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

The Effects of

Nuclear Weapons

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Editor

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Foreword

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

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

Robert S. McNamara

Secretary of Defense

Glenn T. Seaborg

Chairman

Atomic Energy Commission

Preface

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

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

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

Although every effort has been made to include the best possible information in this book, it should be kept in mind that, where numerical values are given, inevitable uncertainties are involved. For example, there are inherent difficulties in making exact measurements of weapons effects. The results are often dependent upon circumstances which are difficult, and sometimes impossible, to control even in tests, and would certainly be unpredictable in the event of an attack. Furthermore, two weapons of different design may have the same explosive energy yield yet differ markedly in their actual effects. Where such possibilities exist, the text calls attention to the limitations of the data presented and of the appropriate scaling laws.

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

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

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

Los Alamos, N. Mex. SAMUEL GLASSTONE
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Contents

The Radioactive Cloud

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

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

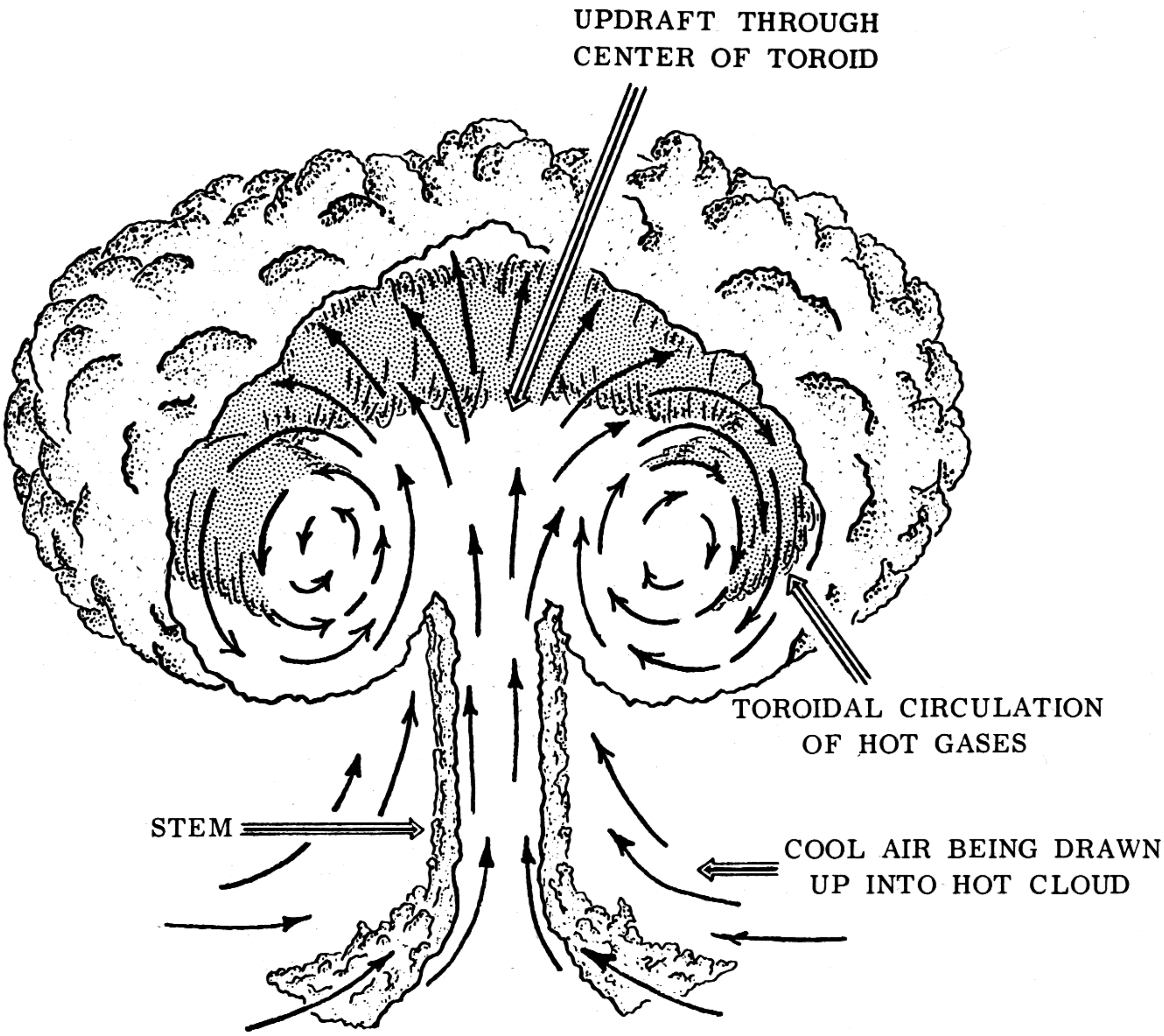

Figure 2.07a. Cutaway showing artist's conception of toroidal circulation within the radioactive cloud from a nuclear explosion.

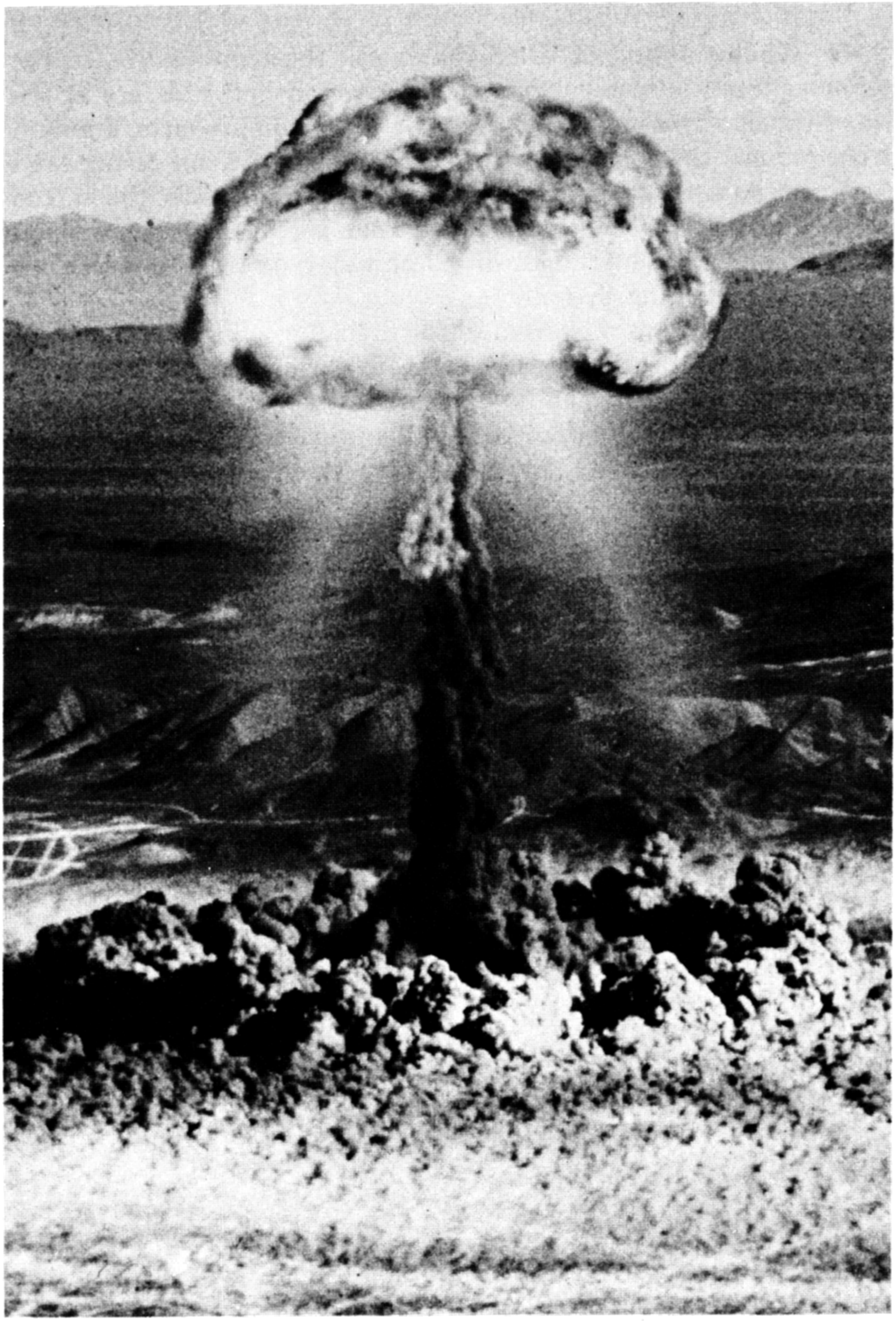

Figure 2.07b. Low air burst showing toroidal fireball and dirt cloud.

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

2.08 The color of the radioactive cloud is initially red or reddish brown, due to the presence of various colored compounds (nitrous acid and oxides of nitrogen) at the surface of the fireball. These result from the chemical interaction of nitrogen, oxygen, and water vapor in the air at the existing high temperatures and under the influence of the nuclear radiations. As the fireball cools and condensation occurs, the color of the cloud changes to white, mainly due to the water droplets as in an ordinary cloud.

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

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

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

2.12 The speed with which the top of the radioactive cloud continues to ascend depends on the meteorological conditions as well as on the energy yield of the weapon. An approximate indication of the rate of rise of the cloud from a 1-megaton explosion is given by the results in Table 2.12 and the curve in Fig. 2.12. Thus, in general, the cloud will have attained a height of 3 miles in 30 seconds and 4.5 miles in about 1 minute. The average rate of rise during the first minute or so is approximately 260 miles per hour. These values should be regarded as rough averages only, and large deviations may be expected in different circumstances.

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

TABLE 2.12

RATE OF RISE OF RADIOACTIVE CLOUD

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

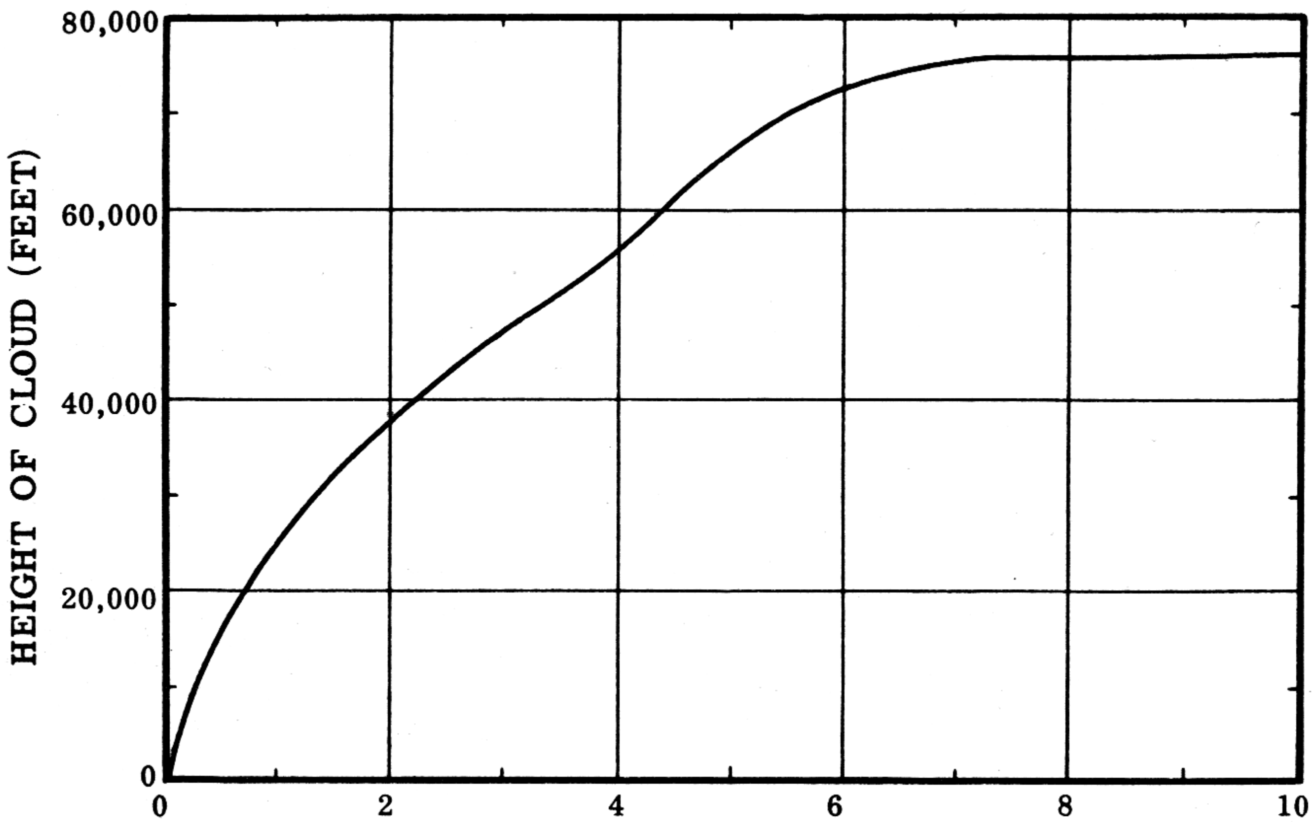

Figure 2.12. Height of cloud top above burst height at various times after a 1-megaton explosion for a moderately low air burst.

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

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

2.15 The cloud attains its maximum height after about 10 minutes

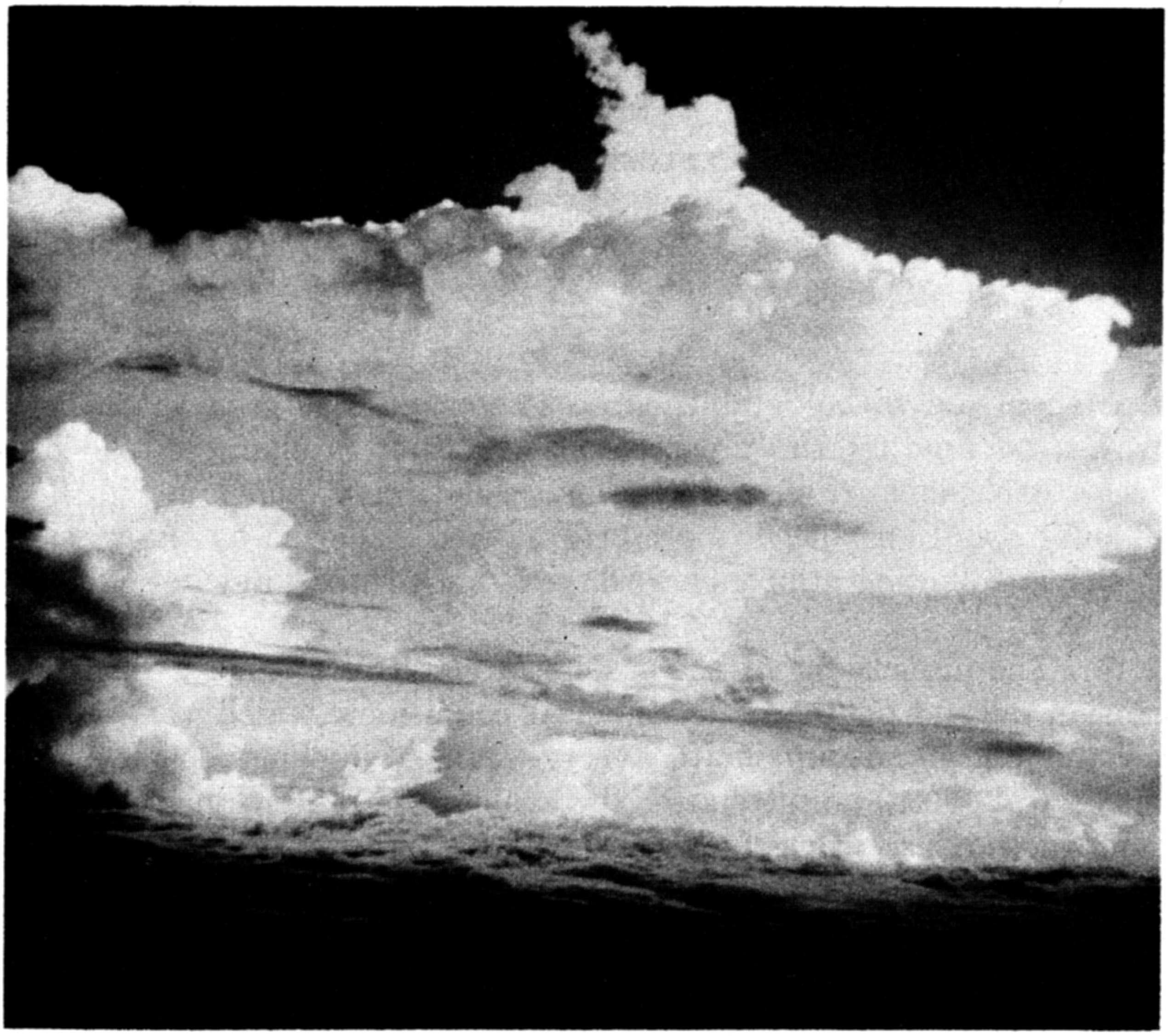

Figure 2.15. The mushroom cloud formed in a nuclear explosion in the megaton energy range, photographed from an altitude of 12,000 feet at a distance of about 50 miles.

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

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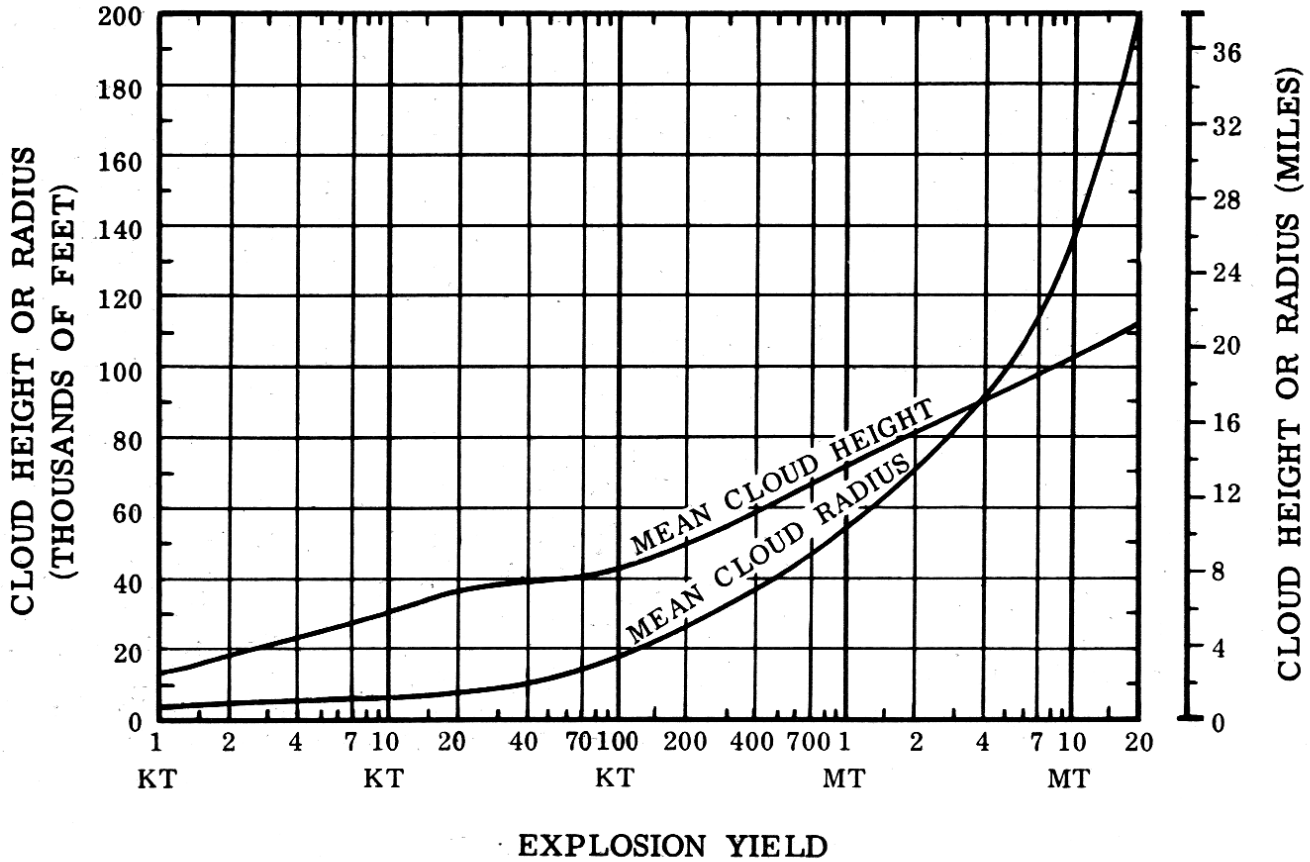

Figure 2.16. Average values of stabilized cloud height and radius as a function of explosion yield.

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

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

be larger than given above. However, at the same time, there is an increase in the rate at which the cloud rises. Similarly for a weapon of lower energy, the effective distance is less, but so also is the rate of ascent of the cloud. The period over which the initial nuclear radiation extends may consequently be taken to be approximately the same, namely, 1 minute, irrespective of the energy release of the explosion.

2.45 Neutrons are the only significant nuclear radiations produced directly in the thermonuclear reactions mentioned in § 1.66. Alpha particles (helium nuclei) are also formed, but they do not travel very far from the explosion. Some of the neutrons will escape but others will be captured by the various nuclei present in the exploding weapon. Those neutrons absorbed by fissionable species may lead to the liberation of more neutrons as well as to the emission of gamma rays. In addition, the capture of neutrons in nonfission reactions is usually accompanied by gamma rays. It is seen, therefore, that the initial radiations from an explosion in which both fission and fusion (thermonuclear) processes occur consist essentially of neutrons and gamma rays. The relative proportions of these two radiations may be somewhat different than for a weapon in which all the energy release is due to fission, but for present purposes the difference may be disregarded.

Other Nuclear Explosion Phenomena

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

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

2.48 The condensation cloud which was observed in the ABLE Test at Bikini in 1946 is shown in Fig. 2.48. Since the device was detonated just above the surface of the lagoon, the air was nearly saturated with water vapor and the conditions were suitable for the production of a Wilson cloud. It can be seen from the photograph that the cloud formed some way ahead of the fireball. The reason is

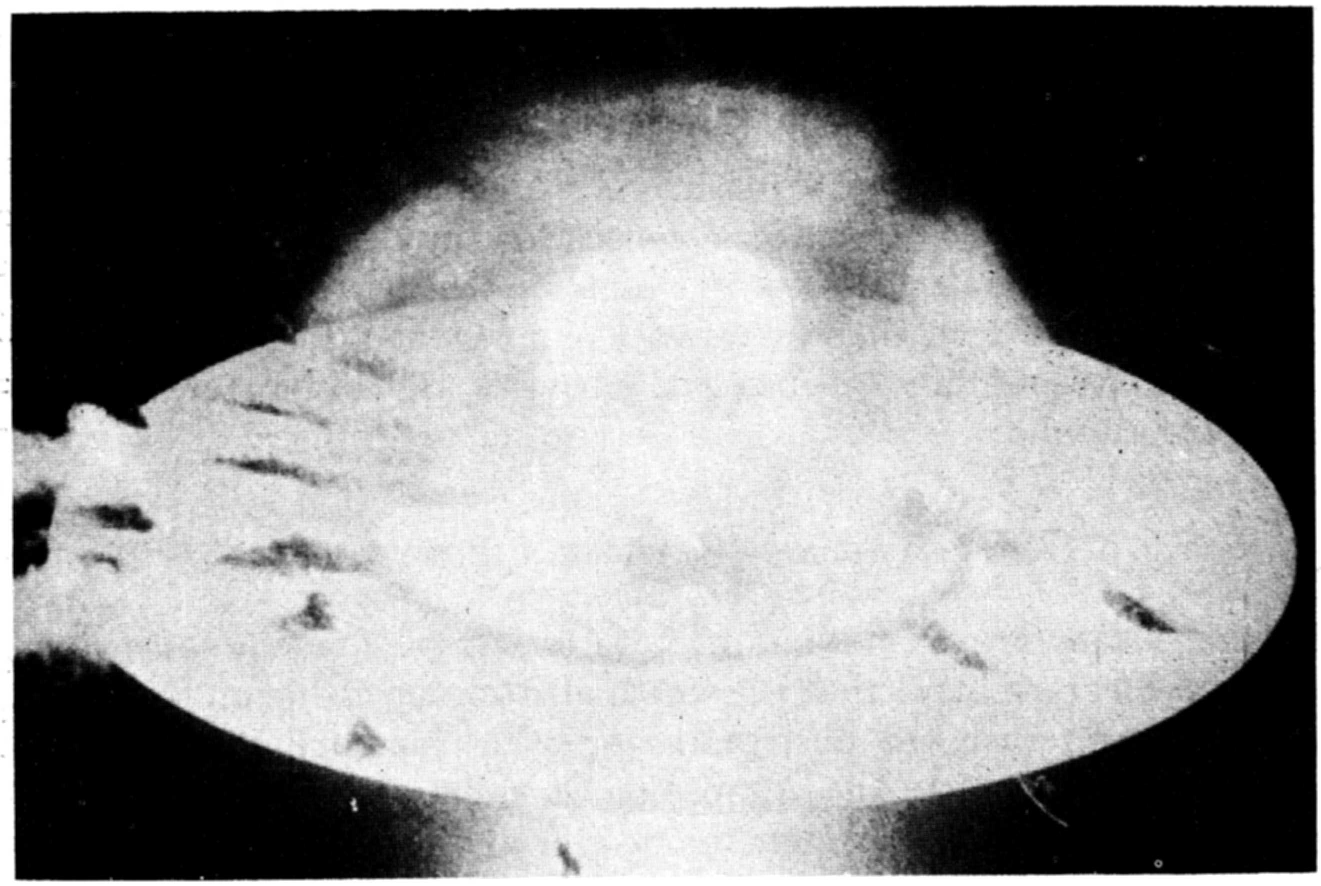

Figure 2.48. Condensation cloud formed in an air burst over water.

that the shock front must travel a considerable distance before the blast pressure has fallen sufficiently for a low temperature to be attained in the subsequent decompression phase. At the time the temperature has dropped to that required for condensation to occur, the blast wave front has moved still further away, as is apparent in Fig. 2.48, where the disk-like formation on the surface of the water indicates the passage of the shock wave.

2.49 The relatively high humidity of the air makes the conditions for the formation of the condensation cloud most favorable in nuclear explosions occurring over (or under) water, as in the Bikini tests in

1946. The cloud commenced to form 1 to 2 seconds after the detonation, and it had dispersed completely within another second or so, as the air warmed up and the water droplets evaporated. The original dome-like cloud first changed to a ring shape, as seen in Fig. 2.49, and then disappeared.

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

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

Chronological Development of an Air Burst

2.51 The more important aspects of the description given above of a nuclear explosion in the air are summarized in a series of drawings, Figs. 2.51 a, b, c, d, and e, which are presented at the end of this chapter (pp. 87 to 91). In these figures, a 20-kiloton TNT equivalent detonation is assumed to take place at an altitude of 1,760 feet, and a 1-megaton burst at 6,500 feet. Because of the operation of certain simple rules, called scaling laws (see Chapter III), it is possible to represent times and distances for these two different explosion energies on one set of drawings. The specified heights of burst for the two cases were chosen because it is expected that the conditions would be such as to lead to the maximum blast damage to an average city. The figures show the chronological development of the various phenomena associated with the air bursts defined above.

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

DESCRIPTION OF HIGH-ALTITUDE BURST

Introduction

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

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

High-Altitude Burst Phenomena

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

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

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

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

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

2.57 At about a minute or so after the detonation, the TEAK fireball had risen to a height of over 90 miles, and it was then directly (line-of-sight) visible from Hawaii, over 700 miles away. The rate of rise of the fireball was estimated to be some 3,300 feet per second and it was expanding horizontally at a rate of about 1,000 feet per second. The large red luminous sphere was observed for a few minutes; at roughly 6 minutes after the explosion it was nearly 600 miles in diameter.

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

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

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

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

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

2.101 There is another mechanism, in addition to the one just described, for the transfer of part of the kinetic energy of the fission fragments to the surroundings. This arises from what is called "hydrodynamic coupling" of the explosion energy with the ambient medium. Because of the very high pressure within the exploding weapon, the residue, consisting of fission products and all other weapon materials, moves outward from the center of the explosion at a very high velocity. The random kinetic energy of the individual atoms, etc., is thus being converted into directed mass energy, that is, energy of motion of the mass of residues. After a few microseconds nearly all of the debris is contained in a moderately thin shell of high density called the "hydrodynamic front." Its initial temperature is about a million degrees and it is traveling at a speed of several hundred miles per second. When the hydrodynamic front reaches the ambient medium it acts like a fast-moving piston. Energy is thus transferred to the medium by impulse, and a compression wave, which rapidly becomes a steepfronted shock wave, as shown in Fig. 1.01, moves outward. The mass energy of the weapon debris is thus transferred to the surroundings as blast and shock.

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

Development of the Fireball in an Air Burst

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

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

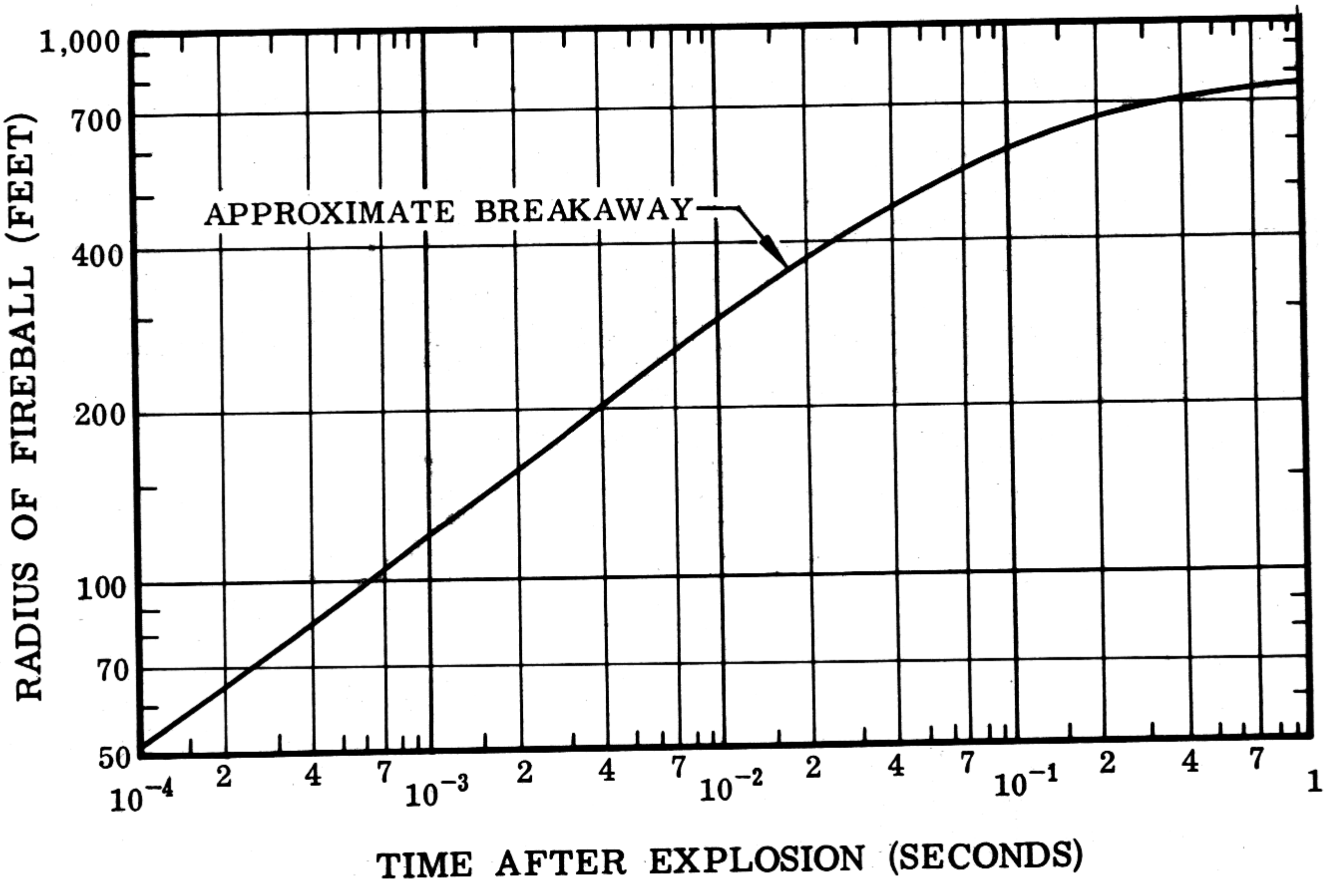

Figure 2.111. Variation of radius of luminous fireball with time in a 20-kiloton explosion.

Temperature of the Fireball

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

2.113 From about the time the fireball temperature has fallen to 300,000° C, when the shock front begins to move ahead of the isothermal sphere, until close to the time of the first temperature minimum (§ 2.38), the expansion of the fireball is governed by the laws of hydrodynamics. It is then possible to calculate the temperature of the shocked air from the measured shock velocity, i.e., the rate of growth of the fireball. The variation of the temperature of the shock front with time, obtained in this manner, is shown by the full line from 10^{-4} to 10^{-2} second in Fig. 2.113, for a 20-kiloton explosion. However, photographic and spectroscopic observations of the surface brightness of the advancing shock front, made from a distance, indicate the much lower temperatures represented by the broken curve in the figure. The reason for this discrepancy is that both the nuclear and thermal radiations emitted in the earliest stages of the detonation interact in depth with the gases of the atmosphere ahead of the shock front to produce ozone, nitrogen dioxide, nitrous acid, etc. These substances are strong absorbers of radiation coming from the fireball, so that the brightness observed some distance away corresponds to a temperature considerably lower than that of the shock front.

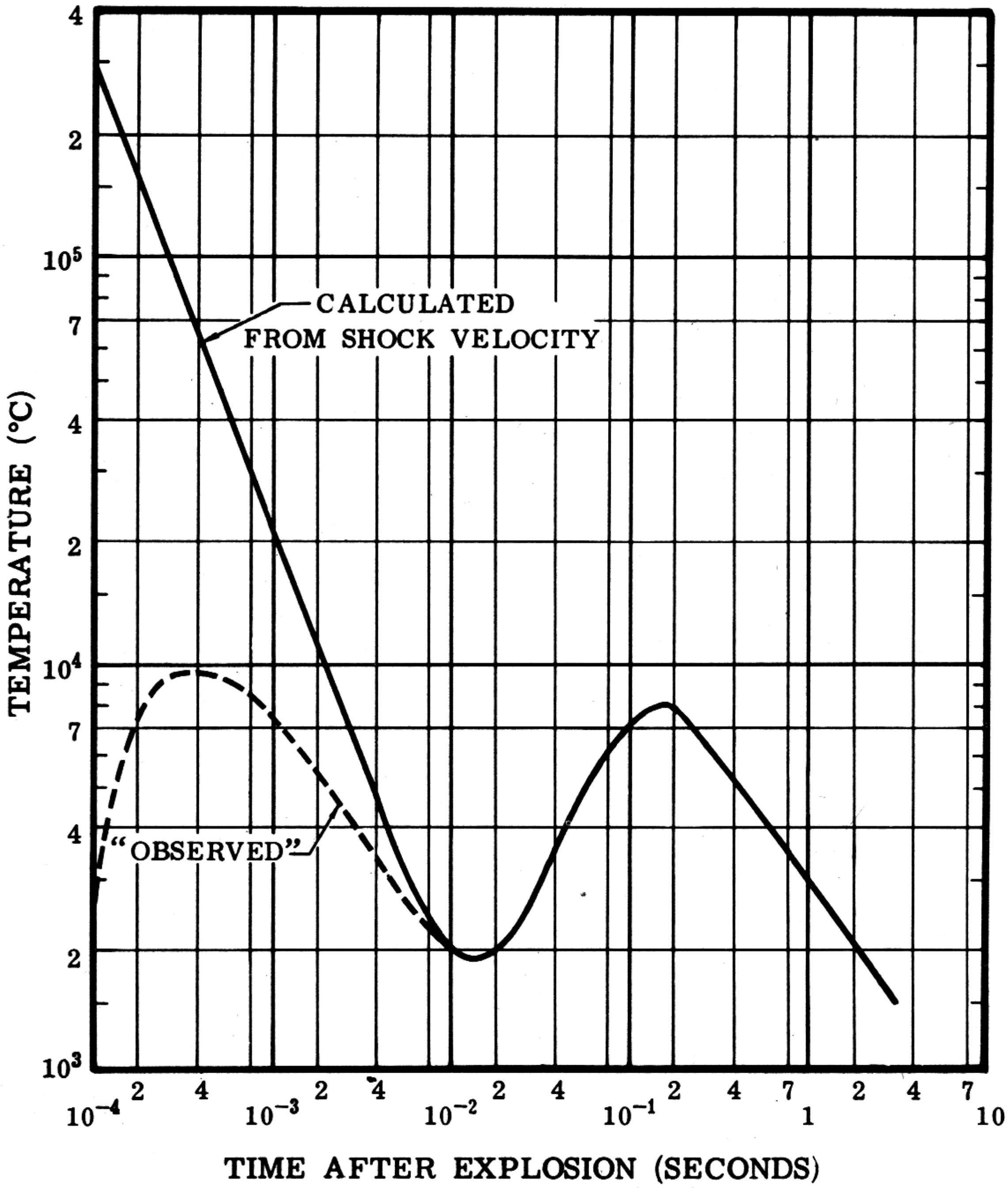

Figure 2.113. Variation of apparent fireball surface temperature with time in a 20-kiloton explosion.

