The Effects of Nuclear Weapons

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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.

Preface

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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ACKNOWLEDGEMENTS

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CHARACTERISTICS OF NUCLEAR EXPLOSIONS

INTRODUCTION

1.01 An explosion, in general, results from the very rapid release of a large amount of energy within a limited space. This is true for a conventional "high explosive," such as TNT, as well as for a nuclear (or atomic) explosion,[1] although the energy is produced in quite different ways (§ 1.11). 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. 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

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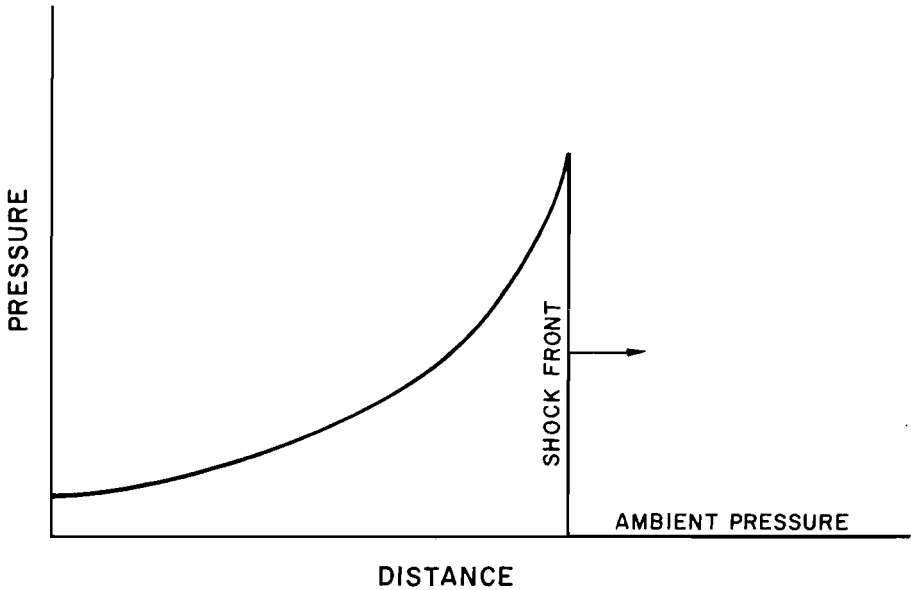
Figure 1.01.   Variation of pressure (in excess of ambient) with distance in an ideal shock wave.

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
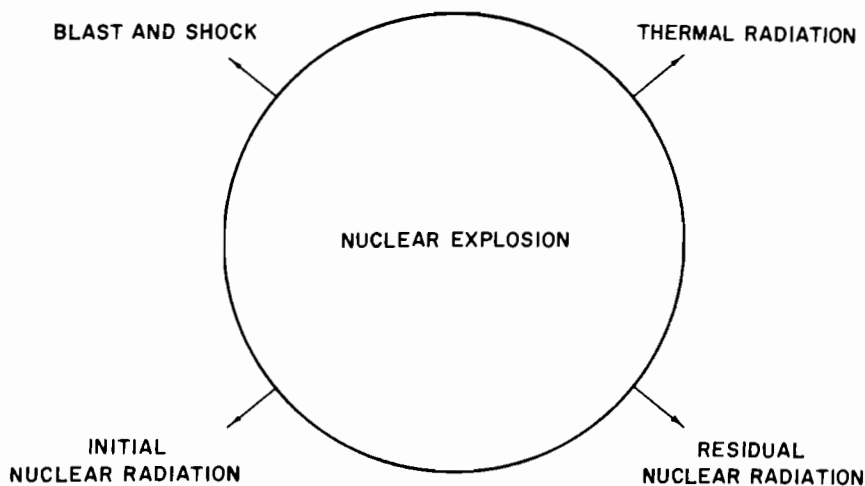
Figure 1.02.   Effects of a nuclear explosion.

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.

ATOMIC STRUCTURE AND ISOTOPES

1.06 All substances are made up from one or more of about 90 different kinds of simple materials known as "elements." Among the common elements are the gases hydrogen, oxygen, and nitrogen; the solid nonmetals carbon, sulfur, and phosphorus; and various metals, such as iron, copper, and zinc. A less familiar element, which has attained prominence in recent years because of its use as a source of 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 con-

sequently 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 accompany-

ing 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 lib-

erated (see § 1.72). These can cause fission in the most abundant isotope (uranium-238) in ordinary uranium as well as in uranium-235 and plutonium-239. 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.

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.

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 increasing temperature. At the moderate temperatures attained in a chemical explosion, the amount of thermal radiation is comparatively small, and so essentially all the energy released at the time of the explosion appears as kinetic and internal energy. This is almost entirely converted into blast and shock, in the manner described in § 1.01. Because of the very much higher temperatures in a nuclear explosion, however, a considerable proportion of the energy 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.

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 ex-

plosion 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 increasing distance from the explosion is determined by the total amount of air through which the radiation travels. This means that, for a given explosion energy yield, more initial nuclear radiation will be received at the same slant 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 gen-

erally 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.

SCIENTIFIC BASIS OF NUCLEAR EXPLOSIONS[2]

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,

$$
\text{Neutron} + \left\{ \begin{array}{l} \text{uranium-235} \\ \text{(or uranium-233)} \\ \text{(or plutonium-239)} \end{array} \right\}
$$

$$
\rightarrow \begin{array}{l} \text{fission fragments} + \\ \text{2 or 3 neutrons} + \text{energy.} \end{array}
$$
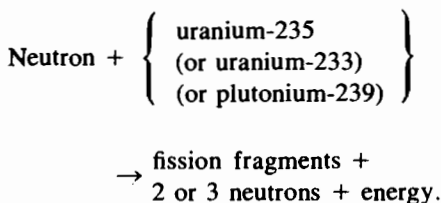
The neutrons liberated in this manner are able to induce fission of additional uranium (or plutonium) nuclei, each such process resulting in the emission of more neutrons which can produce further fission, and so on. Thus, in principle, a single neutron could start off a chain of nuclear fissions, the 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.

Table 1.43

DISTRIBUTION OF FISSION ENERGY

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

1.44   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 reasonably stable so that they can be stored without appreciable decay, that are capable of undergoing fission by neutrons of all energies. Hence, they are the only materials that can 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

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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]

Table 1.45

EQUIVALENTS OF 1 KILOTON OF TNT

Complete fission of 0.057 kg (57 grams or 2 ounces) fissionable material
Fission of 1.45×10^{23} nuclei
10^{12} calories
2.6×10^{25} million electron volts
4.18×10^{19} ergs (4.18×10^{12} joules)
1.16×10^{6} kilowatt-hours
3.97×10^{9} British thermal units

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 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

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[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.

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 arrowhead within the sphere means that fission has occurred and extra neutrons are produced, whereas an arrowhead outside the sphere implies the loss of a neutron. It is evident from Fig. 1.48 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 compres-
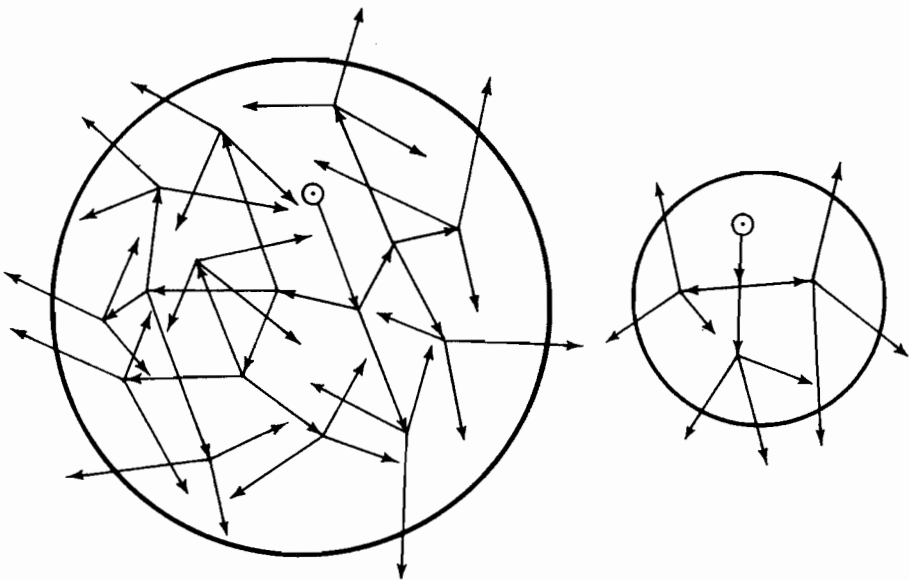

Figure 1.48.   Effect of increased mass of fissionable material in reducing the proportion of neutrons lost by escape.

sion) 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 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.

ATTAINMENT OF CRITICAL MASS IN 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 of fissionable material that is as large as the critical mass for the given conditions. In order to produce an explosion, the material must then be made "supercritical," i.e., larger than the critical mass, in a time so short as to preclude a 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
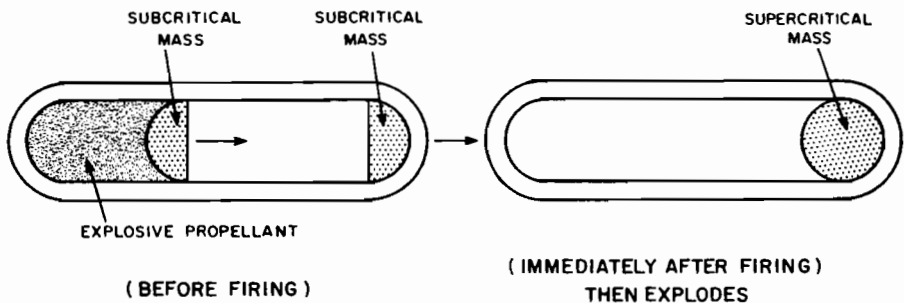
Figure 1.52.   Principle of a gun-assembly nuclear device.

is used to blow one subcritical piece of fissionable material from the breech end of the gun into another subcritical piece firmly held in the muzzle end.

1.53 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.

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

Figure 1.53.   Principle of an implosion-type nuclear device.

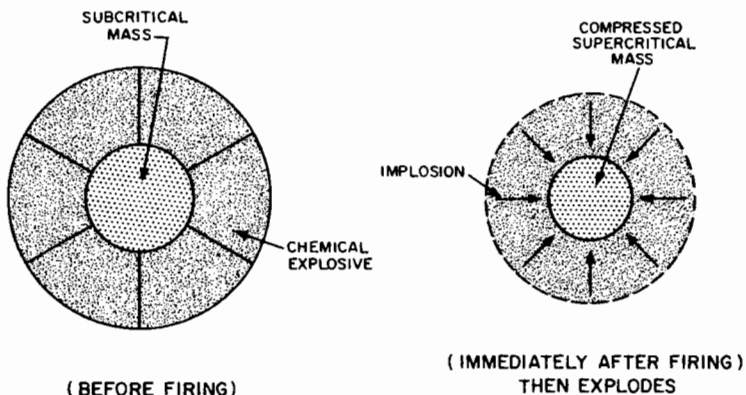fissionable nucleus. This time depends, among other things, on the energy (or speed) of the neutron, and if most of the neutrons are of fairly high energy, usually referred to as "fast neutrons," the generation time is about a one-hundred-millionth part (10^{-8}) of a second, i.e., 0.01 microsecond.[4]

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; hence, the increase in the number of neutrons per generation is $N(f - l) - N$ or $N(f - l - 1)$. For convenience, the quantity $f - l - 1$, 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 t, and if this is represented by n, it follows that

$$N = N_0 e^{xn}. \qquad (1.55.1)$$

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

$$N \approx N_0 e^n \text{ or } N \approx N_0 10^{n/2.3}. \qquad (1.56.1)$$

1.57 According to the data in Table 1.45, it would need 1.45×10^{22} fissions, and hence the same number of neutrons, to produce 0.1 kiloton equivalent of energy. If the fission chain is initiated by one neutron, so that N_0 is 1, it follows from equation (1.56.1) that it would take approximately 51 generations to produce the necessary number of neutrons. Similarly, to release 100 kilotons of energy would require 1.45×10^{25} neutrons and this number would be attained in about 58 generations. It is seen, therefore, that 99.9 percent of the energy of a 100-kiloton fission explosion is released during the last 7 generations, that is, in a period of roughly 0.07 microsecond. 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 ini-

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[4] 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.

tiation 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.

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.[5] 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 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.

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[5]The general term "fission products" is used to describe this complex mixture.
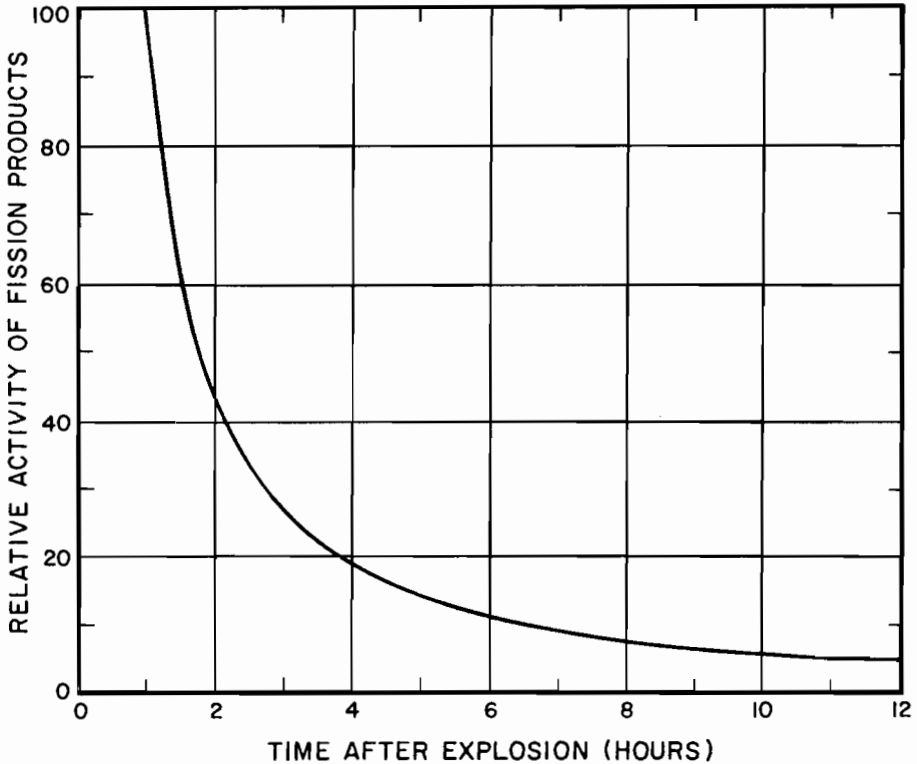
Figure 1.64.   Rate of Decay of fission products after a nuclear explosion (activity is taken as 100 at 1 hour after the detonation).

FUSION (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 (^1H), deuterium (^2H or D), and

tritium (^3H 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 (^1H) 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 sup-

plied 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:

$$D + D = {}^3He + n + 3.2 \text{ MeV}$$
$$D + D = T + {}^1H + 4.0 \text{ MeV}$$
$$T + D = {}^4He + n + 17.6 \text{ MeV}$$
$$T + T = {}^4He + 2n + 11.3 \text{ MeV,}$$
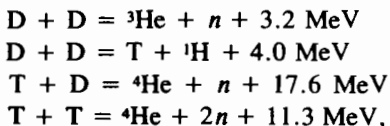
where He is the symbol for helium and n (mass $= 1$) represents a neutron. The energy liberated in each case is given in million electron volt (MeV) units. The first two of these reactions occur with almost equal probability at the temperatures associated with nuclear explosions (several tens of million 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

$$^6Li + n \rightarrow {}^4He + {}^3T + 4.8 \text{ MeV,}$$
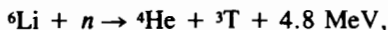
where ^6Li represents the lithium-6 isotope, which makes up about 7.4 percent of natural lithium. Other reactions can occur with lithium-6 or the more abundant isotope lithium-7 and various particles produced in the weapon. However, the reaction shown above is of most interest for two reasons: (1) it 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.

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).

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, 3.00×10^{10} cm per second. According to Planck's theory, the energy of the corresponding "quantum" (or unit) of energy, carried by the "photon," i.e., the postulated particle (or atom) of radiation, is given by

$$E \text{ (ergs)} = h\nu = \frac{hc}{\lambda}$$

$$= \frac{1.99 \times 10^{-16}}{\lambda \text{(cm)}} \qquad (1.74.1)$$

where h is a universal constant equal to 6.62×10^{-27} erg-second. The energy quantum values for the various electromagnetic radiations are included in Fig. 1.74; 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

$$E \text{ (MeV)} = \frac{1.24 \times 10^{-10}}{\lambda \text{(cm)}} \qquad (1.74.2)$$

It is seen that the energy of the radiations decreases from left to right in the
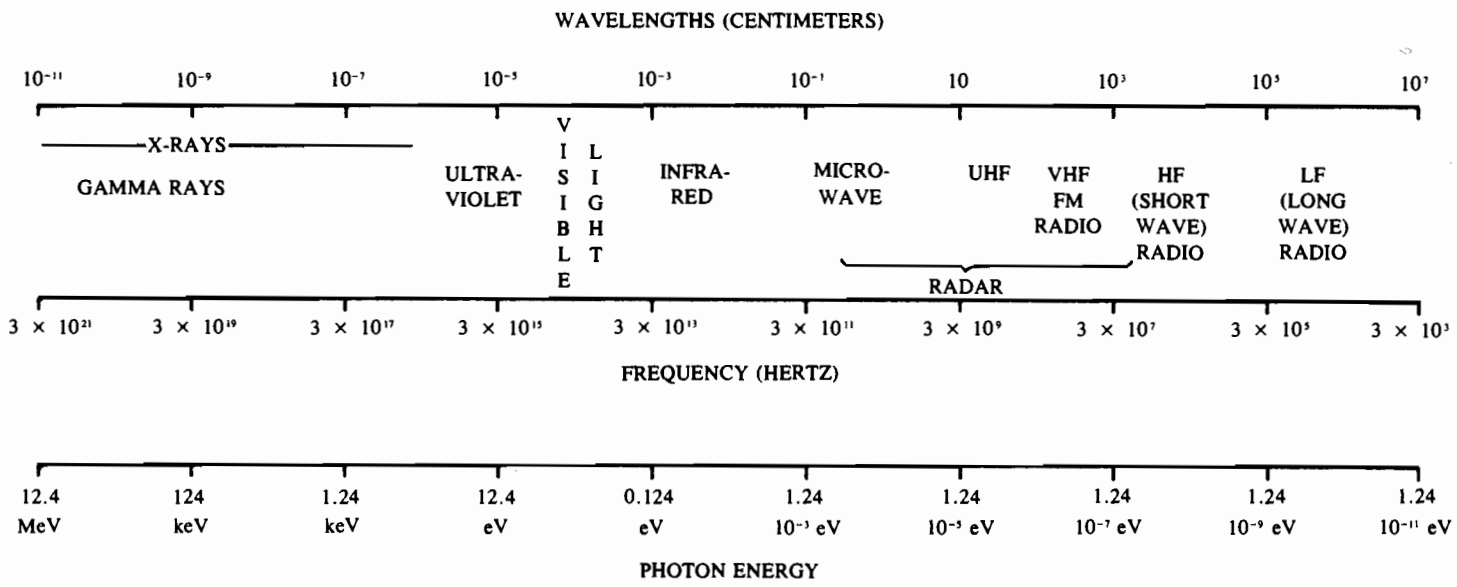
Figure 1.74. Wavelengths, frequencies, and photon energies of electromagnetic radiations.

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

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

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/cm³, compared with roughly 10^8 ergs/cm³ 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/cm³, whereas the material energy is in the range of 10^{14} to 10^{15} ergs/cm³. 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.[6] 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

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[6] 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.

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[7] (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.

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[7]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.

DESCRIPTIONS OF NUCLEAR EXPLOSIONS

INTRODUCTION

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

DESCRIPTION OF AIR AND SURFACE BURSTS

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 baloon. Within seven-tenths of a millisecond

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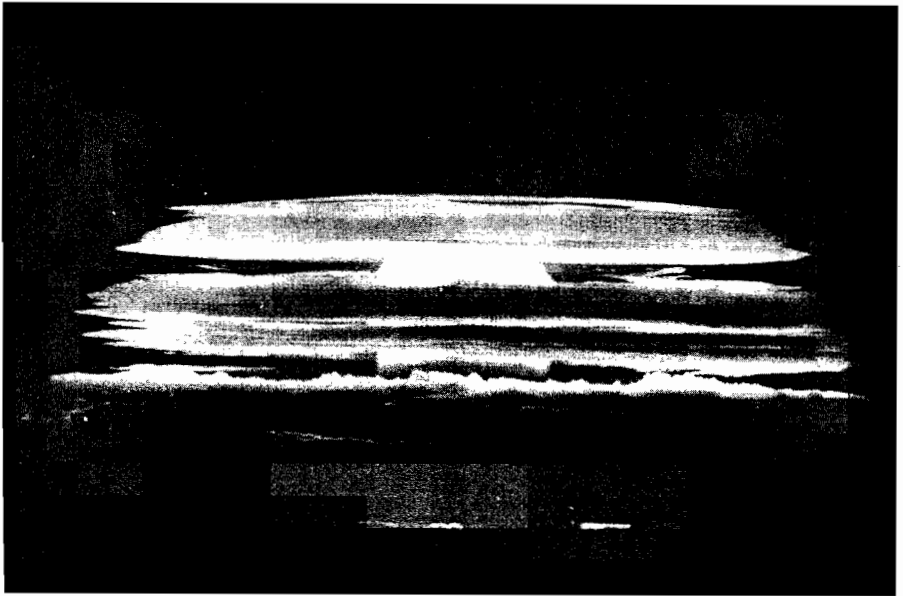[1] A millisecond is a one-thousandth part of a second.

