays is about 15 miles; hence, the results in Fig. 10.159b are applicable only if the debris rises above this altitude. The principal source of error in the figure is that the gamma rays are assumed to originate from a point source at the center of the debris cloud. Since the atmospheric absorption of gamma rays is negligible above the stopping altitude, the straight-line path from the debris to the point of interest in the D-region (40 miles altitude) can lie in any direction,

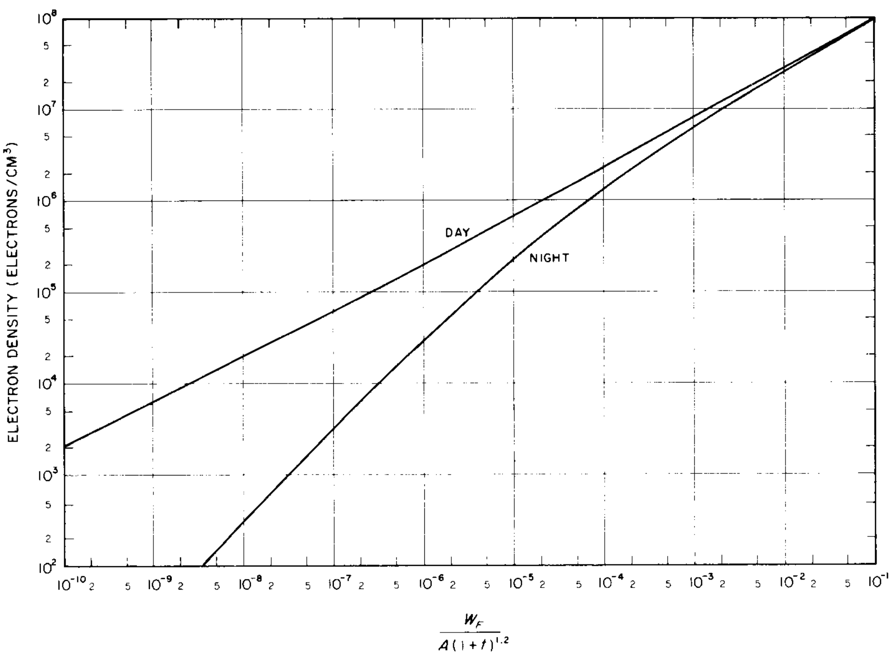

Figure 10.159b: Electron density at 40-mile altitude due to delayed gamma rays (for debris above 15 miles).

provided it does not pass through the stopping altitude.

10.162 As a consequence of the curvature of the earth, the path of the gamma rays, for sufficiently large distances, may intersect the stopping altitude, even when the debris rises above 15 miles. If this occurs, the energy of the gamma rays will be largely absorbed. For the conditions in Region 1 of Fig. 10.162, the straight line from the debris (center) to the observation point at 40 miles altitude does not intersect the stopping altitude for gamma rays, and the electron densities in Fig. 10.159b are applicable. But in Region 2, most of the rays will intersect a volume of air below the stopping altitude before reaching the point of interest. As a result of the gamma-ray absorption, the electron densities will be substantially below those given in Fig. 10.159b. In the intermediate (unshaded) region of Fig. 10.162, part but not all of the gamma rays will encounter the stopping altitude and the electron densities will be somewhat lower than in Fig. 10.159b. When using this figure to determine the expected effects of a nuclear explosion on a radar system, for example, a conservative approach would be to assume that the unshaded portion in Fig. 10.162 is part of Region 1 for the user's radar, but that it is part of Region 2 for the opponent's radar.

10.163 As for prompt radiations (§ 10.149 *et seq.*), an approximate solution to the problem of calculating electron densities arising from the