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

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

2.116 The curves in Figs. 2.111 and 2.113 apply to a 20-kiloton nuclear burst, but similar results are obtained for explosions of other energy yields. The rate of growth of the fireball depends on the actual yield, and so does the maximum radius. The time of thermal minimum increases with the energy yield, a good approximation for an air burst being given by the scaling law

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

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

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

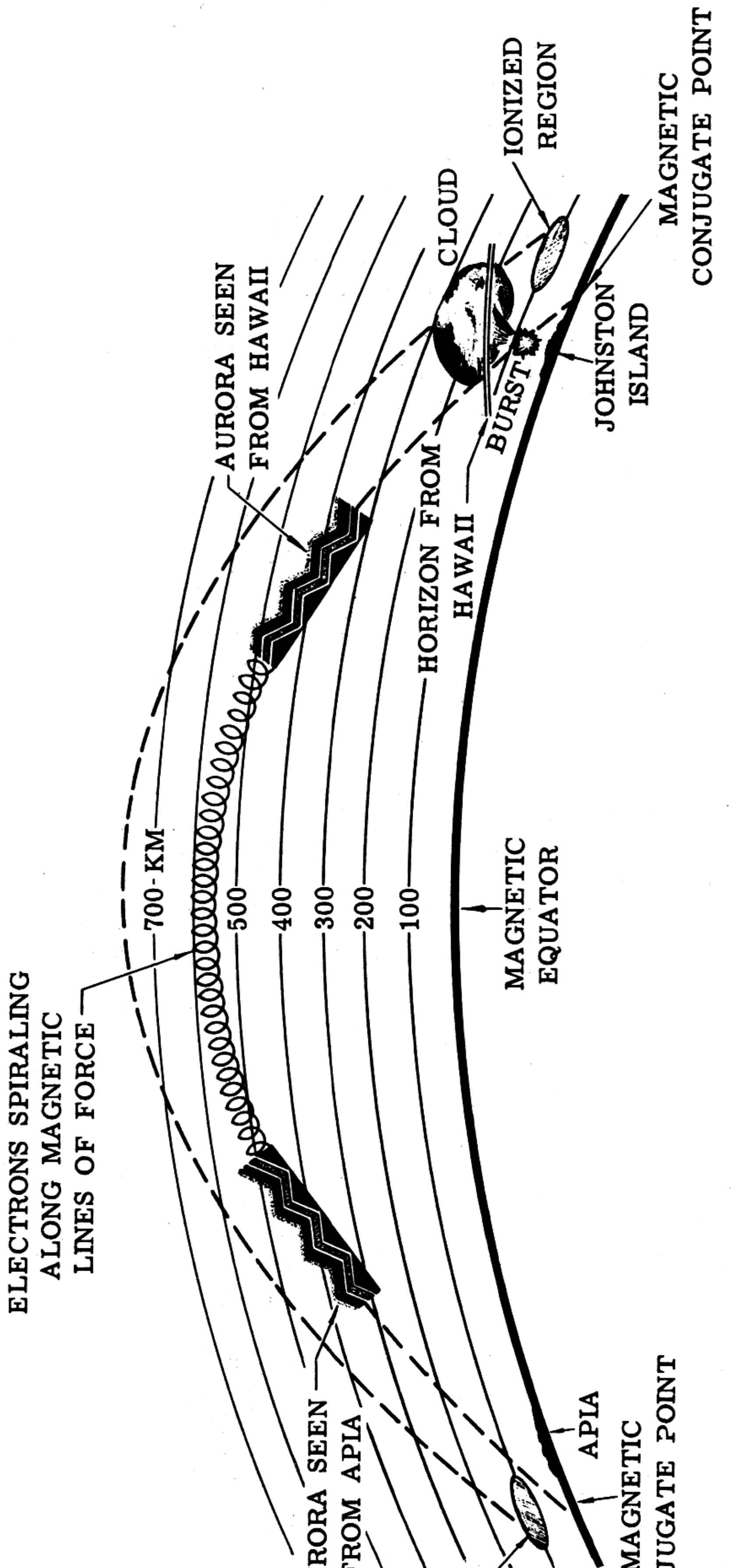

Figure 2.127. Phenomena associated with high-altitude explosions.

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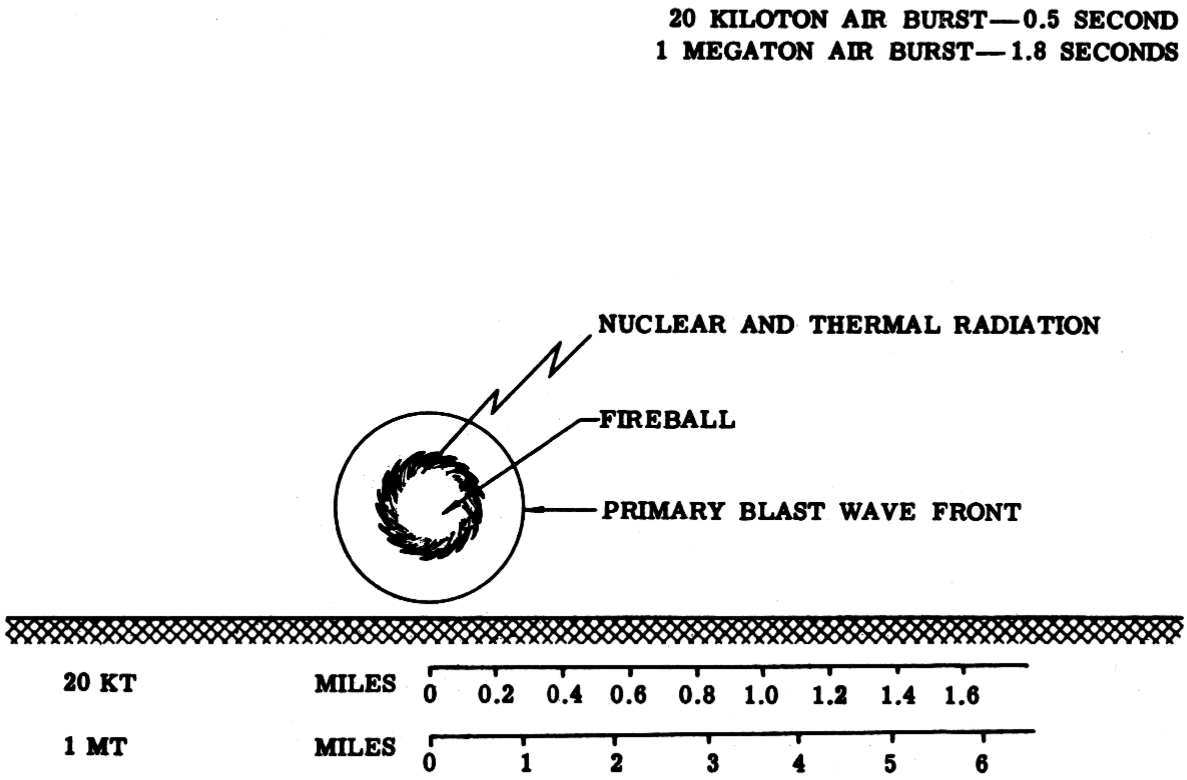


Figure 2.51a. Chronological development of an air burst; 0.5 second after 20-kiloton detonation; 1.8 seconds after 1-megaton detonation.

CHRONOLOGICAL DEVELOPMENT OF AIR BURST

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

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

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

The blast wave front in the air is seen to be well ahead of the fireball, about 800 feet for the 20-kiloton explosion and roughly half a mile for the 1-megaton detonation.

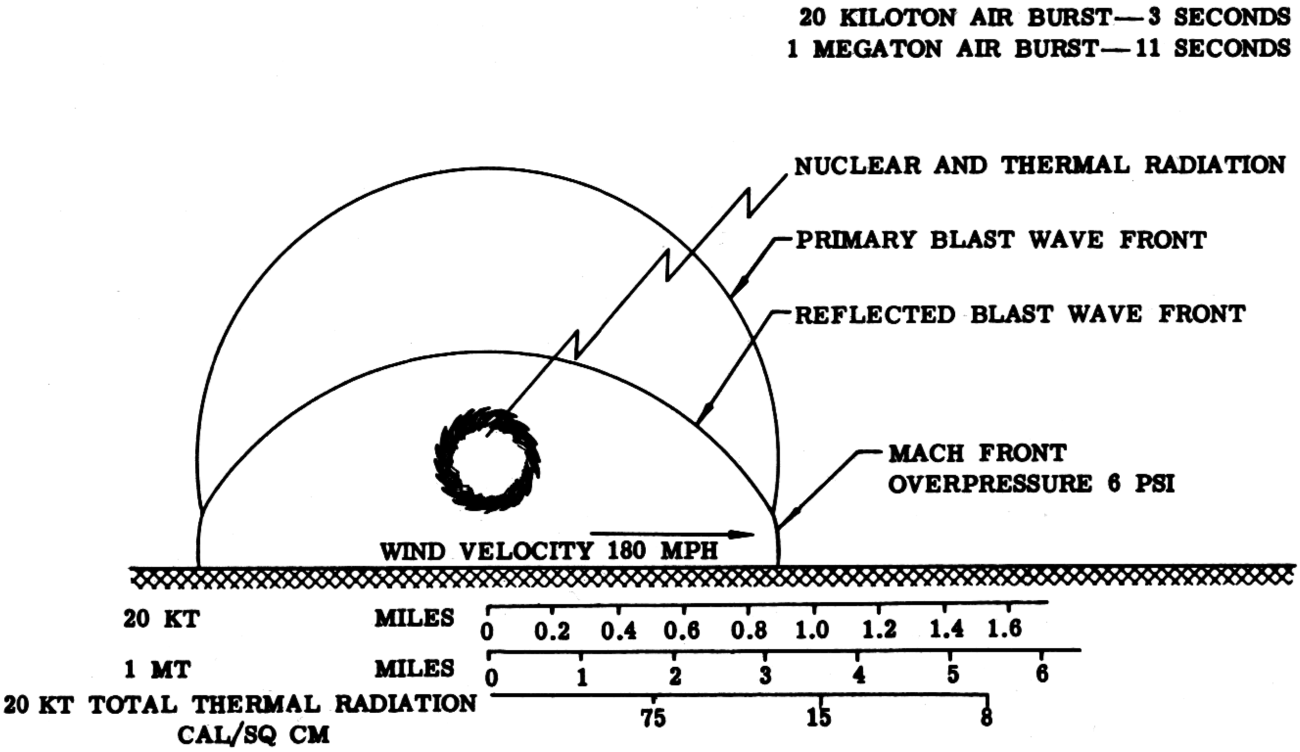


Figure 2.51c. Chronological development of an air burst; 3 seconds after 20-kiloton detonation; 11 seconds after 1-megaton detonation.

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

Explosion yield	*Height of burst (feet)*	*Time after detonation (seconds)*	*Distance from ground zero (miles)*	*Height of stem (feet)*
20 kilotons	1, 760	3	0. 87	185
1 megaton	6, 500	11	3. 2	680

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

Nuclear radiations from the weapon residues in the rising fireball continue to reach the ground. But after 3 seconds from the detonation of a 20-kiloton weapon, the fireball, although still very hot, has cooled to such an extent that the thermal radiation is no longer important. The total accumulated amounts of thermal radiation, expressed in calories per square centimeter, received at various distances from ground zero after a 20-kiloton air burst, at 1,760 feet, are shown on the scale at the bottom of the figure (for further details, see Chapter VII). Appreciable amounts of thermal radiation are still received from the fireball at 11 seconds after a 1-megaton explosion; the thermal radiation emission is spread over a longer time interval than for an explosion of lower energy yield.

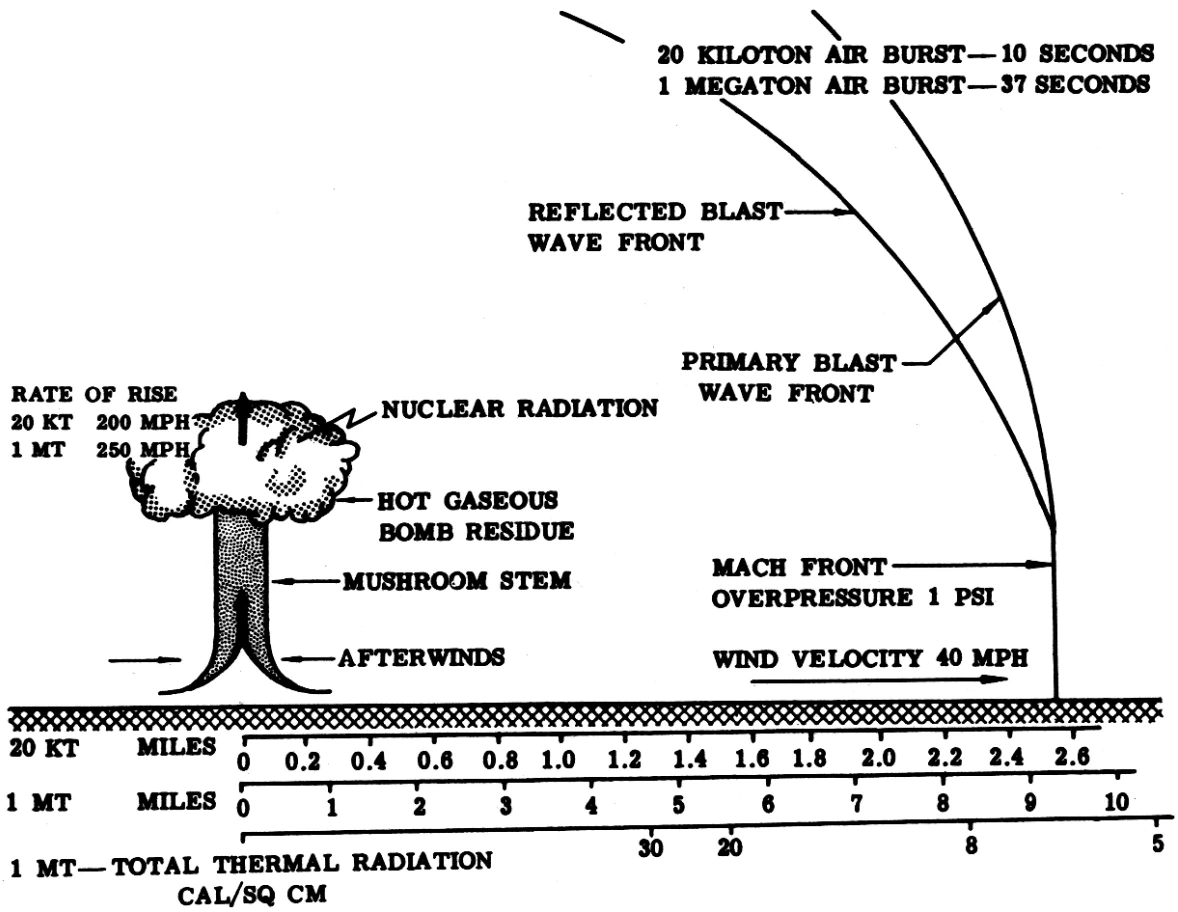


Figure 2.51d. Chronological development of an air burst; 10 seconds after 20-kiloton detonation; 37 seconds after 1-megaton detonation.

At 10 seconds after a 20-kiloton explosion at an altitude of 1,760 feet the Mach front is over 2½ miles from ground zero, and 37 seconds after a 1-megaton detonation at 6,500 feet, it is nearly 9½ miles from ground zero. The overpressure at the front is roughly 1 pound per square inch, in both cases, and the wind velocity behind the front is 40 miles per hour. There will be slight damage to many structures, including doors and window frames ripped off, roofs cracked, and plaster damaged. Glass will be broken at overpressures down to ½ pound per square inch. Thermal radiation is no longer important, even for the 1-megaton burst, the total accumulated amounts of this radiation, at various distances, being indicated on the scale at the bottom of the figure. Nuclear radiation, however, can still reach the ground to an appreciable extent; this consists mainly of gamma rays from the fission products.

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

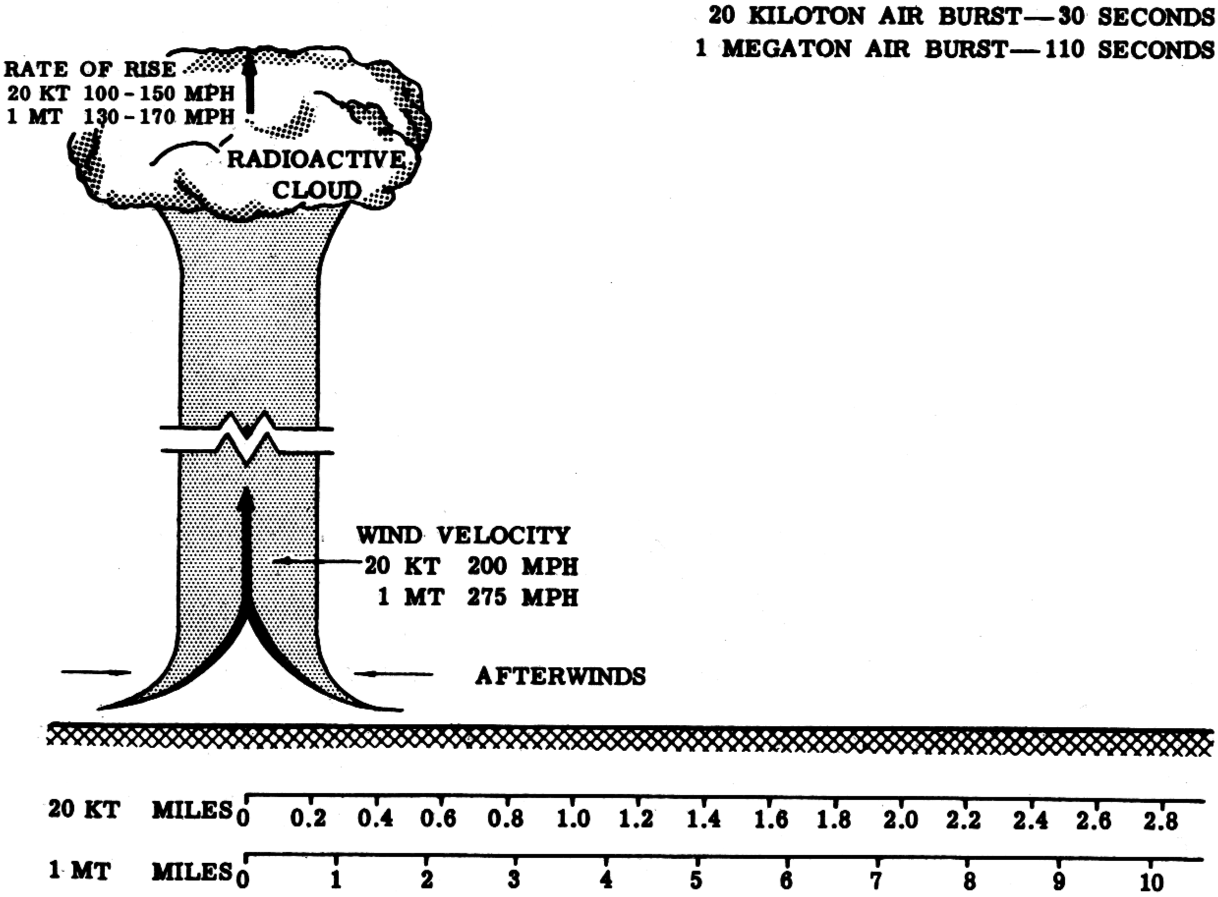


Figure 2.51e. Chronological development of an air burst; 30 seconds after 20-kiloton detonation; 110 seconds after 1-megaton detonation.

The hot residue of the weapon continues to rise and at the same time it expands and cools. As a result, the vaporized fission products and other weapon residues condense to form a cloud of highly radioactive particles. The afterwinds have velocities of 200 or more miles per hour, and for a sufficiently low burst they will continue to raise a column of dirt and debris which will later join with the radioactive cloud to form the characteristic mushroom shape. At the times indicated, the cloud from a 20-kiloton explosion will have risen about 1½ miles and that from a 1-megaton explosion about 7 miles. After about 10 minutes, the maximum heights attained by the clouds will be about 7 miles and 14 miles, respectively. Ultimately, the particles in the cloud will be dispersed by the wind and, unless there is precipitation, there will usually be no early (or local) fallout. Only if the height of burst is less than about 600 feet for a 20-kiloton and 3,000 feet for a 1-megaton explosion would appreciable early fallout be expected.

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

100 KILOTON SHALLOW UNDERWATER BURST—2 SECONDS

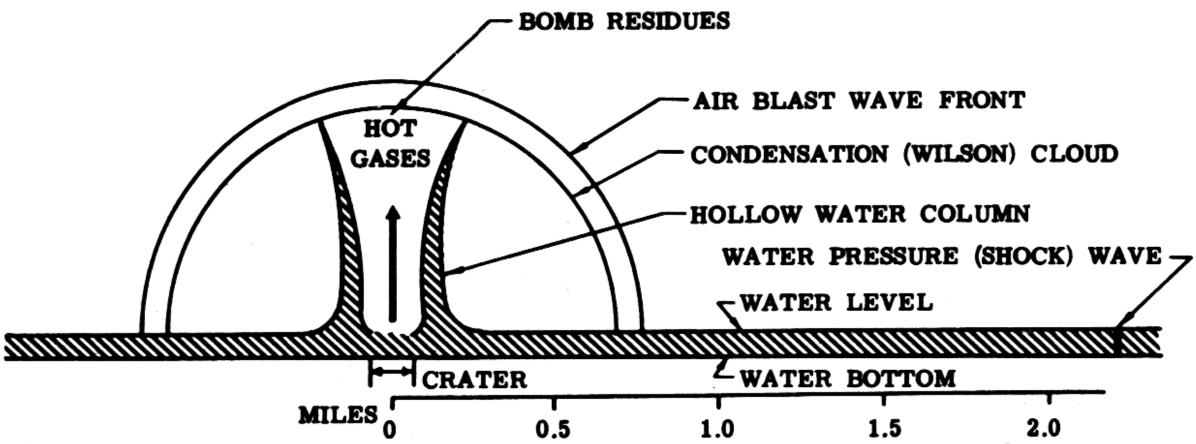


Figure 2.80a. Chronological development of a 100-kiloton shallow underwater burst: 2 seconds after detonation.

CHRONOLOGICAL DEVELOPMENT OF SHALLOW UNDERWATER BURST

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

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

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

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

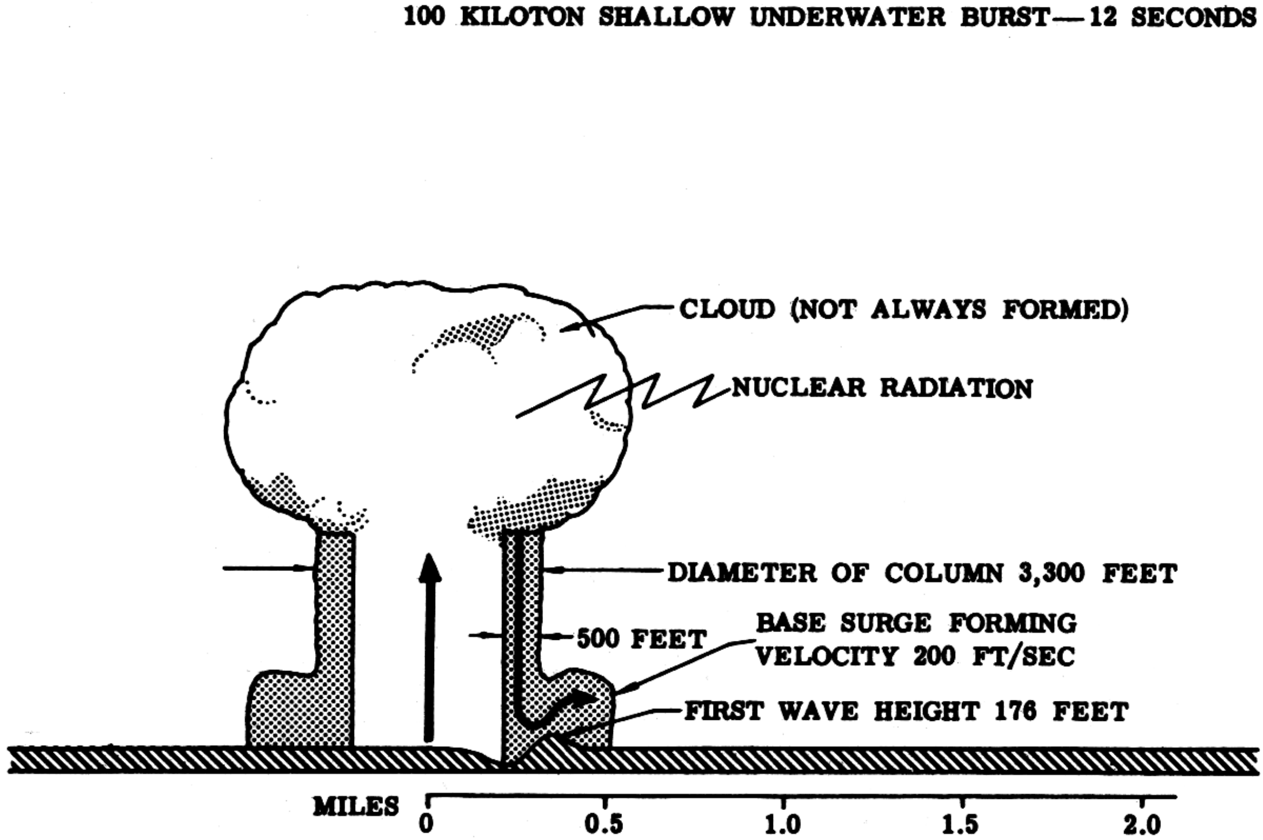


Figure 2.80b. Chronological development of a 100-kiloton shallow underwater burst: 12 seconds after detonation.

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

At 10 to 12 seconds after a shallow underwater explosion, the water falling back from the column reaches the surface and produces around the base of the column a ring of highly radioactive mist, called the base surge. This ring-shaped cloud moves outward, parallel to the water surface, at high speed, initially 200 feet per second (135 miles per hour). For underwater bursts at certain depths, the radioactive cloud may not be formed, although there will generally be a base surge.

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

100 KILOTON SHALLOW UNDERWATER BURST—20 SECONDS

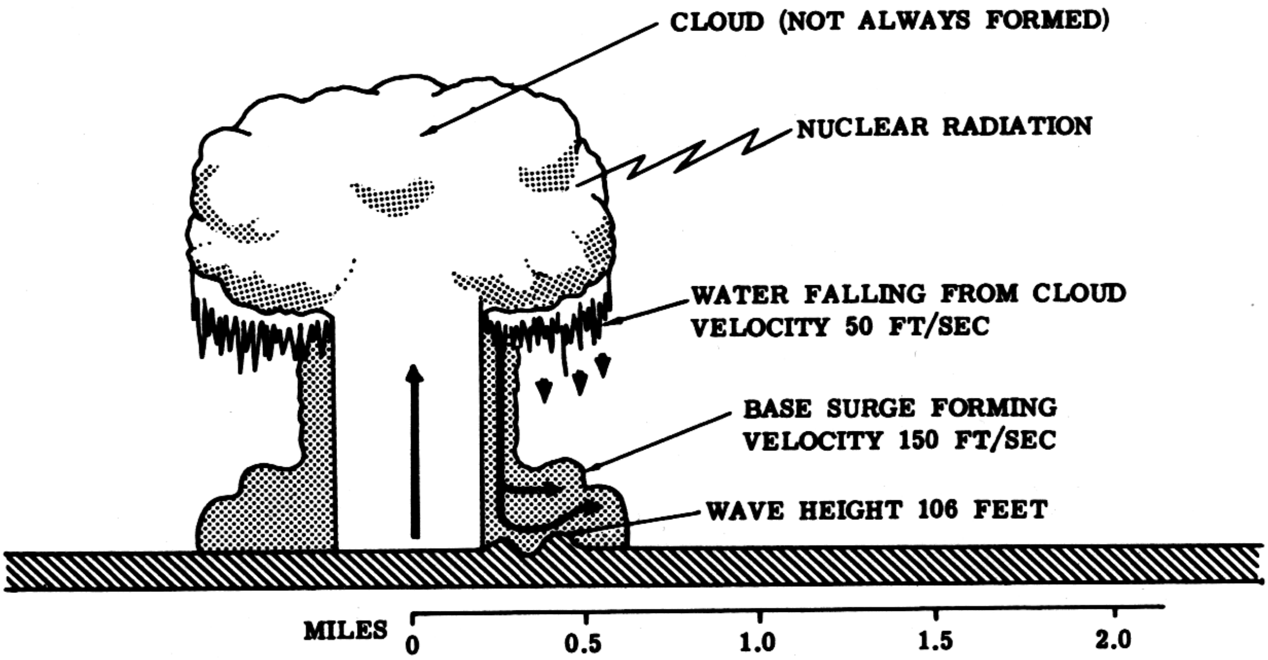


Figure 2.80c. Chronological development of a 100-kiloton shallow underwater burst: 20 seconds after detonation.

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

At about this time, large quantities of water, sometimes referred to as the massive water fallout, begin to descend from the radioactive cloud, if it is formed. The initial rate of fall is about 50 feet per second. The diameter of the column has now decreased to 2,000 feet.

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

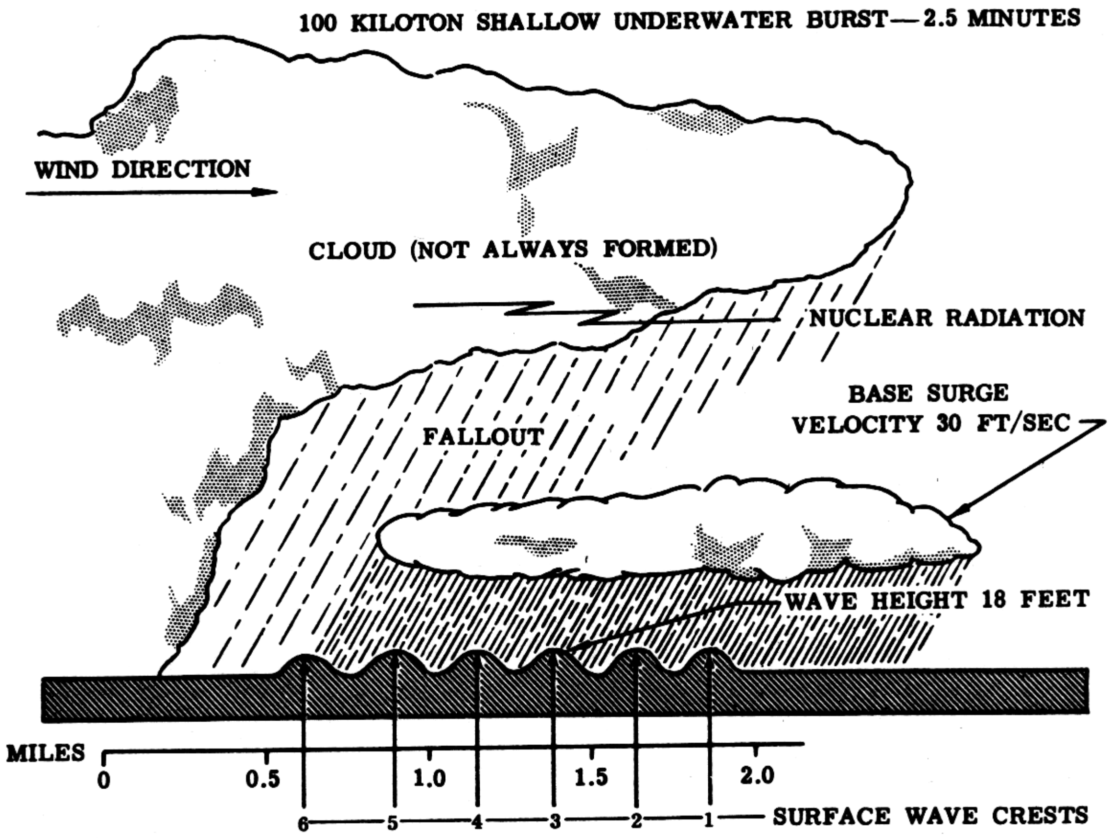


Figure 2.80e. Chronological development of a 100-kiloton shallow underwater burst: 2.5 minutes after detonation.

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

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

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

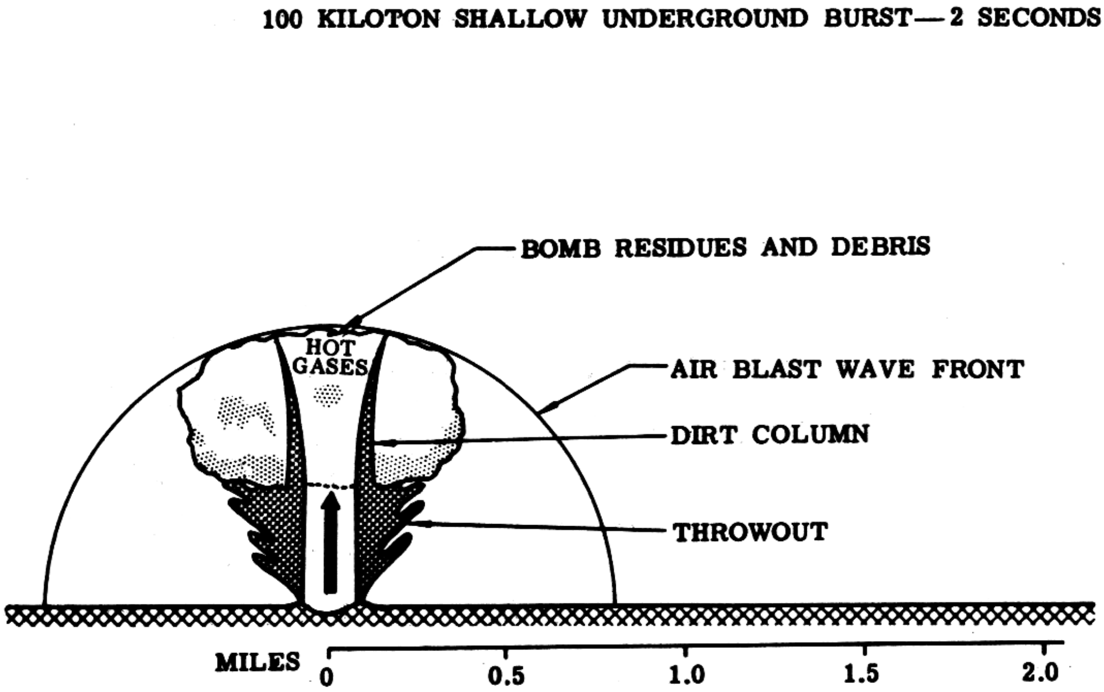


Figure 2.93a. Chronological development of a 100-kiloton shallow underground burst: 2.0 seconds after detonation.

CHRONOLOGICAL DEVELOPMENT OF UNDERGROUND BURST

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

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

100 KILOTON SHALLOW UNDERGROUND BURST—9 SECONDS

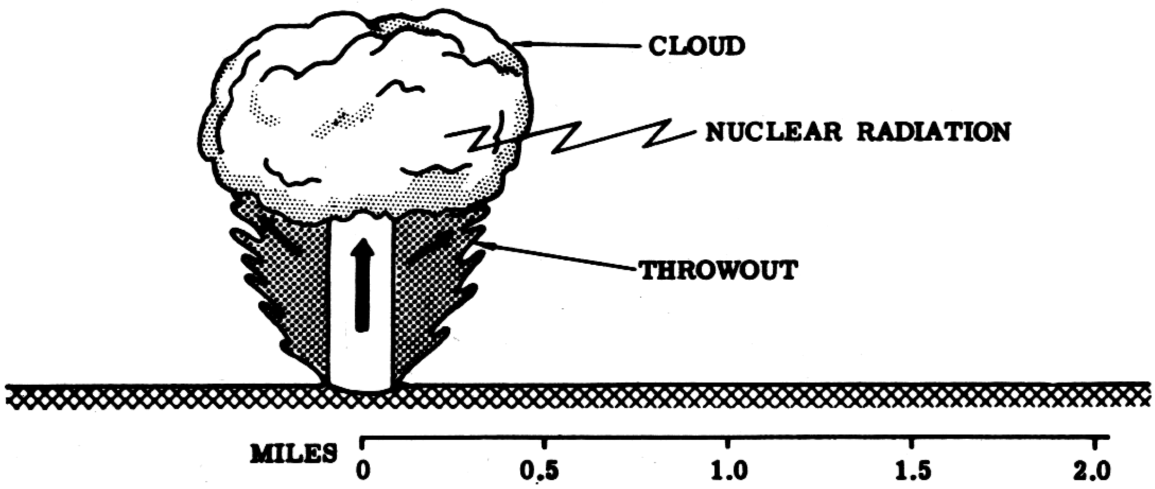


Figure 2.93b. Chronological development of a 100-kiloton shallow underground burst: 9.0 seconds after detonation.

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

100 KILOTON SHALLOW UNDERGROUND BURST—45 SECONDS

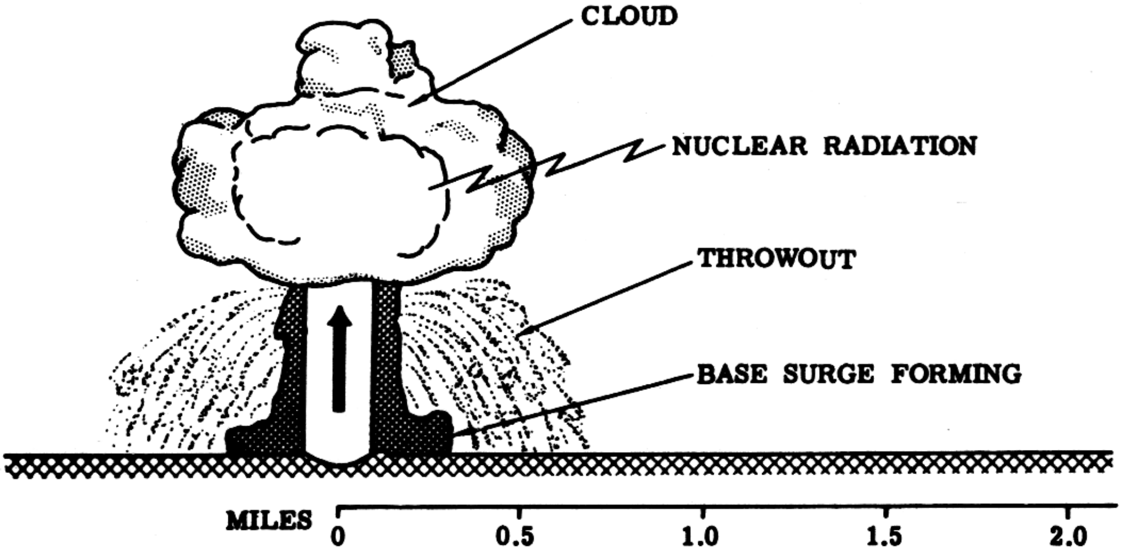


Figure 2.93c. Chronological development of a 100-kiloton shallow underground burst: 45 seconds after detonation.