Figure 2.04.   Fireball from an air burst in the megaton energy range, photographed from an altitude of 12,000 feet at a distance of about 50 miles. The fireball is partially surrounded by the condensation cloud (see § 2.48).

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.

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).

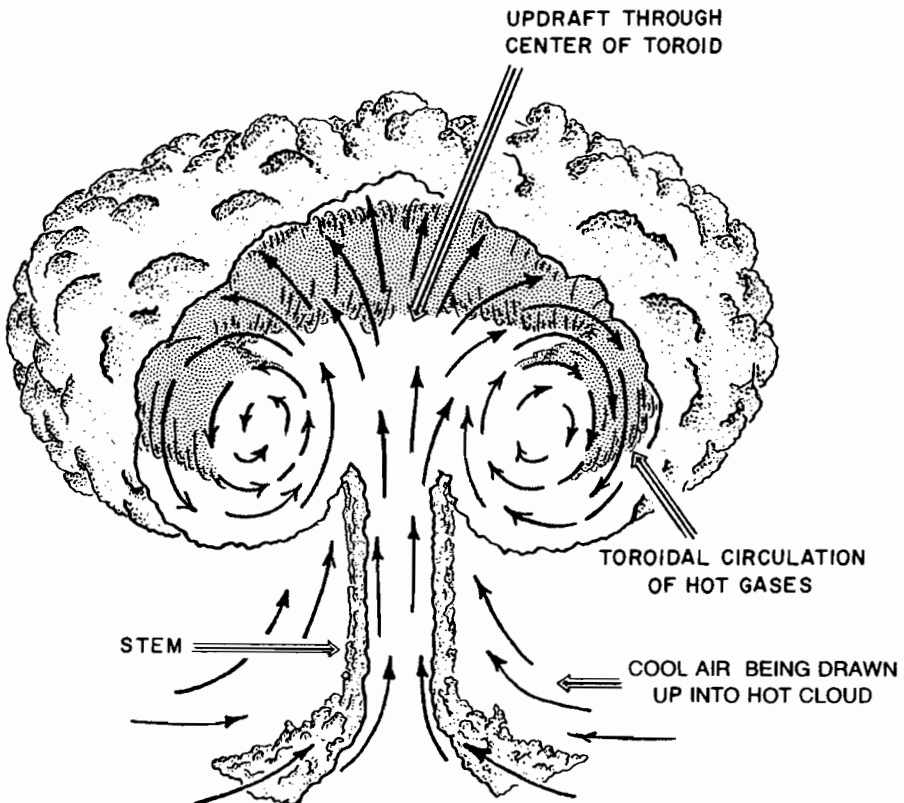**2.10** In an air burst with a moderate (or small) amount of dirt and debris

Figure 2.07a. Cutaway showing artist's conception of toroidal circulation within the radioactive cloud from a nuclear explosion.
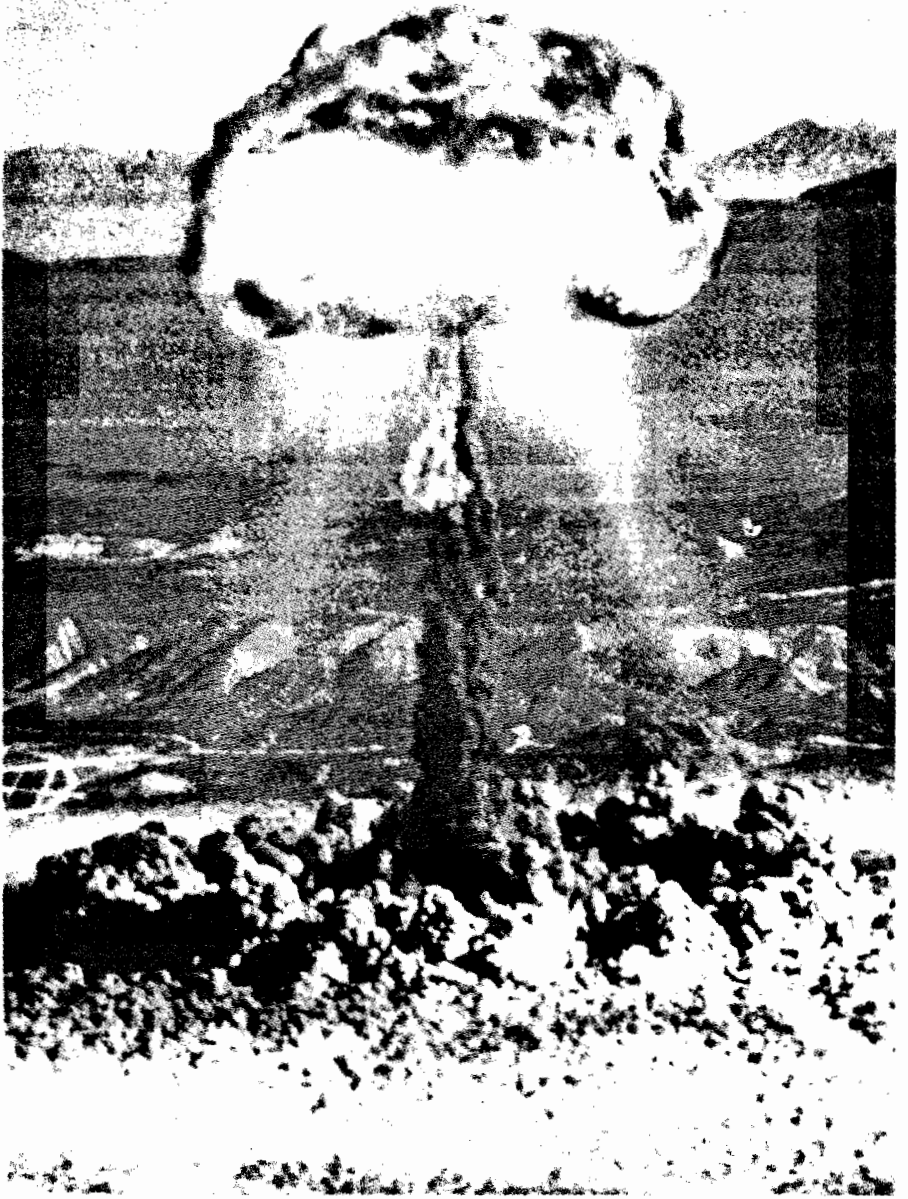
Figure 2.07b.   Low air burst showing toroidal fireball and dirt cloud.

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 min-

Table 2.12
RATE OF RISE OF RADIOACTIVE CLOUD FROM A 1-MEGATON AIR BURST

Height (miles)	Time (minutes)	Rate of Rise (miles per hour)
2	0.3	330
4	0.7	270
6	1.1	220
10	2.5	140
12	3.8	27

ute. 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.[2]

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

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[2]The tropopause is the boundary between the troposphere and the relatively stable air of the stratosphere. It varies with season and latitude, ranging from 25,000 feet near the poles to about 55,000 feet in equatorial regions (§ 9.128).
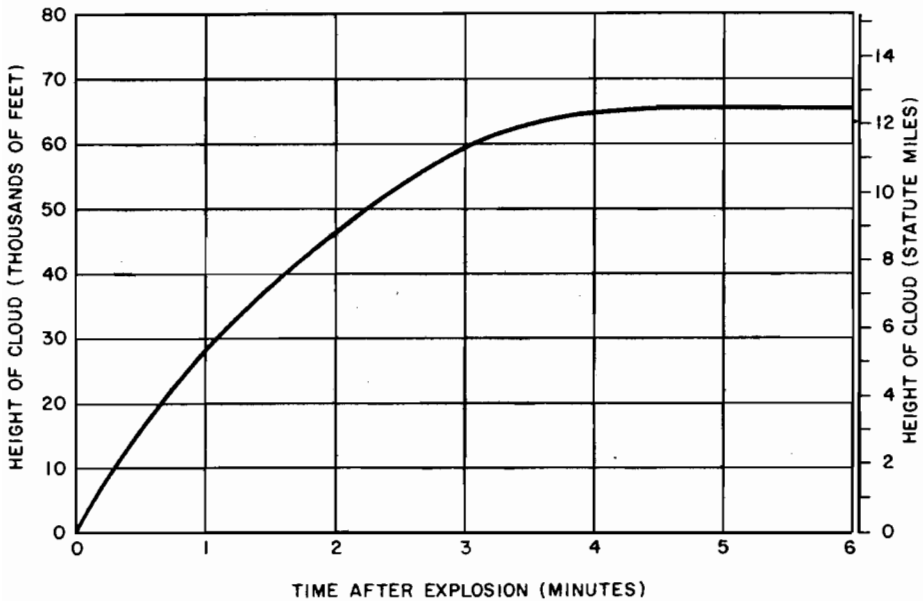
Figure 2.12.   Height of cloud top above burst height at various times after a 1-megaton explosion for a moderately low air burst.

2.15   The cloud attains its maximum 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 of the mushroom head is, very roughly,
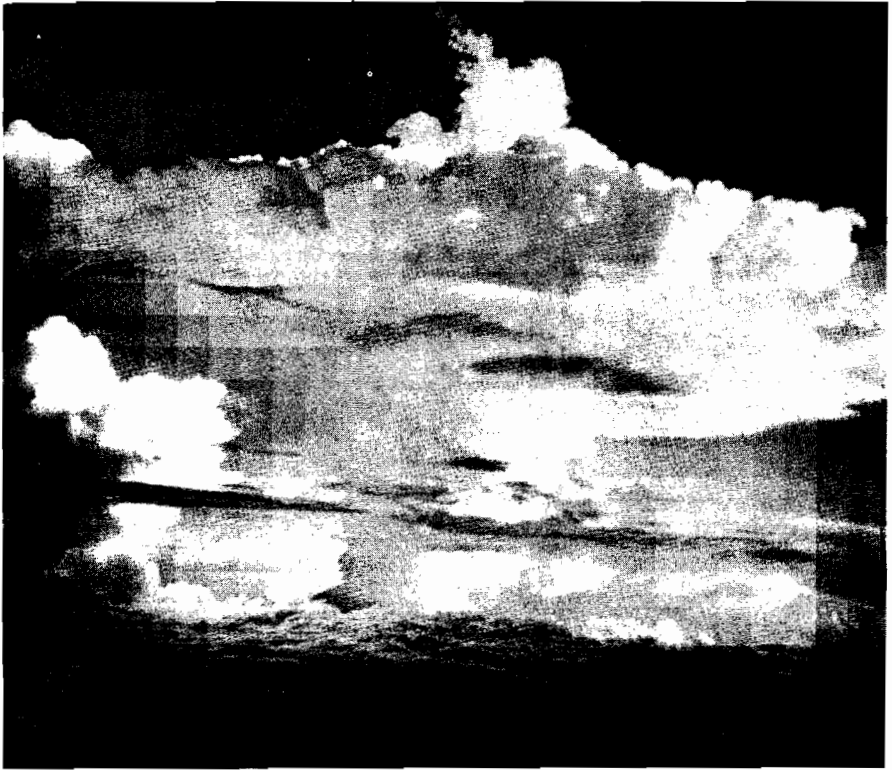
Figure 2.15.   The mushroom cloud formed in a nuclear explosion in the megaton energy range, photographed from an altitude of 12,000 feet at a distance of about 50 miles.

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).

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). Be-
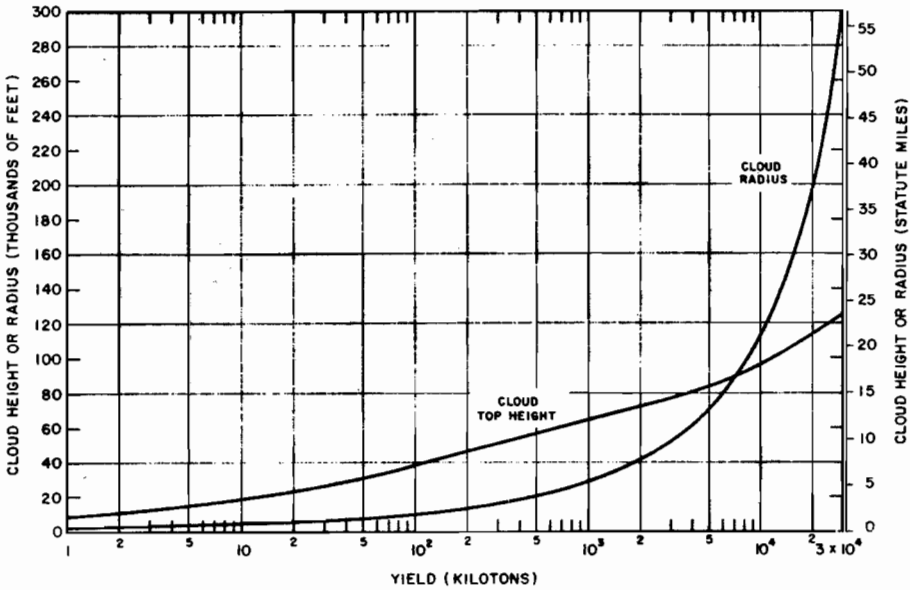
Figure 2.16.   Approximate values of stabilized cloud height and radius as a function of
explosion yield for land surface or low air bursts.

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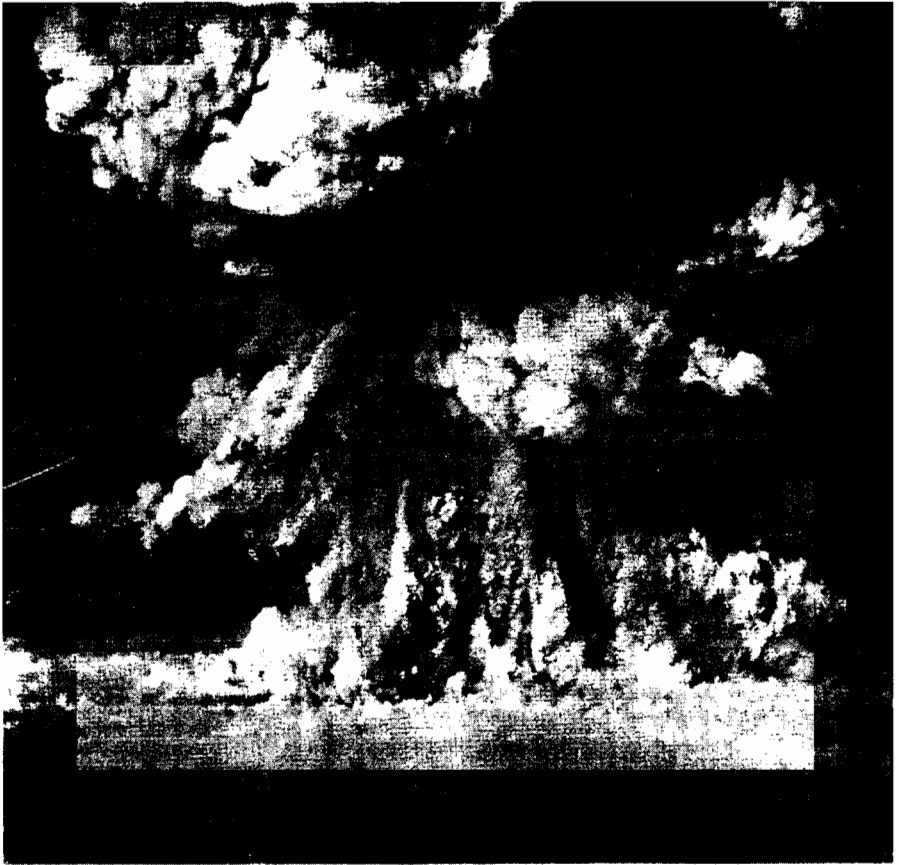
Figure 2.18b. Formation of dirt cloud in surface burst.

cause 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 con-

sists 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.

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

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[3] These residues include radioactive species formed at the time of the explosion by neutron capture in various materials (§ 9.31).

(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 micrometers[4] in diameter, or smaller, in the more distant portions of the fallout area, to pieces about the size of a marble, i.e., roughly 1 cm (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

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

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.

THE BLAST WAVE

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 approx-
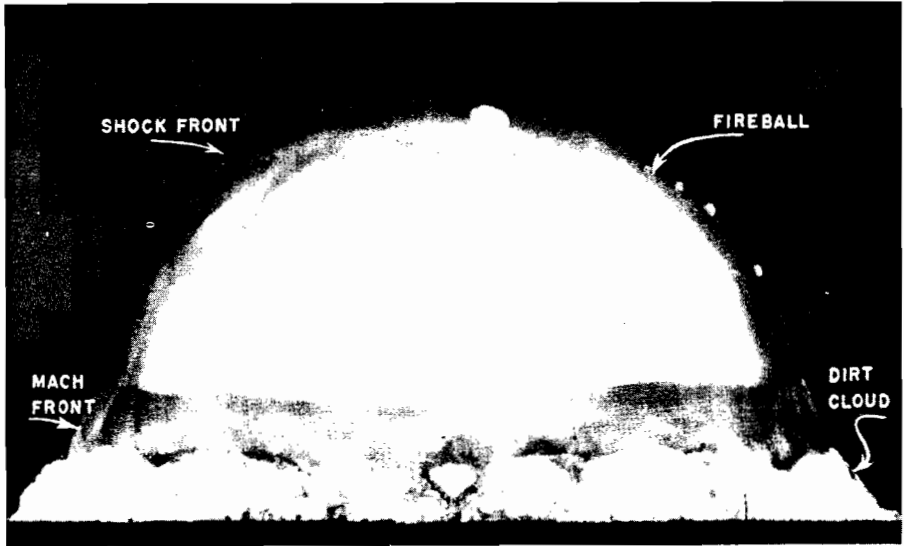
Figure 2.32.   The faintly luminous shock front seen just ahead of the fireball soon after breakaway (see § 2.120).

imately 4.5 seconds after the explosion, in a rough circle at a radius of 1.3 miles from ground zero.[5] The overpressure on the ground at the blast wave front at this time is about 20 pounds per square inch, so that the total air pressure is more than double the normal atmospheric pressure.[6]

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

2.36   The distance from ground zero at which the Mach effect commences varies with the height of burst. Thus, as seen in Fig. 2.32, in the low-altitude (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 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.)

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

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

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.

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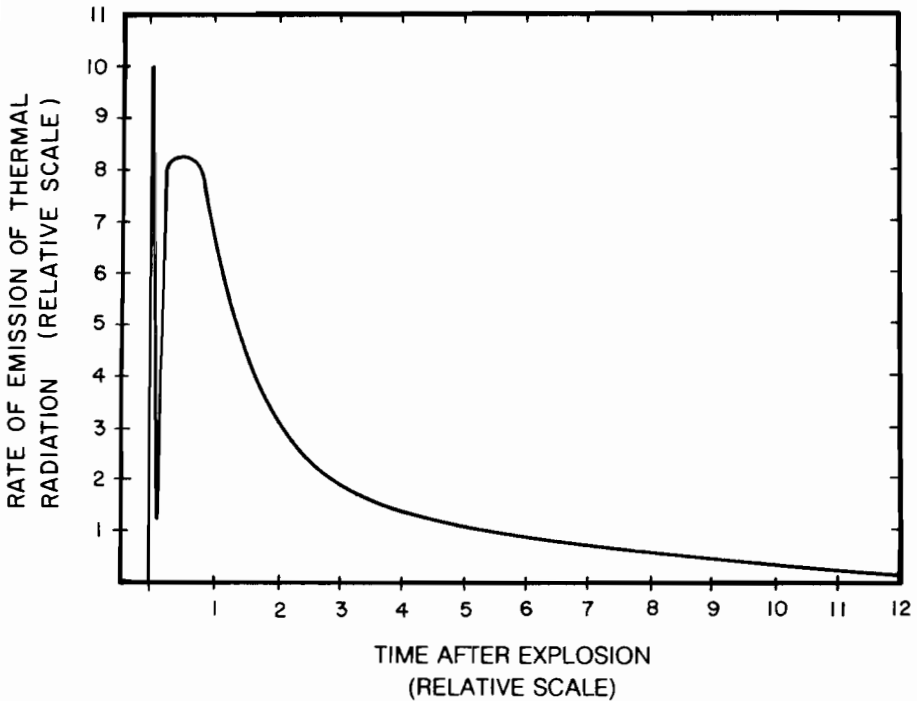
Figure 2.39. Emission of thermal radiation in two pulses in an air burst.

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 1-megaton weapon. For weapons of higher energy, the effective damage range is greater, as will be explained in Chapter VII. The radiation from the second pulse can also cause fires to start under suitable conditions.