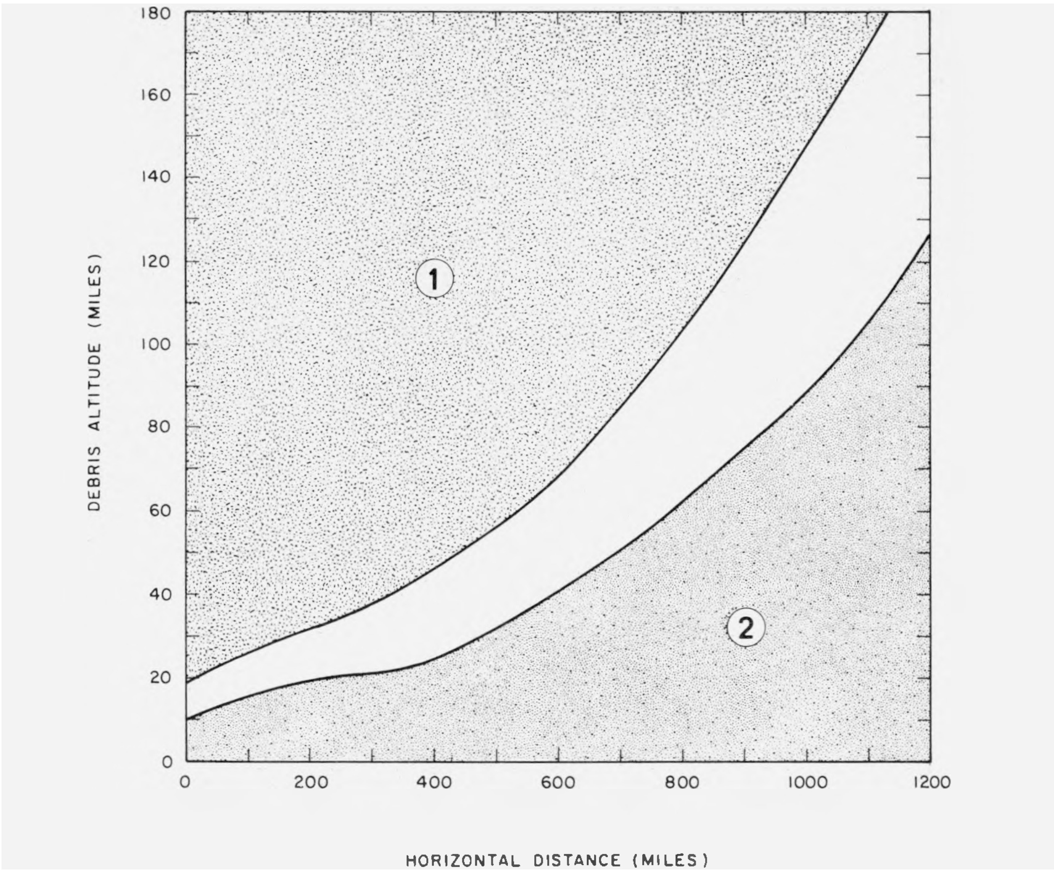

Figure 10.162: Effect of earth's curvature on delayed gamma-ray ionization at 40 miles altitude.

delayed radiations, which is consistent with Figs. 10.159a and b, can be obtained by using the equal alpha approximation to deter mine the loss rate at any instant. The result can be written in the form

$$N_e(t) = \frac{\sqrt{q(t)}}{\sqrt{\alpha}} \frac{S + \sqrt{\alpha q(t)}}{S + K + \sqrt{\alpha q(t))}} \text{ cm}^{-3} \tag{10.163.1}$$

where $q(t)$ is either the value for beta particles from equation (10.157.1), or for gamma rays from equation (10.156.1); the coefficients α, S, and Khave the same significance as before. By using the appropriate values of these coefficients for different altitudes, it has been found that the electron densities peak around an altitude of 40 miles for both daytime and nighttime conditions for slant distances more than 30 miles from the burst point. This is also the altitude for the maximum attenuation of electromagnetic signals by the ionization from delayed radiations (§ 10.159). For smaller distances from the burst point, the electron density peaks near the altitude of the debris region.

10.164 For electron production rates less than 10^6 electrons cm^{-3} sec^{-1}, equation (10.163.1), with the values of α, S, and K given in Table 10.150 for an altitude of 40 miles in the daytime, reduces to

$$N_e(t) \text{ at 40 miles} \approx 10^3\sqrt{q(t)} \text{ cm}^3 \text{ daytime}$$

At night, the values of α, S, and K at an altitude of 40 miles are 3×10^{-8}, 0, and 0.8, respectively, and then

$$N_e(t) \text{ at 40 miles} \approx 10^3 q(t) \text{ cm}^3 \text{ nighttime}$$

for production rates less than about 10^6 cm^{-3} sec^{-1}. For production rates of about 10^7 (or more) electrons cm^{-3} sec^{-1}, the electron density at 40 miles is given approximately by

$$N_e(t) \text{ at 40 miles} \approx 3 \times 10^3\sqrt{q(t)} \text{ cm}^3,$$

for both daytime and nighttime. This result is consistent with Figs. 10.159a and b, in which the curves for day and night coincide when the circumstances are such as to lead to high electron densities. The conditions of applicability of these figures, as described in §10.160 *et seq.*, also apply to the expressions given above.