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

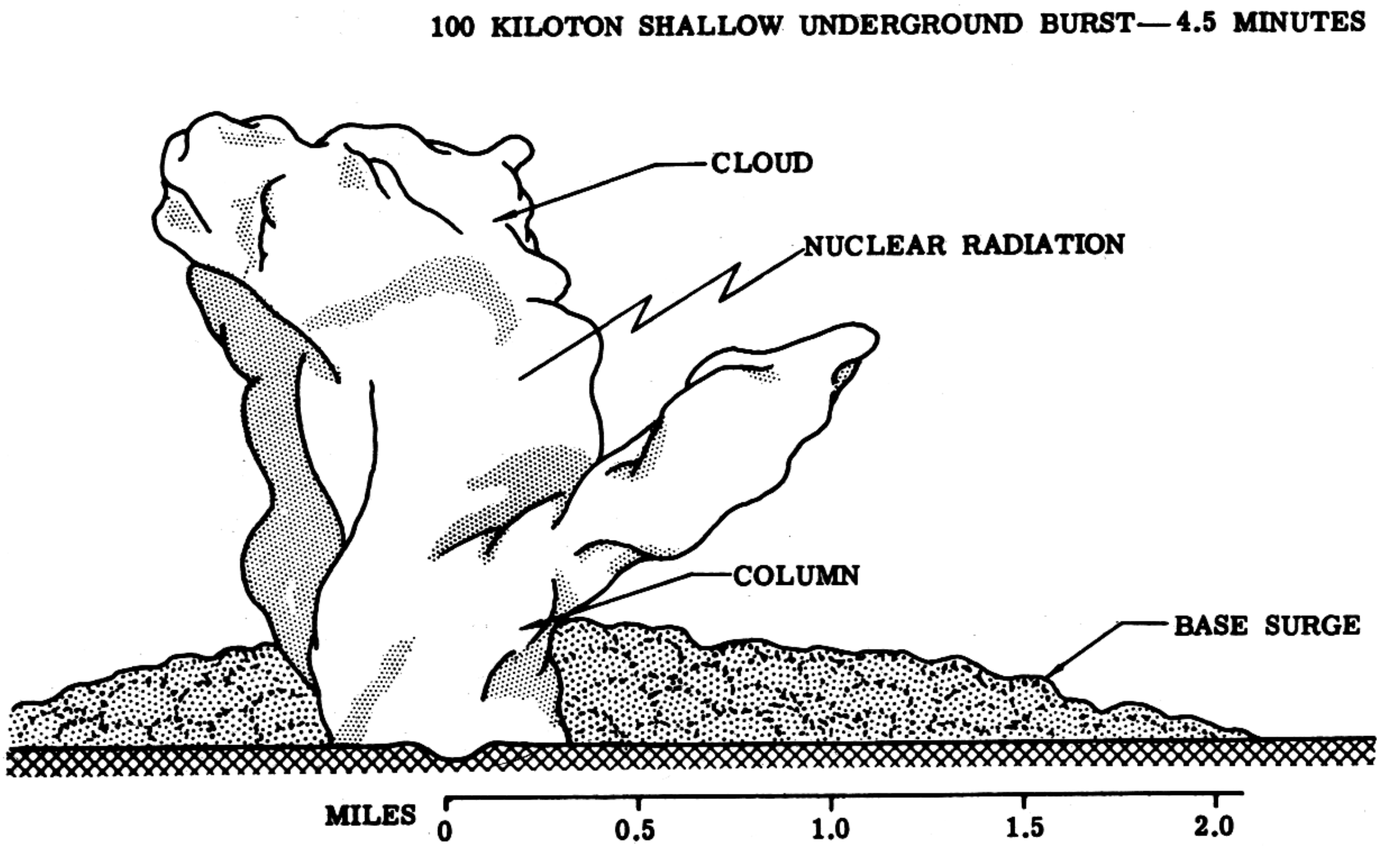


Figure 2.93d. Chronological development of a 100-kiloton shallow underground burst: 4.5 minutes after detonation.

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

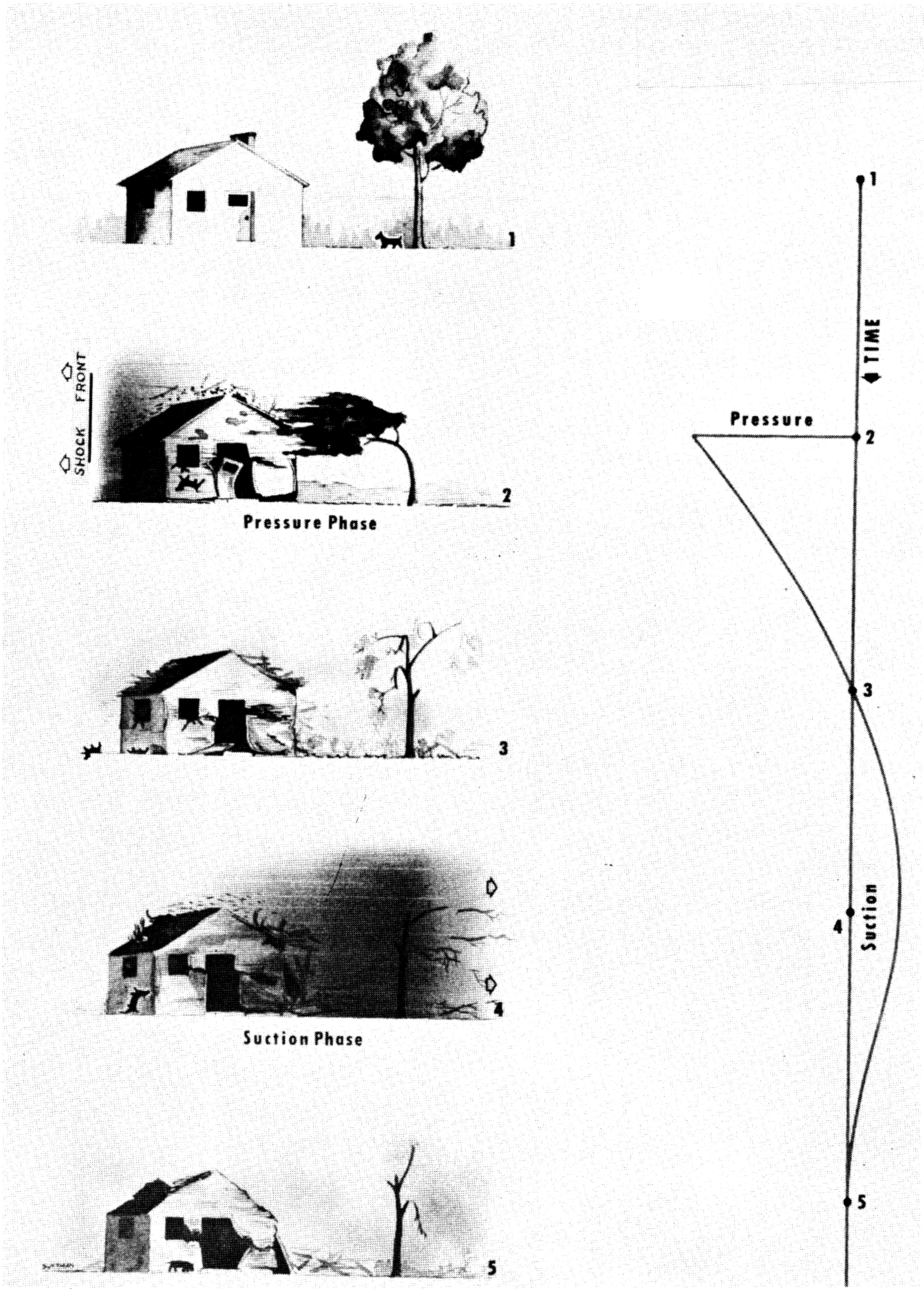


Figure 3.06. Variation of pressure with time at a fixed location and effect of blast wave passing over a structure.

Meteorological Conditions

3.35 The presence of large amounts of moisture in the atmosphere may affect the properties of a blast wave in the low overpressure region. But the probability of encountering significant concentrations of atmospheric liquid water that would influence damage is considered to be small. Meteorological conditions, however, can sometimes either enlarge or contract the area over which light structural damage would normally be expected. For example, window breakage and noise have been experienced hundreds of miles from the burst point. Such phenomena, which have been observed with large TNT detonations as well as nuclear explosions, are caused by the bending back to the earth of the blast wave by the atmosphere.

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

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

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

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

Effect of Altitude

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

3.41 For a surface burst, the peak overpressure at a given distance from the explosion will depend on the ambient atmospheric pressure and this will vary with the burst altitude. There are a number of simple correction factors, which will be given later (see § 3.59), that can be used to allow for differences in the ambient conditions, but for the present it will be sufficient to state the general conclusions. With increasing altitude of both target and burst point, the overpressure at a given distance from an explosion of specified yield will generally decrease. Correspondingly, an increase may usually be expected in

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

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

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

Surface Effects

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

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

Ground Shock from Air Blast

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

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

TECHNICAL ASPECTS OF BLAST WAVE PHENOMENA[4]

PROPERTIES OF THE BLAST WAVE

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

3.48 The blast wave properties in the region of regular reflection are somewhat complex and depend on the angle of incidence of the wave with the ground and the overpressure. For a contact surface burst, when there is but a single hemispherical (fused) wave, as stated in § 3.30, and in the Mach region below the triple point path for an air burst, the various blast wave characteristics at the shock front are uniquely related by the Rankine-Hugoniot equations. It is for these conditions, in which there is a single shock front, that the following results are applicable.

3.49 The shock velocity, U, is expressed by

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

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

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

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

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

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

so that for air

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

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

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

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

The dynamic pressure, q, is defined by

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

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

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

$$=\frac{5}{2}\cdot\frac{p^2}{7P_0+p} \qquad (3.49.1)$$

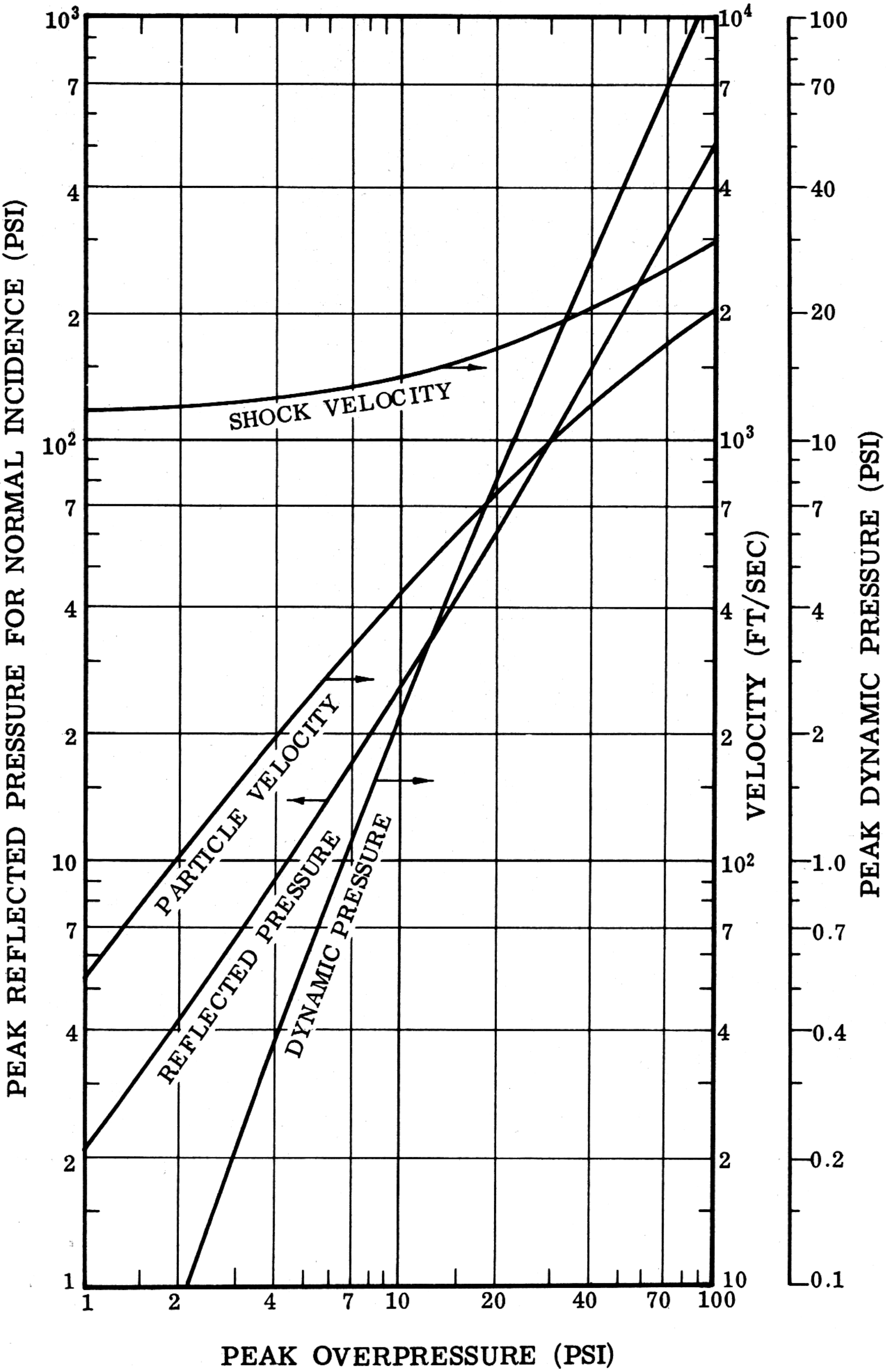
between the peak dynamic pressure in air and the peak overpressure and ambient pressure. The variations of shock velocity, particle (or peak wind) velocity, and peak dynamic pressure with the peak overpressure at sea level, as derived from the foregoing equations, are shown graphically in Fig. 3.49.

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

$$p_r=2p+(\gamma+1)q, \qquad (3.50.1)$$

and using equation (3.49.1) for air, this becomes

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



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

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

3.51 The equations in § 3.49 give the peak values of the various blast wave parameters at the shock front. As seen earlier, however, the overpressure and dynamic pressure both decrease with time, although at different rates. Provided the peak overpressure is low, e.g., about 10 pounds per square inch or less, the variation of the overpressure behind the shock front with time at a given point can be represented to a good approximation by the simple empirical equation

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

where $p(t)$ is the overpressure at any time, t, after the arrival of the shock front, p is the peak overpressure, and t_+ is the duration of the positive phase. In the event of the interaction of the blast wave with a structure, this equation is used to determine the air blast loading as a function of time for low overpressures.

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

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

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

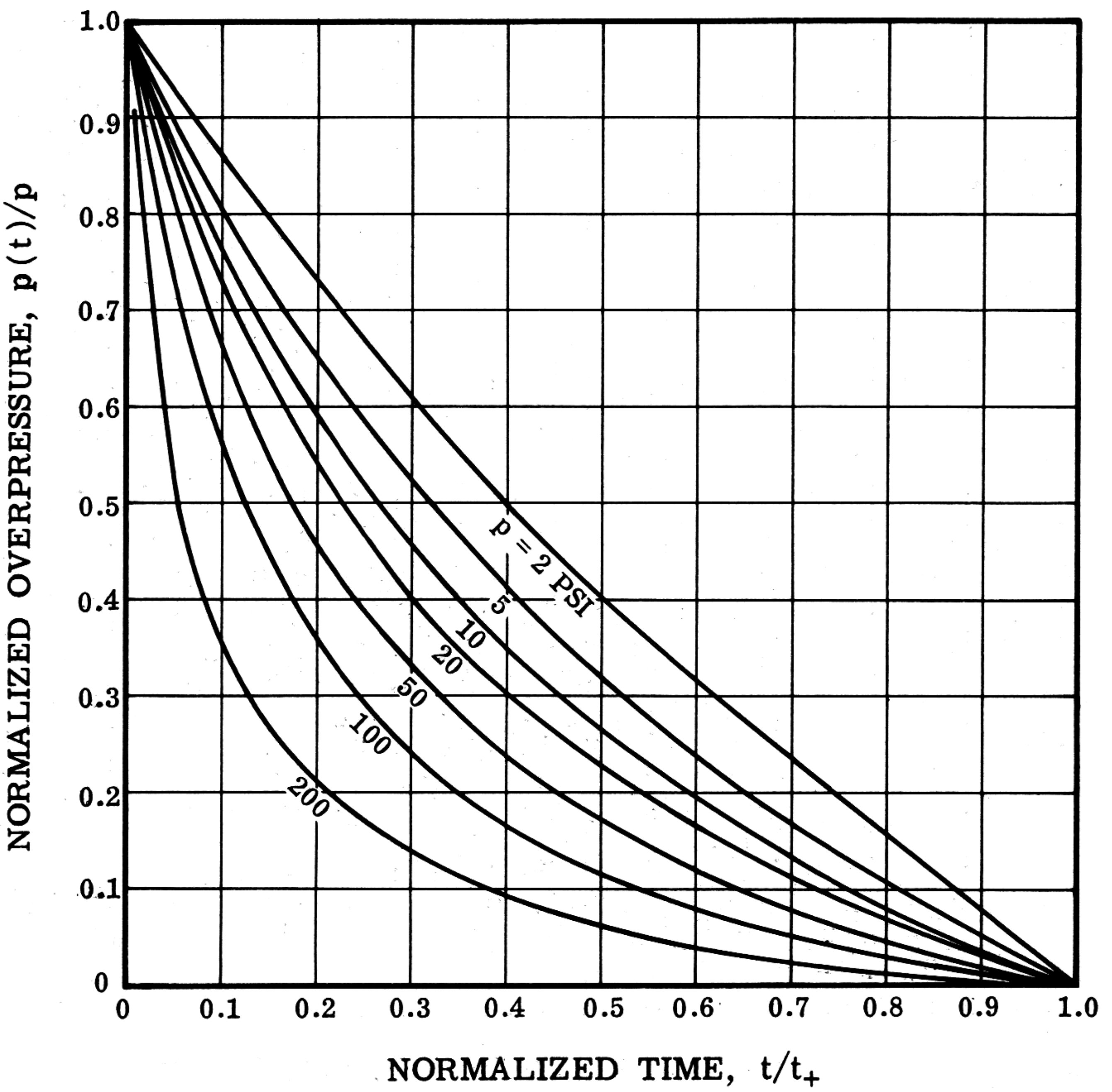


Figure 3.52. Rate of decay of pressure with time for various values of the peak overpressure.

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

3.54 Another important blast damage parameter is the "impulse," which takes into account the duration of the positive phase and the variation of the overpressure during that time. Impulse (per unit

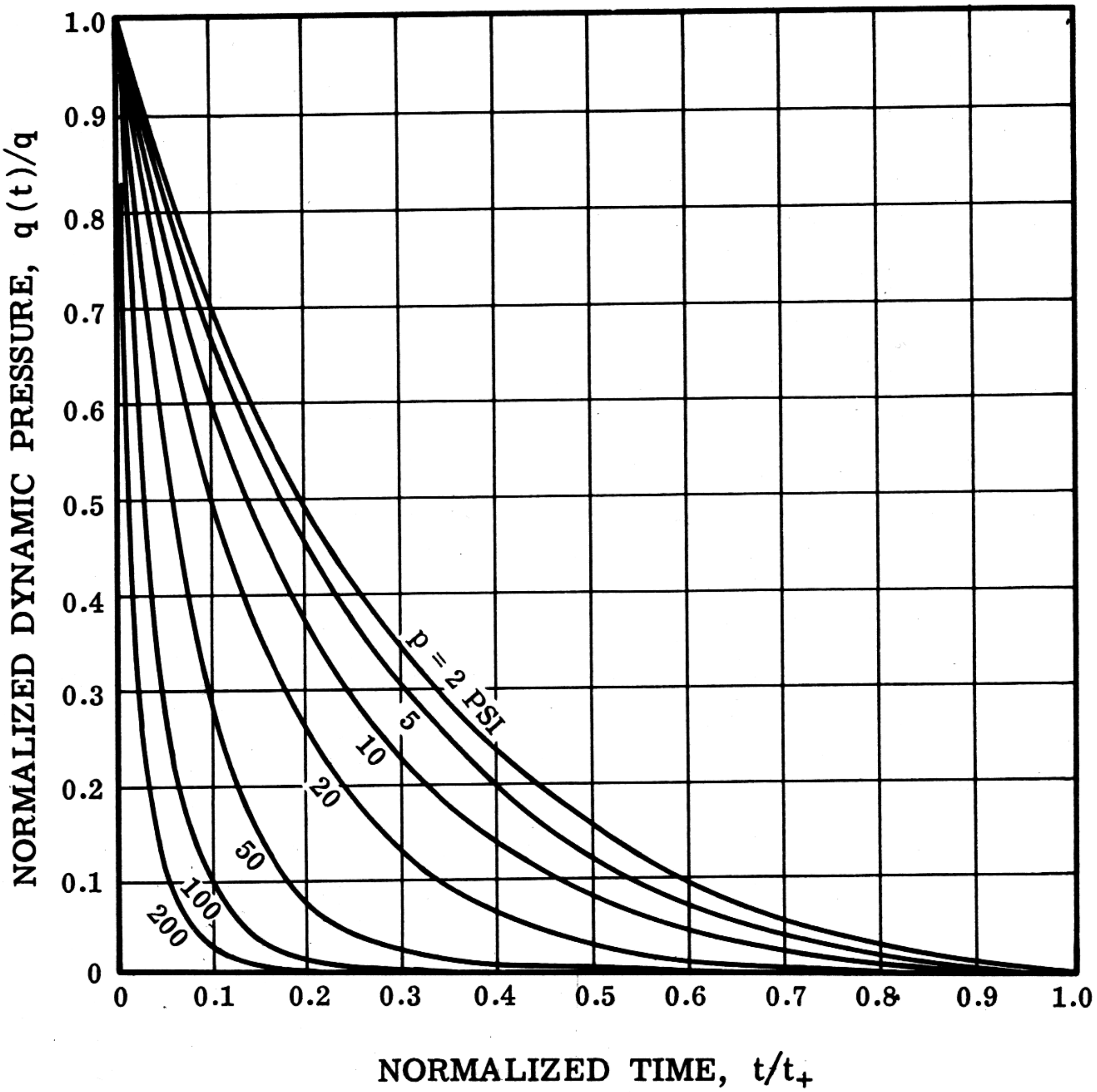


Figure 3.53. Rate of decay of dynamic pressure with time for various values of the peak overpressure.

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

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

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

SCALING LAWS

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

3.56 Theoretically, a given pressure will occur at a distance from an explosion that is proportional to the cube root of the energy yield. Full scale tests have shown this relationship between distance and energy yield to hold for yields up to (and including) the megaton range. Thus, cube root scaling may be applied with confidence over a wide range of explosion energies. According to this law, if D_1 is the distance (or slant range) from a reference explosion of W_1 kilotons at which a certain overpressure or dynamic pressure is attained, then for any explosion of W kilotons energy these same pressures will occur at a distance D given by

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

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

$$D=D_1\times W^{1/3}, \qquad (3.56.2)$$

where D_1 refers to the distance from a 1-kiloton explosion. Consequently, if the distance D is specified, then the value of the explosion energy, W, required to produce a certain effect, e.g., a given peak overpressure, can be calculated. Alternatively, if the energy, W, is specified, the appropriate distance, D, can be evaluated from equation (3.56.2).

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

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

It can be readily seen, therefore, that for explosions of different energies having the same scaled height of burst, the cube root scaling law may be applied to distances from ground zero, as well as to distances from the explosion. Thus, if d_1 is the distance from ground zero at which a particular overpressure or dynamic pressure occurs for a 1-kiloton explosion, then for an explosion of W kilotons energy the same pressures will be observed at a distance d determined by the relationship

$$d = d_1 \times W^{1/3}. \tag{3.57.1}$$

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

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

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

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

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

and

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

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

Altitude Corrections

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

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

THE PRECURSOR

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

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

(Text continued on page 148.)

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

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

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

where, for a given peak overpressure or dynamic pressure, d_1 is the distance from the explosion for 1 KT, and d is the distance from the explosion for W KT.

Example

Given: A 1 MT surface burst.

Find: The distance to which 2 psi extends.

Solution: From Fig. 3.65 the cube root of 1000 is 10. From Fig. 3.66, a peak overpressure of 2 psi occurs at a distance of 2,500 feet from a 1 KT surface burst. Therefore, for a 1 MT surface burst,

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

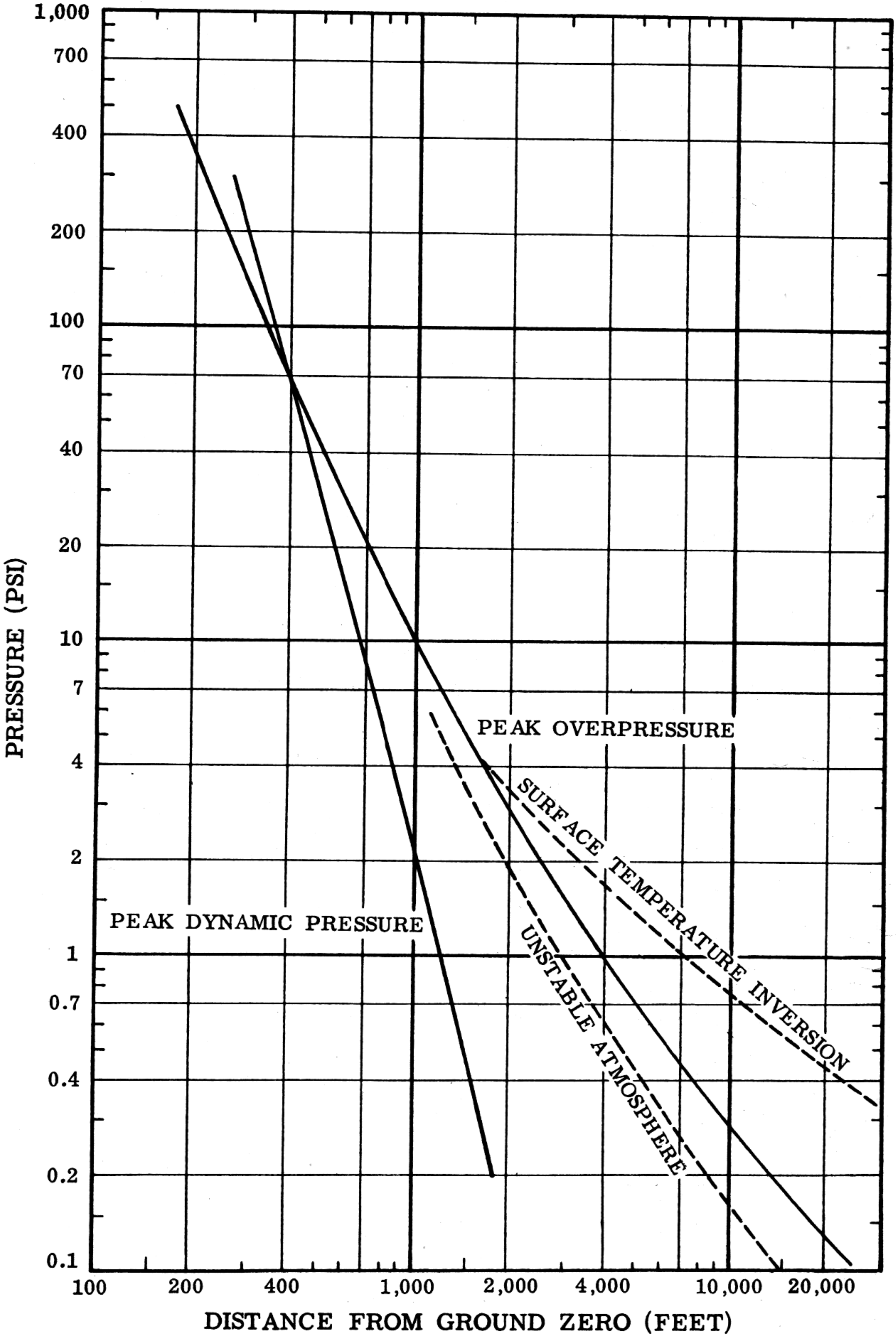


Figure 3.66. Peak overpressure and peak dynamic pressure for 1-kiloton surface burst.

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

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

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

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

Example

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

Find: The distance to which 50 psi extends.

Solution: The corresponding height of burst for 1 KT is

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

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

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

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

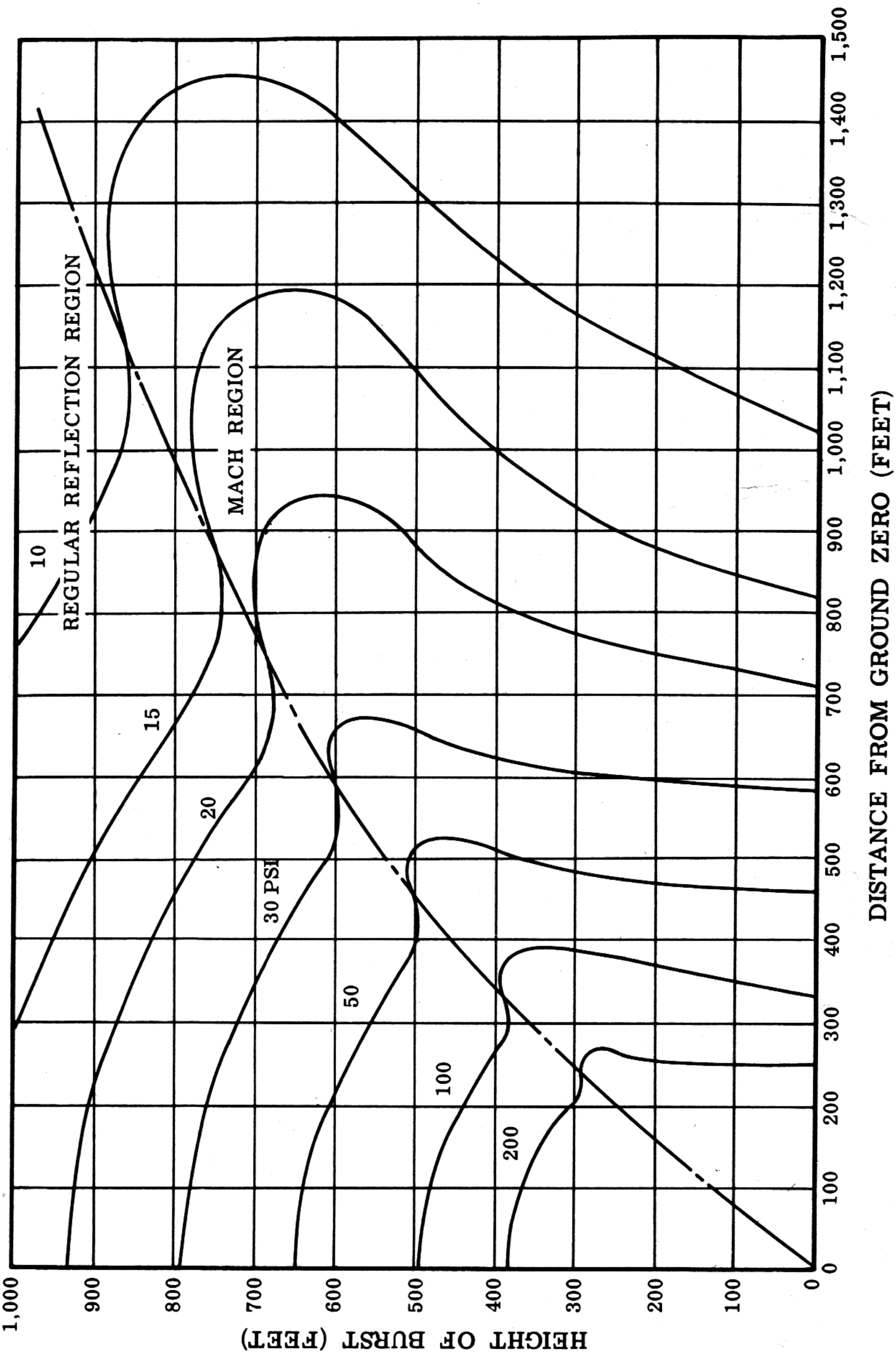


Figure 3.67a. Peak overpressures on the ground for a 1-kiloton burst (high-pressure range).

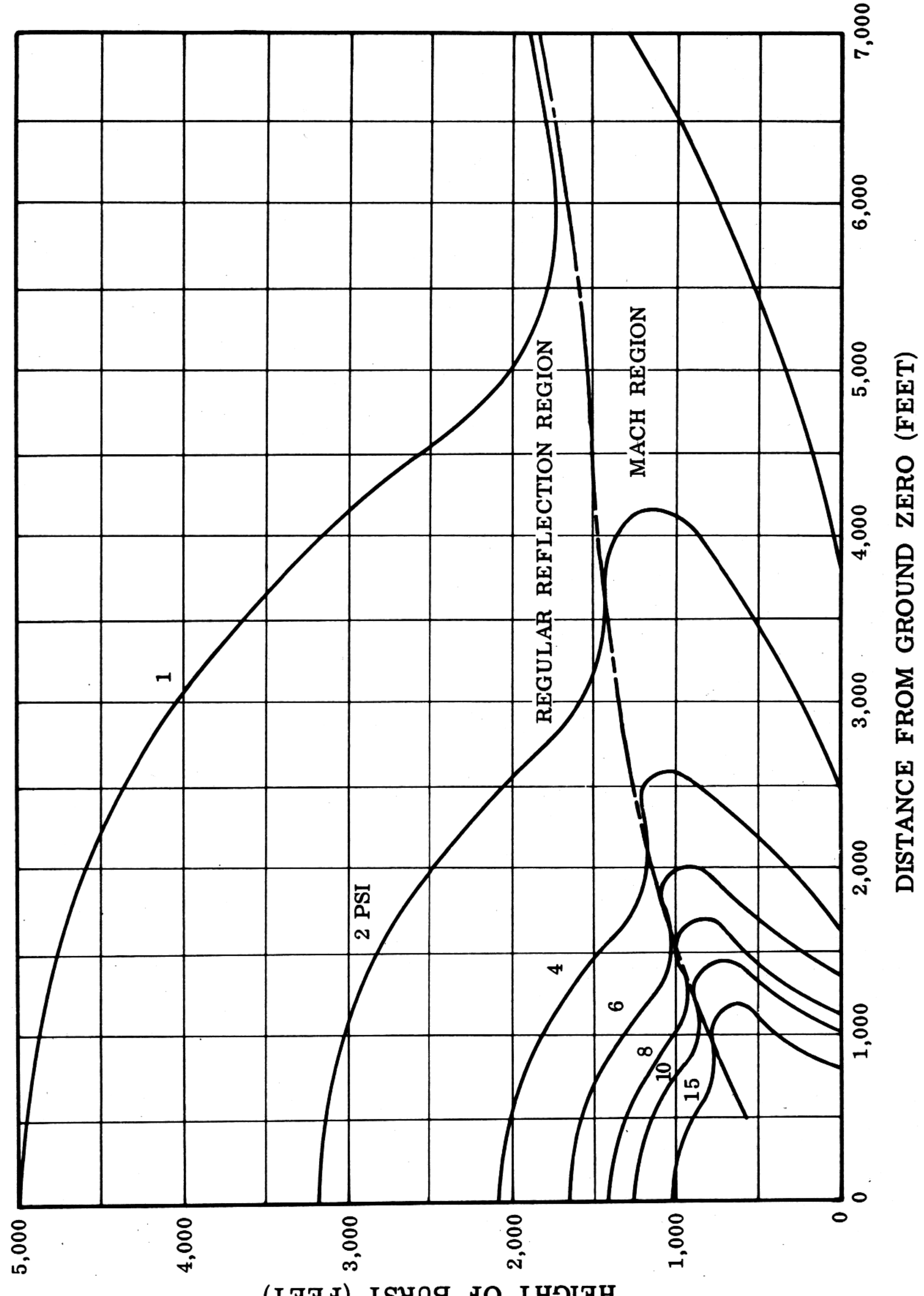


Figure 3.67b. Peak overpressures on the ground for 1-kiloton burst (low-pressure range).