INITIAL NUCLEAR RADIATION FROM AN AIR BURST

2.41 As stated in Chapter I, the explosion of a nuclear weapon is associated with the emission of various nuclear radiations, 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 con-

cerned. Thus, when the radioactive cloud has reached a height of 2 miles, the effects of the initial nuclear radiations are no longer significant. Since it takes roughly a minute for the cloud to rise this distance, the initial nuclear radiation was defined as that emitted in the first minute after the explosion.

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

2.45 Neutrons are the only significant nuclear radiations produced directly in the thermonuclear reactions mentioned in § 1.69. 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.

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).

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
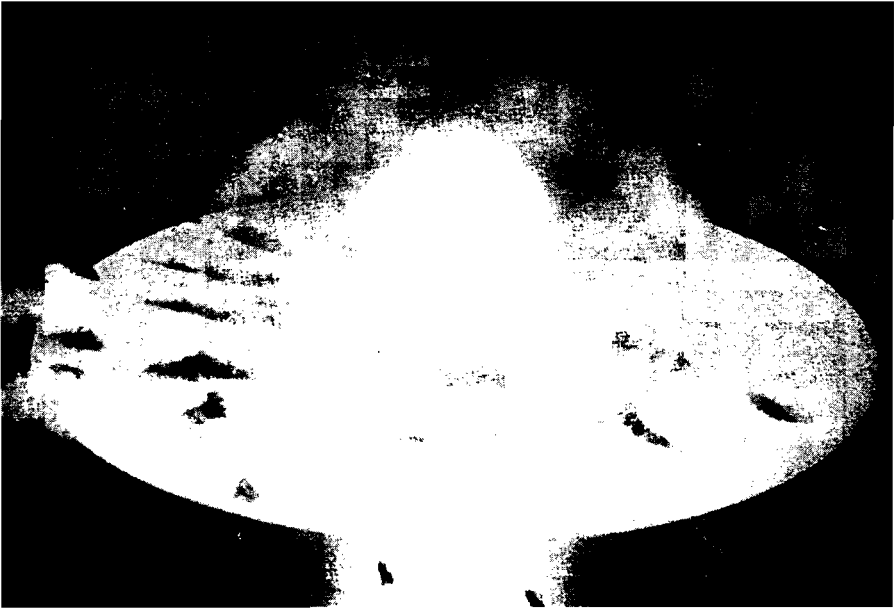
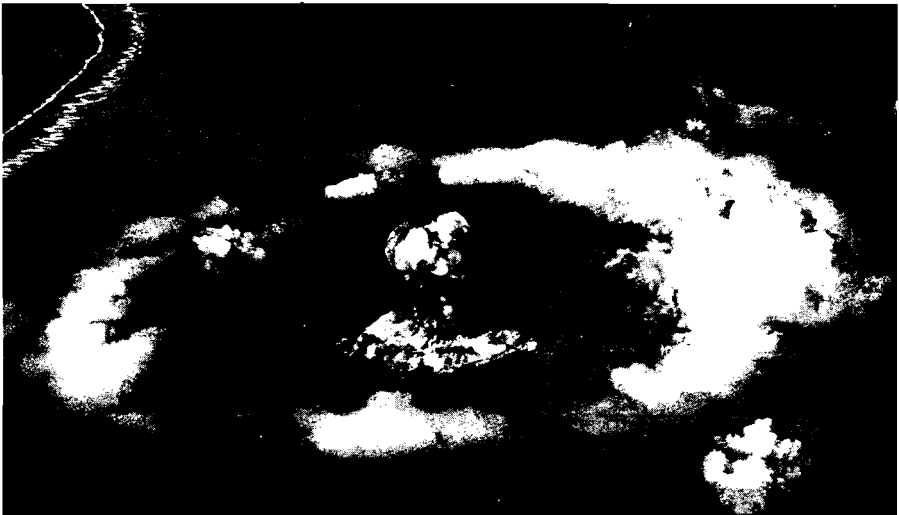Figure 2.49.   Condensation cloud formed in an air burst over water.

Figure 2.50.   Late stage of the condensation cloud in an air burst over water.

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.

DESCRIPTION OF HIGH-ALTITUDE BURSTS

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 FISH-BOWL 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.

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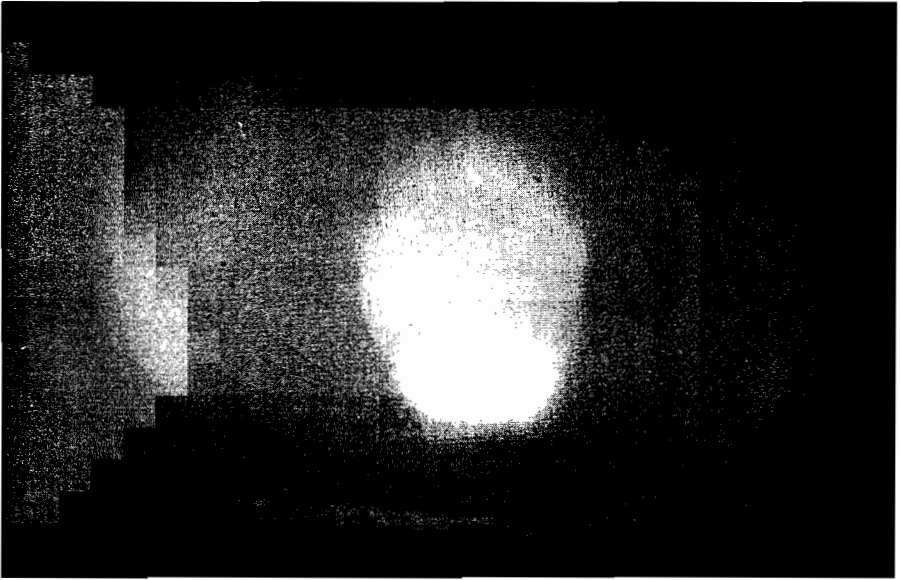
Figure 2.56. Fireball and red luminous spherical wave formed after the TEAK high-altitude shot. (The photograph was taken from Hawaii, 780 miles from the explosion.)

pand. 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 Chapter X). Following the TEAK event, propagation of high-frequency (HF) radio communications (Table 10.91) was de-

graded 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.

DESCRIPTION OF UNDERWATER BURSTS

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 20-kilotons 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

Figure 2.66. The "spray dome" formed over the point of burst in a shallow underwater explosion.

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 radioac-

tive 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 milliseconds after the explosion. Its initial rate of rise was roughly 2,500 feet per second, but this was rapidly diminished by air resistance and gravity. A few milliseconds later, the hot gas bubble reached the surface of the lagoon and the column began to form, quickly overtaking the spray dome. The maximum height attained by the hollow column, through which the gases vented, could not be estimated exactly
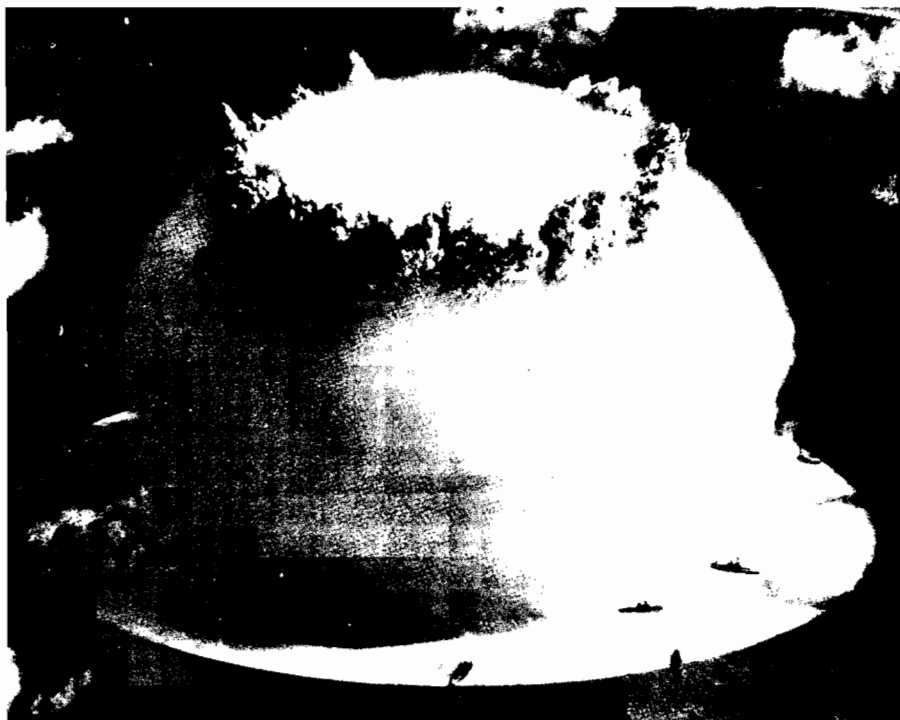
Figure 2.67a.   The condensation cloud formed after a shallow underwater explosion. (The "crack" due to the shock wave can be seen on the water surface.)
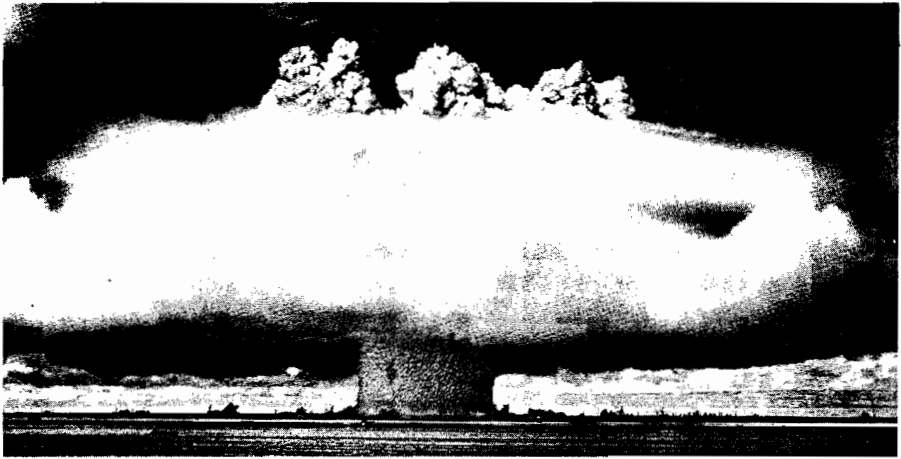
Figure 2.67b.   Formation of the hollow column in a shallow underwater explosion; the top is surrounded by a late stage of the condensation cloud.
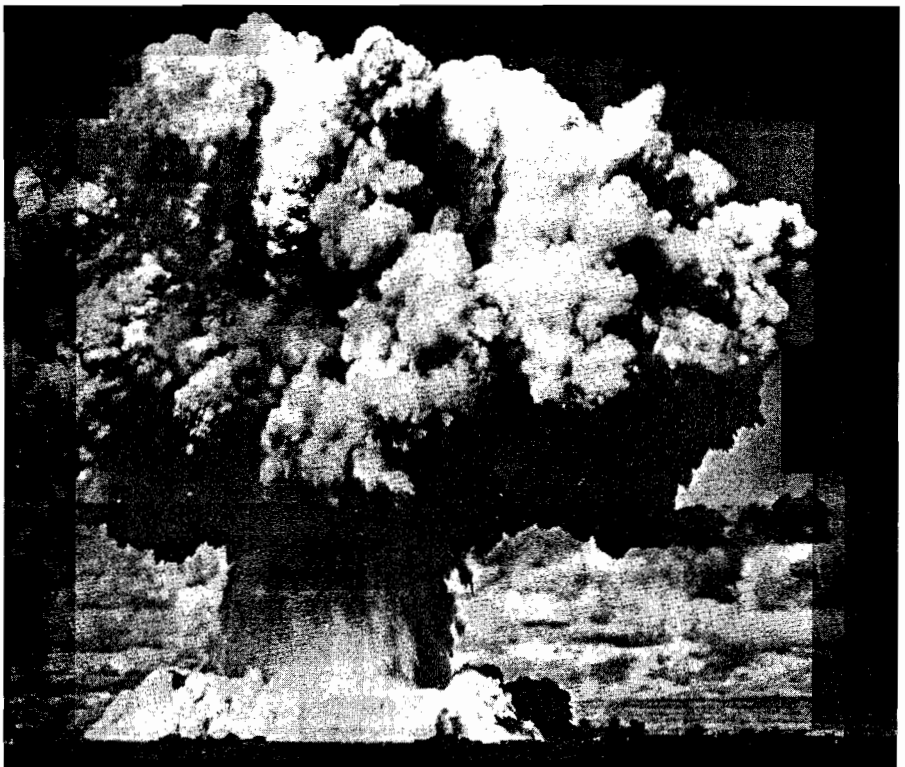
Figure 2.68.   The radioactive cloud and first stages of the base surge following a shallow underwater burst. Water is beginning to fall back from the column into the lagoon

because 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
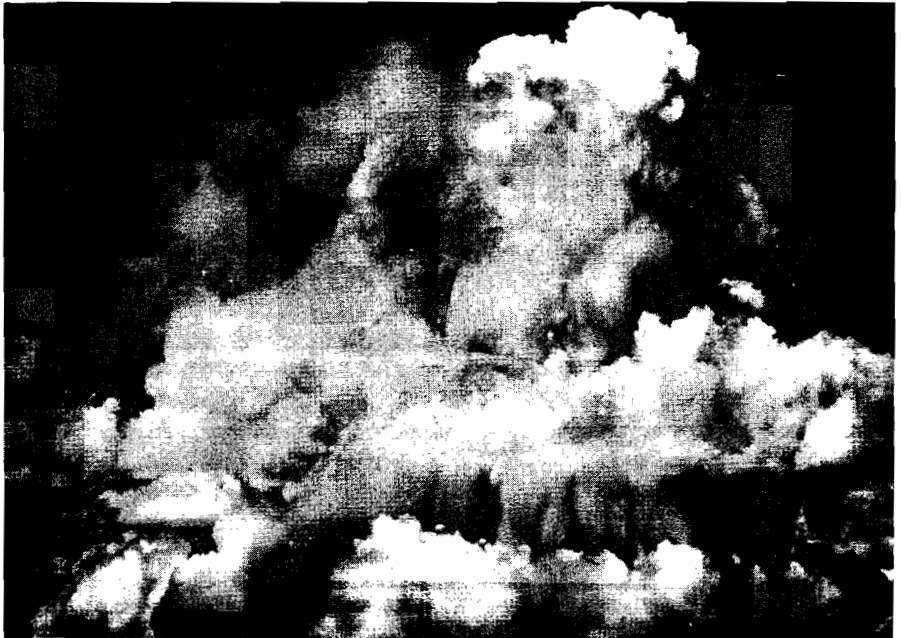

Figure 2.73.   The development of the base surge following a shallow underwater explosion.

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.

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 3½ miles across and its height had then increased to 1,800 feet. At this stage, the base surge gradually rose from the surface of the water and began to merge with the radioactive cloud and other clouds in the sky (Fig. 2.73).

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.

THE RADIOACTIVE BASE SURGE

2.77   From the weapons effects standpoint, the importance of the base
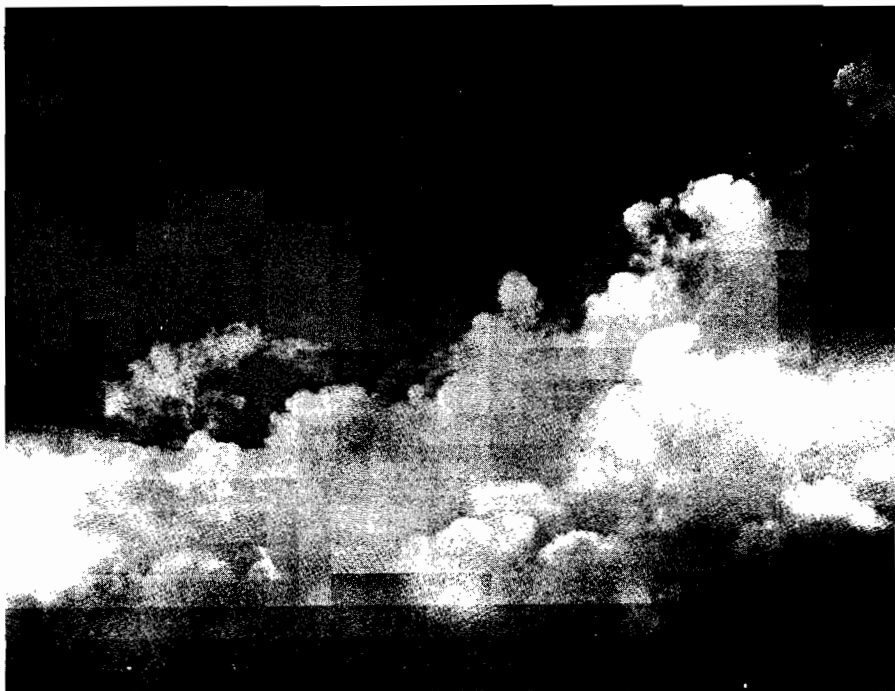
Figure 2.74.   Final stage in the development of the base surge.

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.

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.

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 2½ 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 max-

imum 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

Figure 2.84a.   Spray dome observed 5.3 seconds after explosion in deep water.
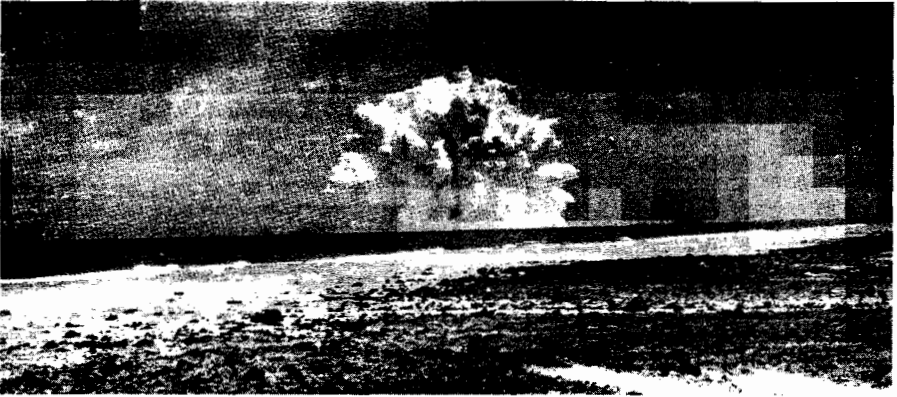

Figure 2.84b.   Plume observed 11.7 seconds after explosion in deep water.

Figure 2.84c.   Formation of base surge at 45 seconds after explosion in deep water.

unlikely. During the pulsation and upward 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.

DESCRIPTION OF UNDERGROUND BURSTS

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

Figure 2.93. Shallow underground burst.

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.

BASE SURGE AND 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.
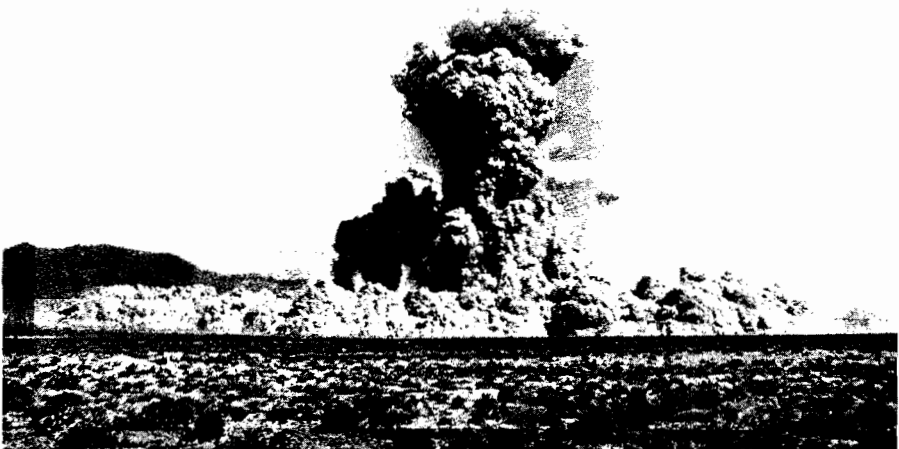

Figure 2.97.   Main cloud and base surge 6 minutes after the SEDAN underground burst.

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.

THERMAL AND NUCLEAR RADIATIONS IN UNDERGROUND BURSTS

2.99 The situations as regards thermal and nuclear radiations from an underground burst are quite similar to those described above in connection with an underwater explosion. As a general rule, the thermal radiation is almost completely absorbed by the ground material, so that it does not represent 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 importance only in the close vicinity of the point of burst. The remainder of the residual radiation will be due to the contaminated base surge and fallout.

2.100 For the reasons given in § 2.82 for an underwater burst, the initial and residual radiations from an underground burst tend to merge into one another. The distinction which is made in the case of air and surface bursts is consequently less significant in a subsurface explosion.