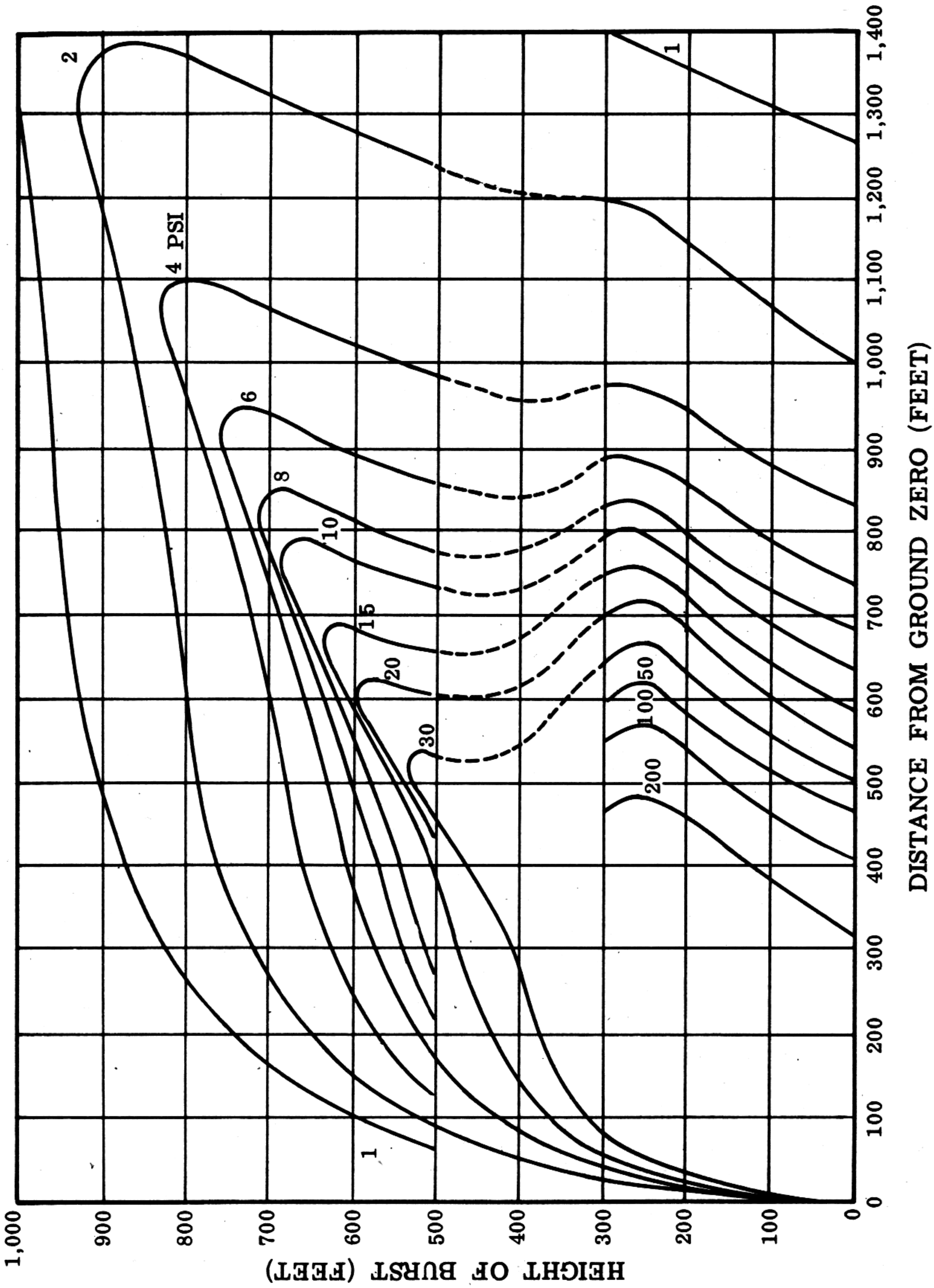


Figure 3.68. Horizontal component of peak dynamic pressure for 1-kiloton burst.

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

Scaling. The required relationships are

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

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

Example

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

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

Solution: The corresponding height of burst for 1 KT is

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

and the corresponding distance from ground zero is

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

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

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

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

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

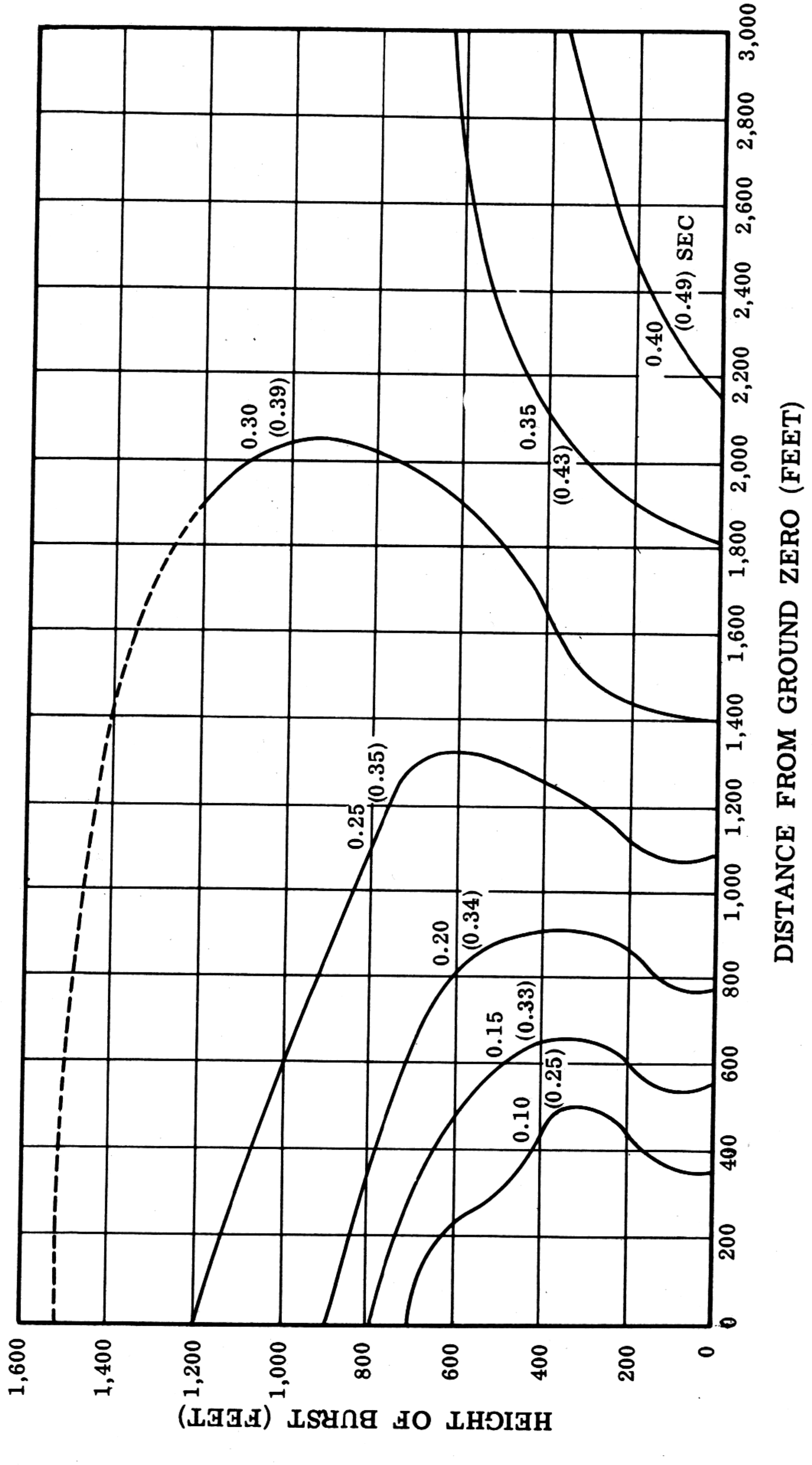


Figure 3.69. Positive phase duration on the ground of overpressure and dynamic pressure (in parentheses) for 1-kiloton burst.

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

Scaling. The required relationships are

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

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

Example

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

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

Solution: The corresponding burst height for 1 KT is

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

The corresponding distance from ground zero for 1 KT is

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

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

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

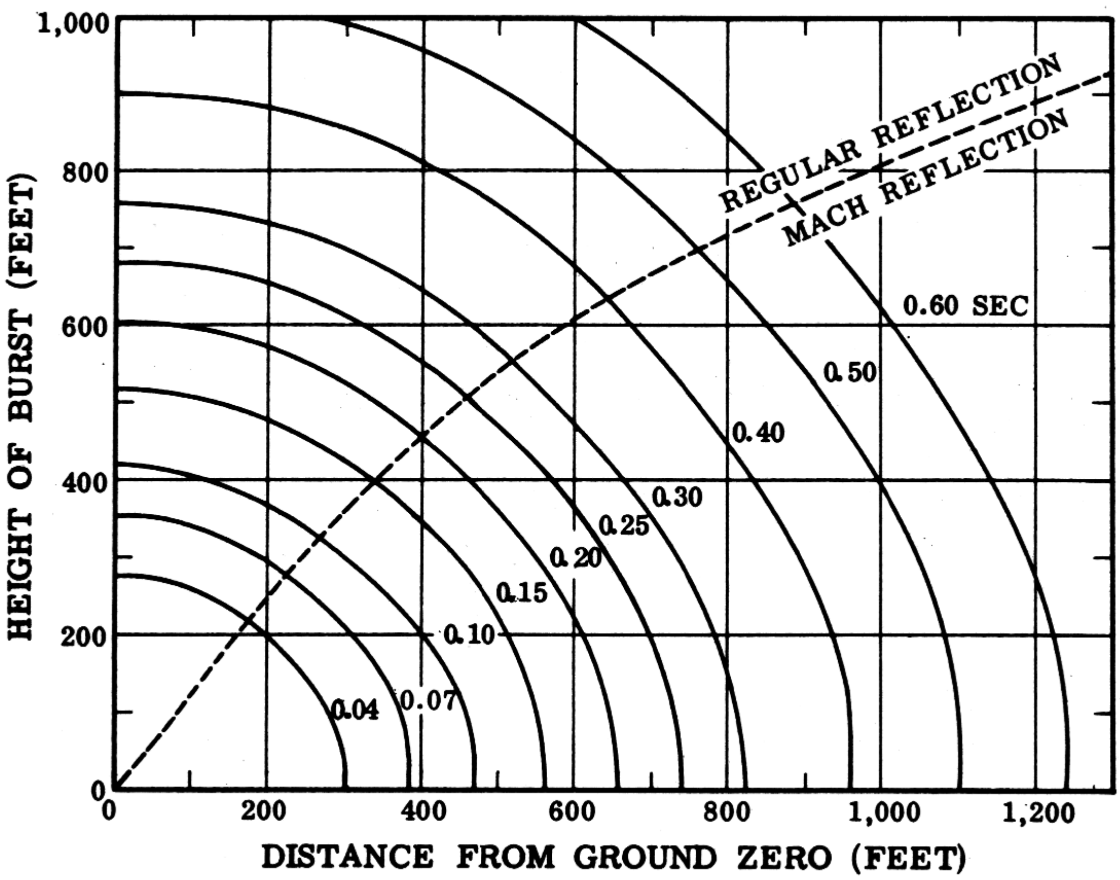


Figure 3.70a. Arrival times on the ground of blast wave for 1-kiloton burst (early times).

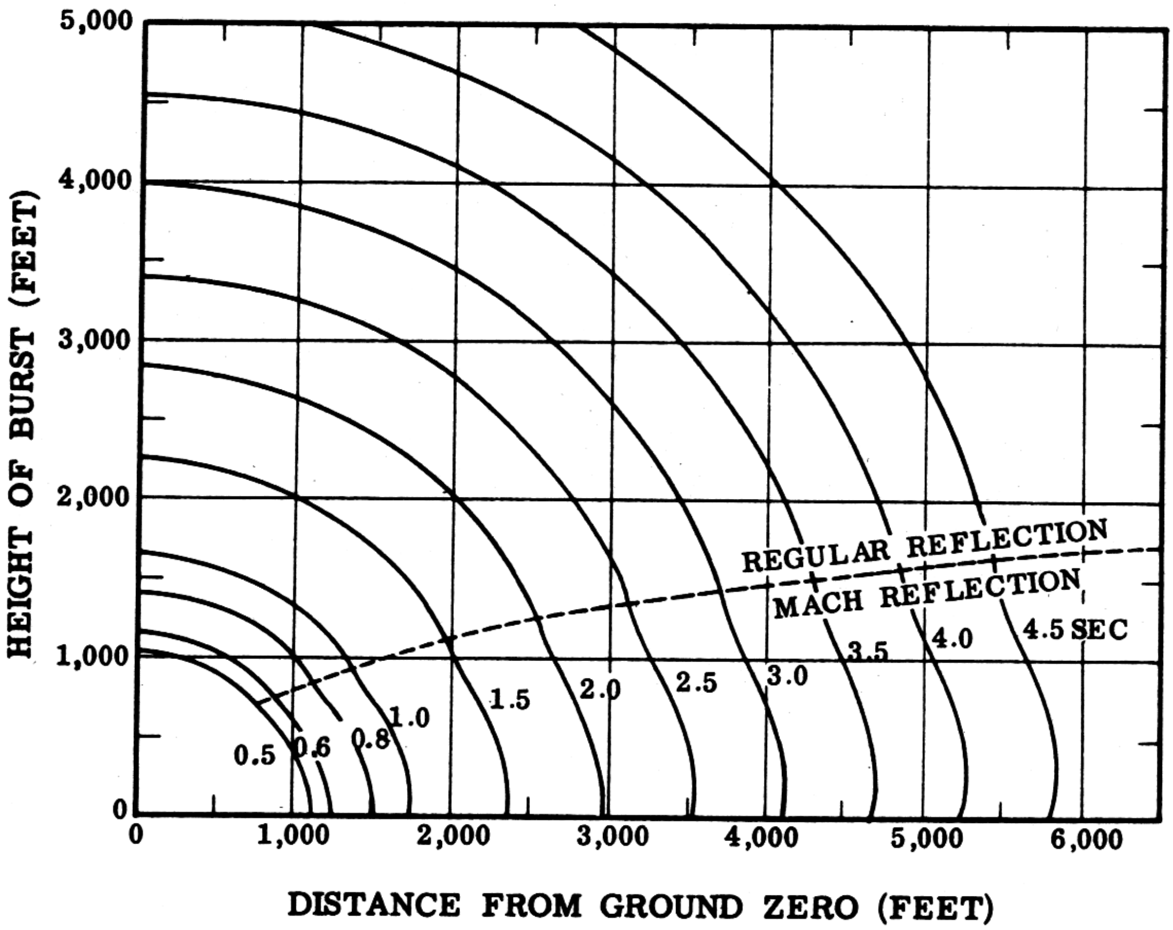


Figure 3.70b. Arrival times on the ground of blast wave for 1-kiloton burst (late times).

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

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

p = initial peak incident overpressure (psi)

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

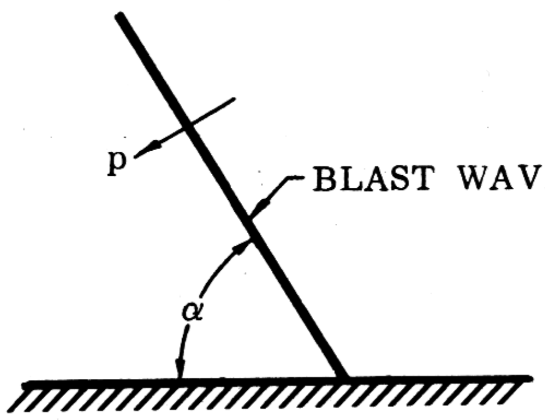


Figure 3.71a. Angle of incidence (α) of blast wave with reflecting surface.

Example

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

Find: The reflected shock wave overpressure.

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

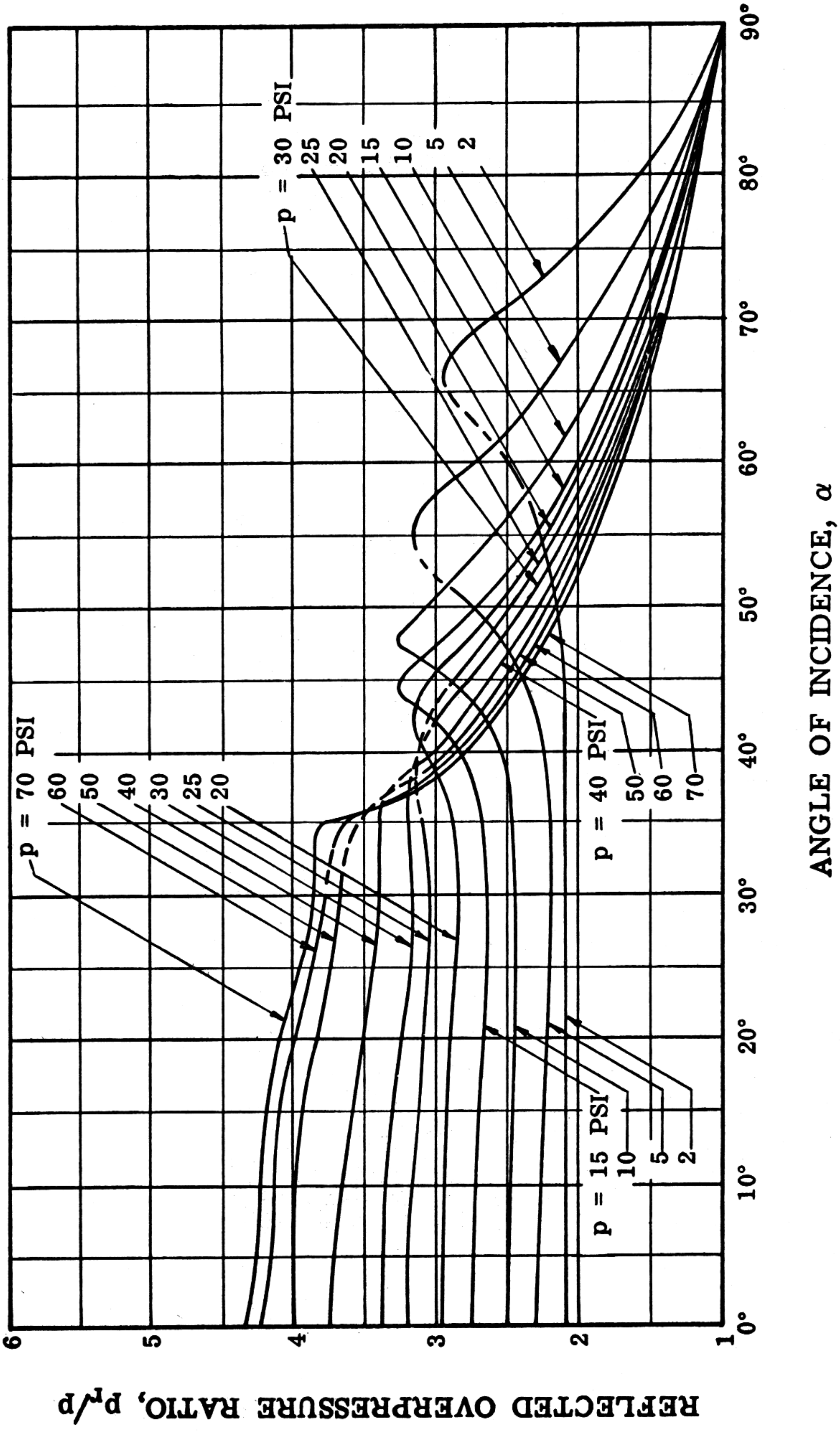


Figure 3.71b. Reflected overpressure ratio as function of angle of incidence for various side-on overpressures.

(Text continued from page 134.)

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

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

4.49 Several factors influence the degree of damage that may be expected for an aircraft of a given type at a specified range from a nuclear detonation. Aircraft that are parked with the nose pointed toward the burst will suffer less damage than those with the tail or either side directed toward the oncoming blast wave. Shielding of one aircraft by another or by structures or terrain features may reduce damage, especially that caused by flying debris. Standard tiedown of aircraft, as used when high winds are expected, will also minimize the extent of damage at ranges where destruction might otherwise occur.

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

TABLE 4.50

DAMAGE CRITERIA FOR PARKED AIRCRAFT

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

TABLE 4.53

DAMAGE CRITERIA FOR SHIPPING FROM AIR BLAST

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

DAMAGE TO FORESTS

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

TABLE 4.55

DAMAGE CRITERIA FOR FORESTS

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

4.56 The distances from ground zero within which severe damage would be experienced by an average forest stand, for a given yield, can be derived from Fig. 4.58b. The results apply, in particular, to unimproved coniferous forests which have developed under unfavorable growing conditions and to most deciduous forests in the temperate zone when foliation is present. Improved coniferous forests, with trees of uniform height and a smaller average tree density per acre, are more resistant to blast than are unimproved forests which have grown under unfavorable conditions. A forest of defoliated deciduous trees is also somewhat more blast resistant than is implied by the data in Fig. 4.58b.

Damage to Storage Tanks

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

Damage-Distance Relationships

4.58 By combining the information collected after the explosions in Japan and the data obtained at various nuclear tests with a theoretical analysis of loading and response, relationships have been developed between the yield of an explosion, the distance from ground zero, and the degree of damage, as already defined, that would be expected for a variety of objects and structures. The results are presented in the form of nomographs in Figs. 4.58 a and b. The data refer to air bursts with the height of burst chosen so that it maximizes the radius of

(Text continued on page 176.)

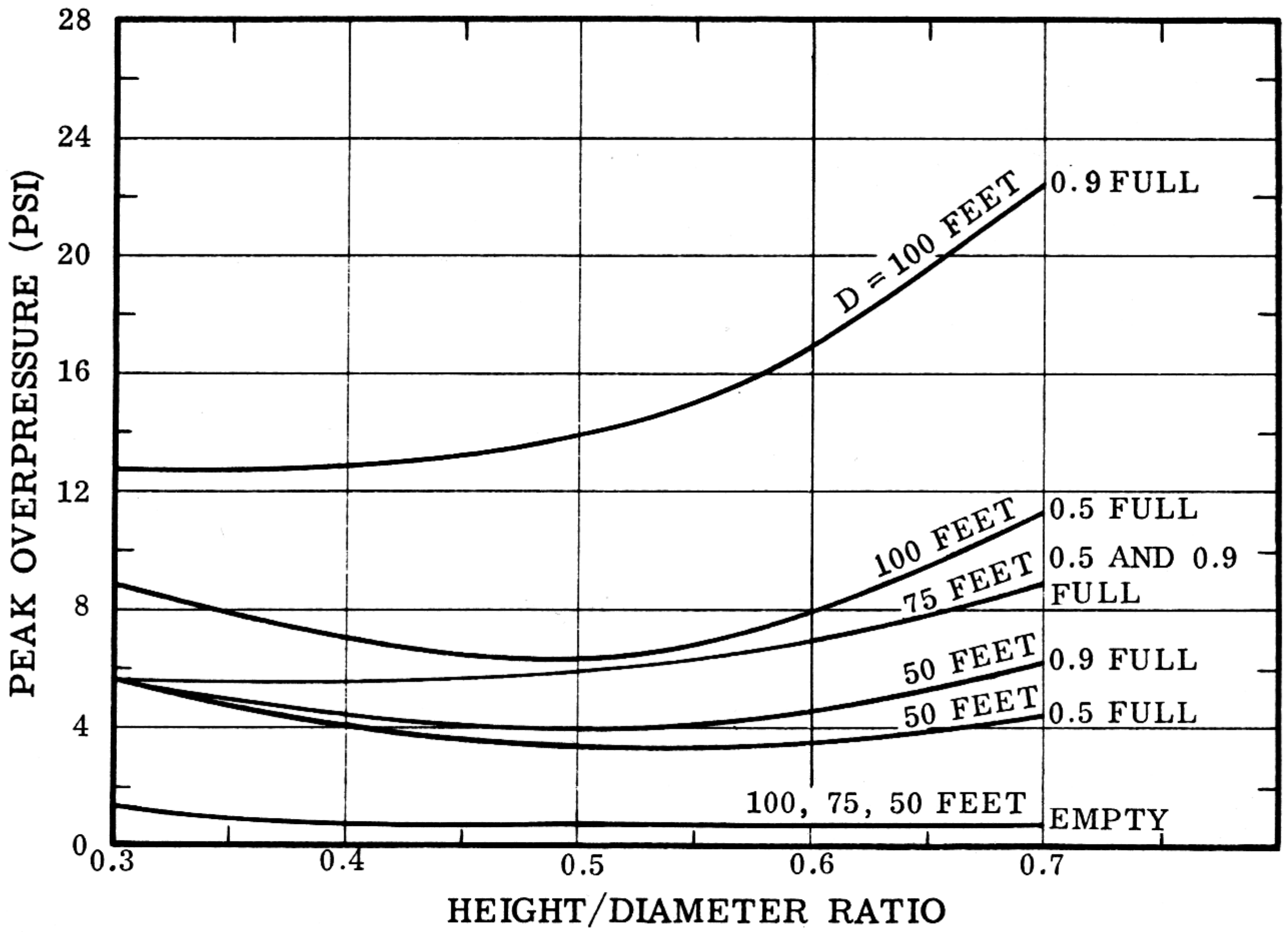

Figure 4.57a. Peak overpressures for severe blast damage to floating- or conical-roof tanks for explosions from 1 to 500 kilotons.

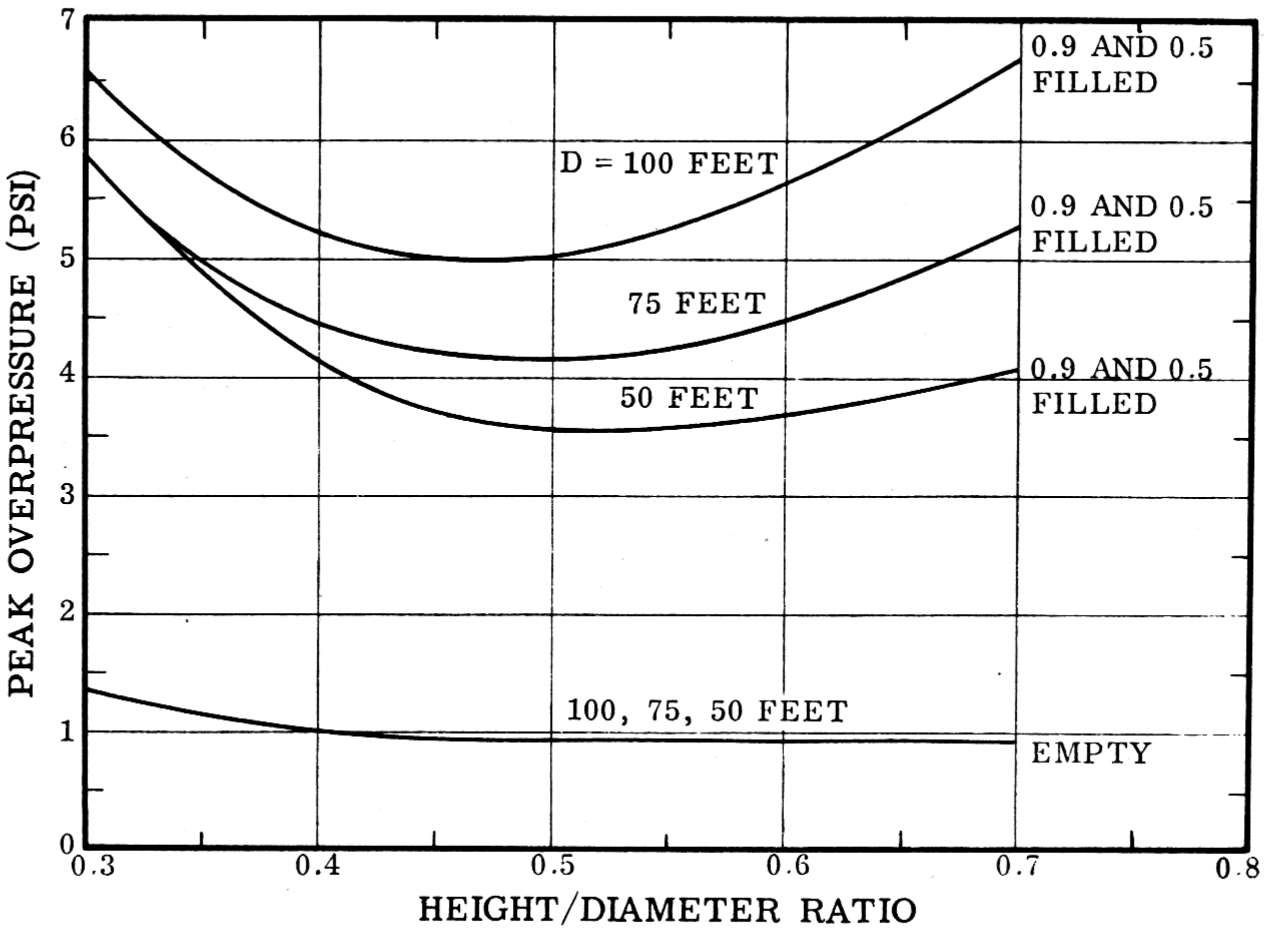

Figure 4.57b. Peak overpressures for severe blast damage to floating- or conical-roof tanks from explosions of 500 kilotons or more.

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

5.14 Some indication of the blast damage suffered by the dwelling nearer to the explosion can be obtained from Fig. 5.14. It is apparent that the house was ruined beyond repair. The first story was completely demolished and the second story, which was very badly damaged, dropped down on the first floor debris. The roof was blown off in several sections which landed at both front and back of the house. The gable end walls were blown apart and outward, and the brick chimney was broken into several pieces.

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

1953

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

5.16 The second house, exposed to an incident peak overpressure of 1.7 pounds per square inch, was badly damaged both internally and externally, but it remained standing (Fig. 5.16). Personnel in the main and upper floors would have suffered injuries ranging from minor cuts from glass fragments to possible fatal injuries from flying debris or as a result of translational displacement of the body as a whole. Some damage would also result to the furnishings and other contents of the house. Although complete restoration would have been very costly, it is believed that, with the window and door openings covered, and shoring in the basement, the house would have been habitable under emergency conditions.

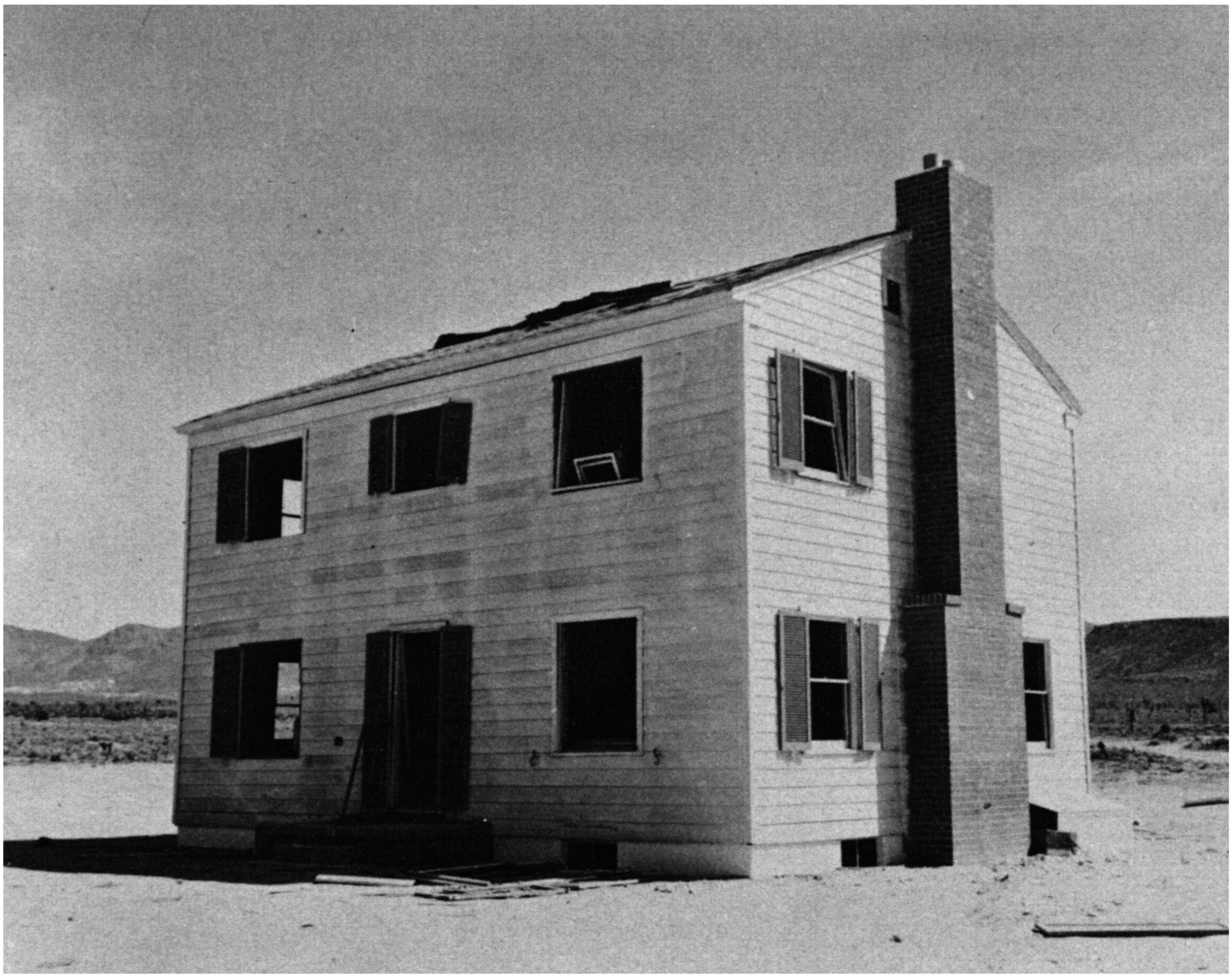

Figure 5.16. Wood-frame house after a nuclear explosion (1.7 psi overpressure).

1953

5.17 The most obvious damage was suffered by doors and windows, including sash and frames. The front door was broken into pieces and the kitchen and basement entrance doors were torn off their hinges. Damage to interior doors varied; those which were open before the explosion suffered least. Window glass throughout the house was broken into fragments, and the force on the sash, especially in the front of the house, dislodged the frames.

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

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

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

Two-Story, Wood-Frame House: 1955 Test

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

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

1955

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

5.22 Even with these improvements, it was expected that almost complete destruction would occur at 5 pounds per square inch peak overpressure, and so one of the houses was located where the overpressure at the Mach front would be 4 pounds per square inch. Partly because of the increased strength and partly because of the lower air blast pressure the house did not collapse (Fig. 5.22). However, the superstructure was so badly damaged that it could not have been occupied without expensive repair which would not have been economically advisable.

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

5.24 The first-floor joists were split or broken and the floor was near collapse; it was held up principally by the sub- and finish-flooring which was largely intact (Fig. 5.24). The second floor and the ceiling of the first floor showed little damage, indicating rapid pressure equalization above and below the floor. This was made possible by the fact that practically all doors and windows were blown out. The upper portion of the chimney fell outward and although the lower part remained standing, it was dislocated in places.

5.25 The other strengthened two-story frame house was in a location where the incident peak overpressure was about 2.6 pounds per square inch; this was appreciably greater than the lower overpressure of the 1953 test. Relatively heavy damage was experienced, but the condition of the house was such that it could be made available for emergency shelter by shoring and not too expensive repairs (Fig. 5.25). Although there were differences in detail, the overall damage was much the same degree as that suffered by the corresponding house without the improved features at an overpressure of 1.7 pounds per square inch.

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

Figure 5.24. First floor joists of strengthened wood-frame house after a nuclear explosion (4 psi overpressure).

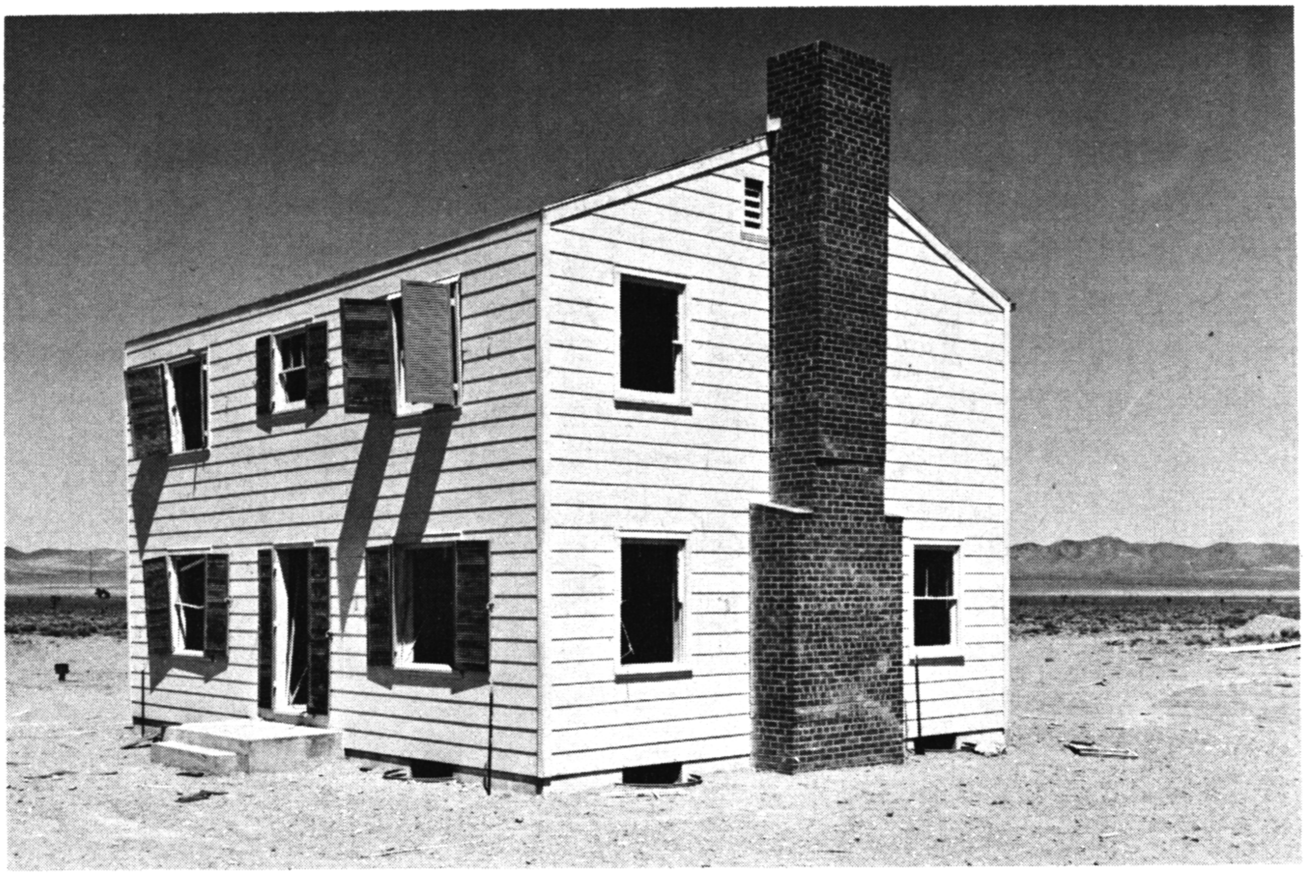

Figure 5.25. Strengthened wood-frame house after a nuclear explosion (2.6 psi overpressure).

1955

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

5.27 The ceilings and walls of the first floor were only slightly affected. The floor joists were cracked and fractured, but no debris was deposited in the basement, as the subflooring remained intact (Fig. 5.27).

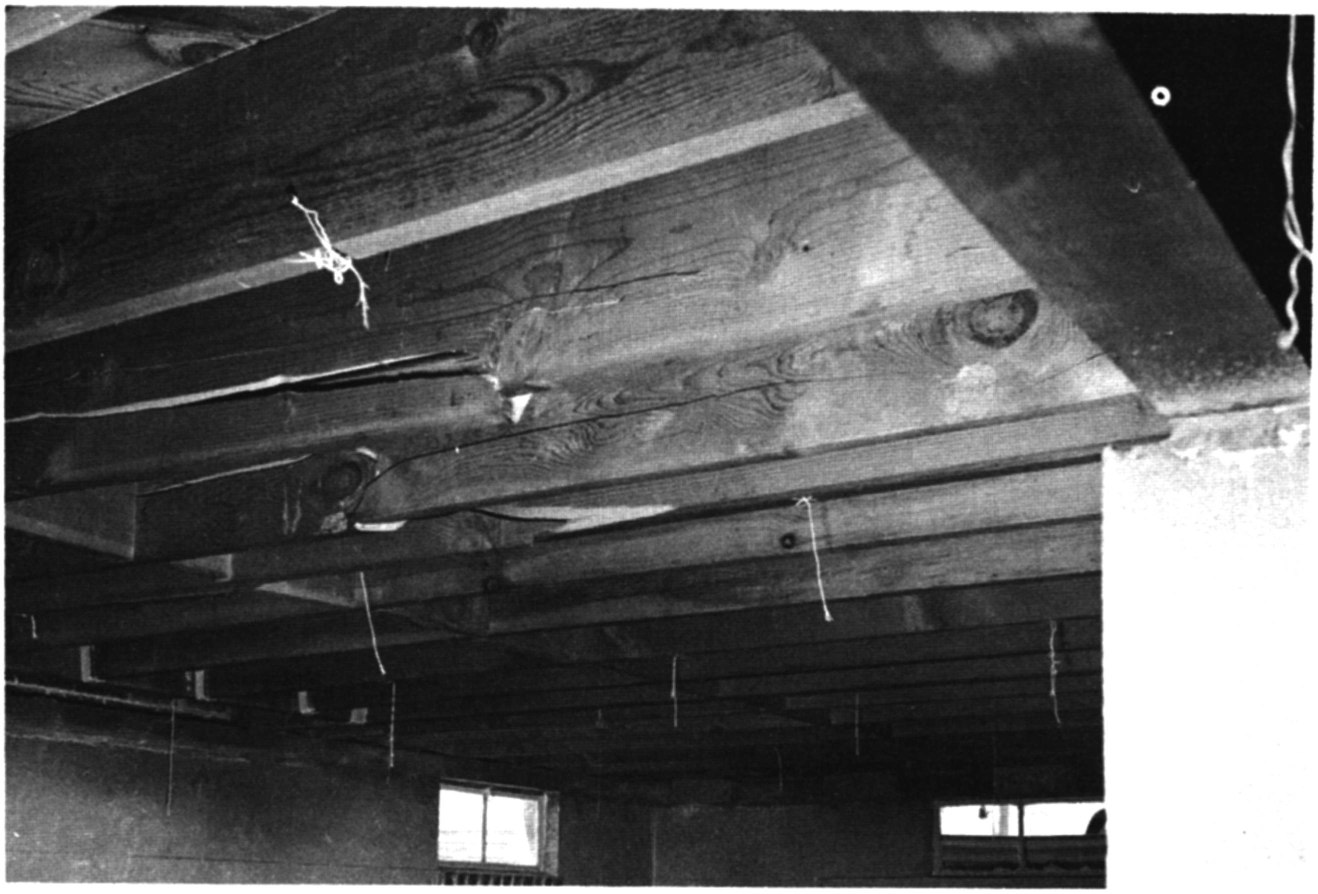

Figure 5.27. First floor joists of strengthened wood-frame house after a nuclear explosion (2.6 psi overpressure).

5.28 The wood window-sashes on the front and sides of the house were blown in and smashed, although at the back they suffered less. Exterior doors were blasted in, and some of the interior doors were blown off their hinges. The brick chimney was sheared in at least two places, but it remained standing.

Two-Story, Brick-Wall-Bearing House

5.29 For comparison with the tests on the two-story wood frame structures, made in 1953, two brick-wall-bearing houses of conventional construction, similar in size and layout, were exposed to 5 and 1.7 pounds per square inch overpressure, respectively, in the 1955 tests (Fig. 5.29). The exterior walls were of brick veneer and cinder block and the foundation walls of cinder block; the floors, partitions, and roof were wood-framed. BRICK VENEER ⇒ NOT U.K. STANDARD (SOLID BRICK)

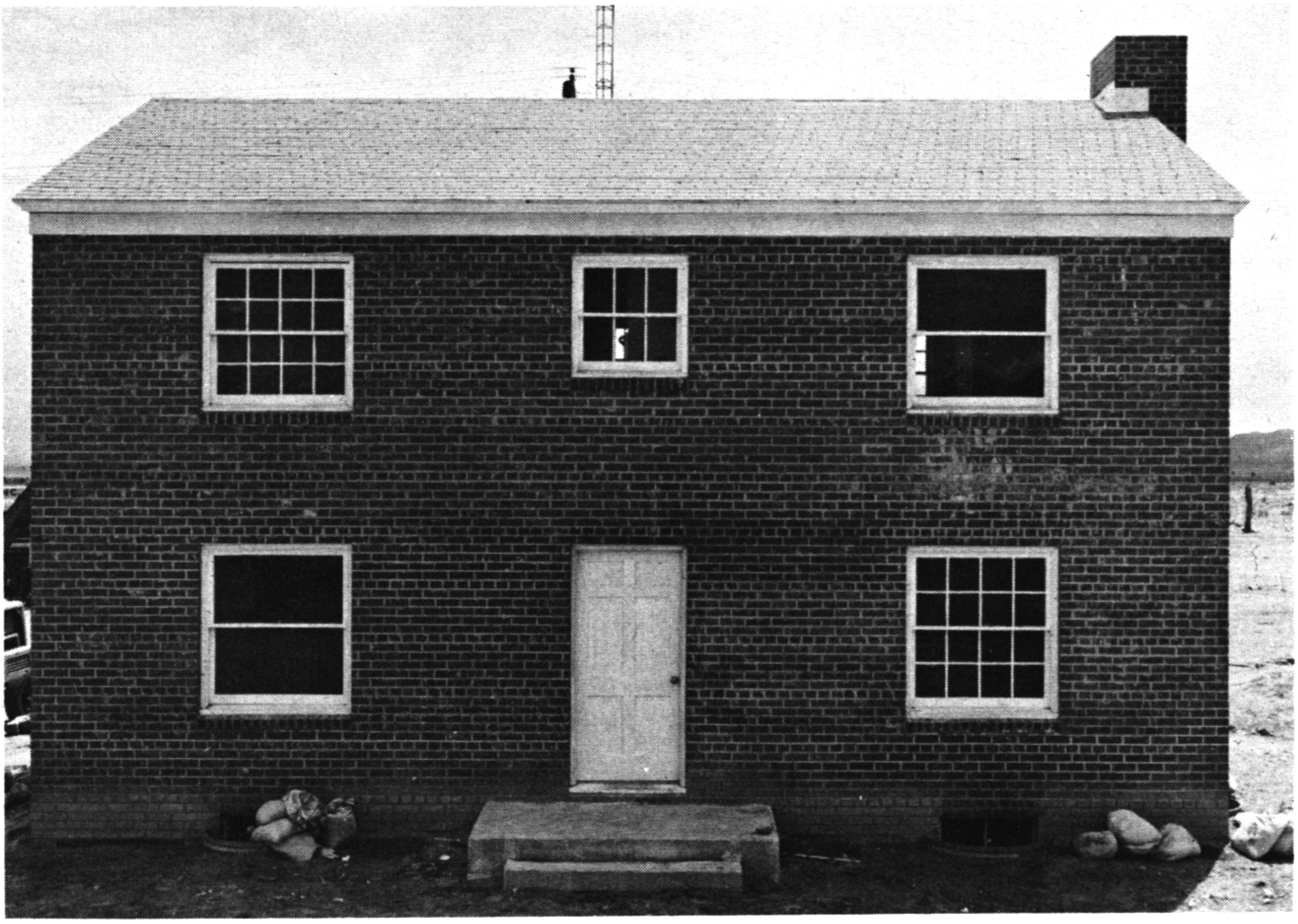

Figure 5.29. Unreinforced brick house before a nuclear explosion, Nevada Test Site.

5.30 At an incident overpressure of 5 pounds per square inch, the brick-wall house was damaged beyond repair (Fig. 5.30). The exterior walls were exploded outward, so that very little masonry debris fell on the floor framing. The roof was demolished and blown off, the rear part landing 50 feet behind the house. The first floor had partially collapsed into the basement as a result of fracturing of the floor joists at the center of the spans and the load of the second floor which fell upon it. The chimney was broken into several large sections.

Figure 5.30. Unreinforced brick house after a nuclear explosion (5 psi over pressure).

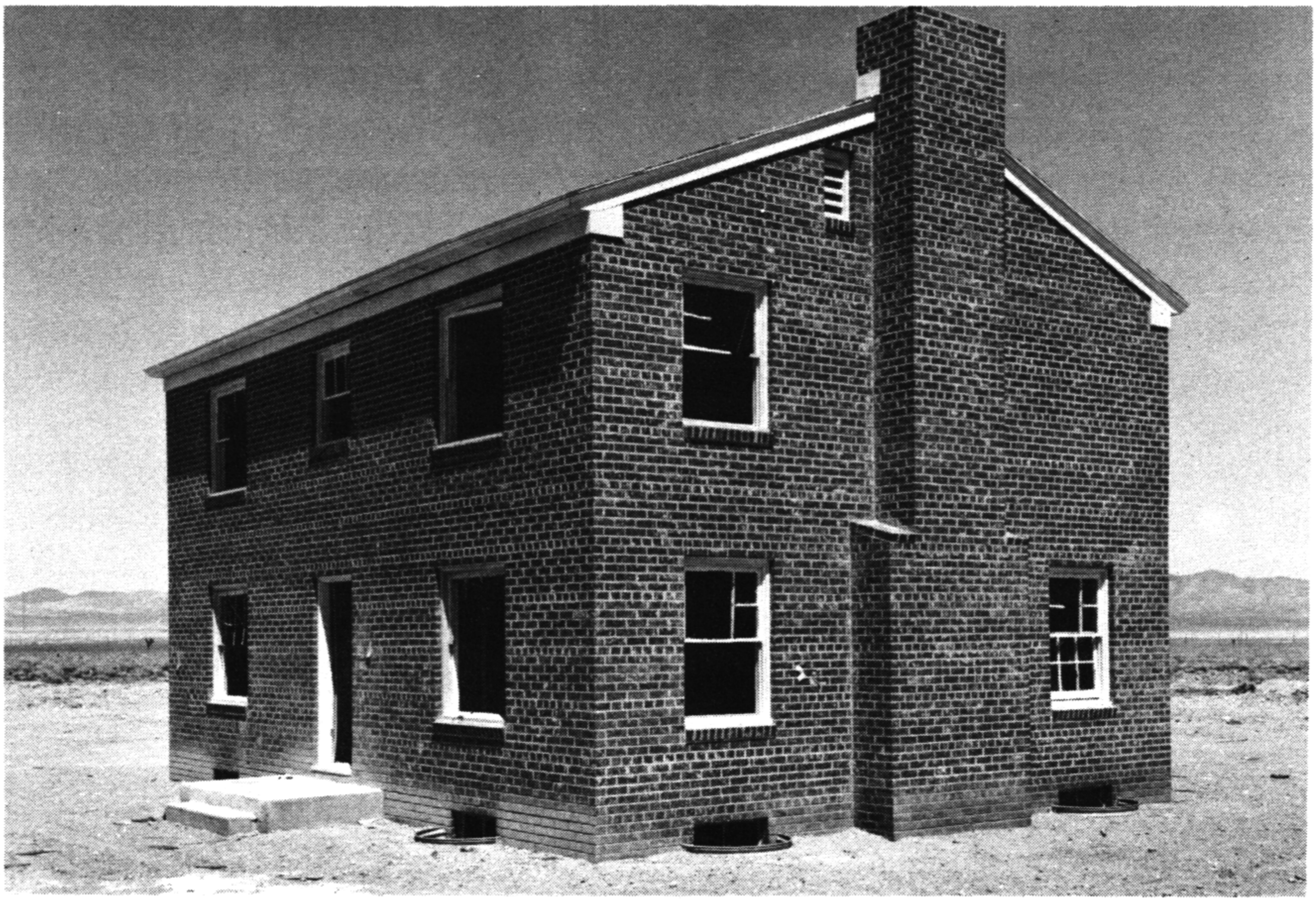

Figure 5.31. Unreinforced brick house after a nuclear explosion (1.7 psi overpressure).

5.31 Farther from the explosion, where the overpressure was 1.7 pounds per square inch, the corresponding structure was damaged to a considerable extent. Nevertheless, its condition was such that it could be made available for habitation by shoring and some fairly inexpensive repairs (Fig. 5.31).

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

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

One-Story, Wood-Frame (Rambler Type) House

5.34 A pair of the so-called "rambler" type, single-story, wood-frame houses were erected on concrete slabs poured in place, at grade. They were of conventional design except that each contained a shelter, above ground, consisting of the bathroom walls, floor, and ceiling of reinforced concrete with blast-door and shutter (Fig. 5.34).

5.35 When exposed to an incident overpressure of about 5 pounds per square inch, one of these houses was demolished beyond repair. However, the bathroom shelter was not damaged at all. Although the latch bolt on the blast shutter failed, leaving the shutter unfastened, the window was found to be still intact. The roof was blown off and the rafters were split and broken. The side walls at gable ends were blown outward, and fell to the ground. A portion of the front wall remained standing, although it was leaning away from the direction of the explosion (Fig. 5.35).

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

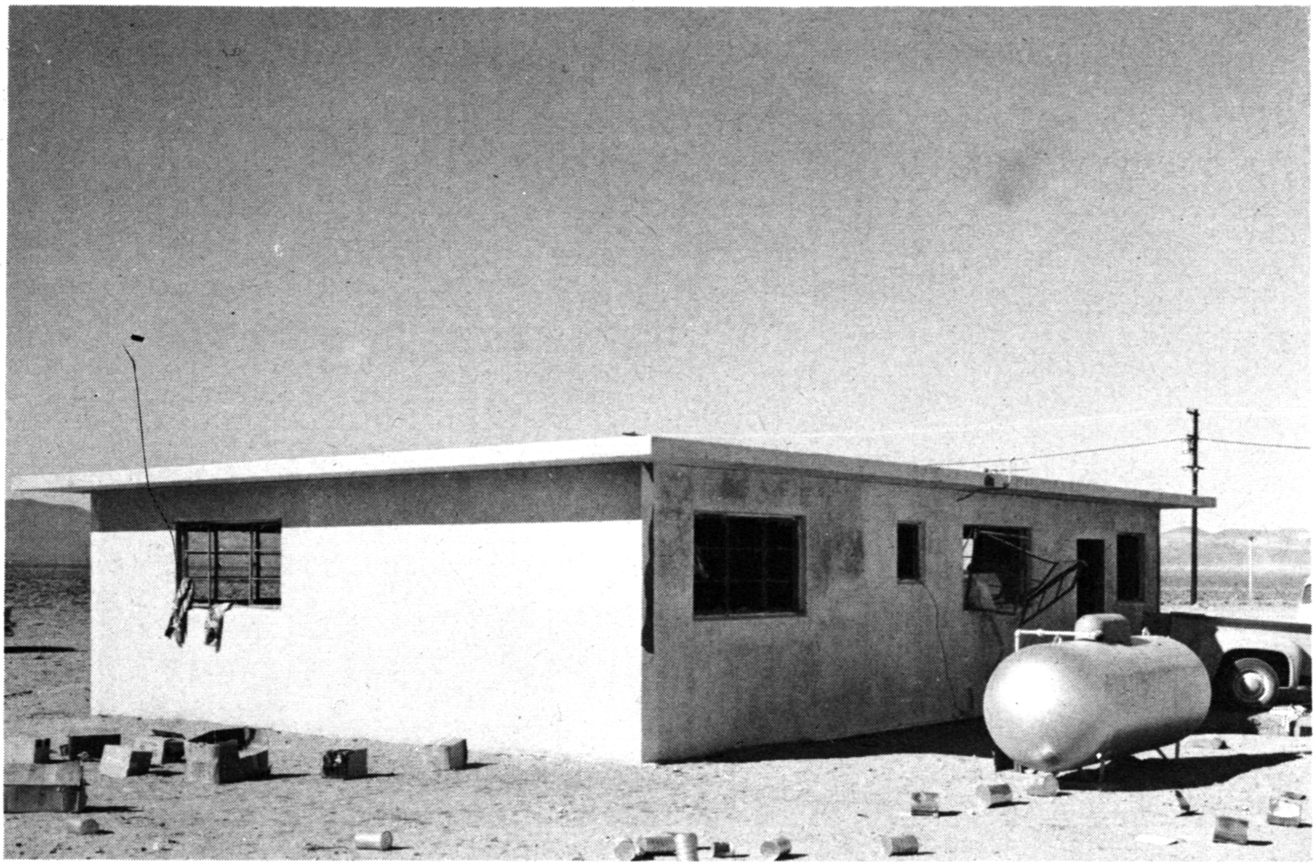

Figure 5.38. Reinforced precast concrete house after a nuclear explosion (5 psi overpressure). The LP-gas tank, sheltered by the house, is essentially undamaged. 1955

slightly and others showed indications of minor movement. In certain areas the concrete around the slab connections was spalled, so that the connectors were exposed. The steel window-sashes were somewhat distorted, but they remained in place.

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

One-Story, Reinforced-Masonry House

5.41 The last type of house subjected to test in 1955 was also of earthquake-resistant design. The floor was a concrete slab, poured in place at grade. The walls and partitions were built of lightweight (expanded shale aggregate) 8-inch masonry blocks, reinforced with vertical steel rods anchored into the floor slab. The walls were also reinforced with horizontal steel rods at two levels, and openings were spanned by reinforced lintel courses. The roof was made of precast, lightweight concrete slabs, similar to those used in the precast concrete houses described above (Fig. 5.41).

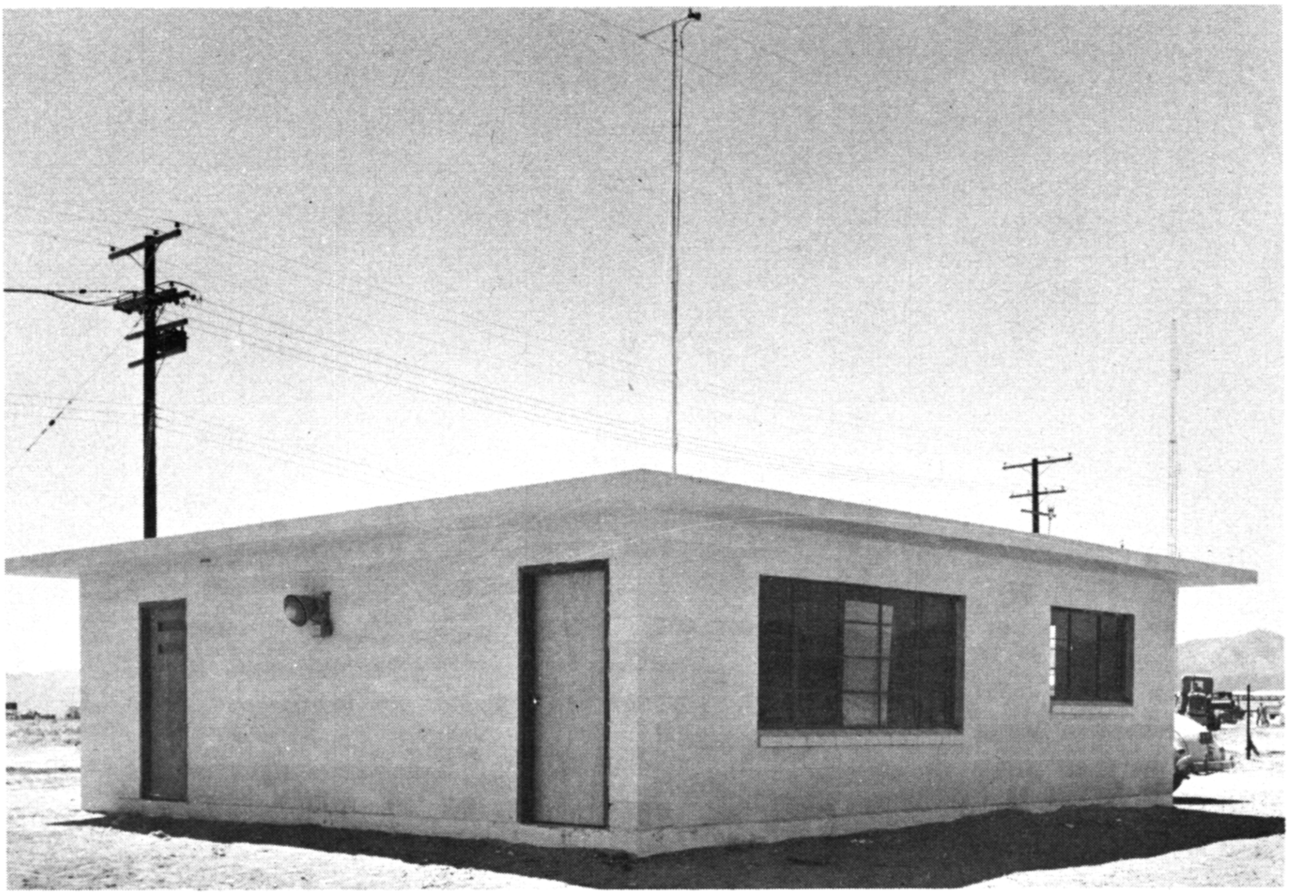

Figure 5.41. Reinforced masonry-block house before a nuclear explosion, Nevada Test Site.

5.42 At a peak overpressure of about 5 pounds per square inch, windows were destroyed and doors blown in and demolished. The steel window-frames were distorted, although nearly all remained in place. The house suffered only minor structural damage and could have been made habitable at relatively small cost (Fig. 5.42).

5.43 There was some evidence that the roof slabs had been moved, but not sufficiently to break any connections. The masonry wall under the large window (see Fig. 5.42) was pushed in about 4 inches on the concrete floor slab; this appeared to be due to the omission of dowels between the walls and the floor beneath window openings. Some cracks developed in the wall above the same window, probably as a result of improper installation of the reinforced lintel course and the substitution of a pipe column in the center span of the window.

5.44 A house of the same type exposed to the blast at a peak overpressure of 1.7 pounds per square inch suffered little more than the usual destruction of doors and windows. The steel window-sash remained in place but was distorted, and some spalling of the concrete around lug connections was noted. On the whole, the damage to the house was of a minor character and it could readily have been repaired.

Trailer-Coach Mobile Homes

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

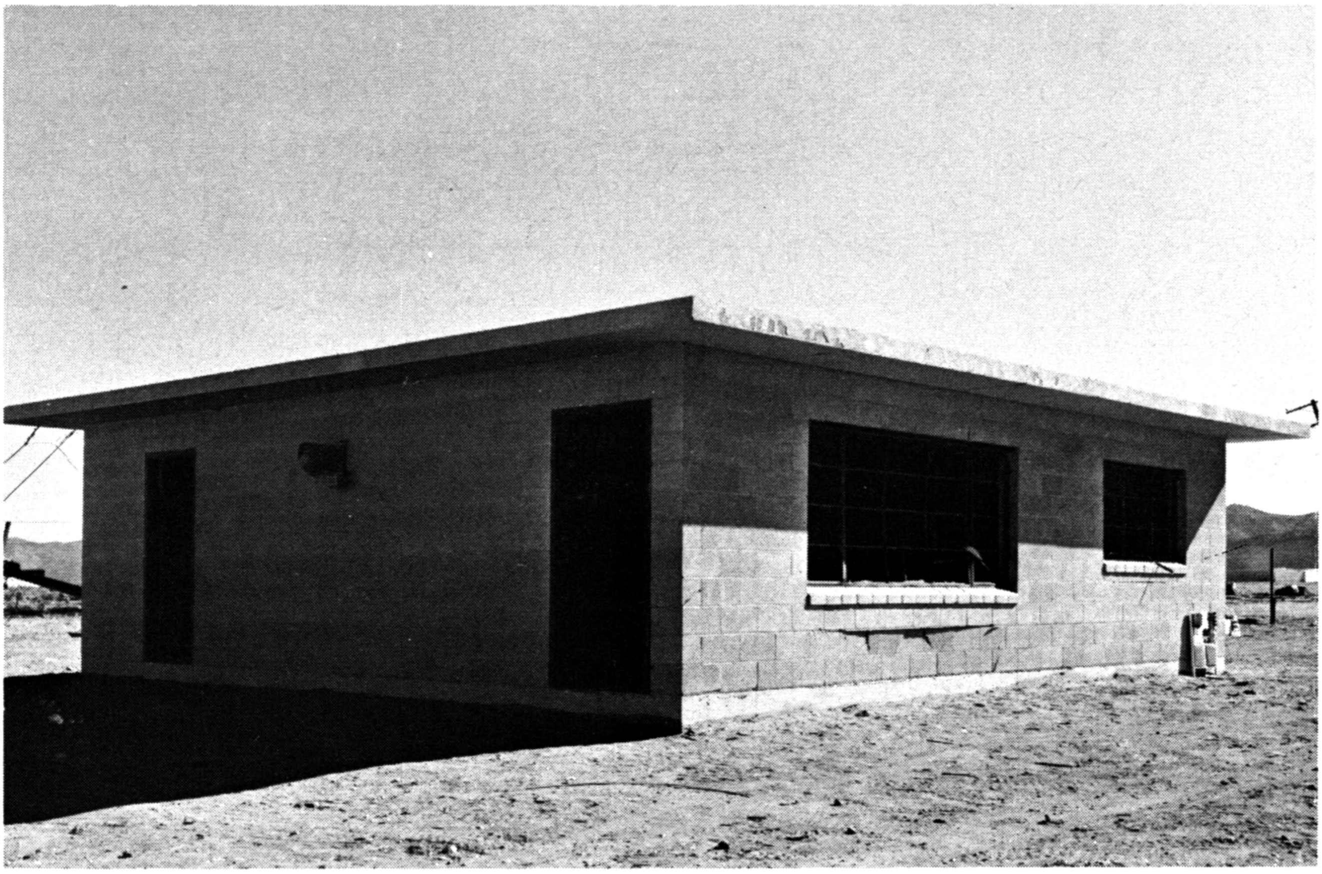

Figure 5.42. Reinforced masonry-block house after a nuclear explosion (5 psi overpressure). 1955

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

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

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

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

Food Products

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

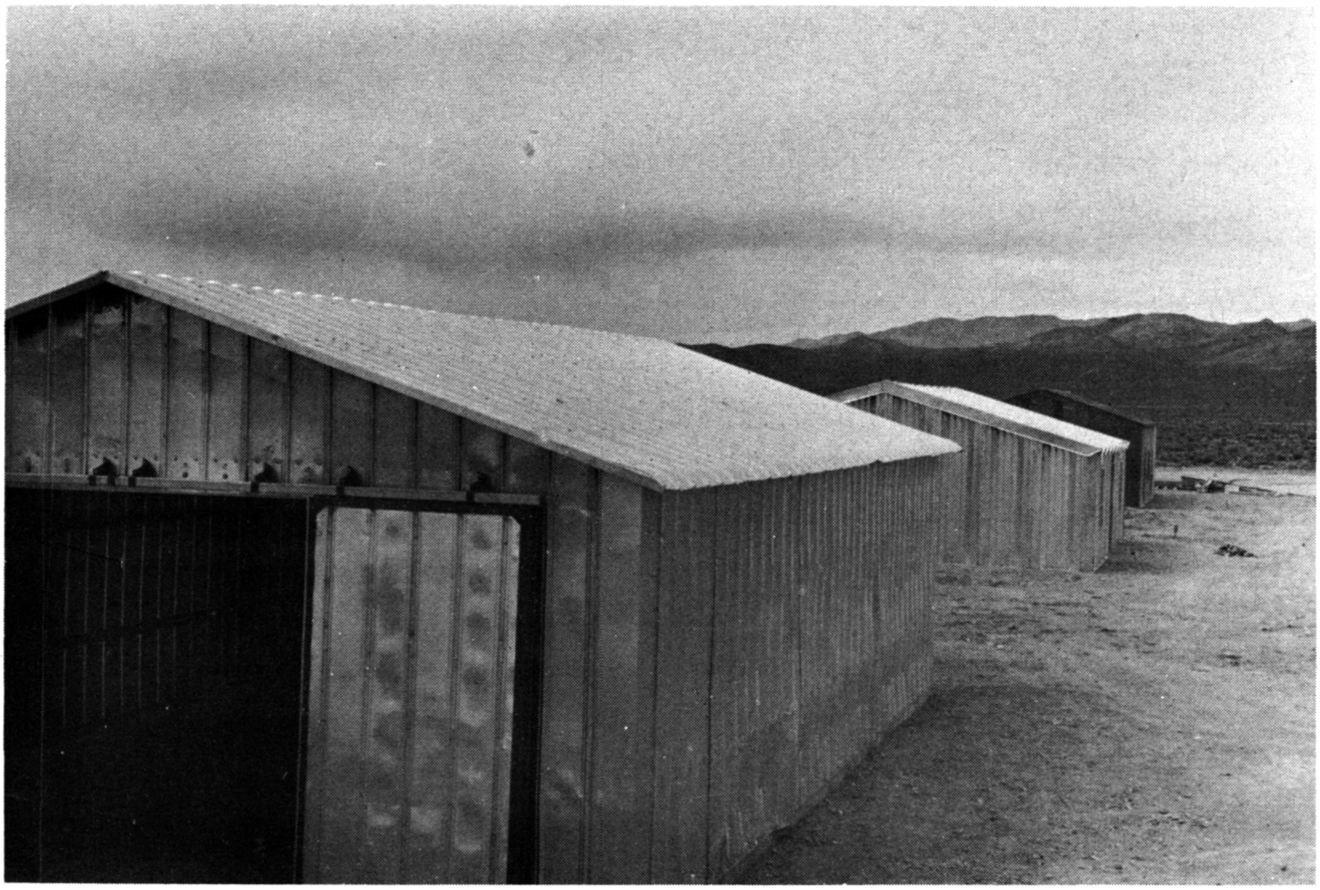

Figure 5.62a. Rigid steel-frame building before a nuclear explosion, Nevada Test Site.

Figure 5.62b. Rigid steel-frame building after a nuclear explosion (3.1 psi overpressure). 1955

exceeding 1 pound per square inch. Increased blast resistance would probably result from improvement in the design of girts and purlins, in particular. Better fastening between sill and wall footing and increased resistance to transverse loading would also be beneficial.

Self-Framing With Steel Panels

5.66 A frameless structure with self-supporting walls and roof of light, channel-shaped, interlocking, steel panels (16 inches wide) represented the second standard type of industrial building (Fig. 5.66a). The one subjected to 3.0 pounds per square inch overpressure (and a dynamic pressure of 0.2 pound per square inch) was completely demolished (Fig. 5.66b). One or two segments of wall were blown as far as 50 feet away, but, in general, the bent and twisted segments of the building remained approximately in their original locations. Most of the wall sections were still attached to their foundation bolts on the side and rear walls of the building. The roof had collapsed completely and was resting on the machinery in the interior.

5.67 Although damage at 1.3 pounds per square inch peak overpressure was much less, it was still considerable in parts. The front wall panels were buckled inward from 1 to 2 feet at the center, but the rear wall and rear slope of the roof were undamaged. In general, the roof structure remained intact, except for some deflection near the center.

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

Self-Framing With Corrugated Steel Panels

5.69 The third type of industrial building was a completely frameless structure made of strong, deeply-corrugated, 43-inch wide panels of 16-gage steel sheet. The panels were held together with large bolt fasteners at the sides, and at the eaves and roof ridge. The wall panels were bolted to the concrete foundation. The entire structure was self-supporting, without frames, girts, or purlins (Fig. 5.69).

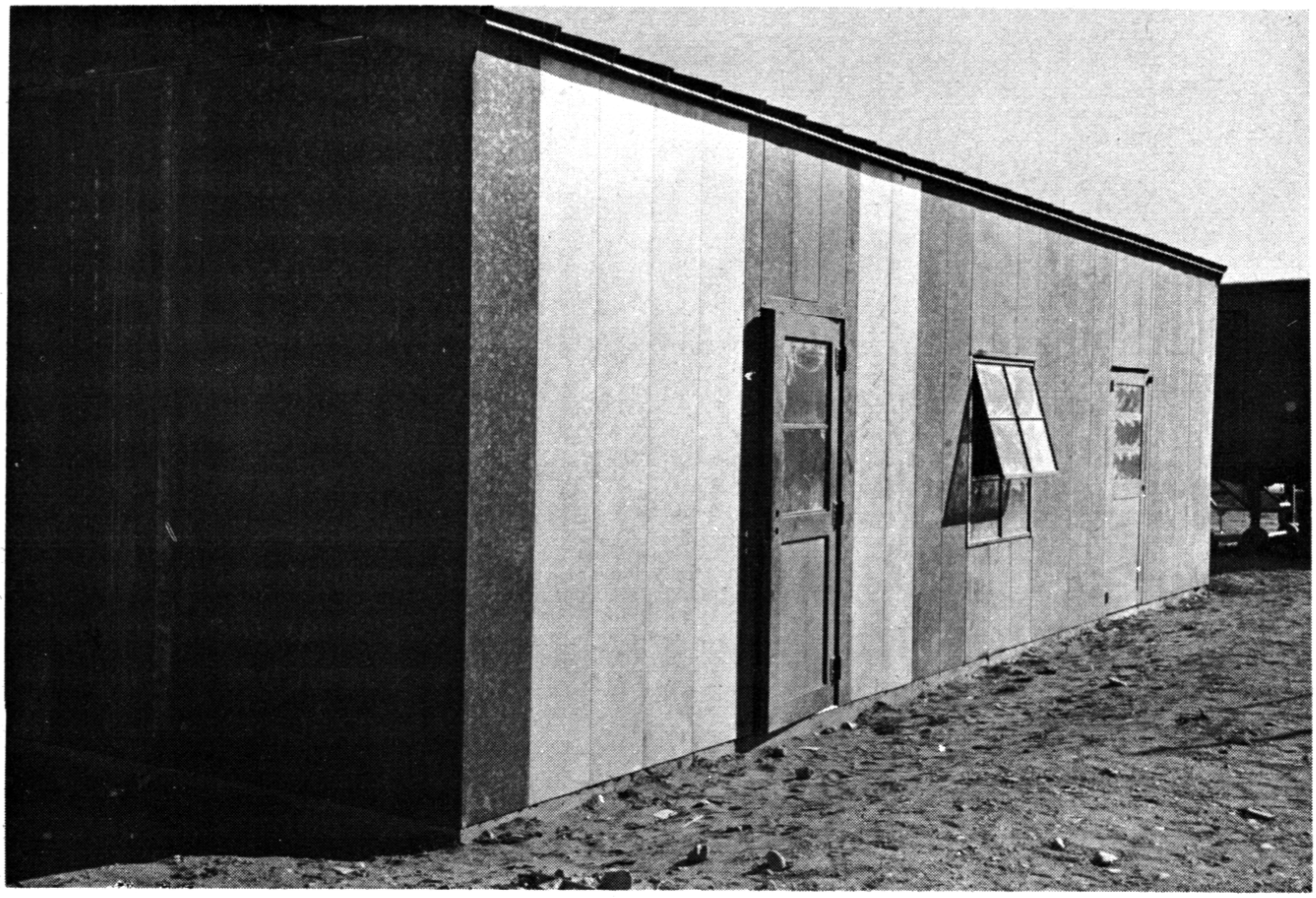

Figure 5.66a. Exterior of self-framing steel panel building before a nuclear explosion, Nevada Test Site.

Figure 5.66b. Self-framing steel panel building after a nuclear explosion (3.1 psi overpressure). 1955

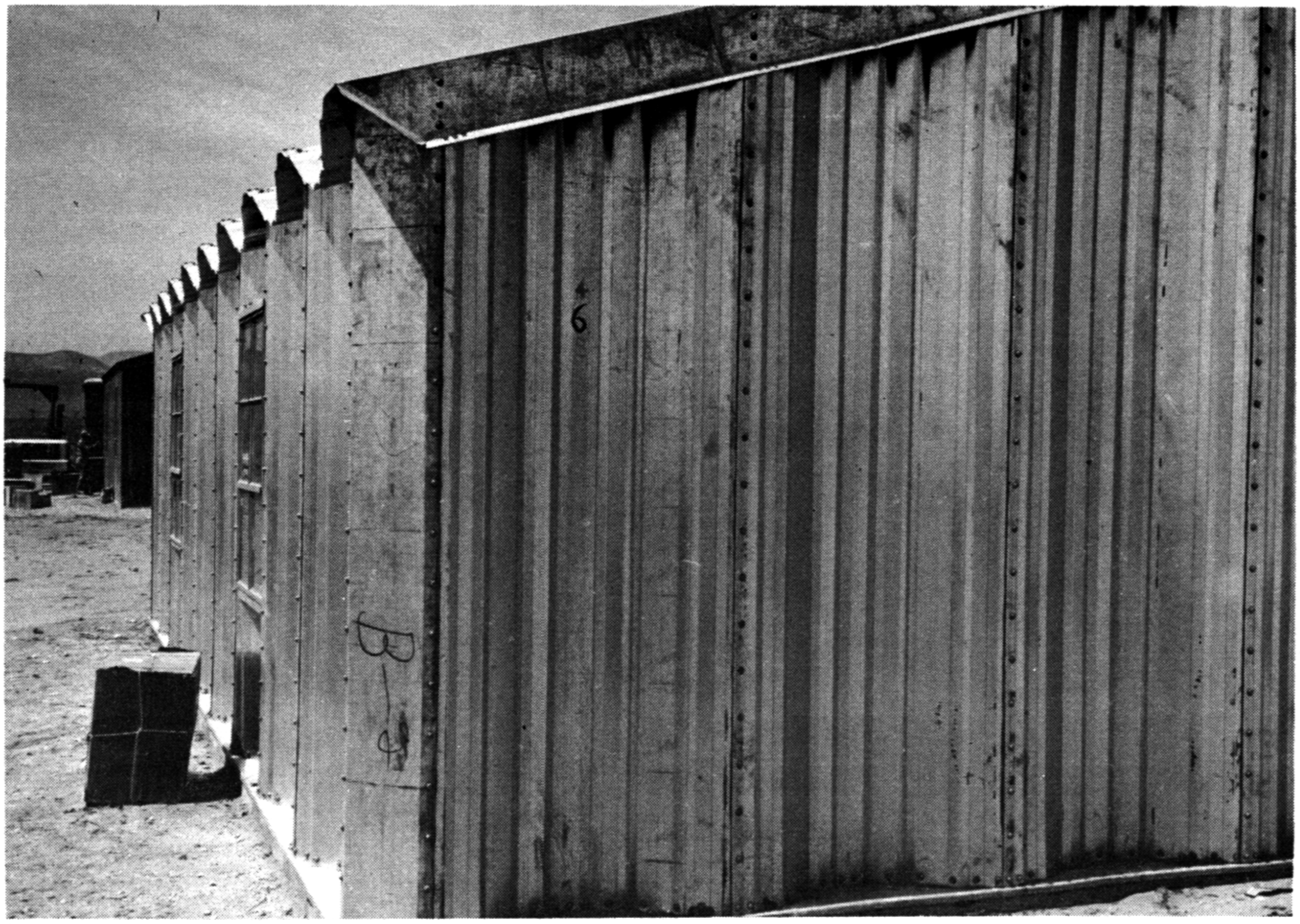

Figure 5.69. Self-framing corrugated steel panel building before a nuclear explosion, Nevada Test Site.