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 detona-

tion. RAINIER was a 1.7-kiloton nuclear device detonated in a chamber 6 × 6 × 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 gener-
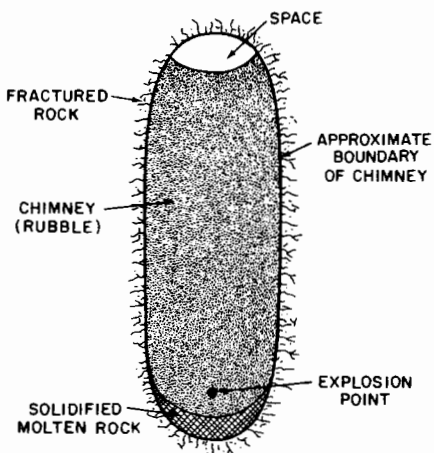

Figure 2.103.   The rubble chimney formed after collapse of the cavity in a deep underground nuclear detonation.

ally 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.*).

SCIENTIFIC ASPECTS OF NUCLEAR EXPLOSION PHENOMENA[7]

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 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. Ul-

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

timately, 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.

DEVELOPMENT OF THE 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 20-kiloton weapon. In the first picture, at 0.1 millisecond, the temperature is shown to be uniform within the fireball and to drop abruptly at the exterior, so that the condition is that of the isothermal sphere. Subsequently, as the shock front begins to move ahead of the isothermal sphere, the temperature is no longer uniform, as indicated by the more gradual fall near the outside of the fireball. Eventually, two separate tem-

perature 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."
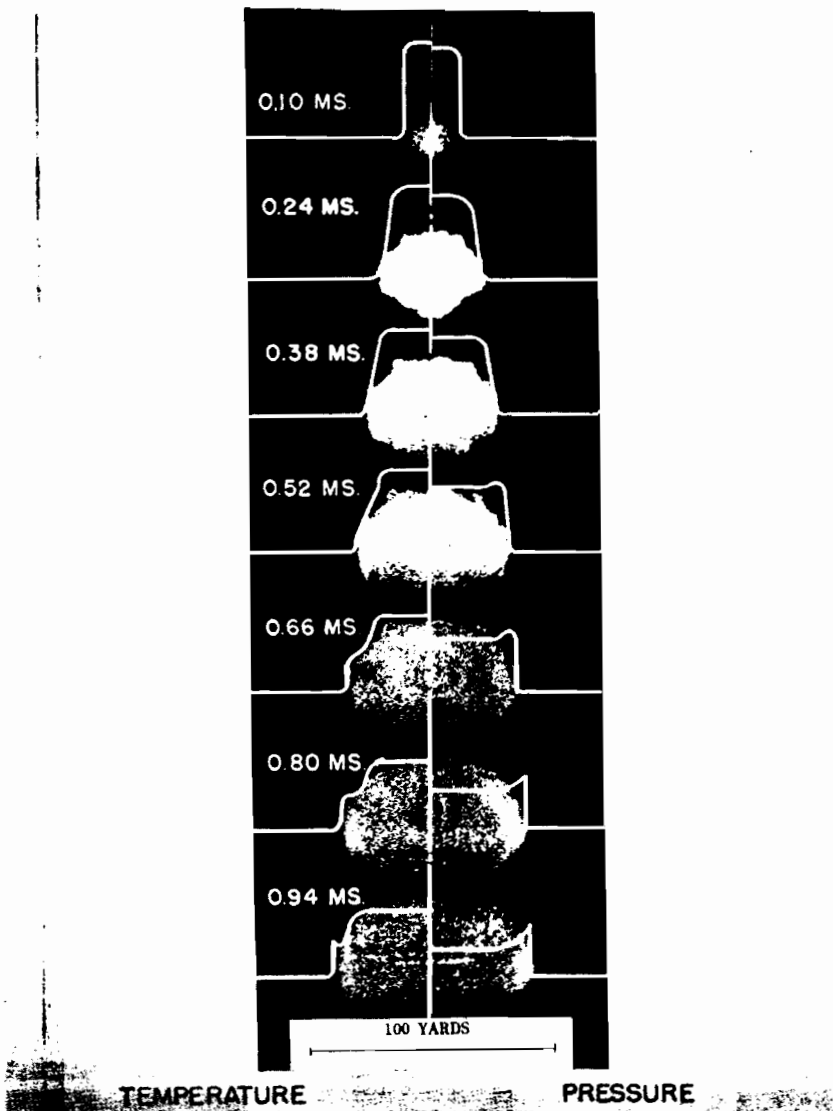
Figure 2.118.   Variation of temperature and pressure in the fireball. (Times and dimensions apply to a 20-kiloton air burst.)

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
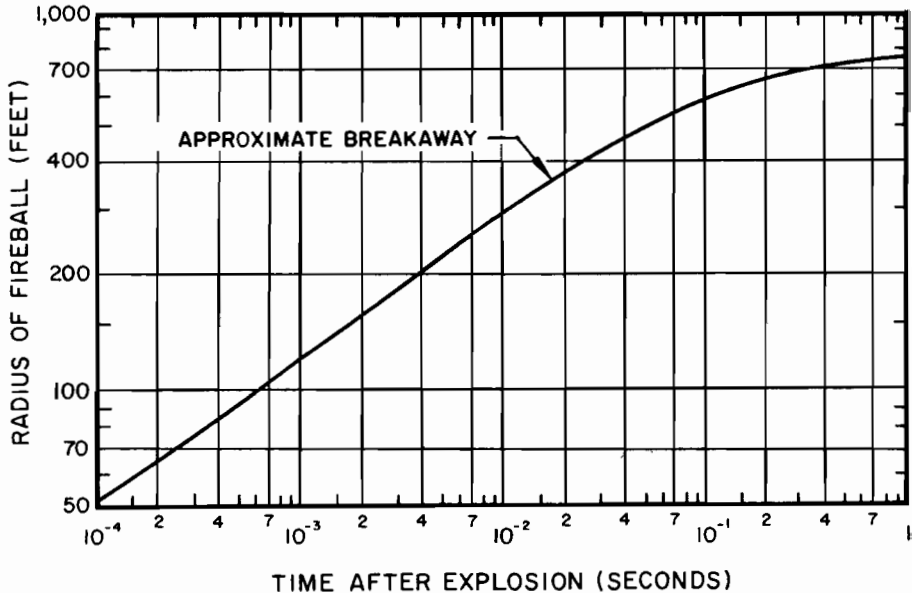
Figure 2.121.   Variation of radius of luminous fireball with time in a 20-kiloton air burst.

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.

TEMPERATURE OF THE FIREBALL

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,
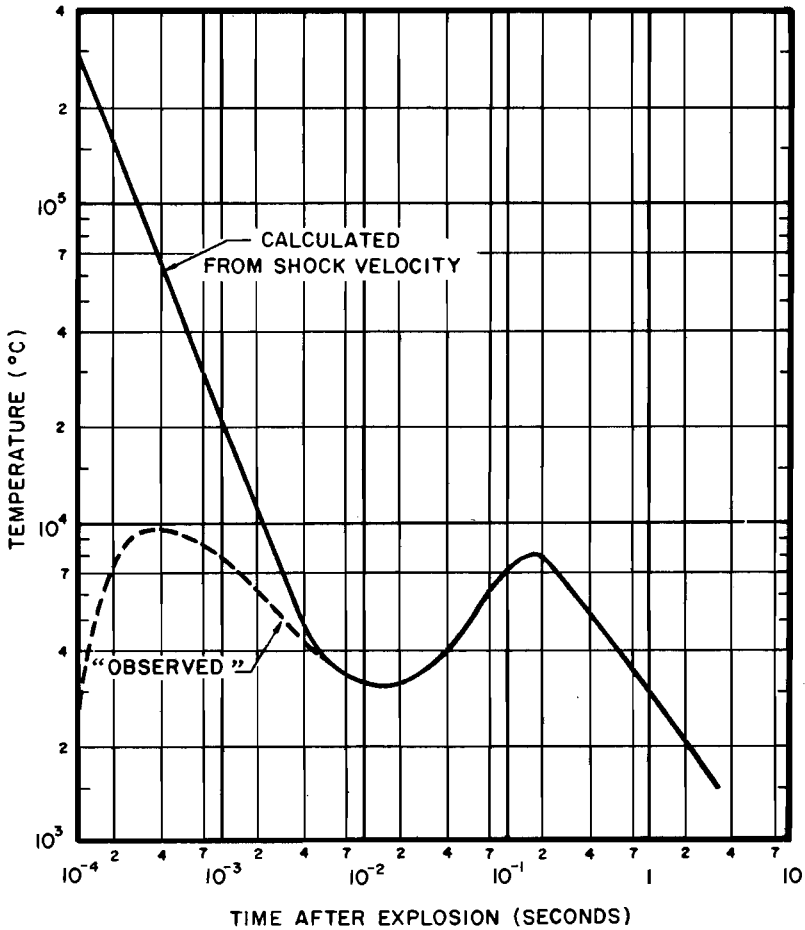
Figure 2.123.   Variation of apparent fireball surface temperature with time in a 20-kiloton air burst.

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.

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

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

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

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

For a contact surface burst, i.e., in which the exploding weapon is actually on the surface,[8] blast wave energy is

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

reflected back from the surface into the fireball (§ 3.34) and W in equation (2.127.1) should probably be replaced by $2W$, where W is the actual yield. Hence, for a contact surface burst,

R (at breakaway) for contact surface
burst $\approx 145\ W^{0.4}$. (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 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 (maximum for local
fallout) $\approx 180\ W^{0.4}$, (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, may

be 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 the 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.

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
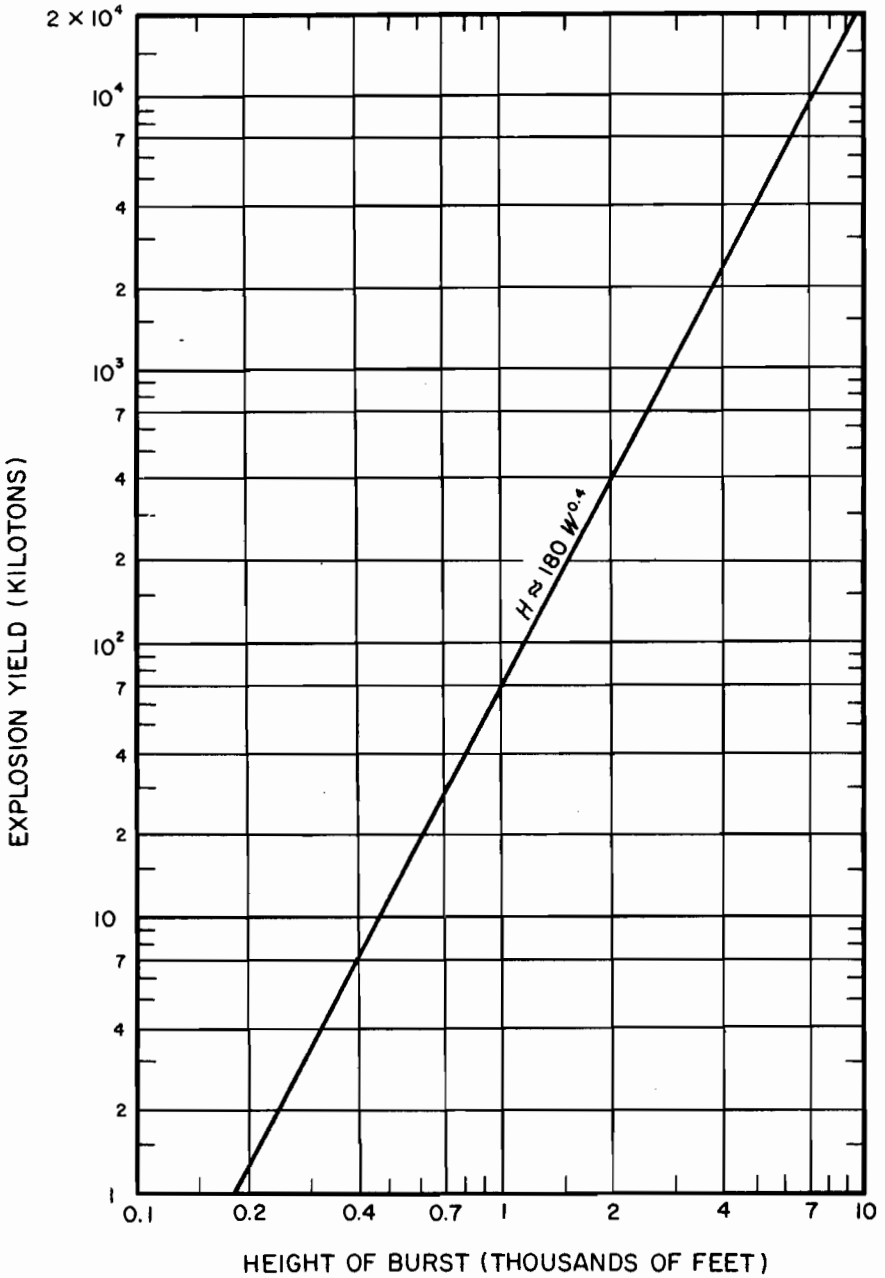
Figure 2.128.   Approximate maximum height of burst for appreciable local fallout.

(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 ex-
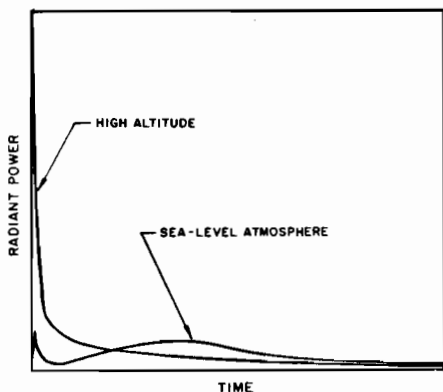
Figure 2.133.   Qualitative comparison of
rates of arrival of thermal
radiation at a given distance
from high-altitude and sea-
level bursts.

plosion 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 up-
ward 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 en-
ergy 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 approxi-
mately equal to the height of burst
minus 270,000 feet. The height and di-
mensions 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 radi-
ations of lower energy (longer wave-
length) re-emitted by these species rep-
resent 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 de-
scribed in detail in Chapter X. The in-
candescent (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 pro-
portion 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 pro-
duced 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 vi-
cinity 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.

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 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.

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 be-
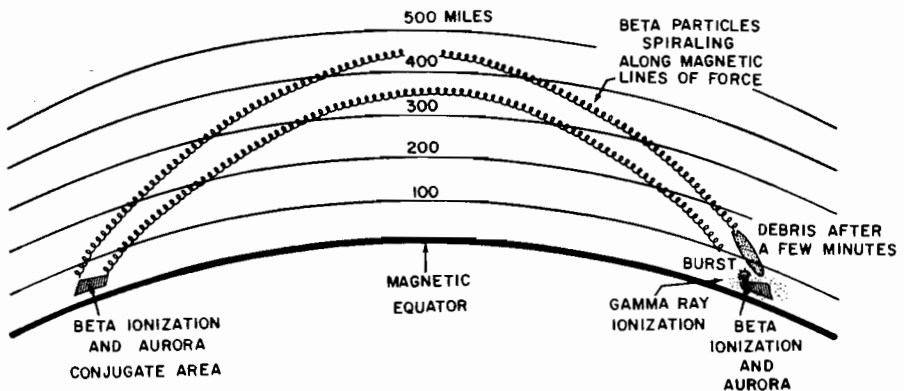

Figure 2.143.   Phenomena associated with high-altitude explosions.

tween 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 bursts 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.

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.

EFFECT ON THE OZONE LAYER

2.148 Ozone (O_3) 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 (O_2). 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 10^{32} 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.

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AIR BLAST PHENOMENA IN AIR AND SURFACE BURSTS

CHARACTERISTICS OF THE BLAST WAVE IN AIR

DEVELOPMENT OF THE BLAST WAVE

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 varia-

tion 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

the pressure behind the front falls off in a regular manner. After a short time, when the shock front has traveled a certain distance from the fireball, the pressure behind the front drops below that of the surrounding atmosphere and a so-called "negative phase" of the blast wave forms. This development is seen in Fig. 3.04, which shows the overpressures at six successive times, indicated by the numbers 1, 2, 3, 4, 5, and 6. In the curves marked t_1 through t_5
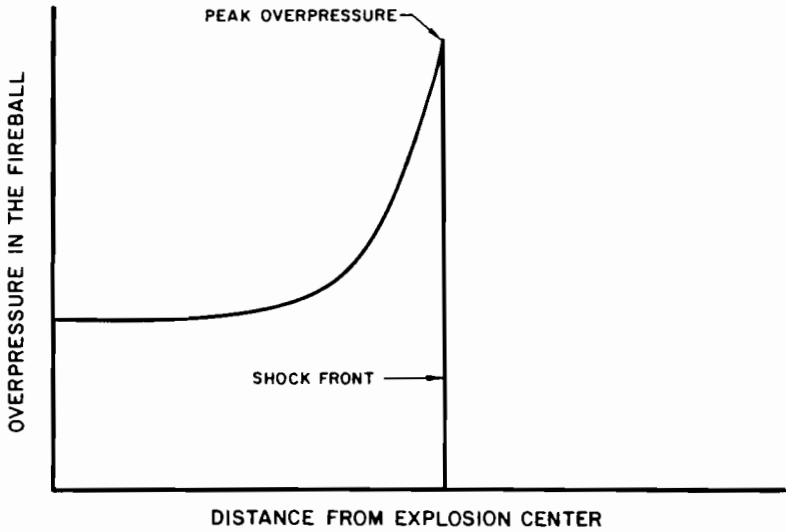
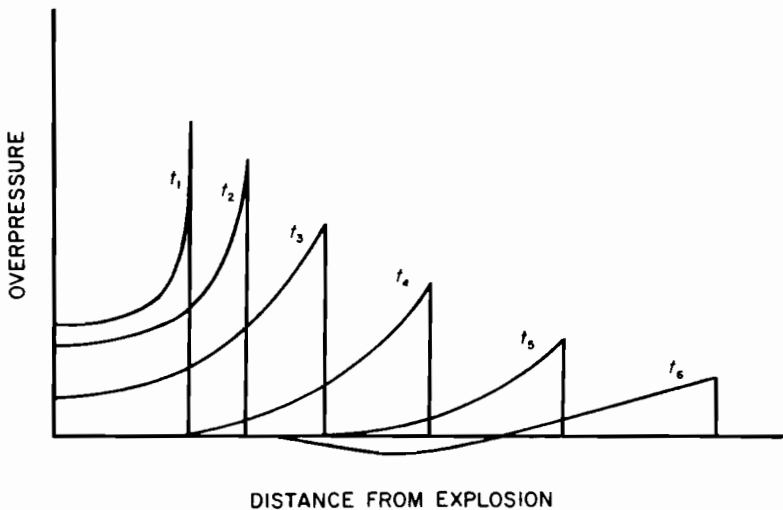Figure 3.03. Variation of overpressure with distance in the fireball.

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

the pressure in the blast wave has not fallen below atmospheric, but in the curve marked t_6 it is seen that at some distance behind the shock front the overpressure has a negative value. In this region the air pressure is below that of the original (or ambient) atmosphere, so that an "underpressure" rather than an overpressure exists.

3.05   During the negative (rarefaction or suction) phase, a partial vacuum is produced and the air is sucked in, instead of being pushed away from the explosion as it is when the overpressure is positive. At the end of the negative phase, which is somewhat longer than the positive phase, the pressure has essentially returned to ambient. The peak (or maximum) values of the underpressure are usually small compared with the peak positive overpressures; the former are generally not more than about 4 pounds per square inch below the ambient pressure whereas the positive overpressure may be much larger. With increasing distance from the explosion, both peak values decrease, the positive more rapidly than the negative,

and they approach equality when the peak pressures have decayed to a very low level.

THE DYNAMIC PRESSURE

3.06   The destructive effects of the blast wave are frequently related to values of the peak overpressure, but there is another important quantity called the "dynamic pressure." For a great variety of building types, the degree of blast damage depends largely on the drag force associated with the strong winds accompanying the passage of the blast wave. The drag force is influenced by certain characteristics—primarily the shape and size—of the structure, but this force also depends on the peak value of the dynamic pressure and its duration at a given location.

3.07   The dynamic pressure is proportional to the square of the wind velocity and to the density of the air behind the shock front. Both of these quantities may be related to the overpressure under ideal conditions at the wave front by certain equations, which will be given later (see § 3.55). For very

Table 3.07

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

Peak overpressure (pounds per square inch)	Peak dynamic pressure (pounds per square inch)	Maximum wind velocity (miles per hour)
200	330	2,078
150	222	1,777
100	123	1,415
72	74	1,168
50	41	934
30	17	669
20	8.1	502
10	2.2	294
5	0.6	163
2	0.1	70

strong shocks the peak dynamic pressure is larger than the peak overpressure, but below 70 pounds per square inch overpressure at sea level the dynamic pressure is the smaller. Like the peak shock overpressure, the peak dynamic pressure generally decreases with increasing distance from the explosion center, although at a different rate. Some peak dynamic pressures and maximum blast wind velocities corresponding to various peak overpressures, as calculated for an ideal shock front in air at sea level (§ 3.53 *et seq.*) are given in Table 3.07. The results are based on 1,116 feet per second (761 miles per hour) as the velocity of sound in air (see Table 3.66).

3.08 The winds referred to above, which determine the dynamic pressure in the shock wave, are a direct consequence of the air blast. More will be said about these winds shortly. There are also other winds associated with nuclear explosions. These include the afterwinds mentioned in § 2.09, and the firestorms which will be described in Chapter VII.

CHANGES IN THE BLAST WAVE
WITH TIME

3.09 From the practical standpoint, it is of interest to examine the changes of overpressure and dynamic pressure with time at a fixed location (or observation point). For a short interval after the detonation, there will be no change in the ambient pressure because it takes some time for the blast wave to travel from the point of the explosion to the given location. This time interval (or arrival time) depends upon the energy yield of the explosion and the slant range. For example, at a distance of 1 mile from a 20-kiloton explosion in the air the arrival time would be about 3 seconds, whereas at 2 miles it would be about 7.5 seconds. The corresponding times for a 1-megaton burst would be roughly 1.4 and 4.5 seconds, respectively.

3.10 It is evident that the blast wave from an explosion of higher yield will arrive at a given point sooner than one for a lower yield. The higher the overpressure at the shock front, the greater is the velocity of the shock wave (see Figure. 3.55). Initially, this velocity may be quite high, several times the speed of sound in air (about 1,100 feet per second at sea level). As the blast wave progresses outward, the pressure at the front decreases and the velocity falls off accordingly. At long ranges, when the overpressure has decreased to less than about 1 pound per square inch, the velocity of the blast wave approaches the ambient speed of sound.

3.11 When the (ideal) shock front arrives at the observation point, the overpressure will increase sharply from zero to its maximum (or peak) value. Subsequently the overpressure decreases, as indicated by the upper curve in Fig. 3.11. The overpressure drops to zero in a short time, and this marks the end of the positive (or compression) phase of the overpressure at the given location. The duration of the overpressure positive phase increases with the energy yield and the distance from the explosion. For a 20-kiloton air burst, for example, this phase lasts roughly 1 second to 1.4 seconds at slant ranges of 1 to 2 miles; for a 1-megaton explosion, the respective durations would be approximately 1.4 to 2.3 seconds.
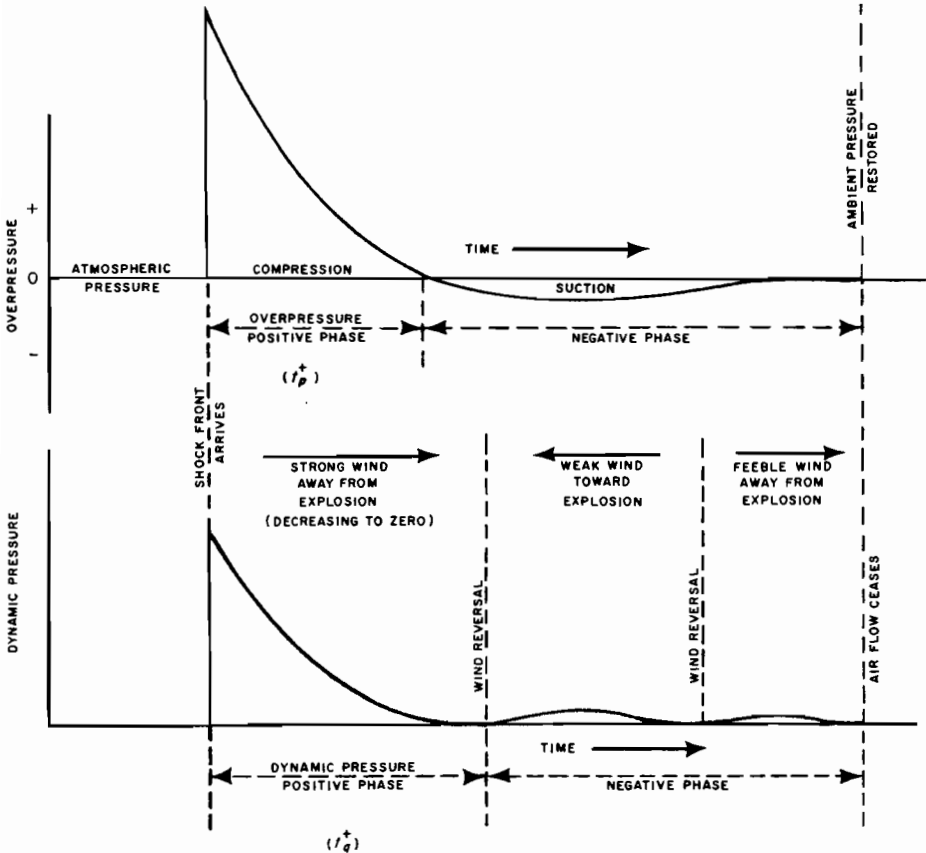
Figure 3.11.   Variation of overpressure and dynamic pressure with time at a fixed location.

3.12   Provided the observation point is at a sufficient distance from the explosion, the overpressure will continue to decrease after it falls to zero so that it becomes negative. During this negative (or suction) phase, the pressure in the shock wave is less than the ambient atmospheric pressure. However, as seen in § 3.05, the underpressure is never very large. After decreasing gradually to a minimum value, the pressure starts to increase until it becomes equal to the normal atmospheric pressure, and the overpressure is zero again. The negative phase of the blast wave is usually longer than the positive phase and it may last for several seconds. When this phase is ended, the blast wave will have passed the given observation point.

3.13   Changes in the wind and in the associated dynamic pressure accompany the changes with time of the overpressure. With the arrival of the shock front at a given location, a strong wind commences, blowing away from the explosion point. This blast wind is often referred to as a "transient wind" because its velocity decreases rapidly with time. The maximum velocity of the transient wind can be quite high, as indicated by

the values corresponding to various peak overpressures given in Table 3.07. The wind velocity decreases as the overpressure decreases, but it continues to blow for a time after the end of the positive overpressure phase (see Fig. 3.11). The reason is that the momentum of the air in motion behind the shock front keeps the wind blowing in the same direction even after the overpressure has dropped to zero and has started to become negative.

3.14 Since the dynamic pressure is related to the square of the wind velocity, the changes in the dynamic pressure with time will correspond to the changes in the wind just described. The dynamic pressure increases suddenly when the (ideal) shock front arrives at the observation point. Then it decreases, but drops to zero some time later than the overpressure, as shown by the lower curve in Fig. 3.11. The dynamic pressure positive phase is thus longer than the overpressure positive phase. The ratio of the dynamic pressure and overpressure positive phase durations depends on the pressure levels involved. When the peak pressures are high, the positive phase of the dynamic pressure may be more than twice as long as for the overpressure. At low peak pressures, on the other hand, the difference is only a few percent.

3.15 As a general rule, the peak overpressure and the peak dynamic pressure behind the shock front are quite different (see Table 3.07). Furthermore, the dynamic pressure takes somewhat longer than the overpressure to drop to zero during the positive phase. Consequently, it is evident that the overpressure and dynamic pressure at a given location change at different rates with

time. This matter will be discussed more fully later in this chapter (§ 3.57 *et seq.*).

3.16 By the time the wind ceases blowing away from the explosion, the overpressure is definitely negative (see Fig. 3.11); that is to say, the pressure in the blast wave is less than the ambient atmospheric pressure. Hence, air is drawn in from outside and, as a result, the wind starts to blow in the opposite direction, i.e., toward the explosion, but with a relatively small velocity. A short time after the overpressure minimum is passed, the wind again reverses direction and blows, once more, away from the explosion point. The feeble wind apparently results from expansion of the air due to an increase of temperature that occur at this stage.

3.17 The changes in the dynamic pressure corresponding to the foregoing wind changes after the end of the dynamic pressure positive phase are indicated in Fig. 3.11. The dynamic pressure finally decreases to zero when the ambient atmospheric pressure is restored and the blast wave has passed the observation point.

3.18 It should be noted that the dynamic pressure remains positive (or zero) even when the overpressure is negative. Since the overpressure is the difference between the actual blast wave pressure and the ambient atmospheric pressure, a negative overpressure merely implies that the actual pressure is less than the atmospheric pressure. The dynamic pressure, on the other hand, is an actual pressure without reference to any other pressure. It is a measure of the kinetic energy, i.e., energy of motion, of a certain volume of air behind the shock front (§ 3.55). The dynamic

pressure is consequently positive if the air is moving or zero if it is not; the direction in which the pressure acts depends on the direction of motion, i.e., the wind direction (see Fig. 3.11).

3.19   Nearly all the direct damage caused by both overpressure and dynamic pressure occurs during the positive overpressure phase of the blast wave. Although the dynamic pressure persists for a longer time, its magnitude during this additional time is usually so low that the destructive effects are not very significant. The damage referred to here is that caused directly by the blast wave. This will be largely terminated by the end of the overpressure positive phase, but the indirect destructive effects, e.g., due to fire (see Chapter VII), may continue long after the blast wave has passed.

3.20   There may be some direct damage to structures during the negative phase of the overpressure; for example, large windows which are poorly held against outward motion, brick veneer, and plaster walls may be dislodged by trapped air at normal pressure. But the maximum underpressure (and corresponding dynamic pressure) is generally quite small in comparison with the peak pressures at the shock front; hence, there is usually much less direct damage in the negative than in the positive overpressure phase of the blast wave.

REFLECTION OF BLAST WAVE AT A SURFACE

INCIDENT AND REFLECTED WAVES

3.21   When the incident blast wave from an explosion in air strikes a more dense medium such as the earth's surface, e.g., either land or water, it is reflected. The formation of the reflected wave in these circumstances is represented in Fig. 3.21. This figure shows four stages in the outward motion of the spherical blast wave originating from an air burst. In the first stage the wave front has not reached the ground; the second stage is somewhat later in time, and in the third stage, which is still later, a reflected wave, indicated by the dashed line, has been produced.

3.22   When such reflection occurs, an individual or object precisely at the surface will experience a single pressure increase, since the reflected wave is formed instantaneously. Consequently, the overpressure at the surface is generally considered to be entirely a reflected pressure. For a smooth (or ideal) surface, the total reflected overpressure in the region near ground zero will be more than twice the value of the peak overpressure of the incident blast wave. The exact value of the peak reflected pressure will depend on the strength of the incident wave (§ 3.56) and the angle at which it strikes the surface (§ 3.78). The nature of the surface also has an important effect (§ 3.47), but for the present the surface is assumed to be smooth so that it acts as an ideal reflector. The variation in overpressure with time, as observed at a point actually on

the surface not too far from ground zero,[1] such as A in Fig. 3.21, is depicted in Fig. 3.22 for an ideal shock front. The point A may be considered as lying within the region of "regular" reflection, i.e., where the incident and reflected waves do not merge except on the surface.
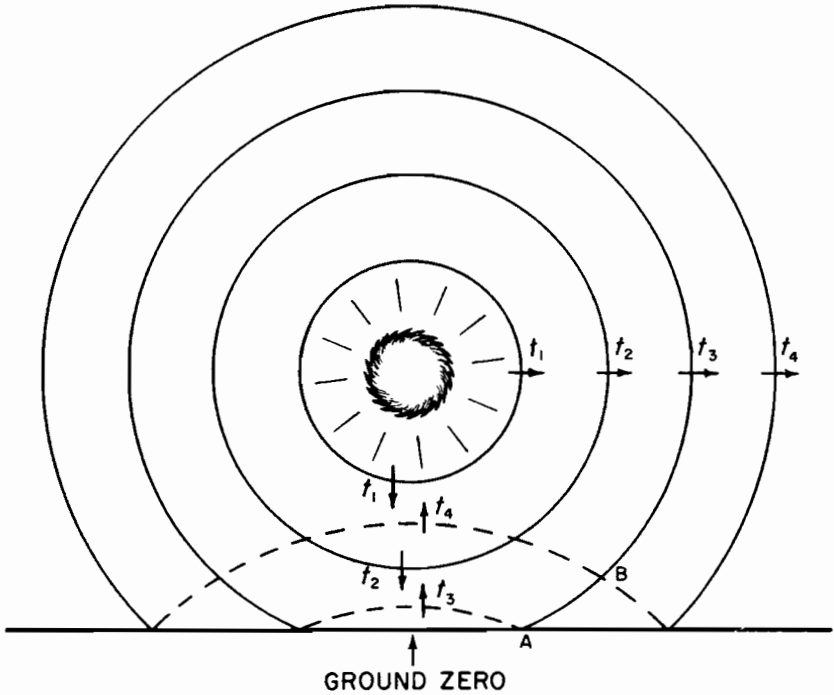

Figure 3.21.   Reflection of blast wave at the earth's surface in an air burst; t_1 to t_4 represent successive times.
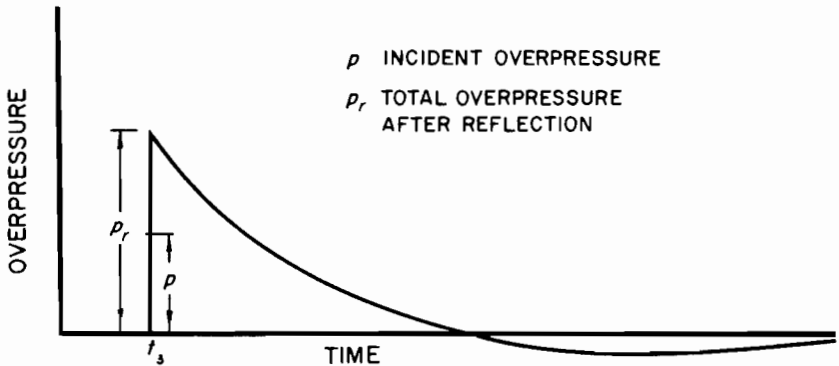

Figure 3.22.   Variation of overpressure with time at a point on the surface in the region of regular reflection.

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

3.23 At any location somewhat above the surface in this region, two separate shocks will be felt, the first being due to the incident blast wave and the second to the reflected wave, which arrives a short time later (Fig. 3.23). This situation can be illustrated by considering the point B in Fig. 3.21, also in the regular reflection region. When the incident wave front reaches this point, at time t_3, the reflected wave is still some distance away. There will, consequently, be a short interval before the reflected wave reaches the point above the surface at time t_4. Between t_3 and t_4, the reflected wave has spread out to some extent, so that its peak overpressure will be less than the value obtained at surface level. In determining the effects of air blast on structures in the regular reflection region, it may be necessary to consider the magnitude and also the directions of motion of both the incident and reflected waves. After passage of the reflected wave, the transient wind direction near the surface becomes essentially horizontal.

3.24 The following discussion concerning the delay between the arrival of the incident and reflected wave fronts at a point above the surface, such as B in Fig. 3.21, is based on the tacit assumption that the two waves travel with approximately equal velocities. This assumption is reasonably justified in the early stages, when the wave front is not far from ground zero. However, it will be evident that the reflected wave always travels through air that has been heated and compressed by the passage of the incident wave. As a result, the reflected wave front moves faster than the incident wave and, under certain conditions, eventually overtakes it so that the two wave fronts merge to produce a single front. This process of wave interaction is called "Mach" or "irregular" reflection. The region in which the two waves have merged is therefore called the Mach (or irregular) region in contrast to the regular region where they have not merged.

3.25 The merging of the incident and reflected waves is indicated schematically in Fig. 3.25, which shows a portion of the profile of the blast wave close to the surface. The situation at a point fairly close to ground zero, such as A in Fig. 3.21, is represented in Fig. 3.25a. At a later stage, farther from
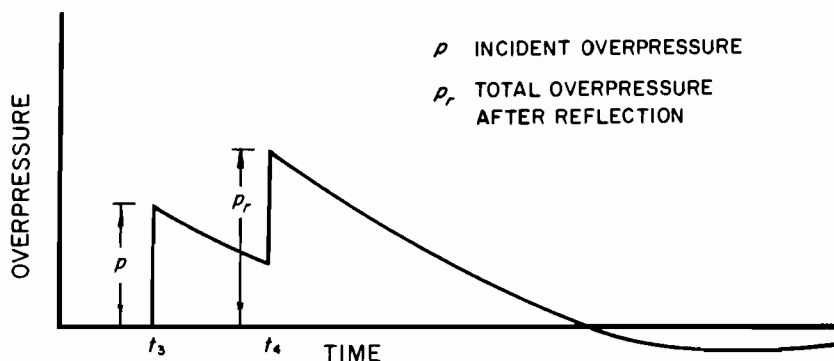

Figure 3.23.   Variation of overpressure with time at a point above the surface in the region of regular reflection.

ground zero, as in Fig. 3.25b, the steeper front of the reflected wave shows that it is traveling faster than, and is overtaking, the incident wave. At the stage represented by Fig. 3.25c, the reflected wave near the ground has overtaken and merged with the incident wave to form a single front called the "Mach stem." The point at which the incident wave, reflected wave, and Mach fronts meet is referred to as the "triple point."[2] The configuration of the three shock fronts has been called the "Mach Y."

3.26 As the reflected wave continues to overtake the incident wave, the triple point rises and the height of the Mach stem increases (Fig. 3.26). Any object located either at or above the ground, within the Mach region and below the triple point path, will experience a single shock. The behavior of this merged (or Mach) wave is the same as that previously described for blast

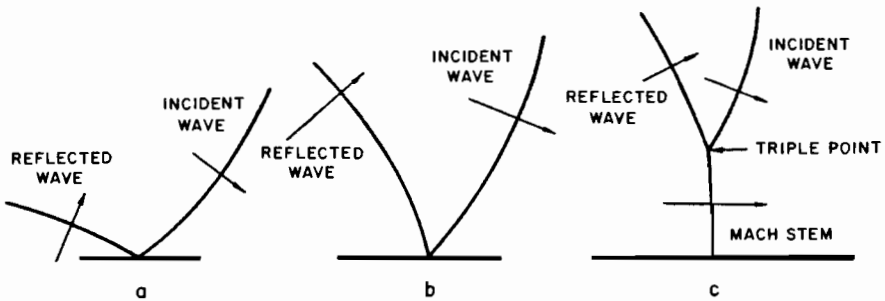Figure 3.25. Merging of incident and reflected waves and formation of Mach Y configuration of shock fronts.
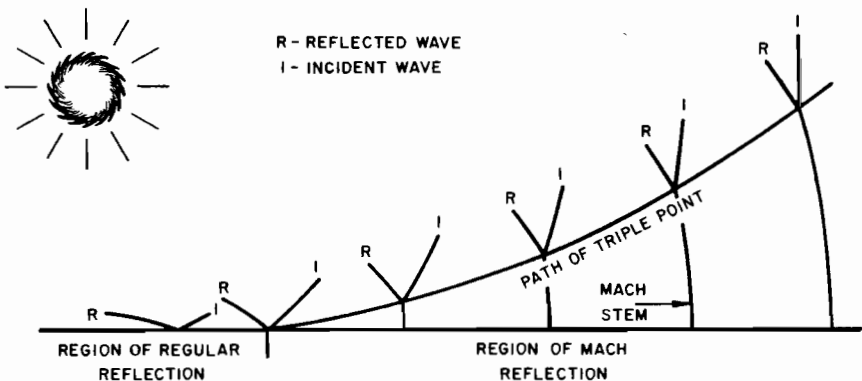

Figure 3.26. Outward motion of the blast wave near the surface in the Mach region.

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[2] At any instant the so-called "triple point" is not really a point, but a horizontal circle with its center on the vertical line through the burst point; it appears as a point on a sectional (or profile) drawing, such as Fig. 3.25c.

waves in general. The overpressure at a particular location will fall off with time and the positive (compression) phase will be followed by a negative (suction) phase in the usual manner.

3.27 At points in the air above the triple point path, such as at an aircraft or at the top of a high building, two pressure increases will be felt. The first will be due to the incident blast wave and the second, a short time later, to the reflected wave. When a weapon is detonated at the surface, i.e., in a contact surface burst (§ 2.127 footnote), only a single merged wave develops. Consequently, only one pressure increase will be observed either on or above the ground.

3.28 As far as the destructive action of the air blast is concerned, there are at least two important aspects of the reflection process to which attention should be drawn. First, only a single pressure increase is experienced in the Mach region below the triple point as compared to the separate incident and reflected waves in the region of regular reflection. Second, since the Mach stem is nearly vertical, the accompanying blast wave is traveling in a horizontal direction at the surface, and the transient winds are approximately parallel to the ground (Fig. 3.25). Thus, in the Mach region, the blast forces on aboveground structures and other objects are directed nearly horizontally, so that vertical surfaces are loaded more intensely than horizontal surfaces.

3.29 The distance from ground zero at which the Mach stem begins to form depends primarily upon the yield of the detonation and the height of the burst above the ground. Provided the height of burst is not too great, the Mach stem forms at increasing distances from

ground zero as the height of burst increases for a given yield, and also as the yield decreases at a specified height of burst. For moderate heights of burst, Mach merging of direct and reflected waves occurs at a distance from ground zero approximately equal to the burst height. As the height of burst is increased, the distance from ground zero at which the Mach effect commences exceeds the burst height by larger and larger amounts.