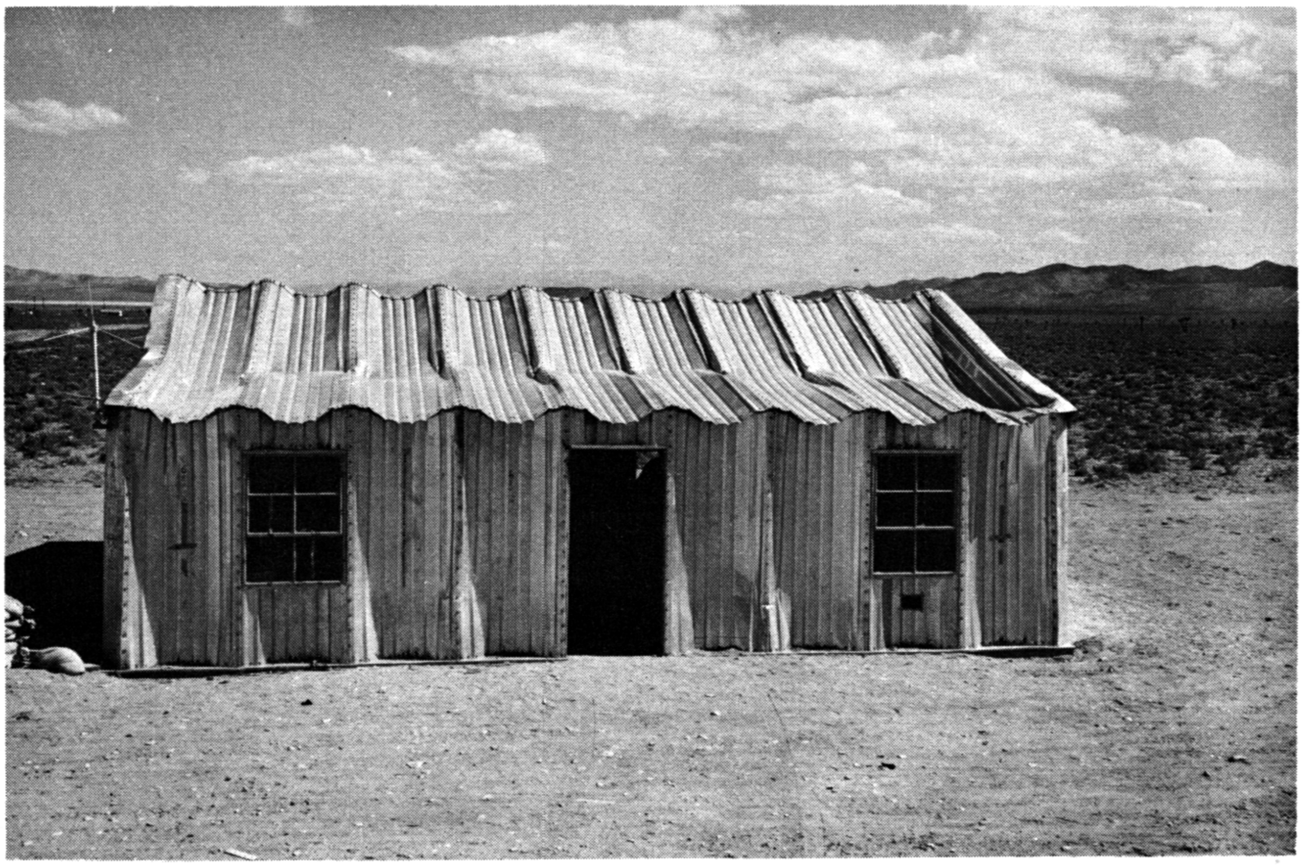

Figure 5.70. Self-framing corrugated steel panel building after a nuclear explosion (3.1 psi overpressure). 1955

5.70 At a peak overpressure of 3.0 and a dynamic pressure of 0.2 pounds per square inch a structure of this type was badly damaged, but all the pieces remained bolted together, so that the structure still provided good protection for its contents from the elements. The front slope of the roof was crushed downward, from 1 to 2 feet, at midsection, and the ridge line suffered moderate deflection. The rear slope of the roof appeared to be essentially undamaged (Fig. 5.70).

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

5.72 Another building of this type, exposed to 1.3 pounds per square inch overpressure, experienced little structural damage. The roof along the ridge line showed indications of downward deflections of only 1 or 2 inches, and there was no apparent buckling of roof or wall panels. Most of the windows were broken, cracked, or chipped. Replacement of the glass when necessary and some minor repairs would have rendered the building completely serviceable.

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

Positive Phase Duration Tests

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

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

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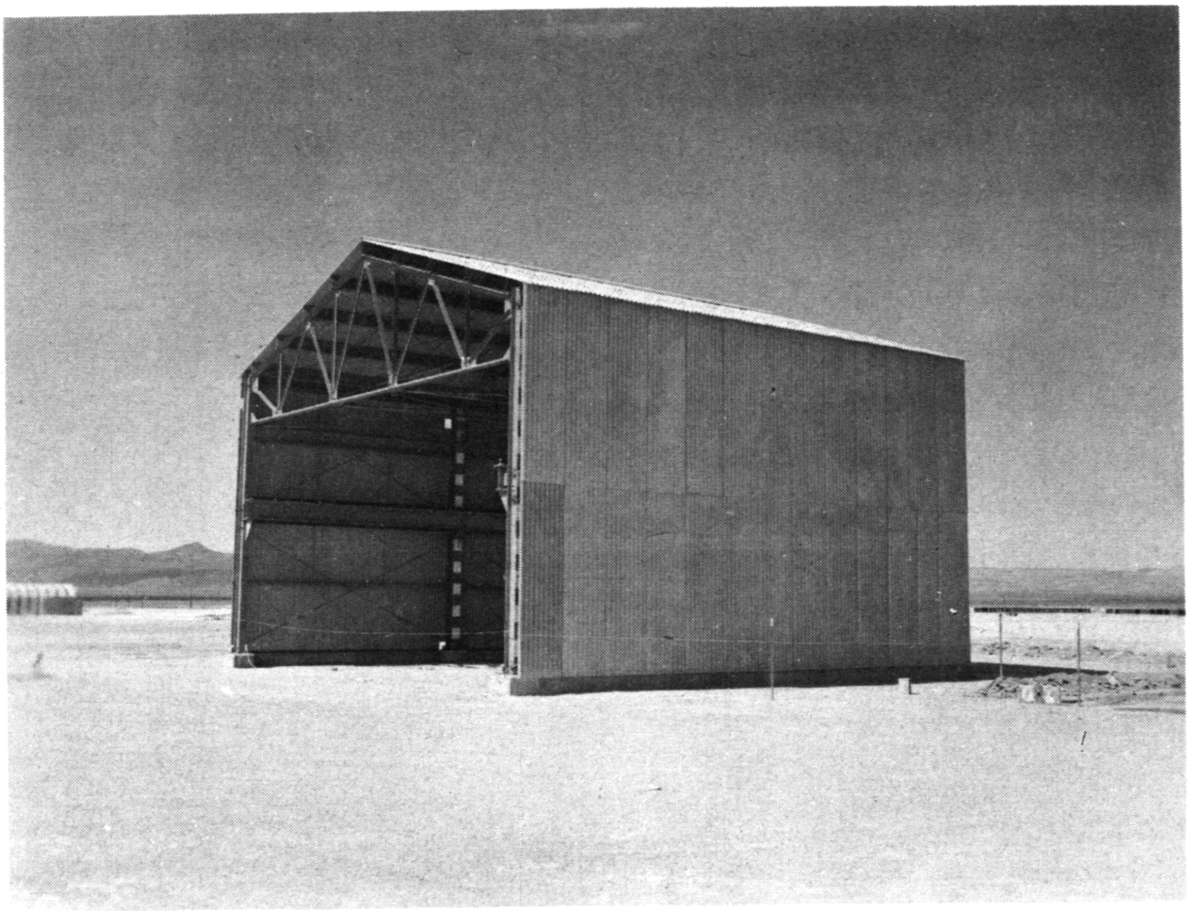


Figure 5.74a. Steel-frame building with siding and roof of frangible material.

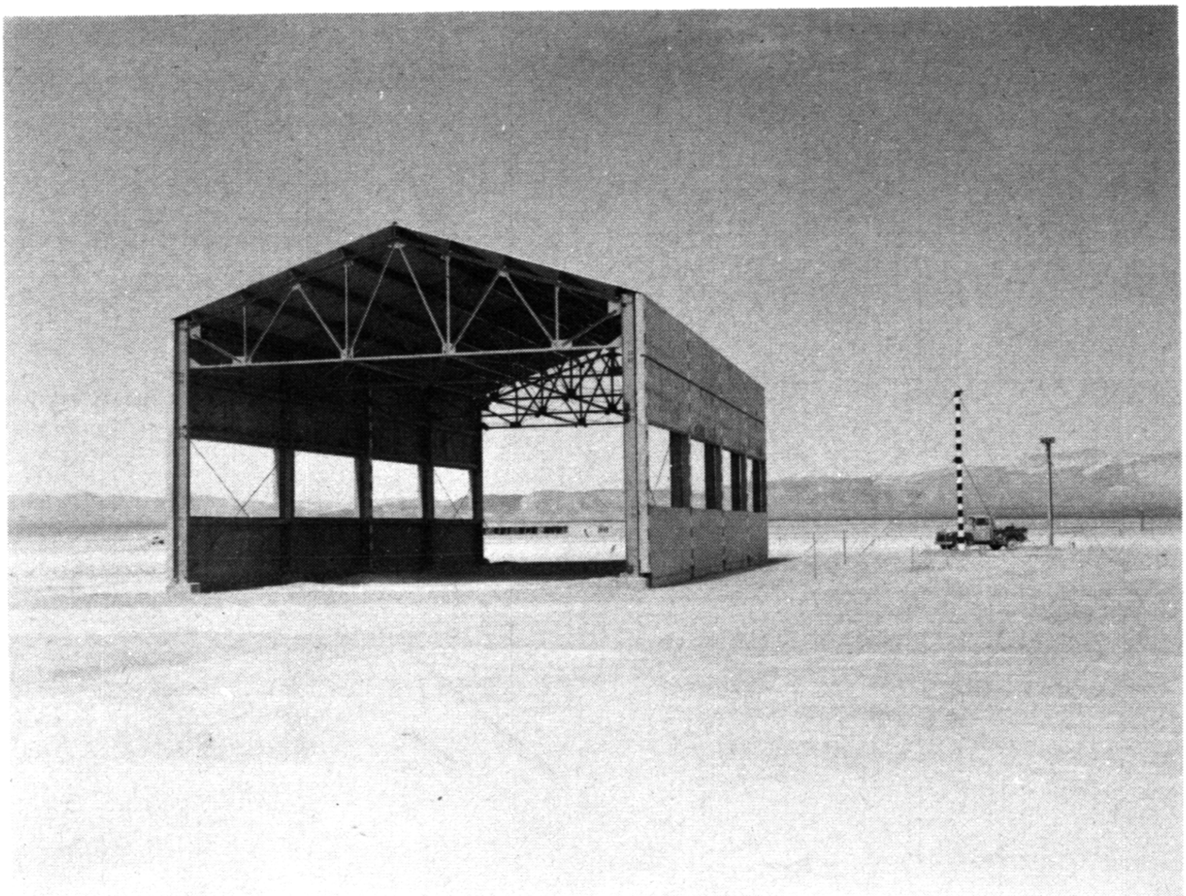
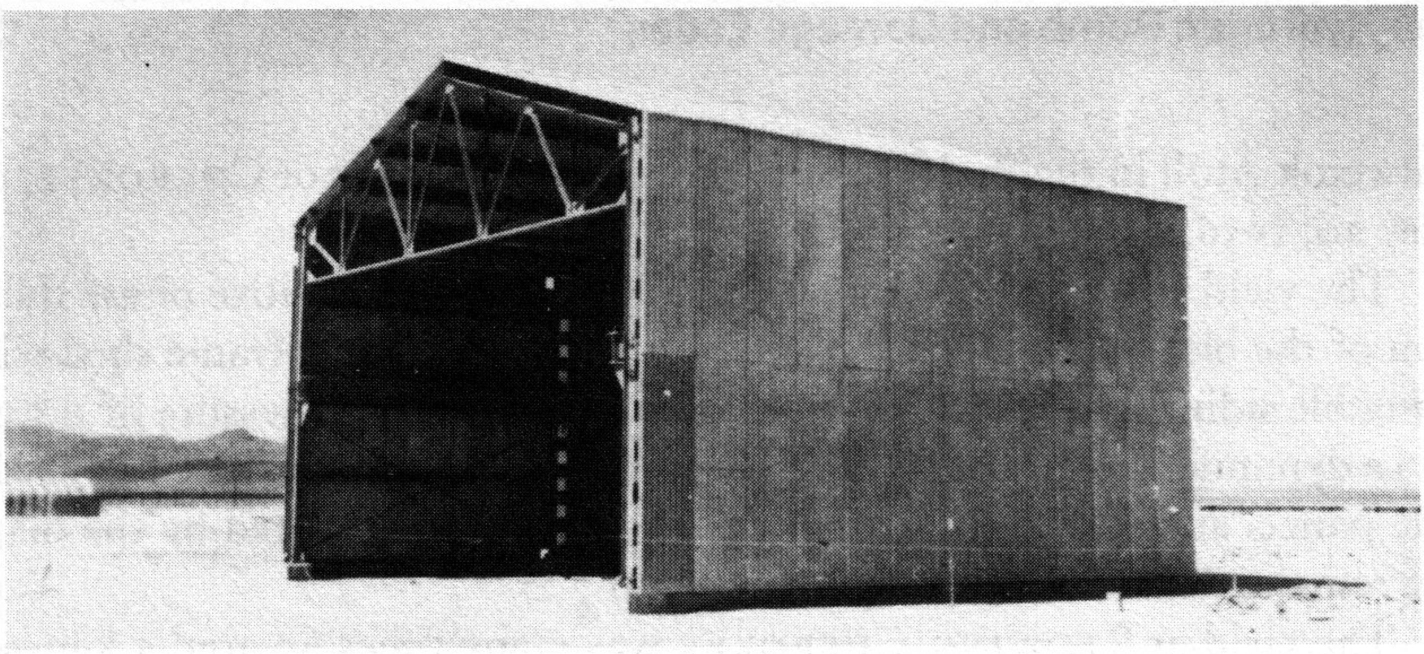
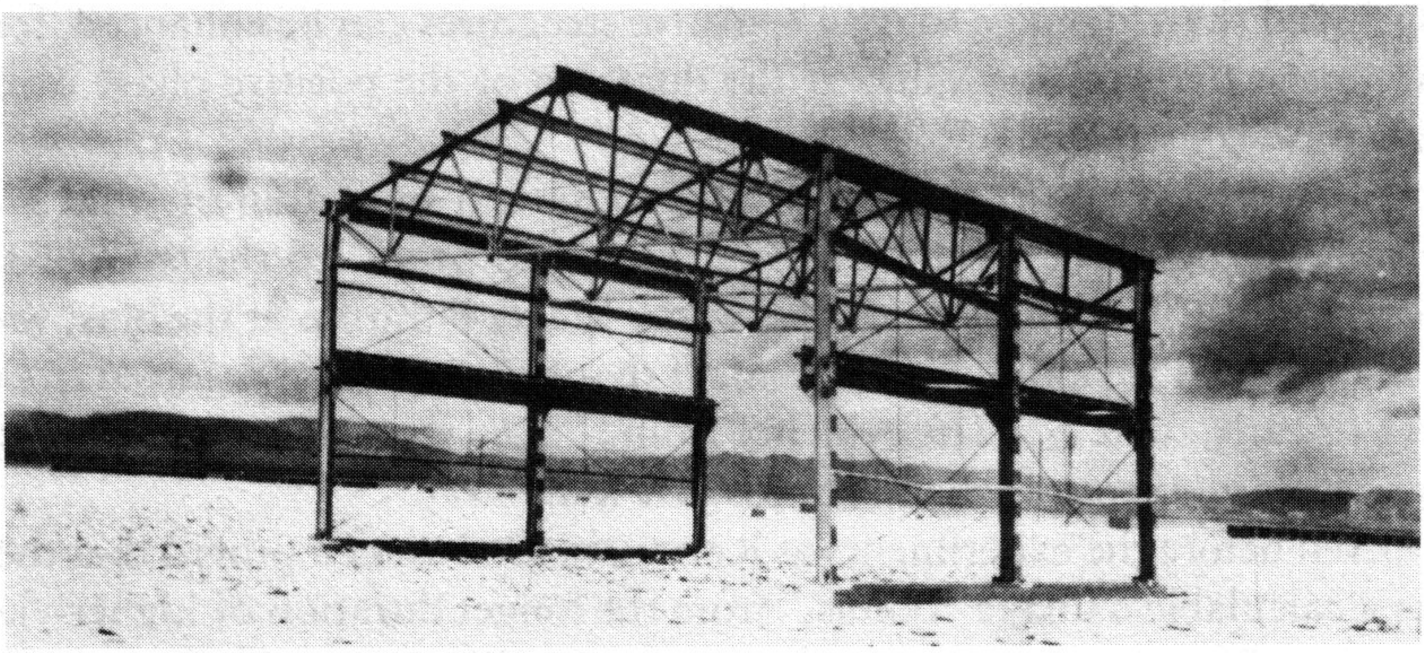


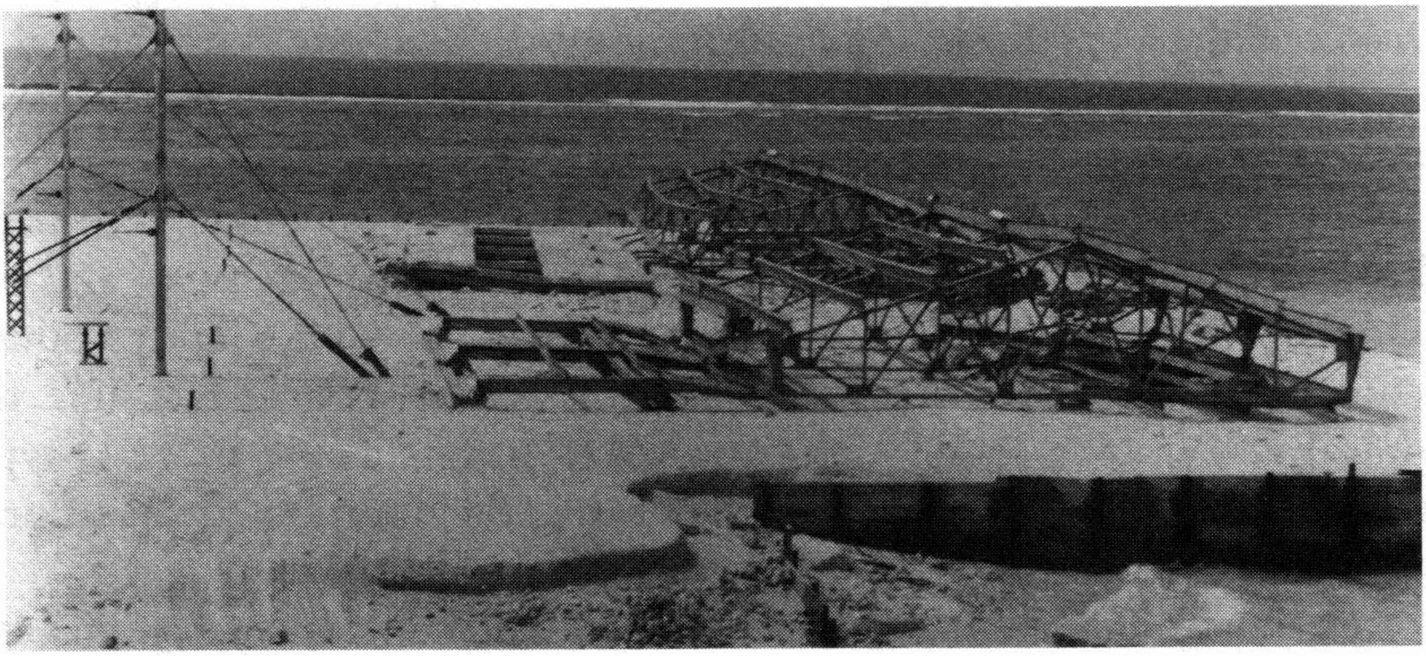
Figure 5.74b. Steel-frame building with concrete siding and window openings of 30 percent of the wall area.



Steel-frame shed before nuclear weapons tests at TEAPOT and REDWING.



Steel-frame shed after TEAPOT MET, 6.5 psi peak overpressure.



Steel-frame shed after REDWING CHEROKEE, 6.1 psi peak overpressure.

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

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

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

Oil Storage Tanks

5.78 Large oil storage tanks (around 50,000 barrels capacity) were not in the damage areas of the Japanese cities and have not been tested in Nevada. However, in the Texas City explosion of April 1947, several tank farms were seriously damaged by blast, missiles, and fire. Oil storage tanks, particularly empty ones, received severe blast damage out to the overpressure region estimated to be 3 to 4 pounds per square inch, on the basis that the blast wave from the explosion was comparable to that of a 2- to 4-kiloton nuclear weapon. The serious fire hazard represented by the fuel stored in such tanks is obvious from Fig. 5.78a which shows both blast and fire destruction. Figure 5.78b indicates minor blast damage and some missile damage to the storage tank walls. ← TEXAS CITY STEEL SHIP EXPLOSION: HOT FLYING DEBRIS FROM SHIP (FRAGMENTS) CAUSED FIRES. A BLAST WAVE AFTER THERMAL PULSE WOULD NOT.

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

3.8 MT REDWING—CHEROKEE

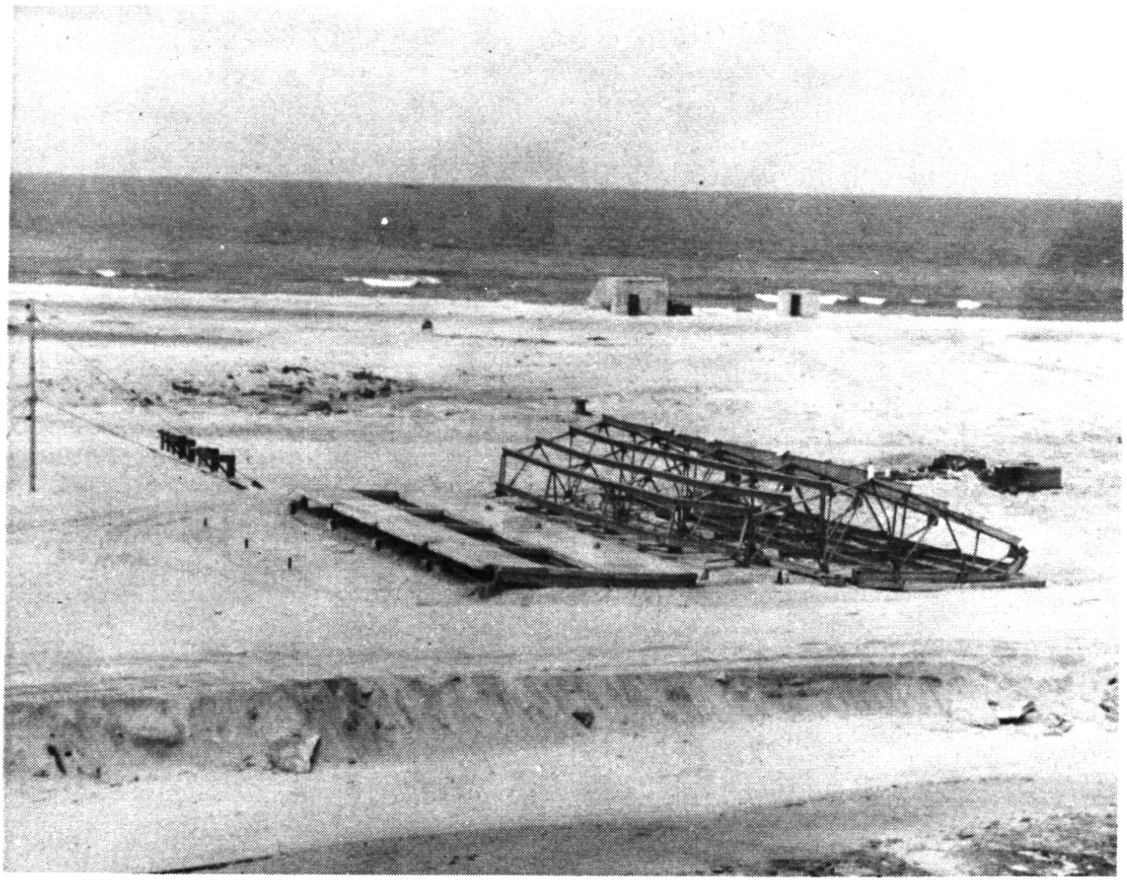


Figure 5.77b. Structure similar to Figure 5.74b after exposure to 5 psi overpressure and 0.5 psi dynamic pressure; positive phase duration several seconds.

3.8 MT REDWING—CHEROKEE

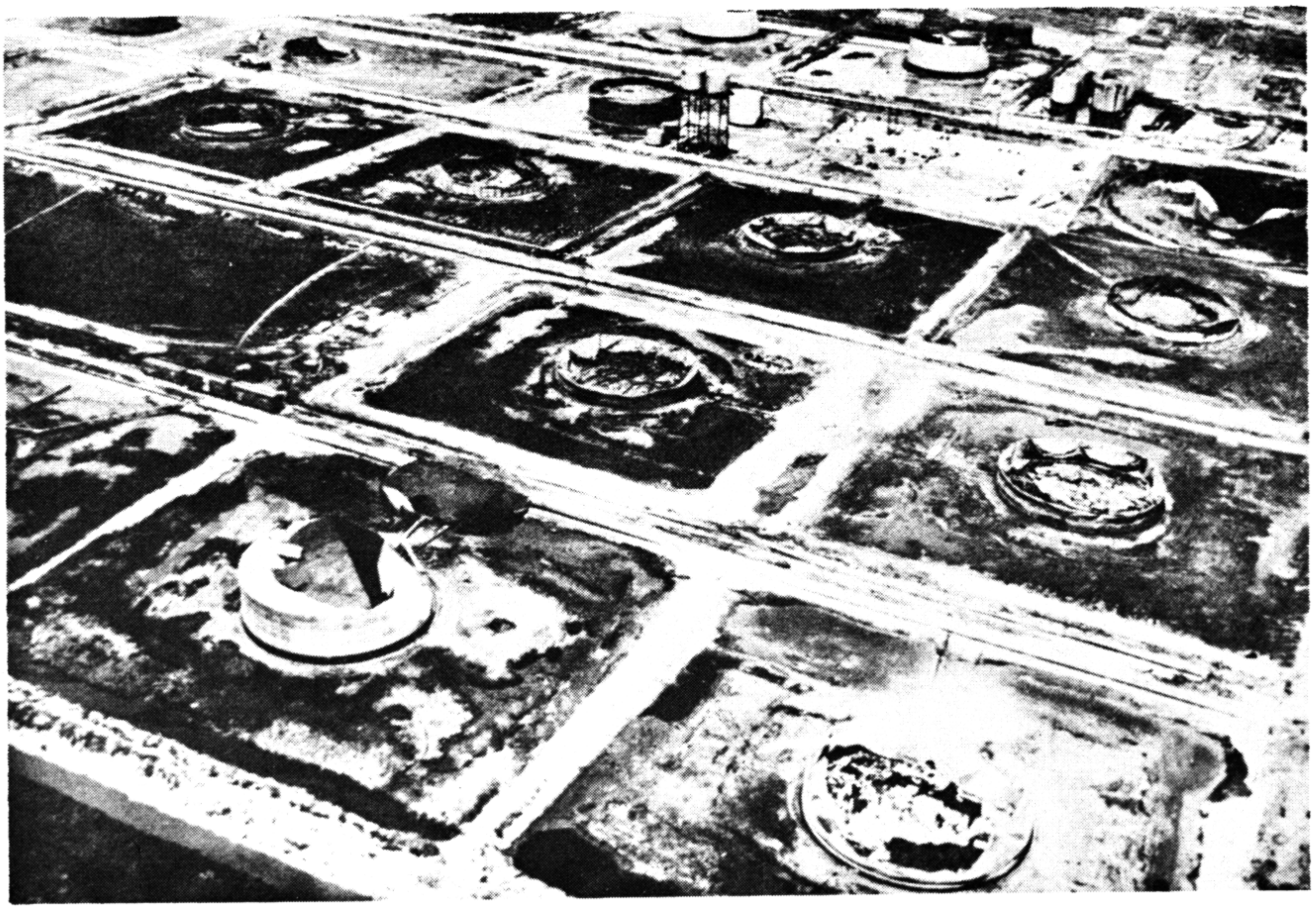


Figure 5.78a. General blast and fire damage at Texas City April 16–17, 1947; distance of foreground from detonation 0.65 mile.

DAMAGE FROM EXPLODING SHIP MISSILES (DEBRIS) NOT APPROPRIATE TO NUCLEAR BLAST

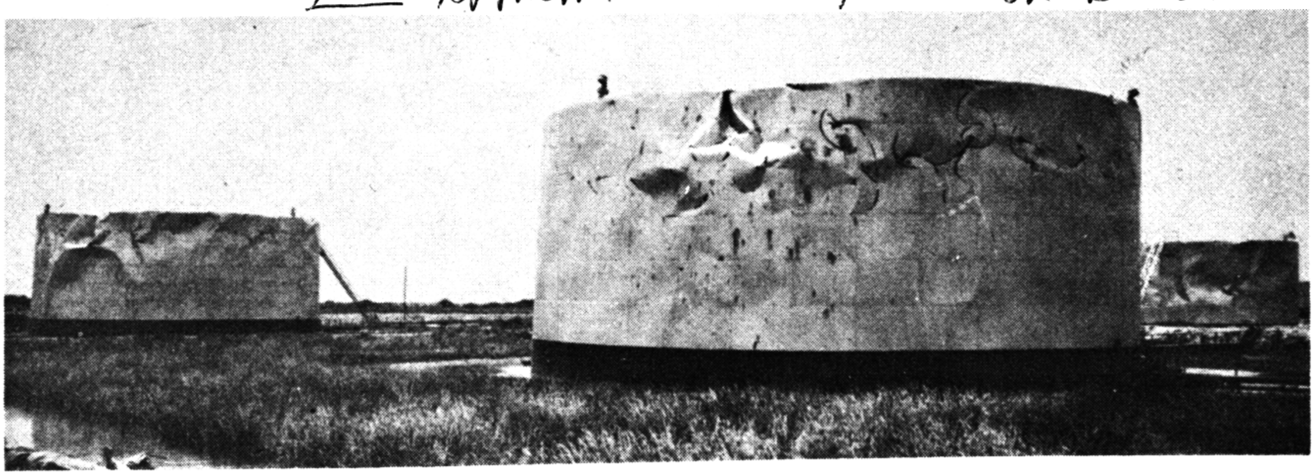


Figure 5.78b. Light missile and blast damage to oil tanks, 0.70 mile from detonation at Texas City April 16–17, 1947.

Heavy-Duty Machine Tools

5.79 Some reference has been made above (§ 5.59) to the damage suffered by machine tools in Japan. However, in the Nevada tests of 1955, the vulnerability of heavy-duty machine tools and their components to nuclear blast was investigated in order to provide infor-

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

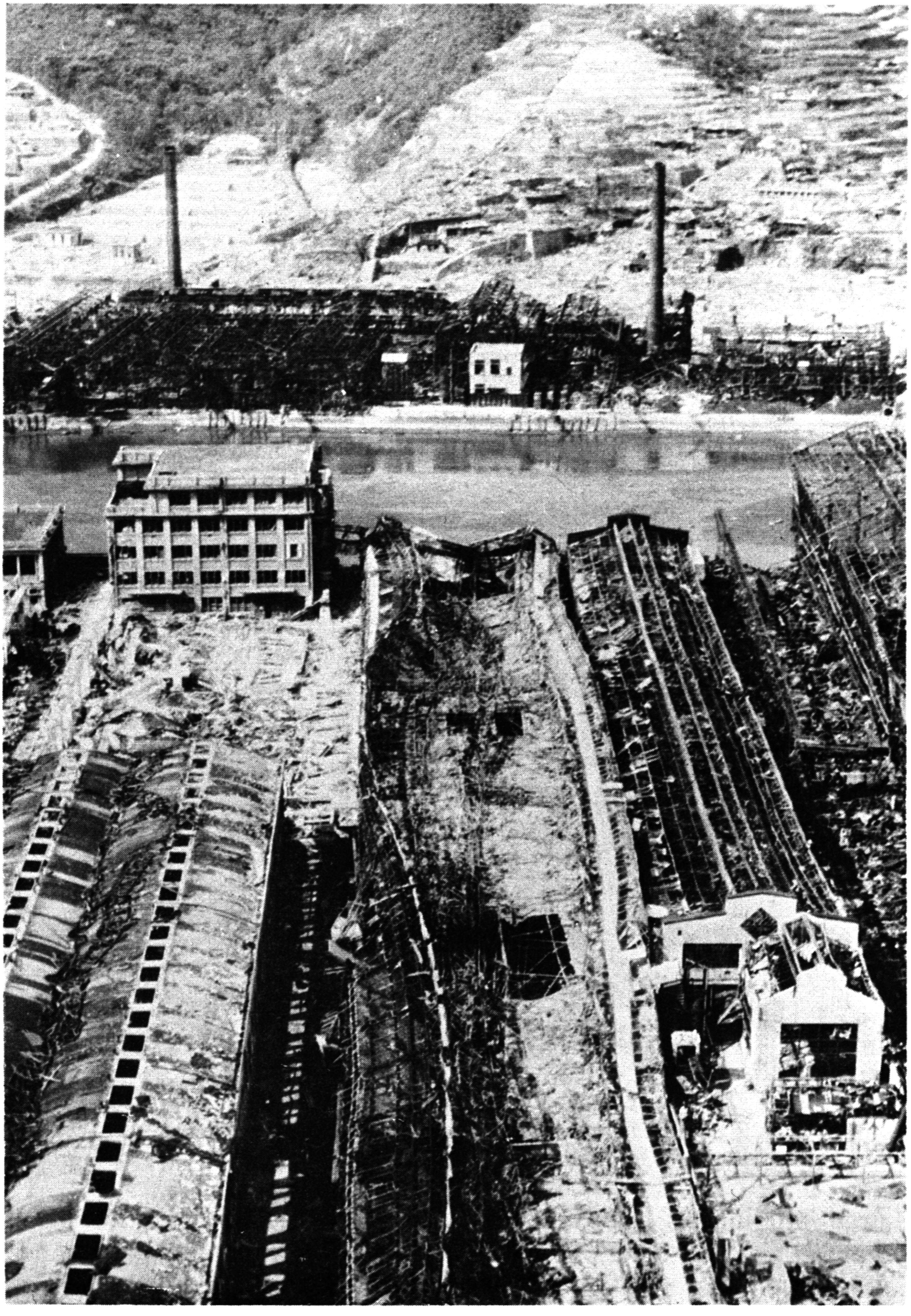


Figure 5.91. At left and back of center is a multistory, steel-frame building (0.85 mile from ground zero at Nagasaki).