HEIGHT OF BURST AND BLAST DAMAGE

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

3.31 Because of the relation between height of burst and energy of the explosion, the air blast phenomena to be expected on the ground from a weapon of large yield detonated at a height of a few thousand feet will approach those of

a near surface burst. On the other hand, explosions of weapons of smaller energy yields at these same or even lower levels will have the characteristics of air bursts. A typical example of the latter situation is found in the nuclear explosion which occurred over Nagasaki, Japan, in World War II when a weapon having a yield of approximately 22 kilotons of TNT equivalent was detonated at a height of about 1,640 feet. By means of certain rules, called "scaling laws," which are described in the technical section of this chapter (§ 3.60 et seq.), it is found that to produce similar blast phenomena at ground distances proportional to the heights of burst, for a 1-kiloton weapon the height of burst would have to be roughly 585 feet and for a 1-megaton explosion about 5,850 feet. In these three cases, the Mach stem formation would occur at distances from ground zero that are not very different from the respective heights of burst.

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

3.33 The variation of blast characteristics with distance from ground zero for air bursts occurring at different heights are most conveniently represented by what are called "height of

burst" curves. Such curves have been prepared for various blast wave properties, e.g., peak overpressure, peak dynamic pressure, time of arrival, and positive phase duration, and will be presented and discussed later (§ 3.69 et seq.). Values of these (and other) properties can be determined from the curves, by application of appropriate scaling factors, for any explosion yield and height of burst.

CONTACT SURFACE BURST

3.34 The general air blast phenomena resulting from a contact surface burst are somewhat different from those for an air burst as described above. In a surface explosion the incident and reflected shock waves merge instantly, as seen in § 3.27, and there is no region of regular reflection. All objects and structures on the surface, even close to ground zero, are thus subjected to air blast similar to that in the Mach region below the triple point for an air burst. For an ideal (absolutely rigid) reflecting surface the shock wave characteristics, i.e., overpressure, dynamic pressure, etc., at the shock front would correspond to that for a "free air" burst, i.e., in the absence of a surface, with twice the energy yield. Behind the front, the various pressures would decay in the same manner as for an air burst. Because of the immediate merging of the incident and reflected air blast waves, there is a single shock front which is hemispherical in form, as shown at successive times, t_1 through t_4, in Figure 3.34. Near the surface, the wave front is essentially vertical and the transient winds behind the front will blow in a horizontal direction.
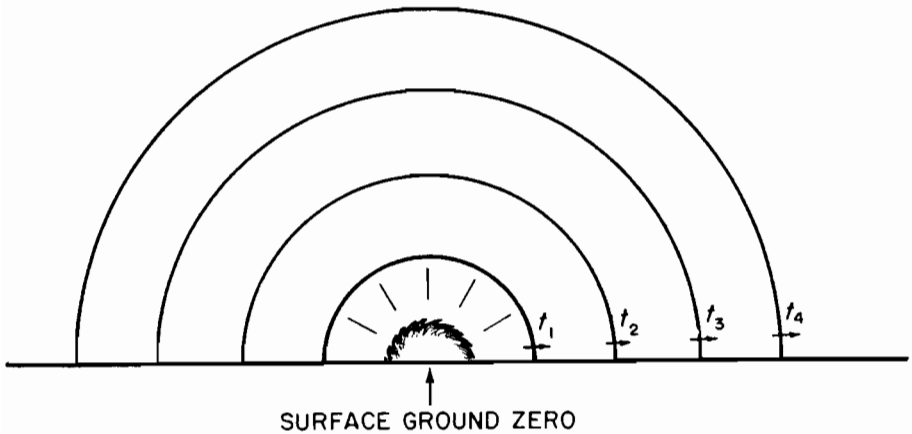
SURFACE GROUND ZERO

Figure 3.34. Blast wave from a contact surface burst; incident and reflected waves coincide.

MODIFICATION OF AIR BLAST PHENOMENA

TERRAIN EFFECTS

3.35 Large hilly land masses tend to increase air blast effects in some areas and to decrease them in others. The change in peak overpressure appears to depend on the slope angle and on the actual value of the pressure. The increase (or "spike") in peak overpressure which occurs at the base of a hill is attributable to the reflection of the blast wave by the front slope. This spike tends to broaden or lengthen with time as the wave travels up the hill. However, a reduction in peak overpressure occurs as the blast wave moves over the crest and down the back slope. The pressure at the wave front does not rise instantaneously, as in an ideal shock wave (see Fig. 3.11), but somewhat more gradually, although the behavior soon becomes normal as the blast wave proceeds down the hill. In general, the variation in peak overpressure at any point on a hill from that expected if the hill were not present depends on the dimensions of the hill with respect to the energy yield and location of the explosion. Since the time interval in which the pressure increase or decrease occurs is short compared to the length of the positive phase, the effects of terrain on the blast wave are not expected to be significant for a large variety of structural types.

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

3.37 Although prominent terrain features may shield a particular target from thermal radiation, and perhaps also to some extent from the initial nuclear radiation, little reduction in blast damage to structures may be expected, except in very special circumstances. Nevertheless, considerable protection from debris and other missiles (§ 3.50) and drag forces may be achieved for such movable objects as heavy construction equipment by placing them below the surface of the ground in open excavations or deep trenches or behind steep earth mounds.

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

METEOROLOGICAL CONDITIONS

3.39 The presence of large amounts of moisture in the atmosphere may affect the properties of a blast wave in the low overpressure region. But the probability of encountering significant concentrations of atmospheric liquid water that would influence damage is considered to be small. Meteorological conditions, however, can sometimes either enlarge or contract the area over which light structural damage would normally be expected. For example, window breakage and noise have been experi-

enced hundreds of miles from the burst point. Such phenomena, which have been observed with large TNT detonations as well as with nuclear explosions, are caused by the bending back to the earth of the blast wave by the atmosphere.

3.40 Four general conditions which can lead to this effect are known. The first is a temperature "inversion" near the earth's surface. Normally, the air temperature in the lower atmosphere (troposphere) decreases with increasing altitude in the daytime. In some cases, however, the temperature near the surface increases instead of decreasing with altitude; this is called a temperature inversion. It can arise either from night-time cooling of the ground surface by the radiation of heat or from a mass of warm air moving over a relatively cold surface. The result of an inversion is that the overpressure on the ground at a distance from the explosion may be higher than would otherwise be expected. Conversely, when unstable conditions prevail, and the temperature near the earth's surface decreases rapidly with altitude, as in the afternoon or in tropical climates, the blast wave is bent away from the ground. The overpressure then decays with distance faster than expected.

3.41 The second situation exists when there are high-speed winds aloft. If the normal decrease in the temperature of the air with increasing altitude is combined with an upper wind whose speed exceeds 3 miles per hour for each 1,000 feet of altitude, the blast wave will be refracted (or bent) back to the ground. This usually occurs with jet-stream winds, where maximum velocities are found between 25,000- and

50,000-feet altitudes. These conditions may cause several "rays" to converge into a sharp focus at one location on the ground, and the concentration of blast energy there will greatly exceed the value that would otherwise occur at that distance. The first (or direct striking) focus from a jet stream duct may be at 20 to 50 miles from the explosion. Since the blast energy is reflected from the ground and is again bent back by the atmosphere, the focus may be repeated at regularly spaced distances. In an explosion of a 20-kiloton weapon in the air at the Nevada Test Site, this effect caused windows to break 75 to 100 miles away.

3.42 Bending of blast waves in the downwind direction can also be produced by a layer of relatively warm air at a height of 20 to 30 miles in the lower mesosphere (see Fig. 9.126). In these levels winds blow from the west in winter and from east in summer, enhancing blast pressures and noise at downwind distances from 70 to 150 miles (first direct strike). Reflections from the ground, and subsequent refractions by the lower mesosphere, cause the usual repeat focus pattern. Focusing of this type has resulted in the breakage of windows on the second ground strike at 285 miles downwind from a 17-kiloton nuclear air burst. Large explosions have been distinctly heard at even greater distances.[3]

3.43 The fourth condition is brought about by the very high temperatures in the thermosphere, the region of the atmosphere above an altitude of about 60 miles (Fig. 9.126). Blast waves are ducted in the thermosphere so that they reach the ground at distances beyond 100 miles from the burst, generally in the opposite direction from the principal mesospheric signals, i.e., in the upwind direction. Most of the blast wave energy is absorbed in the low-density air at high altitudes, and no structural damage has been reported from thermospheric ducting. However, sharp pops and crackles have been heard when the waves from large explosions reach the ground.

EFFECT OF ALTITUDE

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

3.45 For an air burst, the peak overpressure at a given distance from the explosion will depend on the ambient atmospheric pressure and this will vary with the burst altitude. There are a number of simple correction factors, which will be given later (§ 3.65 *et seq.*), that can be used to allow for differences in the ambient conditions, but for the present it will be sufficient to state the general conclusions. With increasing altitude of both target and burst point, the overpressure at a given distance from an explosion of specified

[3]The situations described here and in § 3.43 could also be considered as temperature inversions.

yield will generally decrease. Correspondingly, an increase may usually be expected in both the arrival time of the shock front and in the duration of the positive phase of the blast wave. For elevations of less than 5,000 feet or so above sea level, the changes are small, and since most surface targets are at lower altitudes, it is rarely necessary to make the corrections.

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

SURFACE EFFECTS

3.47   For a given height of burst and explosion energy yield, some variation in blast wave characteristics may be expected over different surfaces. These variations are determined primarily by the type and extent of the surface over which the blast wave passes. In considering the effects of the surface, a distinction is made between ideal (or nearly ideal) and nonideal surface conditions. An "ideal" surface is defined as a perfectly flat surface that reflects all (and absorbs none) of the energy, both thermal (heat) and blast, that strikes it. No area of the earth's surface is ideal in this sense, but some surfaces behave almost like ideal surfaces and they are classified as "nearly ideal." For an ideal (or nearly ideal) surface the properties of the blast wave are essentially free of mechanical and thermal effects. If the surface is such that these effects are significant, it is said to be "nonideal."

3.48   The terrain phenomena described in § 3.35 et seq. are examples of mechanical factors that can change the characteristics of the blast wave. In general, the nature of the reflecting surface can affect the peak overpressure and the formation and growth of the Mach stem. Absorption of some of the blast energy in the ground, which will be considered in § 3.51, is to be regarded as another type of mechanical effect on the blast wave due to a nonideal surface.

3.49   Many surfaces, especially when the explosion can raise a cloud of dust, are nonideal because they absorb substantial amounts of heat energy. In these circumstances, the properties of the blast wave may be modified by the formation of an auxiliary wave, called a "precursor," that precedes the main incident wave. The characteristics of the blast wave will then be quite different from those that would be observed on an ideal (or nearly ideal) surface. Precursor phenomena, which are complex, are discussed more fully in § 3.79 et seq.

3.50 Somewhat related to the condition of the surface are the effects of objects and material picked up by the blast wave. Damage may be caused by missles such as rocks, boulders, and pebbles, as well as by smaller particles such as sand and dust. This particulate matter carried along by the blast wave does not necessarily affect the overpressures at the shock front. In dusty areas, however, the blast wave may pick up enough dust to increase the dynamic pressure over the values corresponding to the overpressure in an ideal blast wave. There may also be an increase in the velocity of air particles in the wave due to precursor action. Consequently, the effect on structures which are damaged mainly by dynamic pressure will be correspondingly increased, especially in regions where the precursor is strong.

GROUND SHOCK FROM AIR BLAST

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

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

TECHNICAL ASPECTS OF BLAST WAVE PHENOMENA[4]

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

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

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

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

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

The dynamic pressure, q, is defined by

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

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 ρ and u given above leads to the relation

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

$$= \frac{5}{2} \cdot \frac{p^2}{7P_0 + p} \qquad (3.55.1)$$

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.
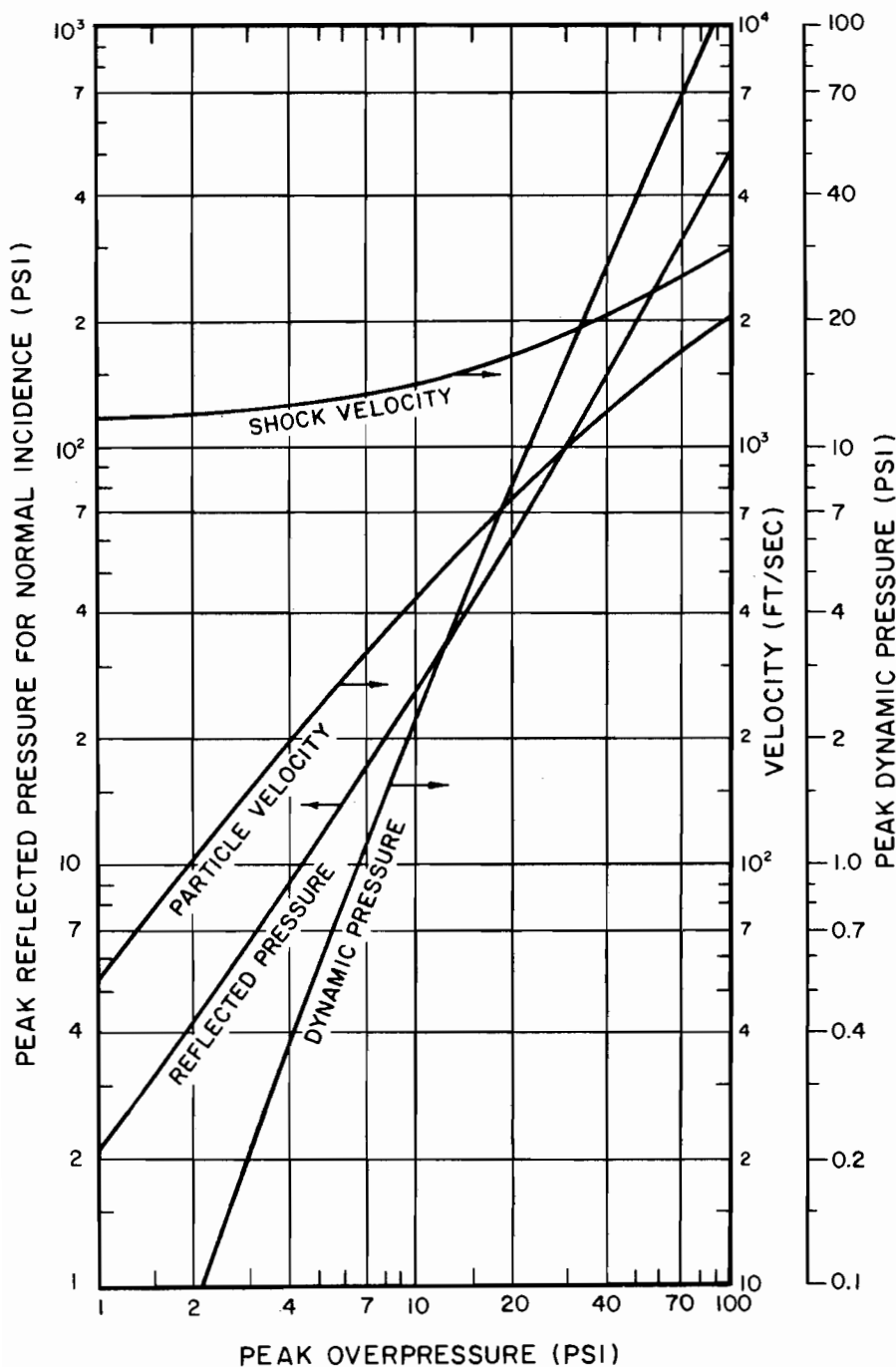
Figure 3.55. Relation of ideal blast wave characteristics at the shock front to peak overpressure.

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

$$p_r = 2p + (\gamma + 1)q. \qquad (3.56.1)$$

Upon using equation (3.55.1) for air, this becomes

$$p_r = 2p \frac{7P_0 + 4p}{7P_0 + p} \qquad (3.56.2)$$

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
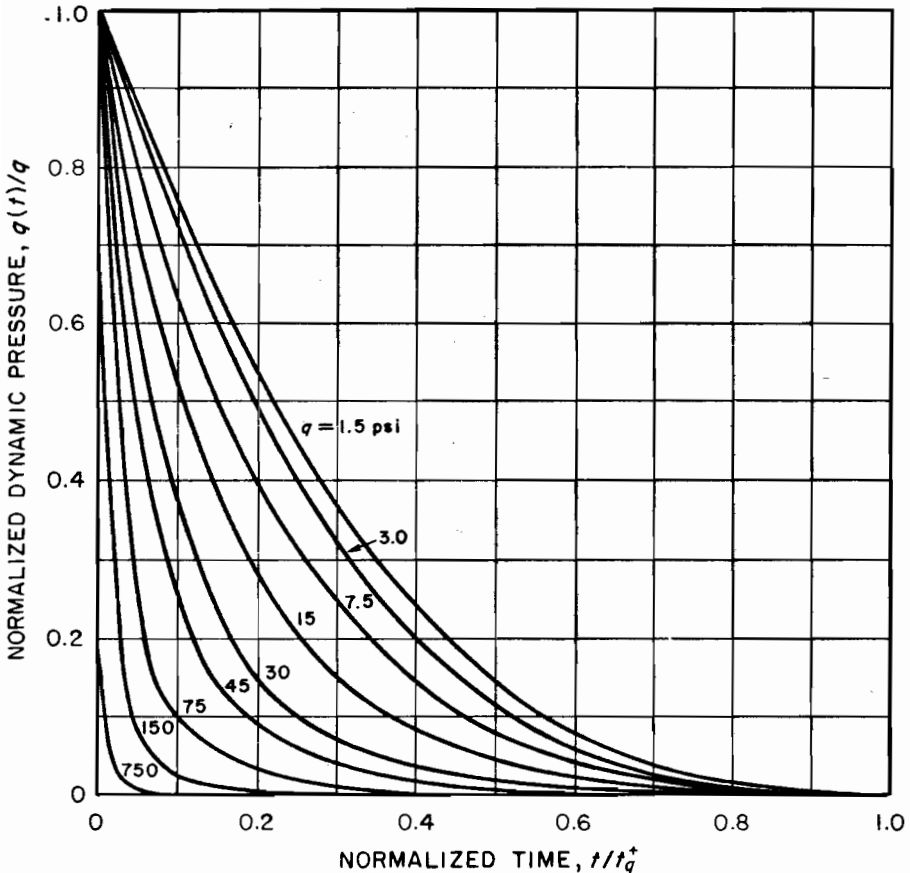
Fig. 3.58.   Rate of decay of dynamic pressure with time for several values of the dynamic pressure.

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

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

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

$$D = D_1 \times W^{1/3}, \qquad (3.61.2)$$

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, re-

quired 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

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

$$d = d_1 \times W^{1/3} \qquad (3.62.1)$$

This expression can be used for calculations of the type referred to in the preceding paragraph, except that the distances involved are from ground zero instead of from the explosion (slant ranges).[5]

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

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

and

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

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

ALTITUDE CORRECTIONS

3.64 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

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

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

$$p = p_1 \frac{P}{P_0}, \qquad (3.65.1)$$

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

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

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

$$t = t_1 W^{1/3} \left(\frac{P_0}{P} \right)^{1/3} \left(\frac{T_0}{T} \right)^{1/2} \qquad (3.65.3)$$

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

$$I = I_1 W^{1/3} \left(\frac{P}{P_0} \right)^{2/3} \left(\frac{T_0}{T} \right)^{1/2} \qquad (3.65.4)$$

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):

$$S_p = \frac{P}{P_0}$$

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

$$S_t = \left(\frac{P_0}{P} \right)^{1/3} \left(\frac{T_0}{T} \right)^{1/2},$$

so that

$$p = p_1 S_p \qquad (3.66.1)$$

$$D = D_1 W^{1/3} S_d \text{ and}$$
$$d = d_1 W^{1/3} S_d . \qquad (3.66.2)$$

$$t = t_1 W^{1/3} S_t \qquad (3.66.3)$$

$$I = I_1 W^{1/3} S_p S_t . \qquad (3.66.4)$$

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.

Table 3.66

AVERAGE ATMOSPHERIC DATA FOR MID-LATITUDES

Altitude (feet)	Temperature (degrees Kelvin)	Pressure (psi)	Altitude Scaling Factors S_p	S_d	S_t	Speed of Sound (ft/sec)
0	288	14.70	1.00	1.00	1.00	1,116
1,000	286	14.17	0.96	1.01	1.02	1,113
2,000	284	13.66	0.93	1.03	1.03	1,109
3,000	282	13.17	0.90	1.04	1.05	1,105
4,000	280	12.69	0.86	1.05	1.07	1,101
5,000	278	12.23	0.83	1.06	1.08	1,097
10,000	268	10.11	0.69	1.13	1.17	1,077
15,000	258	8.30	0.56	1.21	1.28	1,057
20,000	249	6.76	0.46	1.30	1.39	1,037
25,000	239	5.46	0.37	1.39	1.53	1,016
30,000	229	4.37	0.30	1.50	1.68	995
35,000	219	3.47	0.24	1.62	1.86	973
40,000	217	2.73	0.19	1.75	2.02	968
45,000	217	2.15	0.15	1.90	2.19	968
50,000	217	1.69	0.12	2.06	2.37	968
55,000	217	1.33	0.091	2.23	2.57	968
60,000	217	1.05	0.071	2.41	2.78	968
65,000	217	0.83	0.056	2.61	3.01	968
70,000	218	0.65	0.044	2.83	3.25	971
75,000	219	0.51	0.035	3.06	3.50	974
80,000	221	0.41	0.028	3.31	3.78	978
85,000	222	0.32	0.022	3.57	4.07	981
90,000	224	0.25	0.017	3.86	4.38	984
95,000	225	0.20	0.014	4.17	4.71	988
100,000	227	0.16	0.011	4.50	5.07	991
110,000	232	0.10	0.0070	5.23	5.82	1,003
120,000	241	0.067	0.0045	6.04	6.61	1,021
130,000	249	0.044	0.0030	6.95	7.47	1,038
140,000	258	0.029	0.0020	7.95	8.41	1,056
150,000	266	0.020	0.0013	9.06	9.43	1,073

3.67 The correction factors in § 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 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	Blast Efficiency Factor	
(feet)	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

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 overpres-

sures (§ 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 $p_r(\alpha)$ 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 $p_r(\alpha)/p$ 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 $p_r(\alpha)/p$ 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).

The curve in Fig. 3.72 shows the variation of peak overpressure with distance for a 1 KT free air burst in a standard sea-level atmosphere.

Scaling. For targets below 5,000 feet and for burst altitudes below 40,000 feet, the range to which a given peak overpressure extends for yields other than 1 KT scales as the cube root of the yield, i.e.,

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

where, for a given peak overpressure, D_1 is the distance (slant range) from the explosion for 1 KT, and D is the distance from the explosion for W KT. (For higher target or burst altitudes, see § 3.64 *et seq.*)

Example

Given: A 2 MT burst at an altitude of 100,000 feet.

Find: The highest value of peak overpressure that reasonably may be expected to be incident on a target (an aircraft or missile) at an altitude of 60,000 feet.

Solution: The blast efficiency factor is based on the burst altitude, but the altitude scaling factors are based on target altitude (§ 3.64). The highest value of peak overpressure will occur with the upper limit of the blast efficiency factor.

From Table 3.68, this upper limit for a burst at an altitude of 100,000 feet is somewhat less than 0.9. Hence, the effective yield is approximately

$$0.9W = 0.9 \times 2$$
$$= 1.8 \text{ MT} = 1,800 \text{ KT}.$$

The shortest distance from burst point to target, i.e., where the overpressure would be largest, is

$$D = 100,000 - 60,000 = 40,000 \text{ feet}.$$

From equation (3.66.2), the corresponding distance from a 1 KT burst for sea-level conditions is

$$D_1 = \frac{D}{W^{1/3}} \cdot \frac{1}{S_d}.$$

From Table 3.66, S_d at the target altitude of 60,000 feet is 2.41; hence;

$$D_1 = \frac{40,000}{(1,800)^{1/3}} \cdot \frac{1}{2.41}$$
$$= 1,360 \text{ feet}.$$

From Fig. 3.72, the peak overpressure at a distance of 1,360 feet from a 1 KT free air burst at sea-level conditions is 4.2 psi. The corresponding overpressure at an altitude of 60,000 feet is obtained from equation (3.66.1) and Table 3.66; thus

$$p = p_1 S_p = 4.2 \times 0.071$$
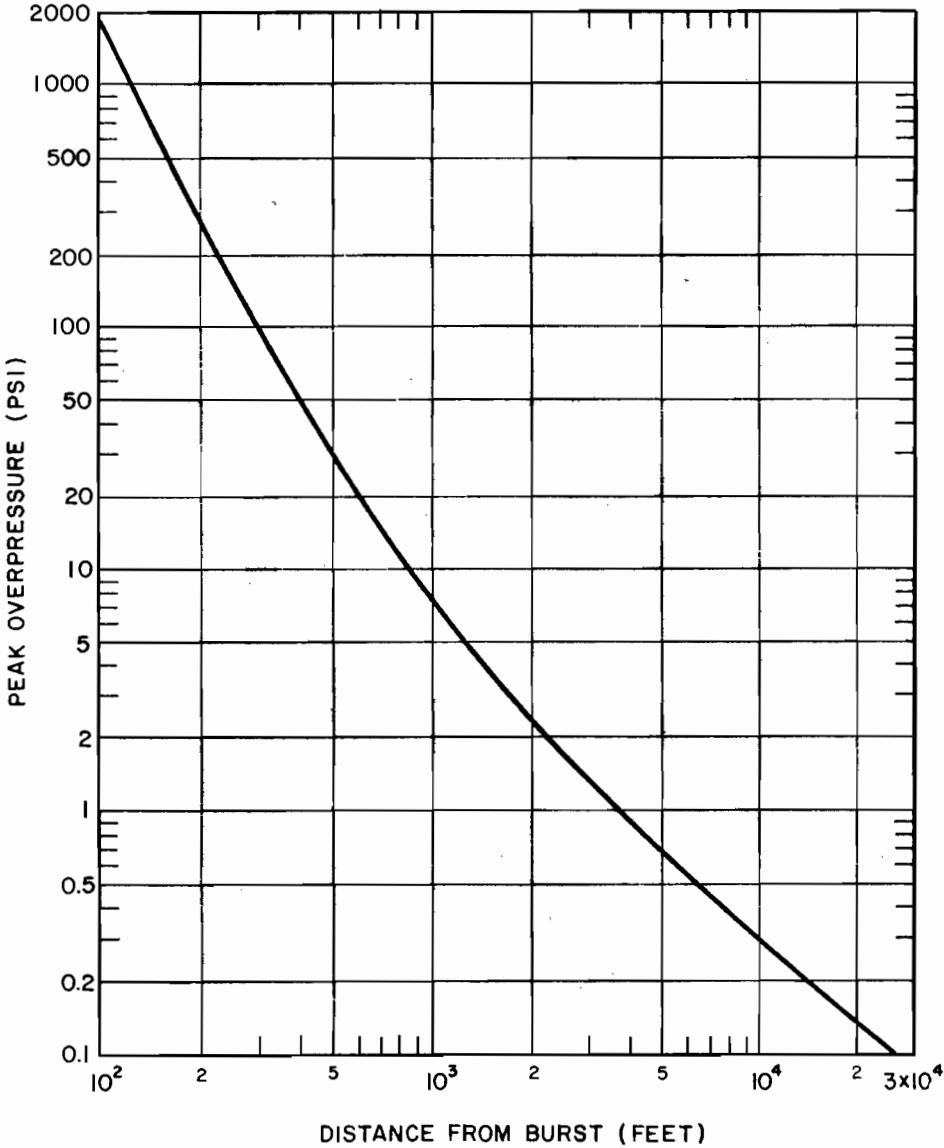$$= 0.30 \text{ psi}.$$
Answer

Figure 3.72. Peak overpressure from a 1-kiloton free air burst for sea-level ambient conditions.

The curves in Fig. 3.73a show peak overpressures on the ground in the high-pressure range as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The broken line separates the regular reflection region from the Mach region and indicates where the triple point is formed (§ 3.24 et seq.). The data are considered appropriate to nearly ideal surface conditions. (For terrain, surface, and meteorological effects, see §§ 3.35–3.43, §§ 3.47–3.49, and § 3.79 et seq.)

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

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

where, for a given peak overpressure, d_1 and h_1 are distance from ground zero and height of burst for 1 KT, and d and h are the corresponding distance and height of burst for W KT. For a height of burst of 5,000 feet or less, a homogeneous sea-level atmosphere may be assumed.

Example

Given: An 80 KT detonation at a height of 860 feet.

Find: The distance from ground zero to which 1,000 psi overpressure extends.

Solution: The corresponding height of burst for 1 KT, i.e., the scaled height, is

$$h_1 = \frac{h}{W^{1/3}} = \frac{860}{(80)^{1/3}} = 200 \text{ feet.}$$
$$d = d_1 W^{1/3} =$$
$$110 \times (80)^{1/3} = 475 \text{ feet.}$$
Answer.

From Fig. 3.73a, an overpressure of 1,000 psi extends 110 feet from ground zero for a 200-foot burst height for a 1 KT weapon. The corresponding distance for 80 KT is

$$d = d_1 W^{1/3} =$$
$$110 \times (80)^{1/3} = 475 \text{ feet.}$$
Answer.

The procedure described above is applicable to similar problems for the curves in Figs. 3.73b and c.
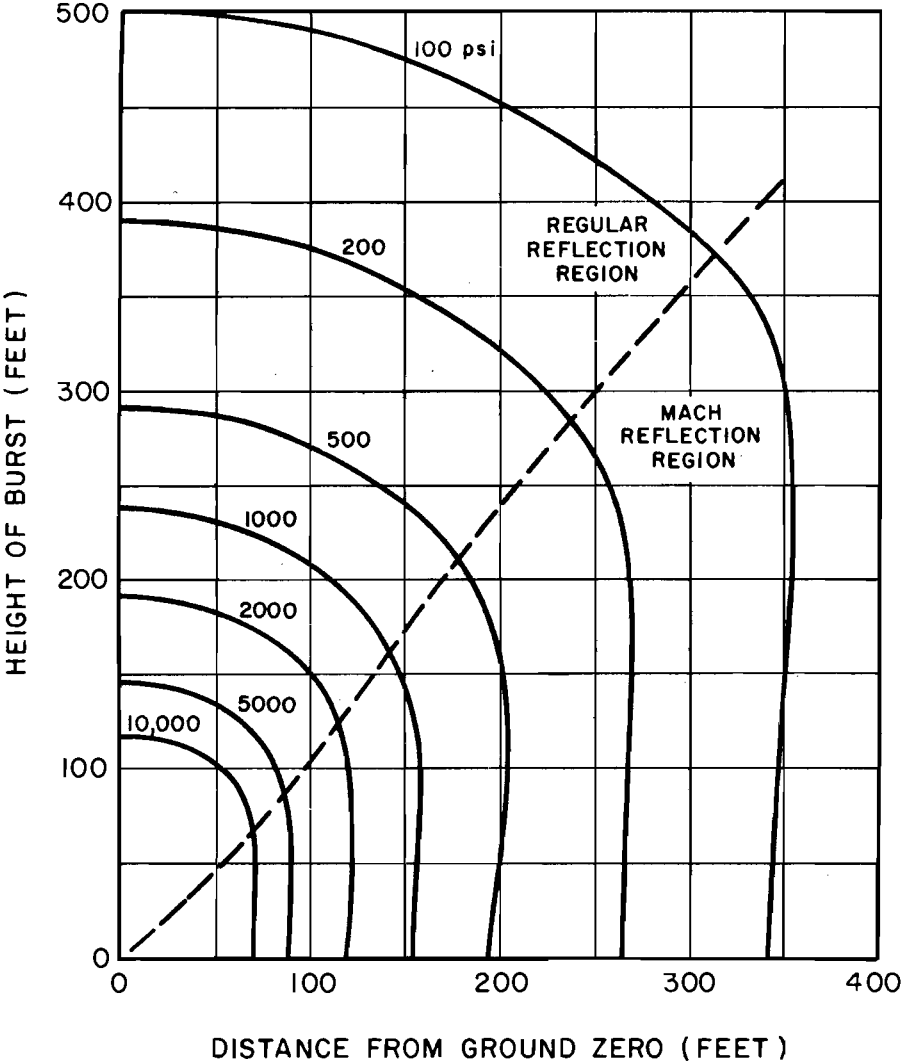
Figure 3.73a.   Peak overpressures on the ground for a 1-kiloton burst (high-pressure range).

The curves in Fig. 3.73b show peak overpressures on the ground in the intermediate-pressure range as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The broken line separates the regular reflection region from the Mach region and indicates where the triple point is formed (§ 3.24 *et seq.*). The data are considered appropriate for nearly ideal surface conditions. (For terrain, surface, and meteorological effects, see (§ 3.35–3.43, § 3.47–3.49, and § 3.79 *et seq.*).

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

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

where, for a given peak overpressure, d_1 and h_1 are distance from ground zero and height of burst for 1 KT, and d and h are the corresponding distance and height of burst for W KT. For a height of burst of 5,000 feet or less, a homogeneous sea-level atmosphere may be assumed.

Example

Given: A 100 KT detonation at a height of 2,320 feet.

Find: The peak overpressure at 1,860 feet from ground zero.

Solution: The corresponding height of burst for 1 KT is

$$h_1 = \frac{h}{W^{1/3}} = \frac{2,320}{(100)^{1/3}} = 500 \text{ feet.}$$

and the ground distance is

$$d_1 = \frac{d}{W^{1/3}} = \frac{1,860}{(100)^{1/3}} = 400 \text{ feet.}$$

From Fig. 3.73b, at a ground distance of 400 feet and a burst height of 500 feet, the peak overpressure is 50 psi. *Answer.*

The procedure described above is applicable to similar problems for the curves in Figs. 3.73a and c.
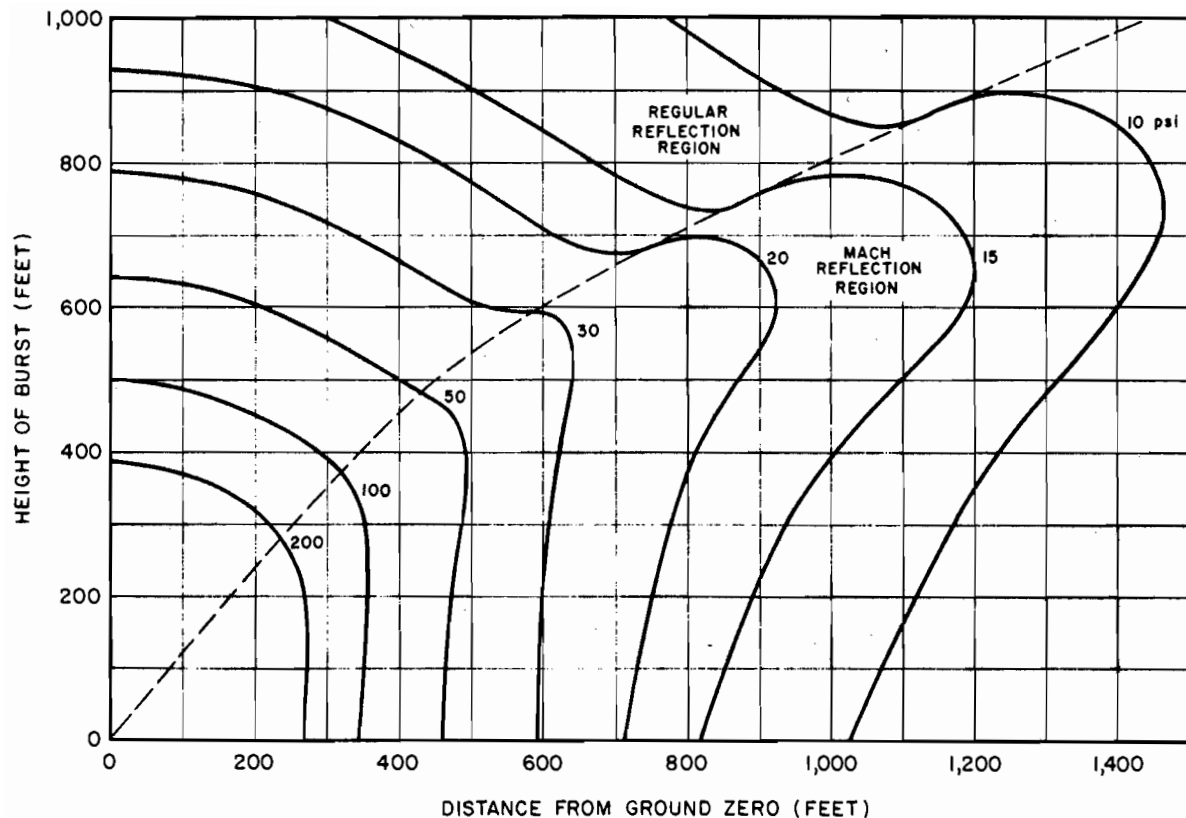
Figure 3.73b.   Peak overpressures on the ground for a 1-kiloton burst (intermediate-pressure range).

The curves in Fig. 3.73c show peak overpressures on the ground in the low-pressure range as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The broken line separates the regular reflection region from the Mach region and indicates where the triple point is formed (§ 3.24 *et seq.*). The data are considered appropriate for nearly ideal surface conditions. (For terrain, surface, and meteorological effects, see §§ 3.35–3.43, §§ 3.47–3.49, and § 3.79 *et seq.*)

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

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

where, for a given peak overpressure, d_1 and h_1 are the distance from ground zero and height of burst for 1 KT, and d and h are the corresponding distance and height of burst for W KT. For a height of burst of 5,000 feet or less, a homogeneous sea-level atmosphere may be assumed.

Example

Given: A 125 KT detonation.

Find: The maximum distance from ground zero to which 4 psi extends, and the height of burst at which 4 psi extends to this distance.

Solution: From Fig. 3.73c, the maximum ground distance to which 4 psi extends for a 1 KT weapon is 2,600 feet. This occurs for a burst height of approximately 1,100 feet. Hence, for a 125 KT detonation, the required burst height is

$$h = h_1 W^{1/3} = 1,100 \times (125)^{1/3}$$
$$= 5,500 \text{ feet.}$$

This is sufficiently close to 5,000 feet for a homogeneous atmosphere to be assumed. The distance from ground zero is then

$$d = d_1 W^{1/3} = 2,600 \times (125)^{1/3}$$
$$= 13,000 \text{ feet.} \quad \textit{Answer.}$$

The procedure described above is applicable to similar problems for the curves in Figs. 3.73a and b.
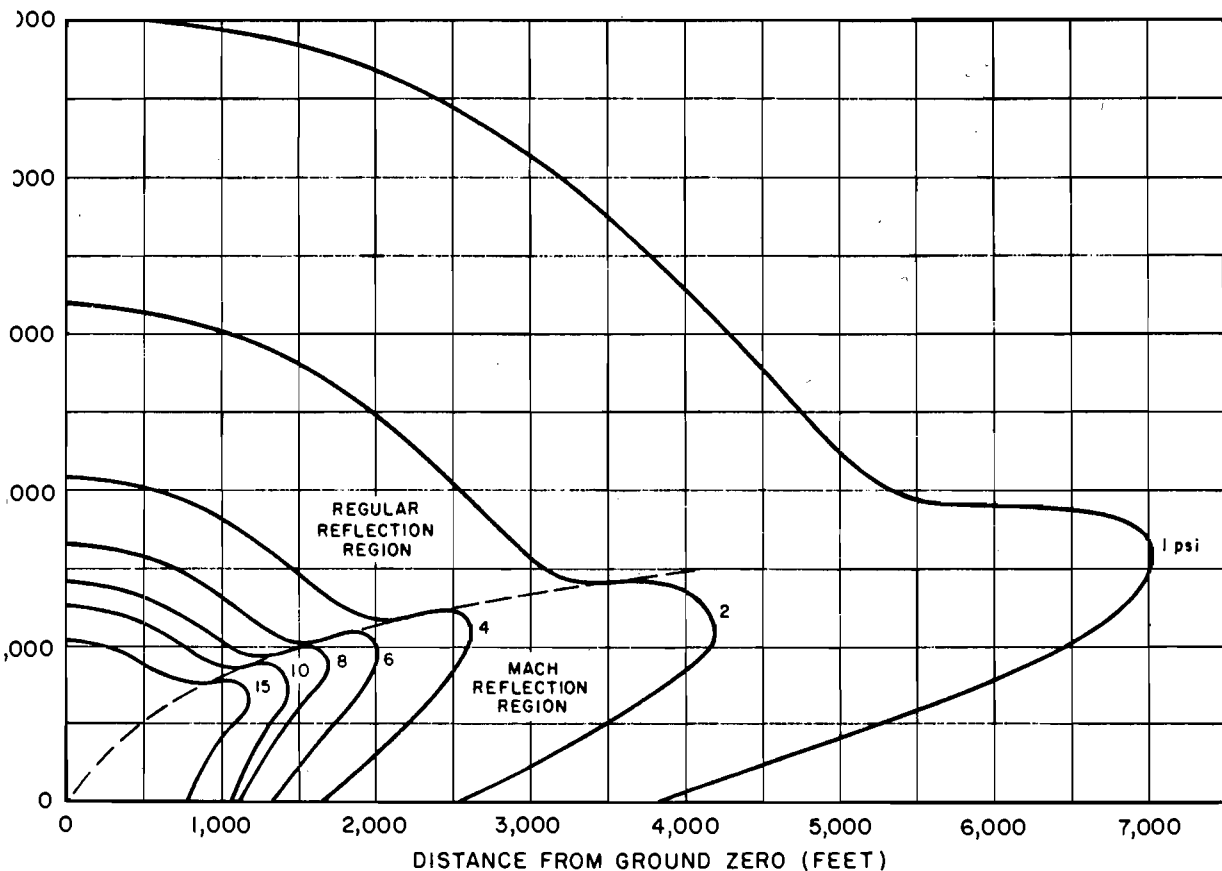
Figure 3.73c. Peak overpressures on the ground for 1-kiloton burst (low-pressure range).

The curves in Fig. 3.75 show the horizontal component of peak dynamic pressure on the ground as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The data are considered appropriate for nearly ideal surface conditions. (For terrain, surface, and meteorological effects, see §§ 3.35–3.43, §§ 3.47–3.49, and § 3.79 *et seq.*)

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

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

where, for a given peak dynamic pressure, h_1 and d_1 are the height of burst and distance from ground zero for 1 KT, and h and d are the corresponding height of burst and distance for W KT. For a height of burst of 5,000 feet or less, a homogeneous sea-level atmosphere may be assumed.