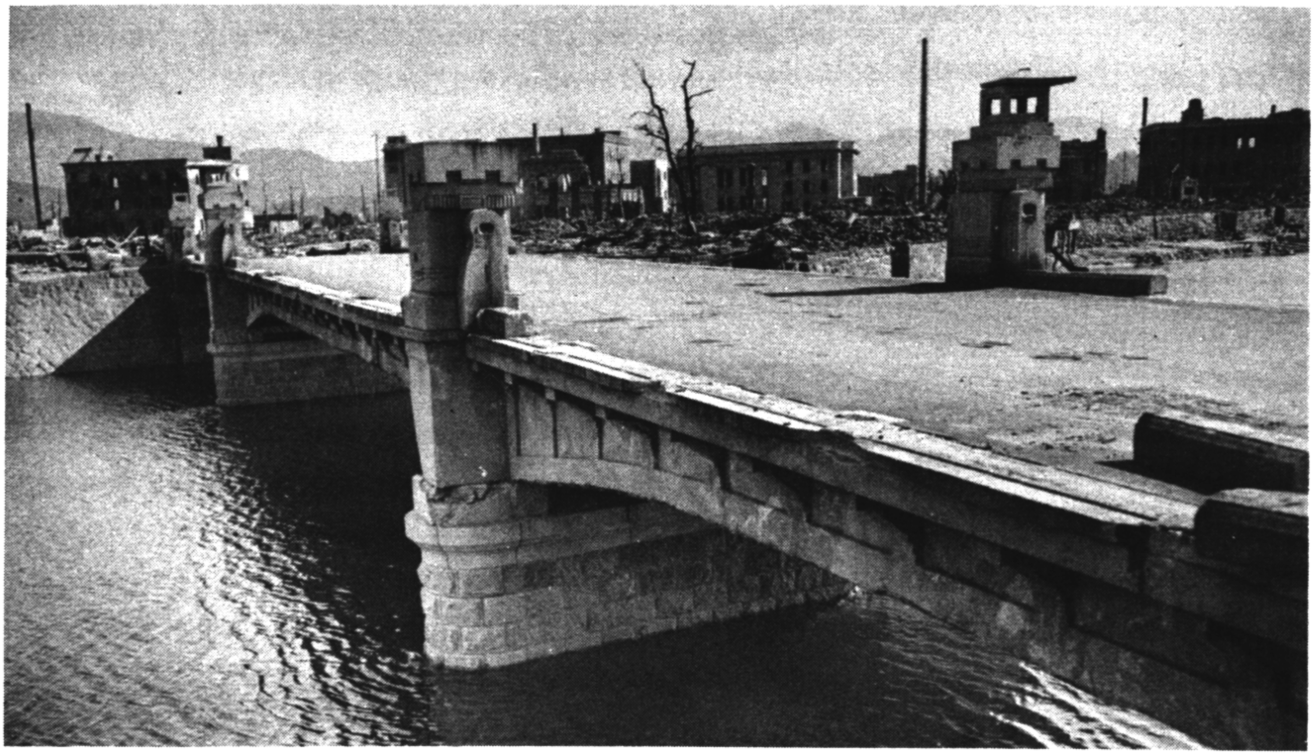


Figure 5.94a. Bridge with deck of reinforced concrete on steel-plate girders; outer girder had concrete facing (270 feet from ground zero at Hiroshima). The railing was blown down but the deck received little damage so that traffic continued.

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

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

Emergency Vehicles

5.97 During the 1955 explosions in Nevada, tests were made to determine the extent to which various emergency vehicles and their equipment would be available for use immediately following a nuclear attack. The vehicles used included a rescue truck, gas and electric utility service or repair trucks, telephone service trucks, and fire pumpers and ladder trucks One vehicle was exposed to an overpressure of about 30 pounds per square inch, two at 5 pounds per square inch, two at 1.7 pounds per square inch, and six at about 1 pound per square inch. It should be emphasized, however, that, as for automobiles, the overpressure is not the sole criterion of damage, as stated above.

5.98 The rescue truck at the 30 pounds per square inch location was completely destroyed, and only one wheel and part of the axle were found after the blast. At 5 pounds per square inch overpressure a truck, with an earth-boring machine bolted to the bed, was broadside to the blast. This truck was overturned and somewhat damaged, but still operable (Fig. 5.98). The earth-boring machine was knocked loose and was on its side, leaking gasoline and water. At the same location, shown to the left of the overturned truck in Fig. 5.98, was a

Figure 5.96c. Typical public bus damaged by a nuclear explosion, Nevada Test Site; this bus, like the one in the left background, was overturned, coming to rest as shown after a displacement of 50 feet.

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

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

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

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

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

Railroad Equipment

5.101 Railroad equipment suffered blast damage in Japan and also in one of the tests in Nevada. Like motor vehicles, these targets are primarily drag sensitive and damage cannot be directly related to overpressure. At a peak overpressure of 2 pounds per square inch an empty wooden boxcar may be expected to receive relatively minor damage. At 4 pounds per square inch overpressure, the damage to a loaded wooden boxcar was more severe (Fig. 5.101a). At a peak overpressure of 6 pounds per square inch, the body of an empty wooden boxcar, weighing about 20 tons, was lifted off its trucks and landed about 6 feet away. The trucks were themselves pulled off the rails, apparently by the brake rods connecting them to the car body. A similar boxcar, at the same location, loaded with 30 tons of sandbags remained upright (Fig. 5.101b). Although the sides were badly damaged and the roof demolished, the car was capable of being moved on its own wheels. At 7.5 pounds per square inch, a loaded boxcar of the same type was overturned, and at 9 pounds per square inch it was completely demolished.

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

Parked Transport Aircraft

5.103 Transport-type aircraft are damaged by blast effects at levels of peak overpressure as low as 1 to 2 pounds per square inch. Complete destruction or damage beyond economical repair may be expected at peak overpressures of 4 to 6 pounds per square inch. Within this range, the peak overpressure appears to be the main criterion of damage. However, tests indicate that, at a given overpressure, damage to an aircraft oriented with the nose toward the burst will be less than damage to one with the tail or a side directed toward the explosion.

5.104 Damage to an aircraft exposed with its left side to the blast at a peak overpressure of 3.6 pounds per square inch is shown in Fig. 5.104a. The fuselage of this aircraft failed completely just aft of the wing. The skin of the fuselage, stabilizers, and engine cowling was severely buckled. Figure 5.104b shows damage to an aircraft oriented with its tail toward the burst and exposed to a blast of 2.4

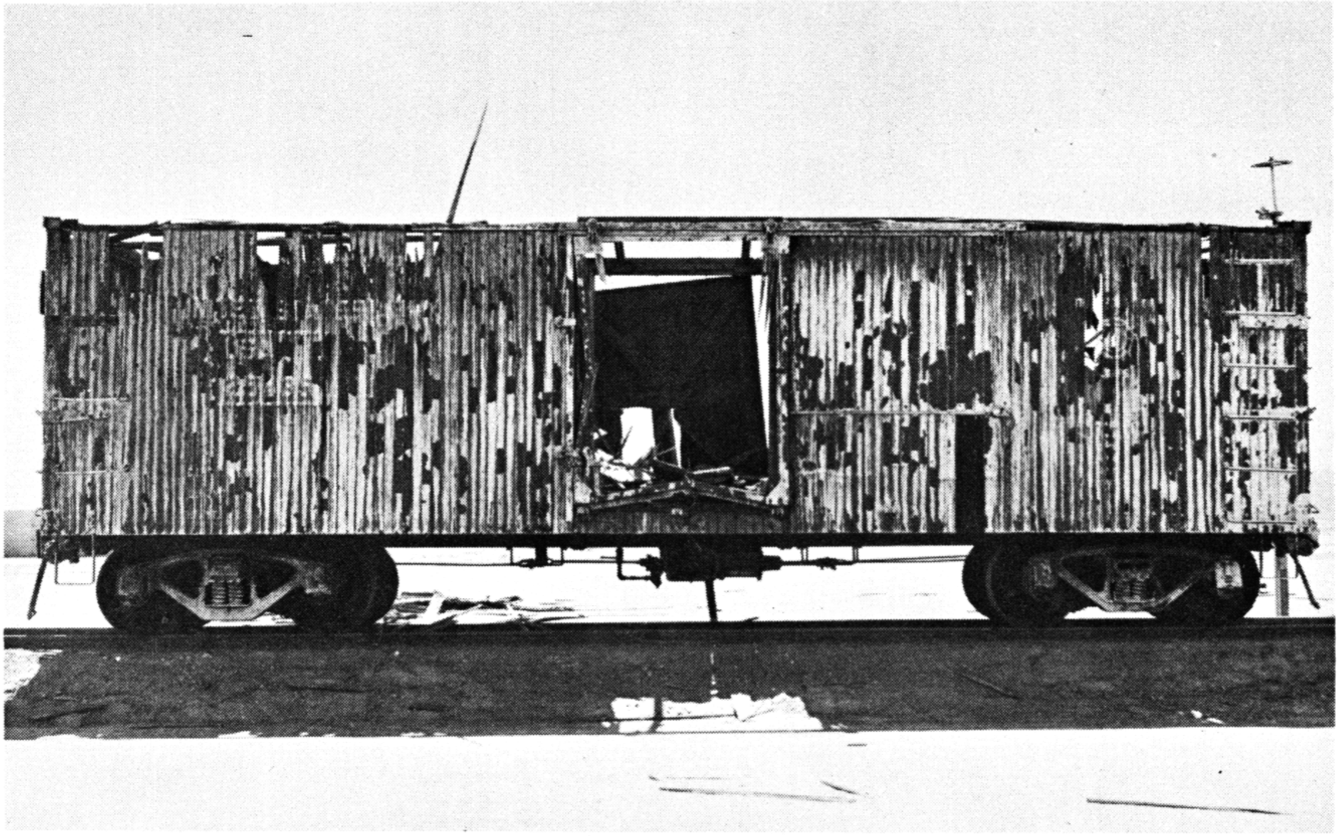


Figure 5.101a. Loaded wooden boxcar after a nuclear explosion (4 psi overpressure).

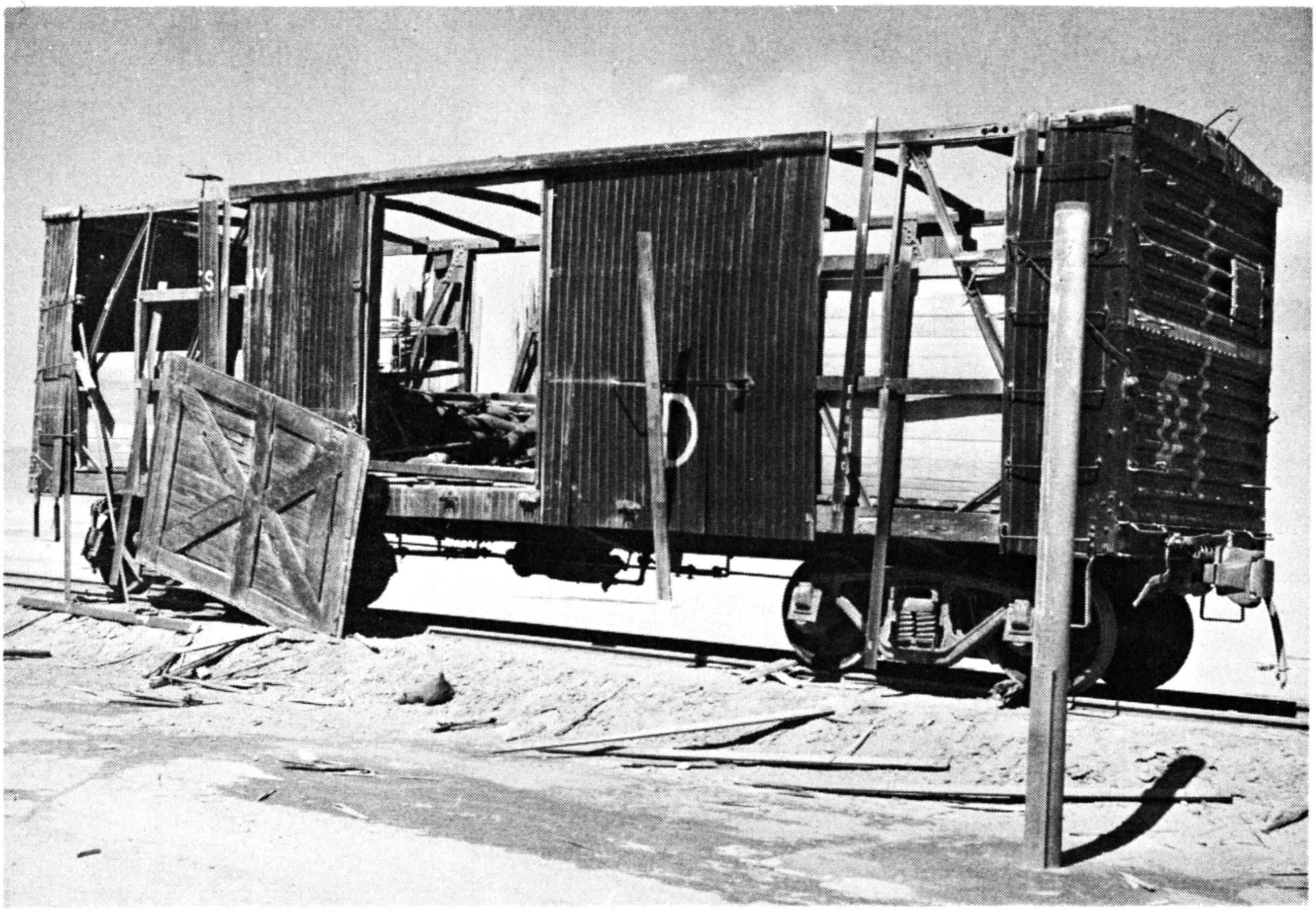


Figure 5.101b. Loaded wooden boxcar after a nuclear explosion (6 psi overpressure).

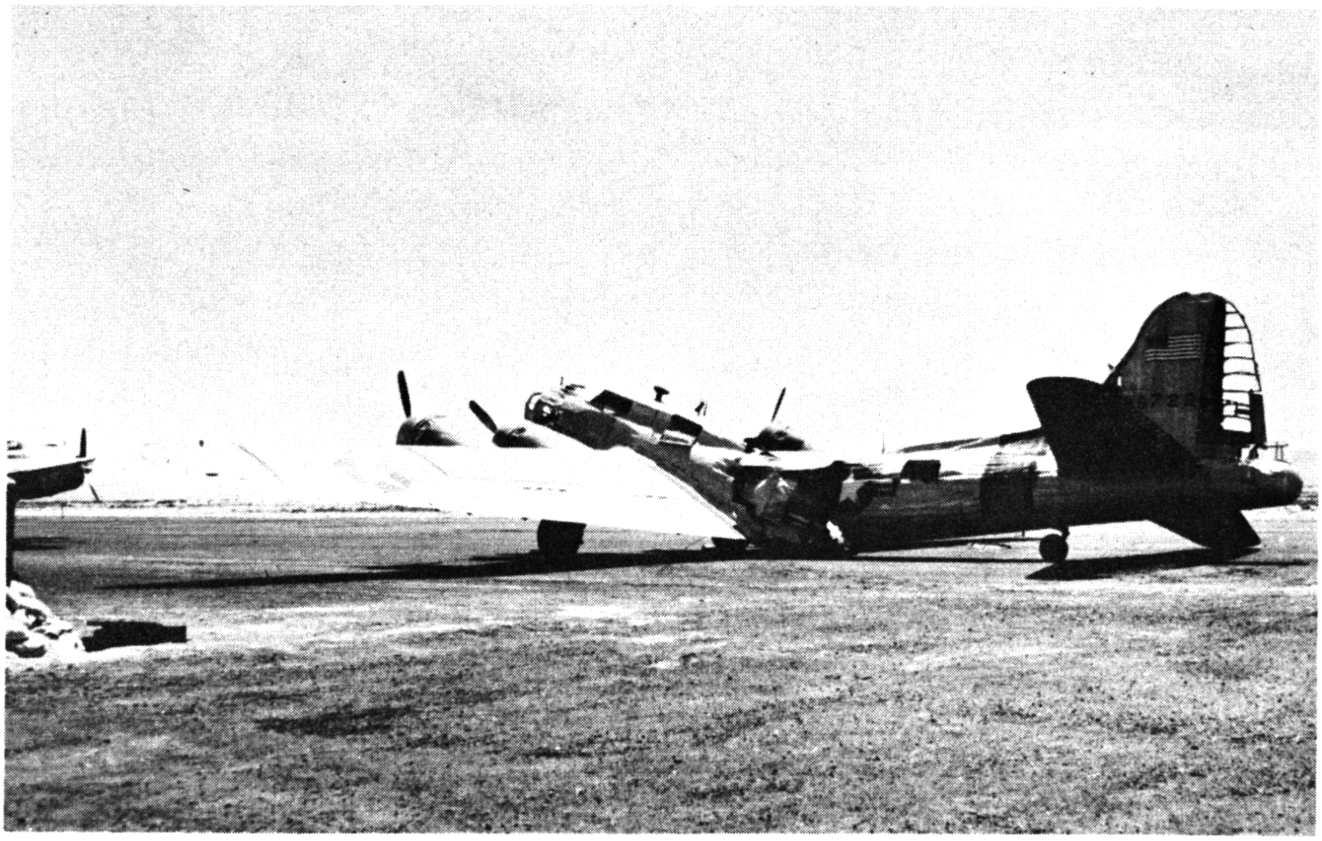


Figure 5.104a. Aircraft after side exposed to a nuclear explosion (3.6 psi overpressure).

Figure 5.104b. Aircraft after tail exposed to a nuclear explosion (2.4 psi overpressure).

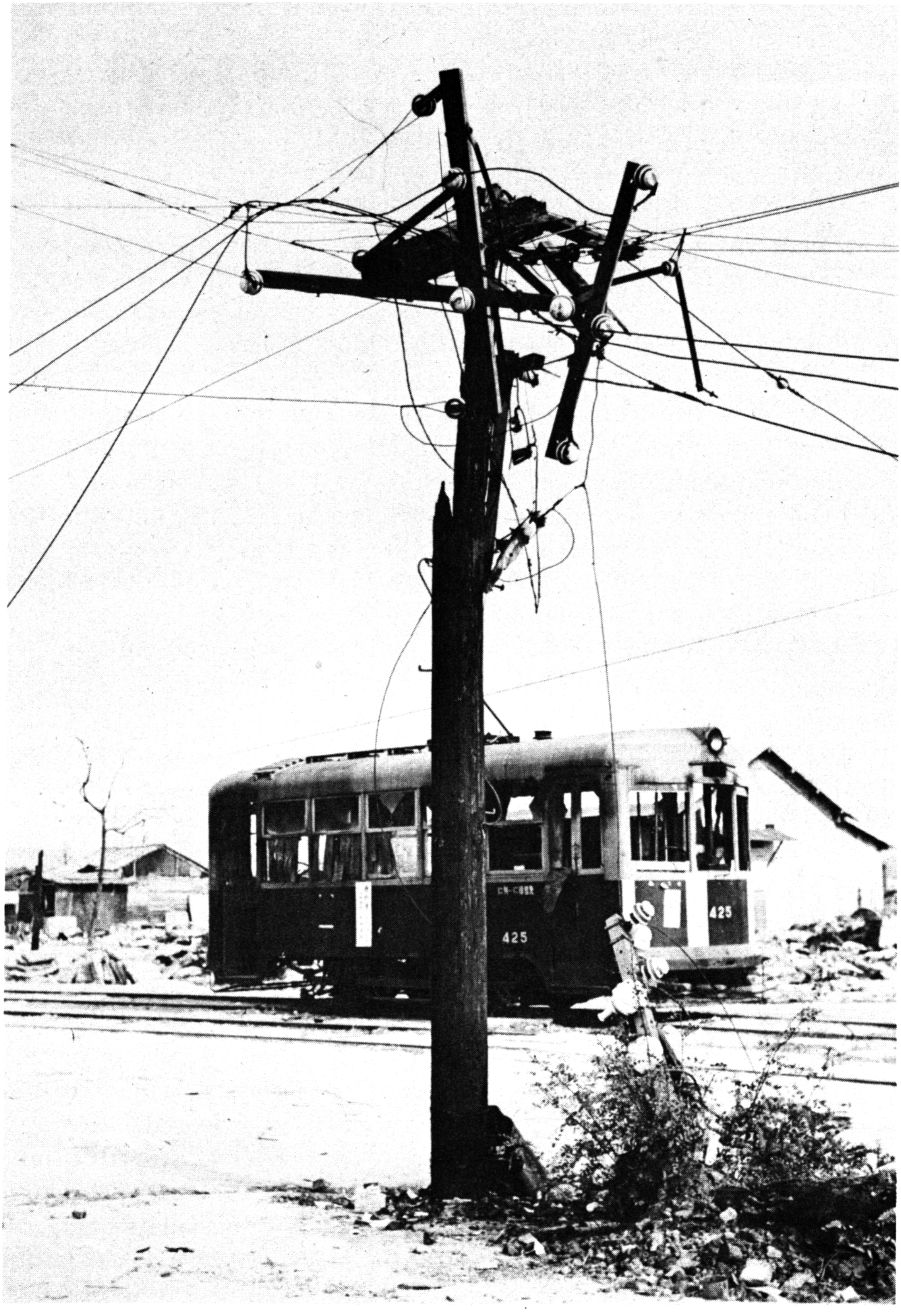


Figure 5.109. Damage to utility pole (0.80 mile from ground zero at Hiroshima).

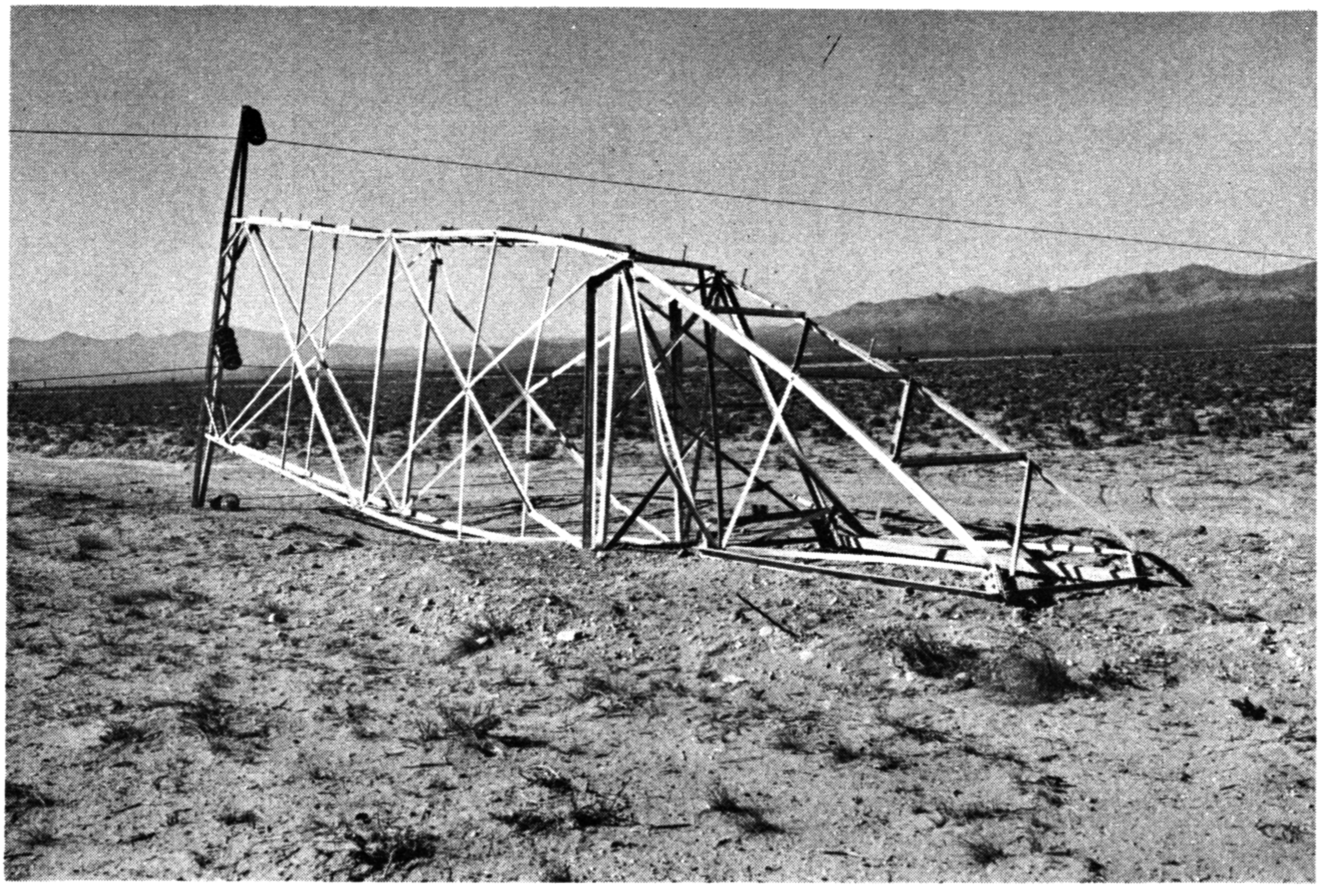


Figure 5.113a Collapsed suspension tower (5 psi overpressure, 0.6 psi dynamic pressure from 30-kiloton explosion), Nevada Test Site.

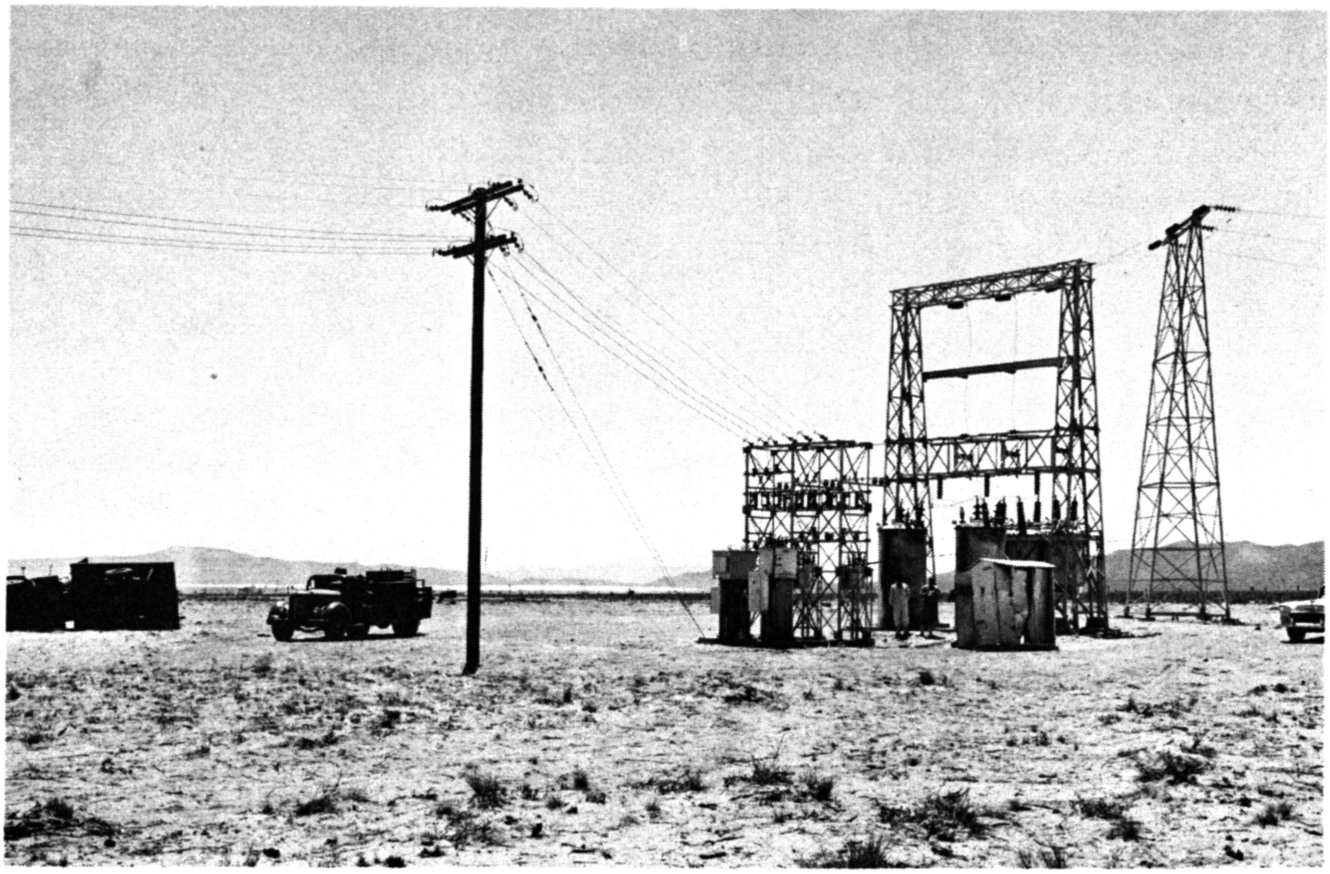


Figure 5.113b. Dead-end tower, suspension tower, and transformers (5 psi overpressure, 0.6 psi dynamic pressure from 30-kiloton explosion), Nevada Test Site. The trucks at the left of the photograph are those in Figure 5.98.

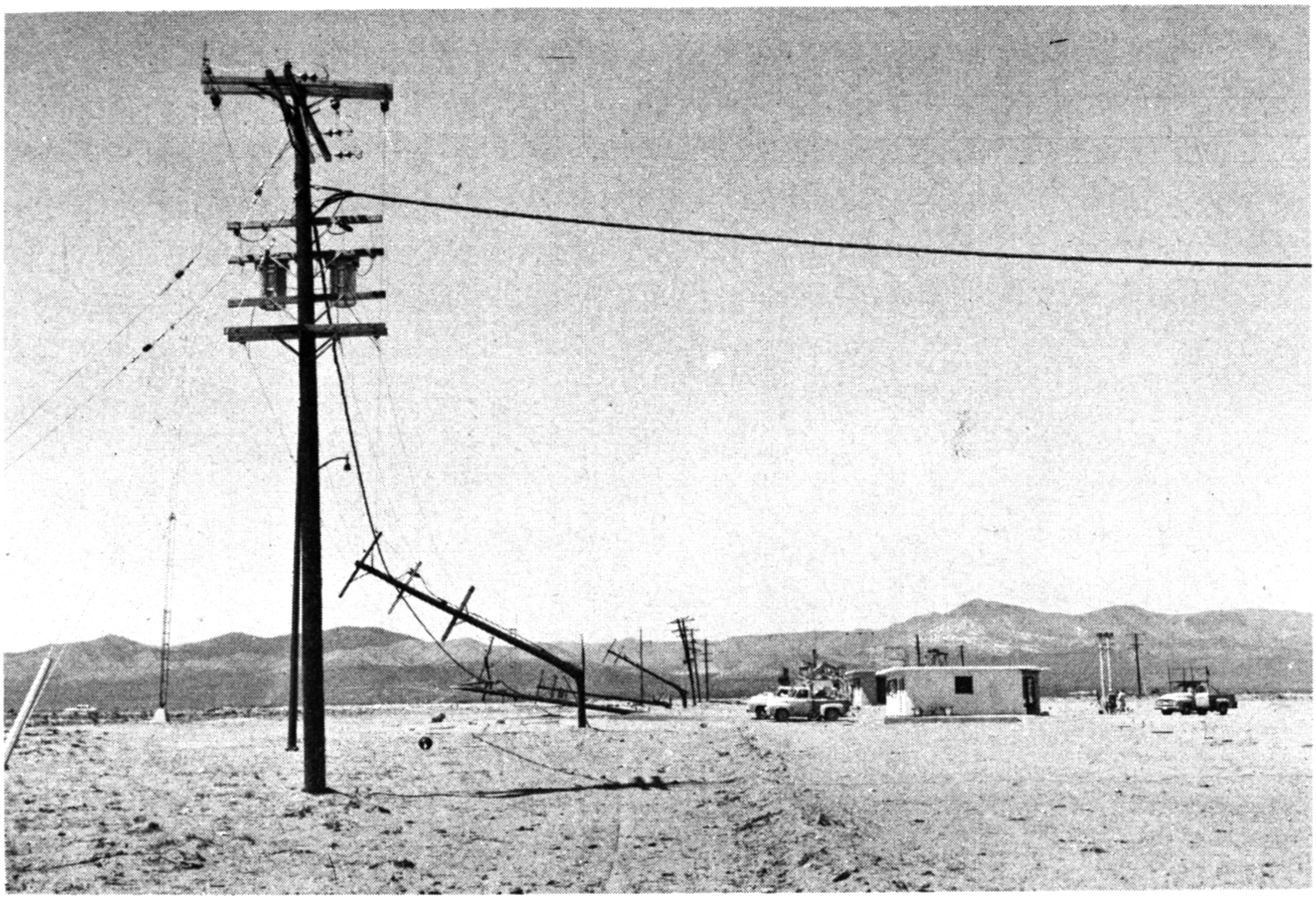


Figure 5.115. Collapse of utility poles on line (5 psi overpressure, 0.6 psi dynamic pressure from 30-kiloton explosion), Nevada Test Site.

mary conductors of both aluminum and copper, and the aerial cables were unharmed. Although the pole line would have required some rebuilding, the general damage was such that it could have been repaired within a day or so with materials normally carried in stock by electric utility companies.

GAS, WATER, AND SEWERAGE SYSTEMS

5.117 The public utility system in Nagasaki was similar to that of a somewhat smaller town in the United States, except that open sewers were used. The most significant damage was suffered by the water-supply system, so that it became almost impossible to extinguish fires. Except for a special case, described below, loss of water pressure resulted from breakage of pipes inside and at entrances to buildings or on structures, rather than from the disruption of underground mains (Figs. 5.117 a and b). The exceptional case was one in which the 12-inch cast iron water pipes were 3 feet below grade in a filled-in area. A number of depressions, up to 1 foot in depth, were produced in the fill, and these caused failure of the underground pipes, presumably due to unequal displacements.

(§ 5.30), the piping in the basement was displaced and bent as a result of the collapse of the first floor. The meter also became detached from the fittings and fell to the ground, but the meter itself and the regulator were undamaged and still operable. All other service piping and equipment were essentially intact.

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

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

Liquid Petroleum (LP) Gas Installations

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

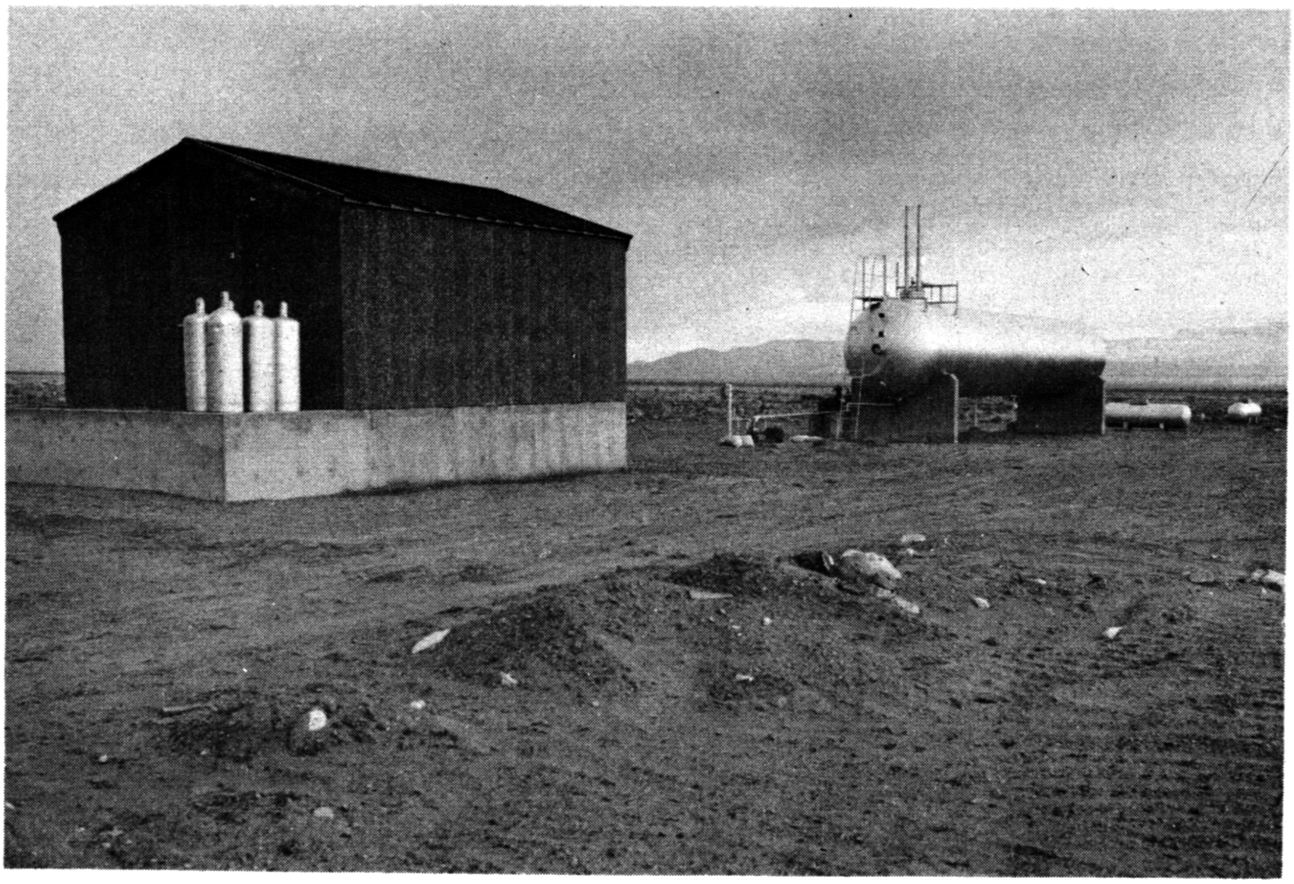
5.128 Two kinds of typical home (or small commercial) LP-gas installations were tested: (1) a system consisting of two replaceable ICC-approved cylinders each of 100-pound capacity; and (2) a 500-gallon bulk storage type system filled from a tank truck. Some of these installations were in the open and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

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

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

5.131 The 500-gallon bulk gas tanks also proved very durable and experienced little damage. The tank closest to the explosion was bounced end-over-end for a distance of some 700 feet; nevertheless, it suffered only superficially and its strength and serviceability were not impaired. The filler valve was damaged, but the internal check valve prevented escape of the contents. The tank exposed at 10 pounds per square inch overpressure was moved about 5 feet, but it sustained little or no damage. All the other tanks, at 5 or 1.7 pounds per square inch, including those at houses piped for service, were unmoved and undamaged (Fig. 5.38).

5.132 The equipment of the 18,000-gallon bulk storage and filling plant received only superficial damage from the blast at 5 pounds per square inch overpressure. The cylinder-filling building was completely demolished; the scale used for weighing the cylinders was wrecked, and a filling line was broken at the point where it entered the building (Fig. 5.132). The major operating services of the plant would, however, not be affected because the transfer facilities were outside and undamaged. All valves and nearly all piping in the plant were intact and there was no leakage of gas. The plant could have been readily put back into operation if power, from electricity or a gasoline engine, were restored. If not, liquid propane in the storage tank could have been made available by taking advantage of gravity flow in conjunction with the inherent pressure of the gas in the tank.