Example

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

Find: The horizontal component of peak dynamic pressure on the surface at 6,000 feet from ground zero.

Solution: The corresponding height of burst for 1 KT is

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

The corresponding distance for 1 KT is

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

From Fig. 3.75, at a distance of 1,110 feet from ground zero and a burst height of 550 feet, the horizontal component of the peak dynamic pressure is approximately 3 psi. *Answer.*

Calculations similar to those described in connection with Figs. 3.74a and c may be made for the horizontal component of the peak dynamic pressure (instead of the peak overpressure) by using Fig. 3.75.
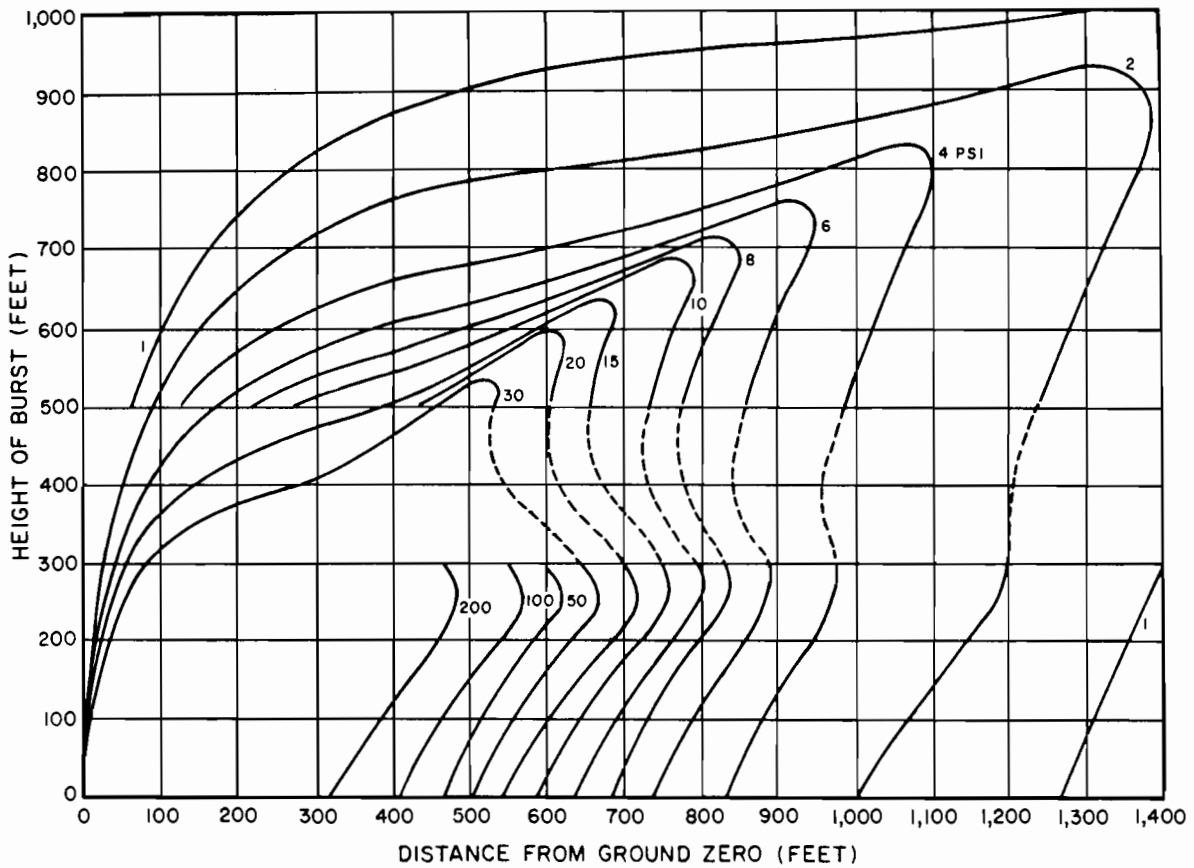
Figure 3.75.   Horizontal component of peak dynamic pressure for 1-kiloton burst.

The curves in Fig. 3.76 show the duration on the ground of the positive phase of the overpressure and of the dynamic pressure (in parentheses) as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The curves are considered appropriate for nearly ideal surface conditions.

Scaling. The required relationships are

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

where d_1, h_1, and t_1 are the distance from ground zero, the height of burst, and duration, respectively, for 1 KT; and d, h, and t are the corresponding distance, height of burst, and duration for W KT. For a height of burst of 5,000 feet or less, a homogeneous sea-level atmosphere may be assumed.

Example

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

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

Solution: The corresponding height of burst for 1 KT is

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

and the corresponding distance from ground zero is

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

(*a*) From Fig. 3.76, the positive phase duration of the overpressure for a 1 KT at 740 feet from ground zero and a burst height of 550 feet is 0.18 second. The corresponding duration of the overpressure positive phase for 160 KT is, therefore,

$$t = t_1 W^{1/3} = 0.18 \times (160)^{1/3}$$
$$= 1.0 \text{ second.} \quad Answer.$$

(*b*) From Fig. 3.76, the positive phase duration of the dynamic pressure for 1 KT at 740 feet from ground zero and a burst height of 550 feet is 0.34 second. The corresponding duration of the dynamic pressure positive phase for 160 KT is, therefore,

$$t = t_1 W^{1/3} = 0.34 \times (160)^{1/3}$$
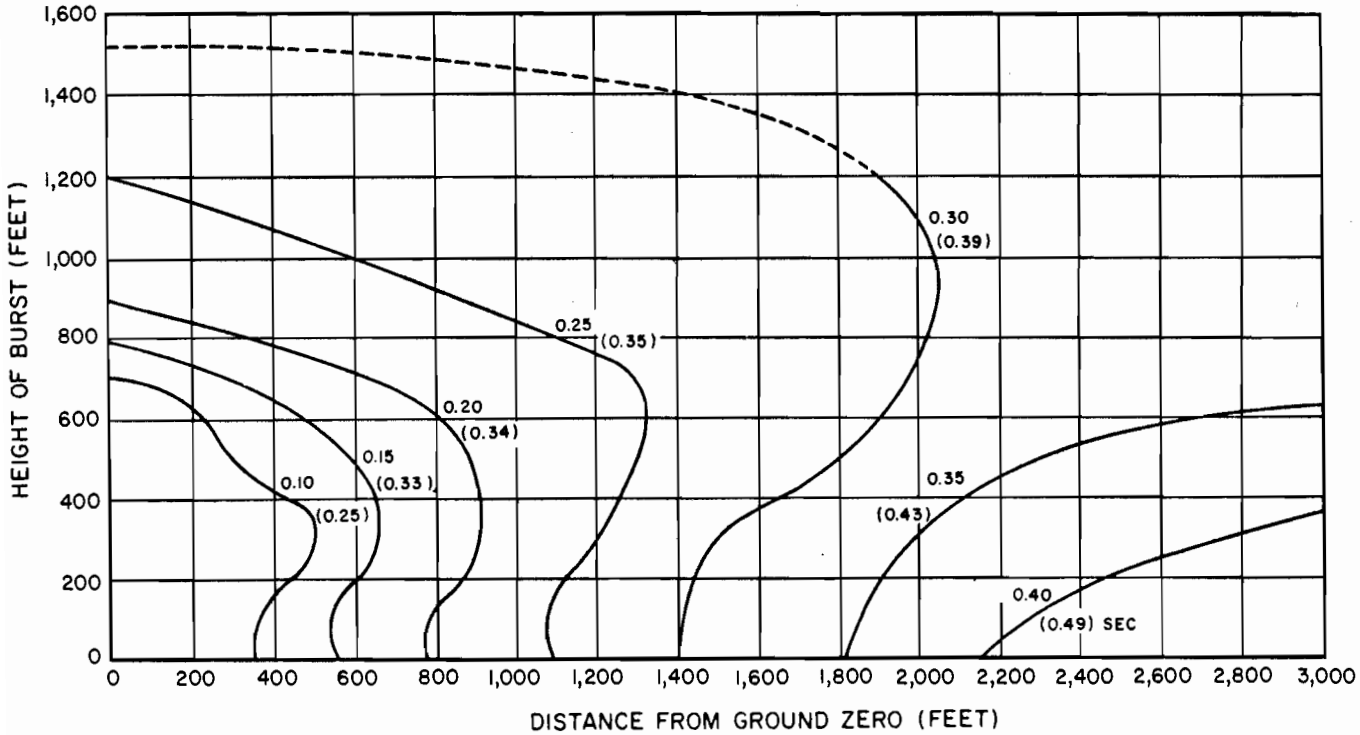$$= 1.8 \text{ second.} \quad Answer.$$

Figure 3.76.   Positive phase duration on the ground of overpressure and dynamic pressure (in parentheses) for 1-kiloton burst.

The curves in Figs. 3.77a and b give the time of arrival in seconds of the blast wave on the ground as a function of distance from ground zero and height of burst for a 1 KT burst in a standard sea-level atmosphere. The curves are considered appropriate for nearly ideal surface conditions.

Scaling. The required relationships are

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

where d_1, h_1, and t_1 are the distance from ground zero, height of burst, and time of arrival, respectively, for 1 KT; and d, h, and t are the corresponding distance, height of burst, and time for W KT. For a height of burst of 5,000 feet or less, a homogeneous sea-level atmosphere may be assumed.

Example

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

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

Solution: The corresponding burst height for 1 KT is

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

The corresponding distance from ground zero for 1 KT is

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

From Fig. 3.77b, at a height of burst of 500 feet and a distance of 5,280 feet from ground zero, the arrival time is 4.0 seconds for 1 KT. The corresponding arrival time for 1 MT is

$$t = t_1 W^{1/3} = 4.0 \times (1,000)^{1/3}$$
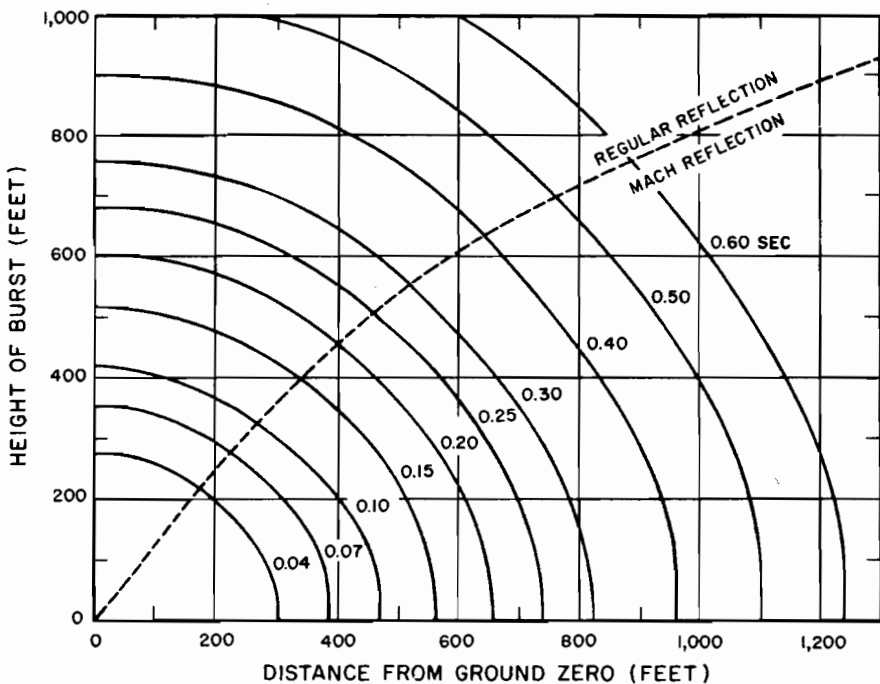$$= 40 \text{ seconds.} \quad Answer.$$

Figure 3.77a.   Arrival times on the ground of blast wave for 1-kiloton burst (early times).
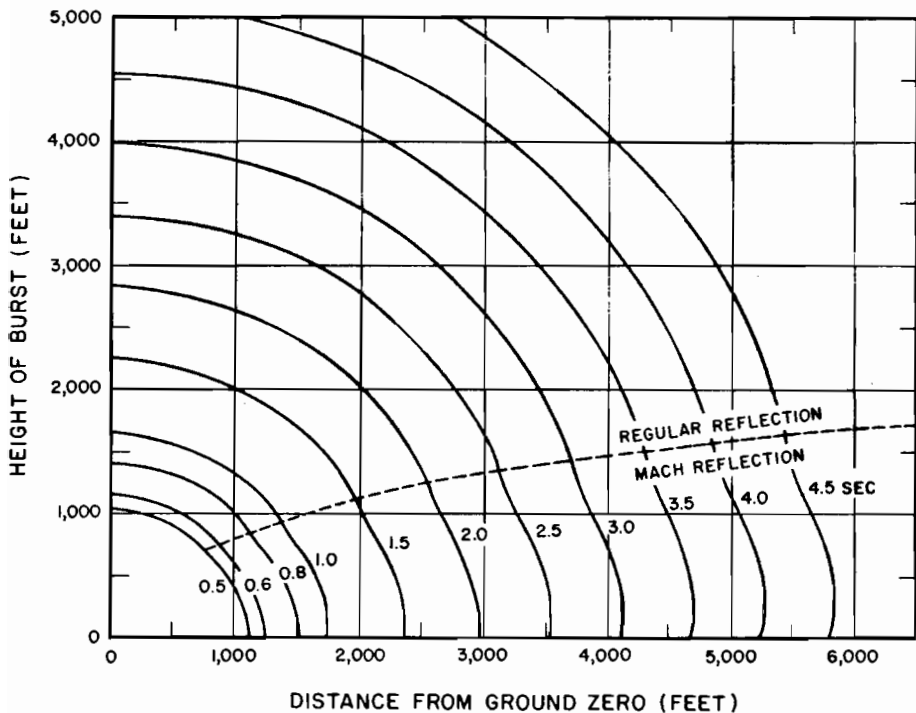

Figure 3.77b.   Arrival times on the ground of blast wave for 1-kiloton burst (late times).

The reflected overpressure ratio $p_{r(\alpha)}/p$ is plotted in Fig. 3.78b as a function of the angle of incidence of the blast wave front for various values of the peak (side-on) overpressure. The curves apply to a wave front striking a reflecting surface, such as a wall of a structure.

$p_{r(\alpha)}$ = reflected blast wave overpressure for any given angle of incidence (psi).

p = initial peak incident overpressure (psi).

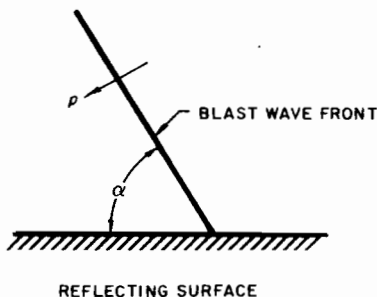α = angle between the blast wave front and the reflecting surface (degrees).

Example

Given: A shock wave of 50 psi initial peak overpressure striking a surface at an angle of 35°.

Find: The reflected shock wave overpressure.

Solution: From Fig. 3.78b, the reflected overpressure ratio, $p_{r(\alpha)}/p$, for 50 psi and an angle of incidence of 35° is 3.6; hence,

$$p_{r(35°)} = 3.6p = 3.6 \times 50$$
$$= 180 \text{ psi. } Answer.$$

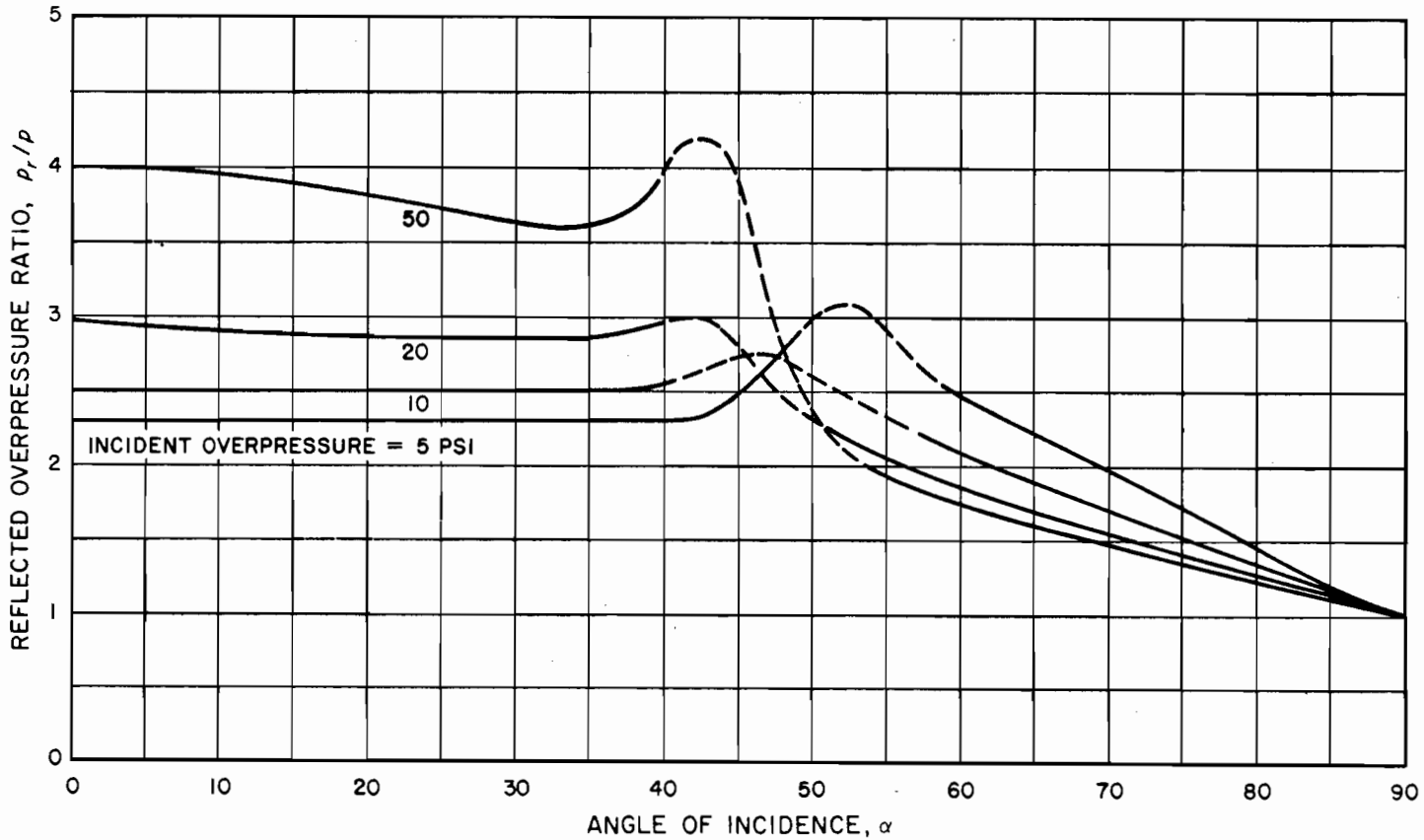

REFLECTING SURFACE

Figure 3.78a.   Angle of incidence (α) of blast wave front with reflecting surface.

Figure 3.78b.   Reflected overpressure ratio as a function of angle of incidence for various
side-on overpressures.

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
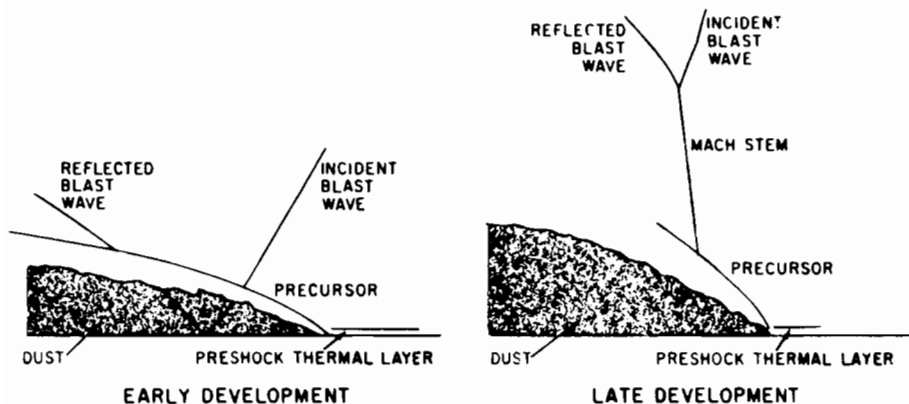
Figure 3.81.   Precursor characteristics.

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

Table 3.83

EXAMPLES OF
THERMALLY NEARLY IDEAL AND
THERMALLY NONIDEAL SURFACES

Thermally Nearly Ideal (precursor unlikely)	Thermally Nonideal (precursor may occur for low air bursts)
Water	Desert sand
Ground covered by white smoke	Coral
	Asphalt
Heat-reflecting concrete	Surface with thick low vegetation
Ice	Surface covered by dark smoke
Packed snow	
Moist soil with sparse vegetation	Most agricultural areas
Commercial and industrial areas	Dry soil with sparse vegetation

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.

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