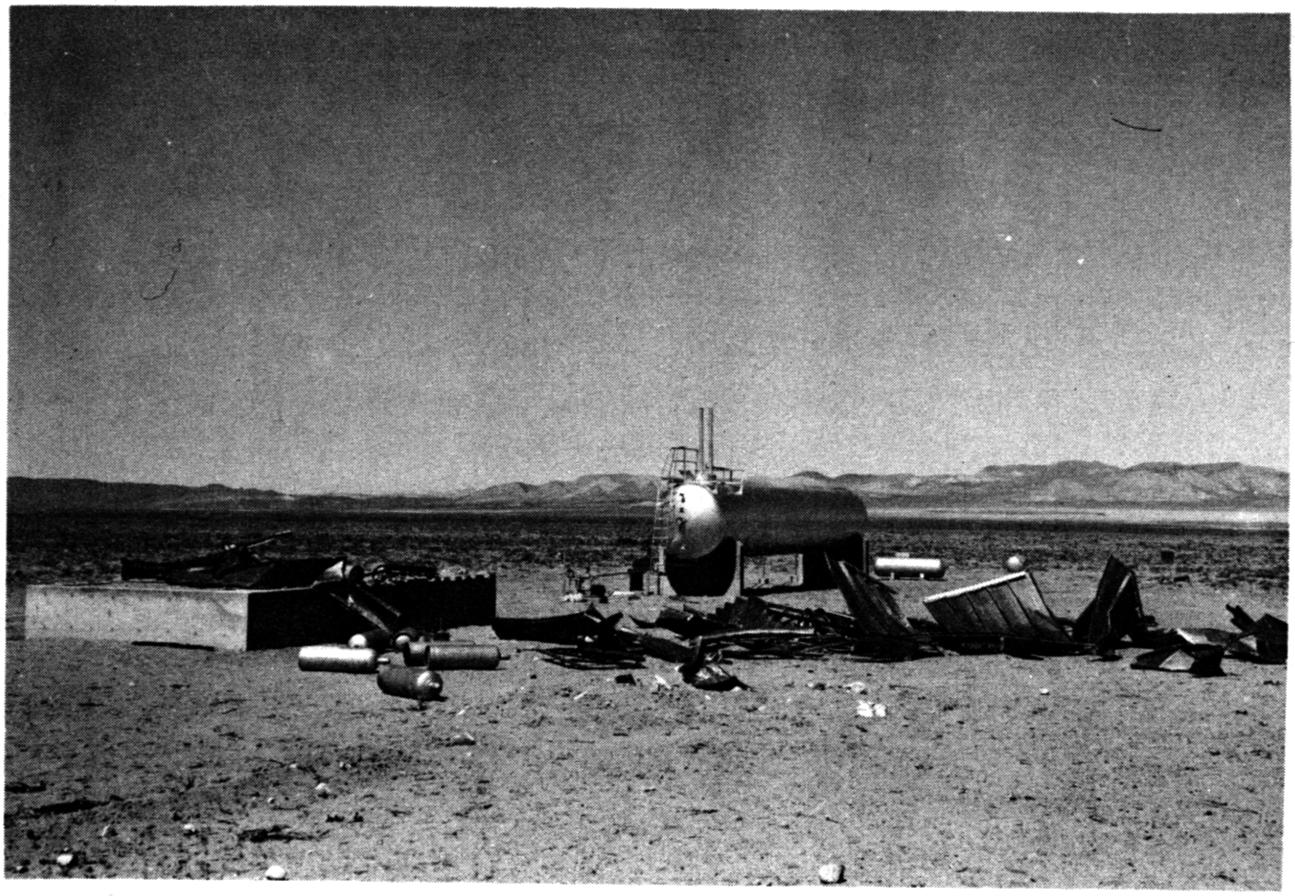


Figure 5.132. Upper photo: LP-gas bulk storage and filling plant before a nuclear explosion. Lower photo: The plant after the explosion (5 psi overpressure).

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

Communications Equipment

5.134 The importance of having communications equipment in operating condition after a nuclear attack is evident and so a variety of such equipment was tested in Nevada in 1955. Among the items exposed were mobile radio-communication systems and units, a standard broadcasting transmitter, antenna towers, home radio and television receivers, telephone equipment (including a small telephone exchange), public address sound systems, and sirens. Some of these were located where the peak overpressure was 5 pounds per square inch, and in most cases there were duplicates at 1.7 pounds per square inch. The damage at the latter location was of such a minor character that it need not be considered here. Damage radii for this type of equipment cannot be directly related to overpressure but should be obtained from Fig. 458b.

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

5.136 A guyed 150-foot antenna tower was unharmed, but an unguyed 120-foot tower, of lighter construction, close by, broke off at a height of about 40 feet and fell to the ground (Fig. 5.136). This represented the only serious damage to any of the equipment tested.

5.137 The base station antennas, which were on the towers, appeared to withstand blast reasonably well, although those attached to the unguyed tower, referred to above, suffered when the tower collapsed. As would have been expected from their lighter construction, television antennas for home receivers were more easily damaged.

Figure 5.136. Unguyed lightweight 120-foot antenna tower (5 psi overpressure, 0.6 psi dynamic pressure from 30-kiloton explosion), Nevada Test Site.

Several were bent both by the blast and the collapse of the houses upon which they were mounted. Since the houses were generally damaged beyond repair at an overpressure of 5 pounds per square inch, the failure of the television antennas is not of great significance.

5.138 It should be mentioned that representative items, such as power lines and telephone service equipment, were frequently attached to utility-line poles. When the poles failed, as they did in some cases (§ 5.115), the communications systems suffered accordingly. Although the equipment operated satisfactorily, after repairs were made to the wire line, it appears that the power supply represents a weak link in the communications chain.

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

of 150 $W^{0.3}$ feet were included in Fig. 6.48. The latter thus shows the range of crater dimensions possible from a surface burst to the approximate maximum for an underground burst, for any explosion energy yield from 1 kiloton to 10 megatons. The correction factor for hard rock is given in connection with the example facing Fig. 6.49.

6.51 In an attempt to explain the physical basis of the 0.3 scaling, it has been found that gravity scaling, i.e., the mass of material excavated is proportional to the explosion yield, taking account of overburden, fits the data better than cube root scaling but not as well as $W^{0.3}$ scaling. If gravity scaling using overburden is found to be correct, then crater dimensions will be smaller than those predicted by the estimates given above.

Deep Underground Explosions

6.52 A number of nuclear test explosions have been carried out at various depths underground. Some of the characteristics of such tests, including the proportion of the residual radioactivity on the surface, are given in Table 6.52. From these data it can be concluded, as a rough generalization, that containment, i.e., no radioactivity detectable at the earth's surface, will result if the scaled depth of burst in tuff is greater than about 500 feet. In other words the requirement for complete containment of the radioactive products of a nuclear explosion in tuff is that there should be a rock and dirt cover of roughly 500 $W^{0.3}$ feet or more, where W is the explosion energy yield in kilotons TNT equivalent.

Table 6.52

CHARACTERISTICS OF UNDERGROUND BURSTS

Test	Medium	Depth of cover	Scaled depth	Radioactivity on surface
		feet	$d/W^{0.3}$	*percent*
Jangle U	Alluvium	17	16	80
Teapot S	Alluvium	67	63	90
Neptune	Tuff	98.5	189	2
Blanca	Tuff	835	342	0.5
Logan	Tuff	830	512	0
Rainier	Tuff	790	680	0

6.53 Some of the data obtained in connection with the RAINIER test were described in Chapter II; others will be given here. The radius of the initial cavity formed by the explosion was equivalent to 47 $W^{0.3}$ feet and the initially melted rock, which was converted to

(Text continued on page 295.)

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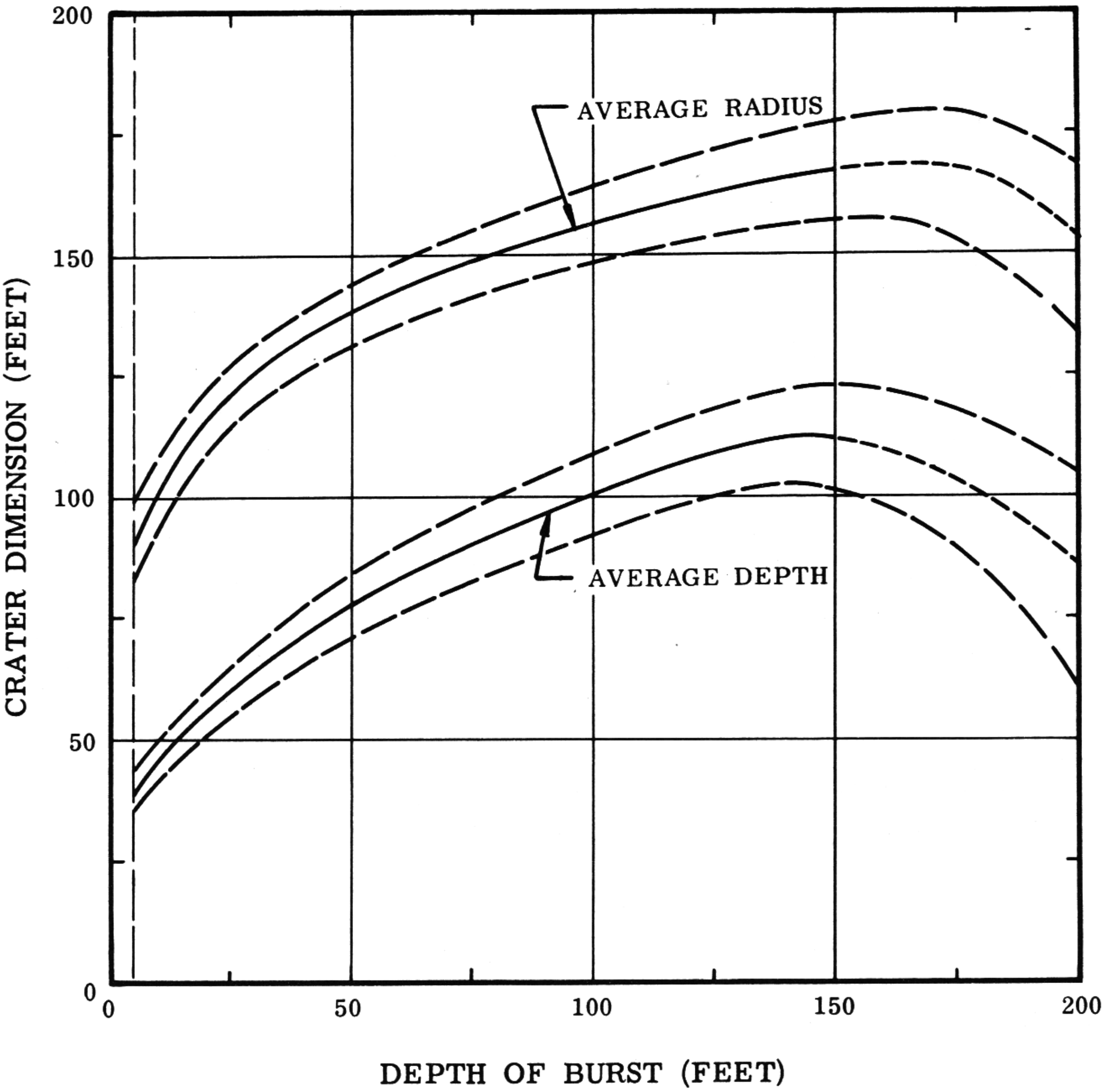

Figure 6.49. Apparent crater radius and depth as function of depth of burst for a 1-kiloton underground explosion in dry soil. (The data are uncertain for scaled depths of burst greater than 150 feet.)

(Text continued from page 291.)

glass upon cooling, amounted to 500±150 tons per kiloton of energy yield. Collapse of the cavity produced a zone of broken permeable material of about 70,000 cubic yards (or 120,000 tons) per kiloton yield. The major portion (65 to 80 percent) of the fission product and induced radioactivity was retained as a dilute solution (0.1 part per million) in the glass formed from the molten rock. The remainder was distributed as a deposit on the surface of the broken material, throughout the collapsed zone of the chimney formed by the falling in of the cavity roof.

6.54 About 30 percent of the total energy release of the RAINIER explosion appeared initially as steam and heated rock at a temperature exceeding 1,200° C. However, because the rock contained a relatively large proportion (15 to 20 percent) of water, the temperature fell rapidly to that of boiling water at the Nevada altitude (about 93° C). A year after the explosion, nearly all of this energy was retained within a volume of radius somewhat less than 80 feet, i.e., slightly more than the radius of the initial cavity.

6.55 From seismographic observations, it has been found that the peak acceleration of the ground at a distance of R miles from an underground burst of W kilotons is roughly equal to 0.06 $gW^{0.75}/R^2$, where g is the normal acceleration of gravity. At the observation post 2.5 miles from the RAINIER explosion, the peak acceleration was about 0.02 g, although very few individuals detected the ground motion (§ 2.97).

LOADING ON BURIED STRUCTURES

Free-Field Pressure and Arching Effect

6.56. If the deformability of a buried structure is the same as that of the surrounding displaced soil, the loads produced on the structure by the air blast from a nuclear detonation will be determined by the free-field pressures, i.e., the pressures in the absence of the structure, induced in the soil by the blast wave. However, structures seldom, if ever, satisfy this postulated condition; consequently, the loads for which a buried structure must be designed can be determined only by considering the interaction of soil and structures. Although this is a difficult matter, certain general observations can be made which probably justify the procedures normally used.

6.57 Results of tests have indicated that there is no significant build-up of pressure due to reflection at the interface between the soil and a buried structure. It may be assumed, therefore, that the free-field pressure, regardless of its direction, can be taken as an upper limit of the pressure acting on the structure. If the structure is more deformable than the surrounding soil, the pressure on the buried structure will be considerably lower than the free-field pressure at the given depth. In this case, as the free-field pressure is exerted initially, the structure deflects away from the soil and a situation is created in which the "arching effect" within the soil serves to transmit part of the blast-induced pressure around the structure rather than through it.

6.58 It is generally accepted that the soil arching phenomenon, which has been observed under static conditions, also exists under

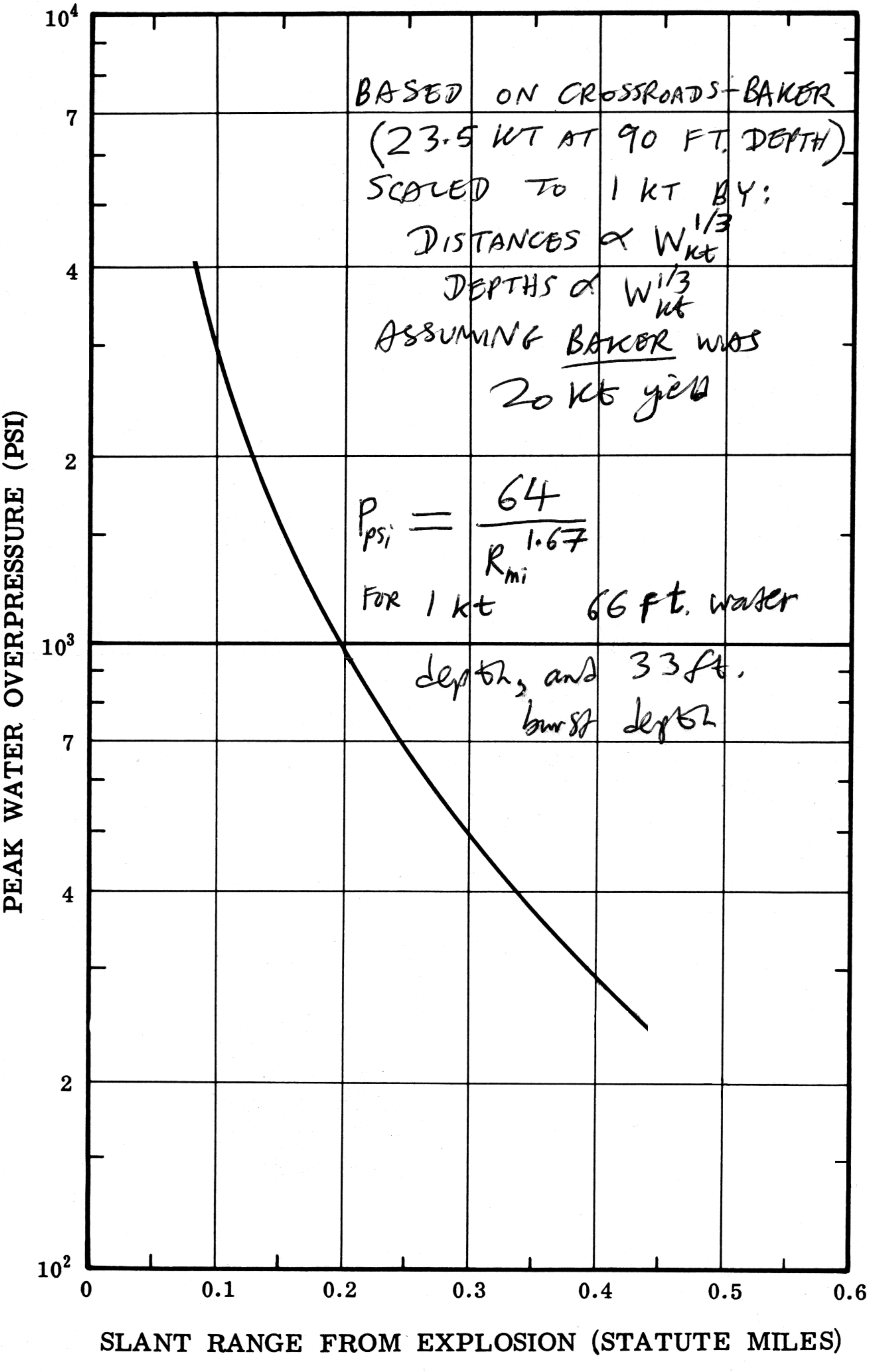

Figure 6.77. Peak water overpressure for a 1-kiloton explosion at mid-depth in water 66 feet deep.

BASED ON BAKER TEST

$$P_{psi} = W_{kt}^{1/3} / R_{mi}$$

$$P_{psi} = 1/R_{mi} \text{ for } 1 \text{ kt yield}$$

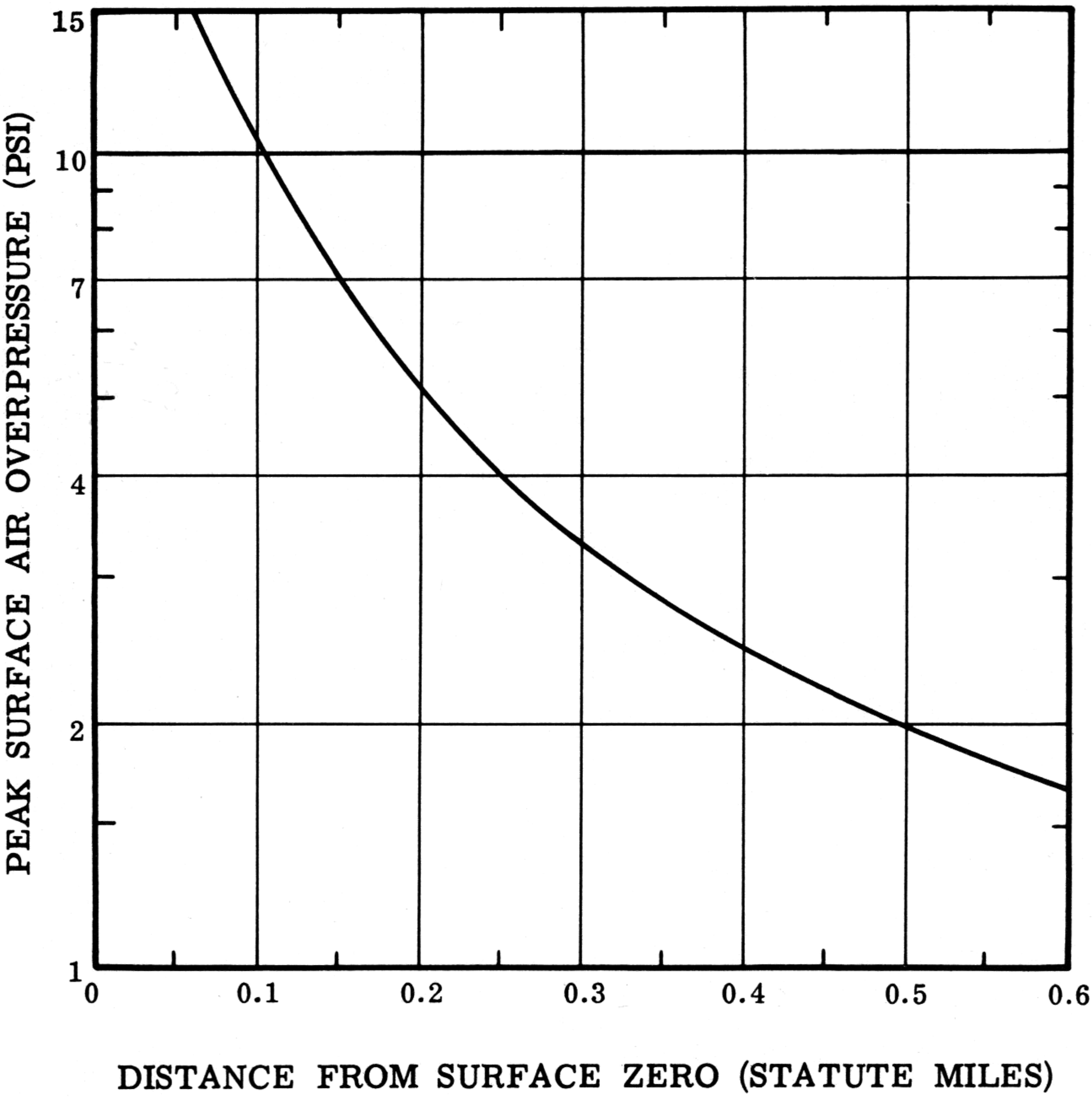

Figure 6.78. Peak air overpressure at surface for a 1-kiloton shallow underwater explosion.

The lower curve in Fig. 6.79 shows the approximate maximum crest-to-trough wave height versus horizontal surface distance for a 1 KT burst in water 85 feet deep. The upper curve is for a 1 KT burst in water more than 400 feet deep, so that the bottom does not affect the mechanism of wave formation.

Scaling. At a given distance from surface zero, the wave height for an explosion of W kilotons is $W^{1/2}$ times the wave height at this distance from a 1 KT burst in water of the same scaled depth, as obtained from Fig. 6.79. The scaled depth is $d/W^{1/4}$, where d is the actual depth in feet. For the lower curve in the figure the scaled depth is 85 feet and for the upper curve it is more than 400 feet.

For scaled water depths less than 85 feet, i.e., actual depths less than $85W^{1/4}$ feet, the estimated maximum wave height is proportional to the depth of water; thus,

CORRECT LAW:

$$h_d = h_{85}\left(\frac{d}{\underline{\underline{85}}\, W_{kt}^{1/4}}\right)$$

85

$$\cancel{h_d = h_{85}(d/W^{1/4})},$$

PRINTING ERROR!!

where h_d=wave height for any scaled water depth less than 85 feet, h_{85}=wave height for a scaled water depth of 85 feet obtained from Fig. 6.79, and d=depth of water in feet.

Example

Given: (*a*) A 30 KT weapon detonated in 200 feet of water.
(*b*) A 30 KT weapon detonated in 100 feet of water.
(*c*) A 30 KT weapon detonated in 1,000 feet of water.

Find: The expected maximum wave height in each case at 4 miles from surface zero.

Solution: (*a*) The scaled depth of the water is

$$200/30^{1/4}=200/2.34=85 \text{ feet;}$$

consequently, the lower curve in Fig. 6.79 is applicable to this case. From the curve, the maximum wave height at 4 miles from the 1 KT explosion is 1.0 feet. Therefore, for a 30 KT weapon in 200 feet of water, the wave height at 4 miles is

$$1.0\times 30^{1/2}=1.0\times 5.5=5.5 \text{ feet, crest to trough.} \quad \textit{Answer.}$$

(*b*) Since 100 feet is less than $85W^{1/4}$ when W is 30 KT, the wave height will now be proportional to the actual depth of the water. When the depth is $85W^{1/4}$, i.e., 200 feet, the wave height at 4 miles from the 30 KT burst is 5.5 feet; hence, for a water depth of 100 feet the wave height at the same distance is

$$5.5\times\frac{100}{200}=2.7 \text{ feet, crest to trough.} \quad \textit{Answer.}$$

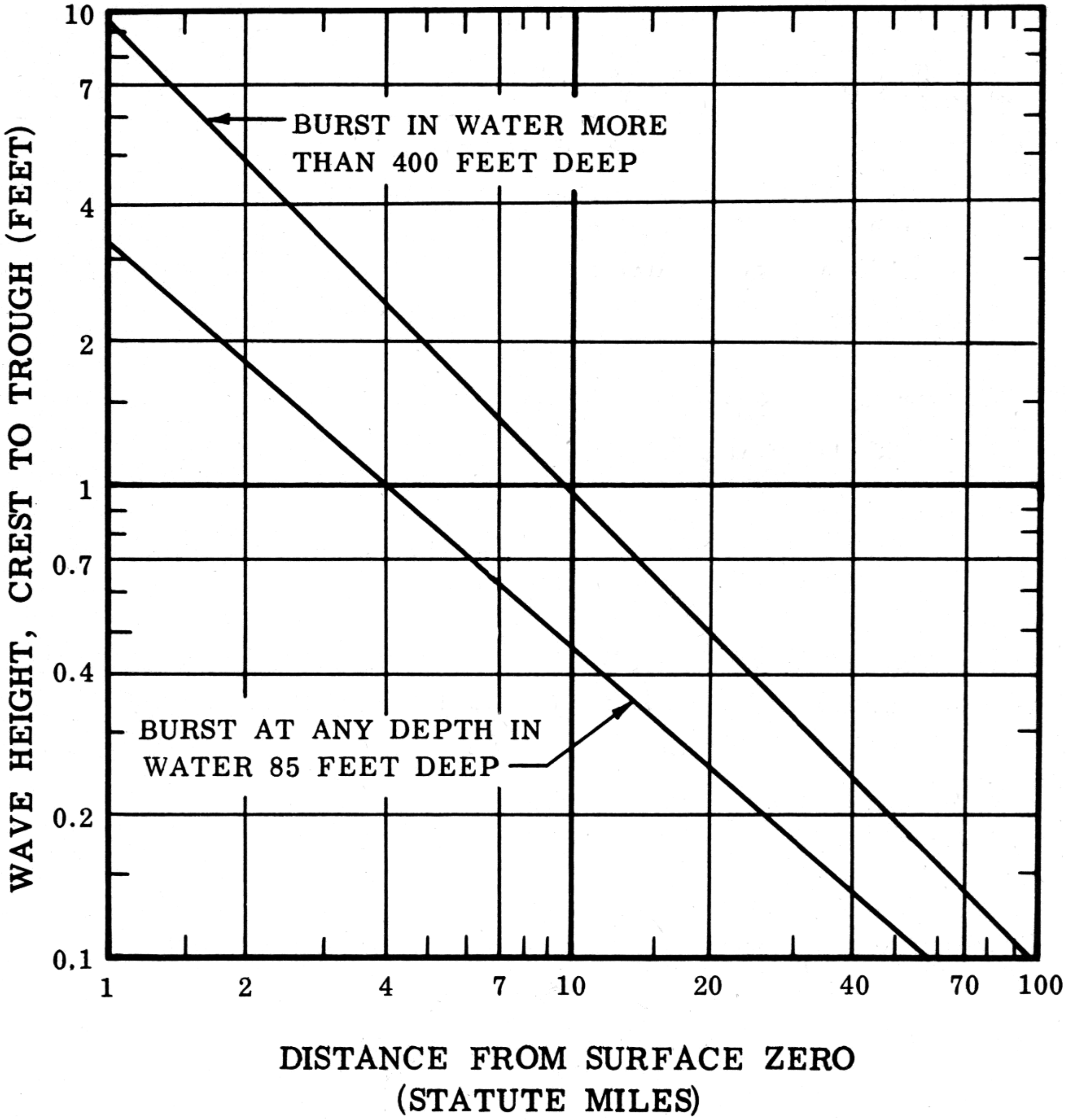

Figure 6.79. Maximum wave height in different types of 1-kiloton underwater bursts.

(*c*) The scaled depth of the water is

$$1{,}000/30^{1/4}=1{,}000/2.34=427 \text{ feet},$$

and since this is greater than 400 feet, the upper curve in Fig. 6.79 must be used. From the curve, the maximum wave height at 4 miles from a 1 KT explosion is 2.4 feet. Therefore, for a 30 KT weapon detonated (at the proper depth) in 1,000 feet of water, the maximum wave height at 4 miles is

$$2.4\times30^{1/2}=2.4\times5.5=13 \text{ feet, crest to trough.} \quad \textit{Answer.}$$

The curves in Fig. 6.81 give the depth, diameter, and lip height of the underwater crater as functions of yield. The results are for a burst less than 15 feet deep and for one on the bottom in 50 feet of water for a sand, sand and gravel, or soft rock bottom.

For other bottom materials the crater dimensions can be estimated by multiplying the values from Fig. 6.81 by the following factors:

Material	*Diameter*	*Depth*	*Lip Height*
Loess	1. 0	1. 7	0. 7
Clay	1. 0	2. 3	2. 3
Hard rock	0. 7	0. 5	0. 4
Mud or muck	0. 7	0. 4	0. 2

Example

Given: A 200 KT weapon detonated in 50 feet of water; the bottom is predominantly clay.

Find: (*a*) The crater dimensions when the detonation is near the surface of the water.

(*b*) The crater dimensions when the detonation occurs on the bottom.

Solution: From Fig. 6.81, the crater dimensions for a 200 KT explosion are as follows:

	(*a*) *Feet*	(*b*) *Feet*
Diameter	1, 000	1, 900
Depth	44	120
Lip height	2. 4	14

For a clay bottom, the multiplication factors are 1.0 for the diameter, and 2.3 for both depth and lip height; hence, the required values are:

	(*a*) *Feet*	(*b*) *Feet*	
Diameter (factor 1.0)	1, 000	1, 900	
Depth (factor 2.3)	100	276	
Lip height (factor 2.3)	5. 5	32	*Answer.*

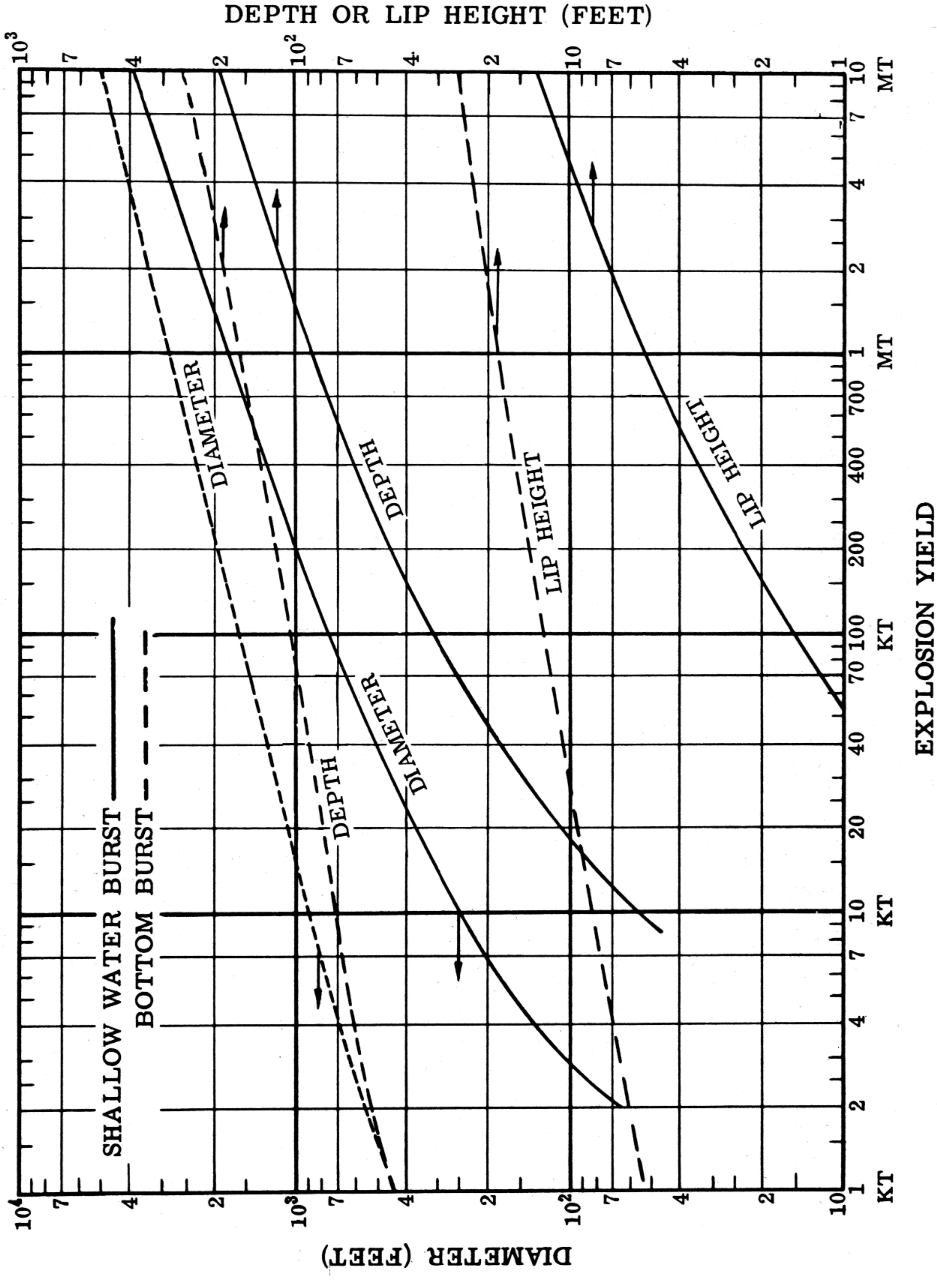

Figure 6.81. Dimensions of crater in underwater bursts as a function of explosion yield.

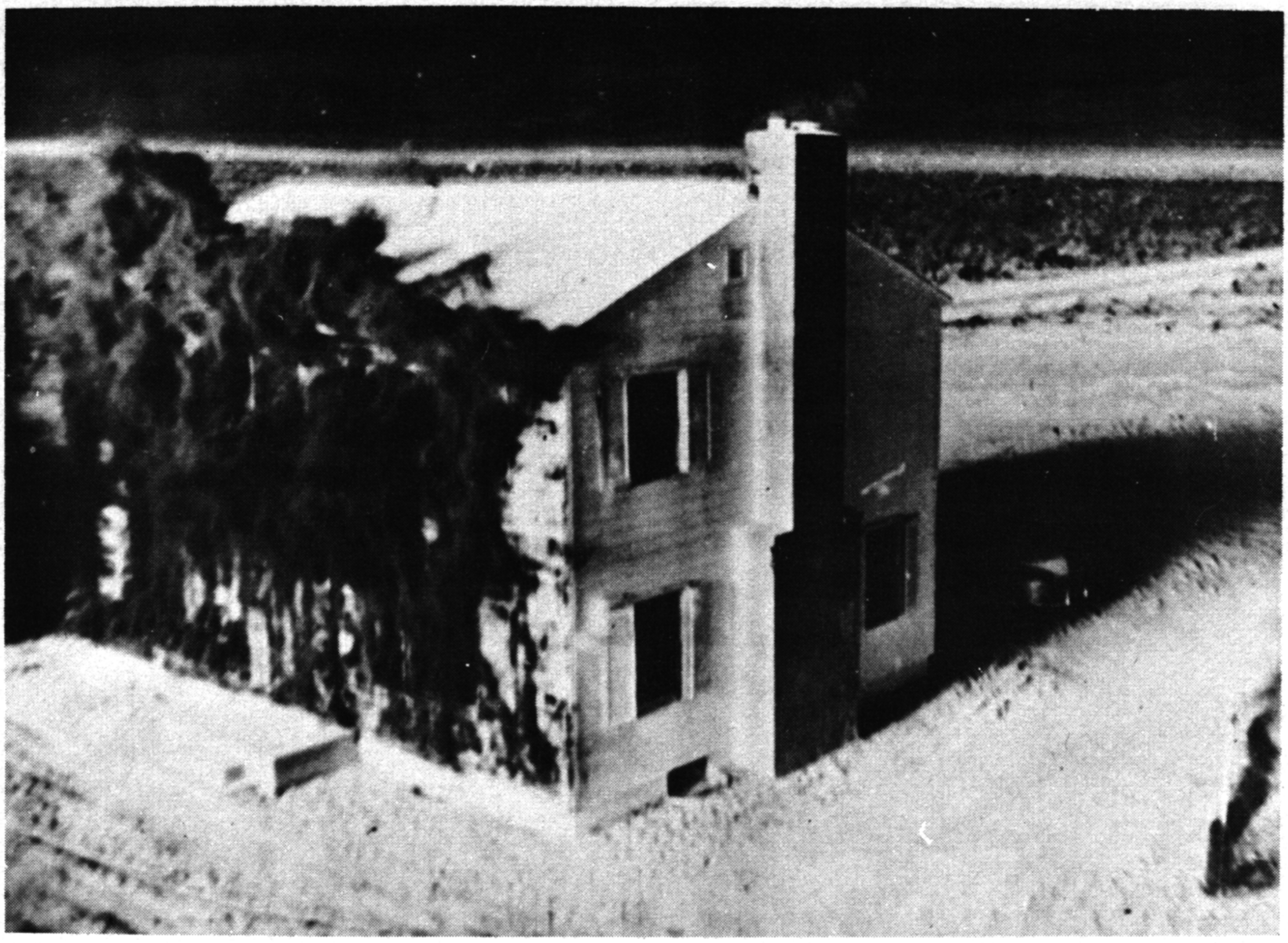

Figure 7.33a. Thermal effects on wood-frame house 1 second after explosion (about 25 cal/sq cm).

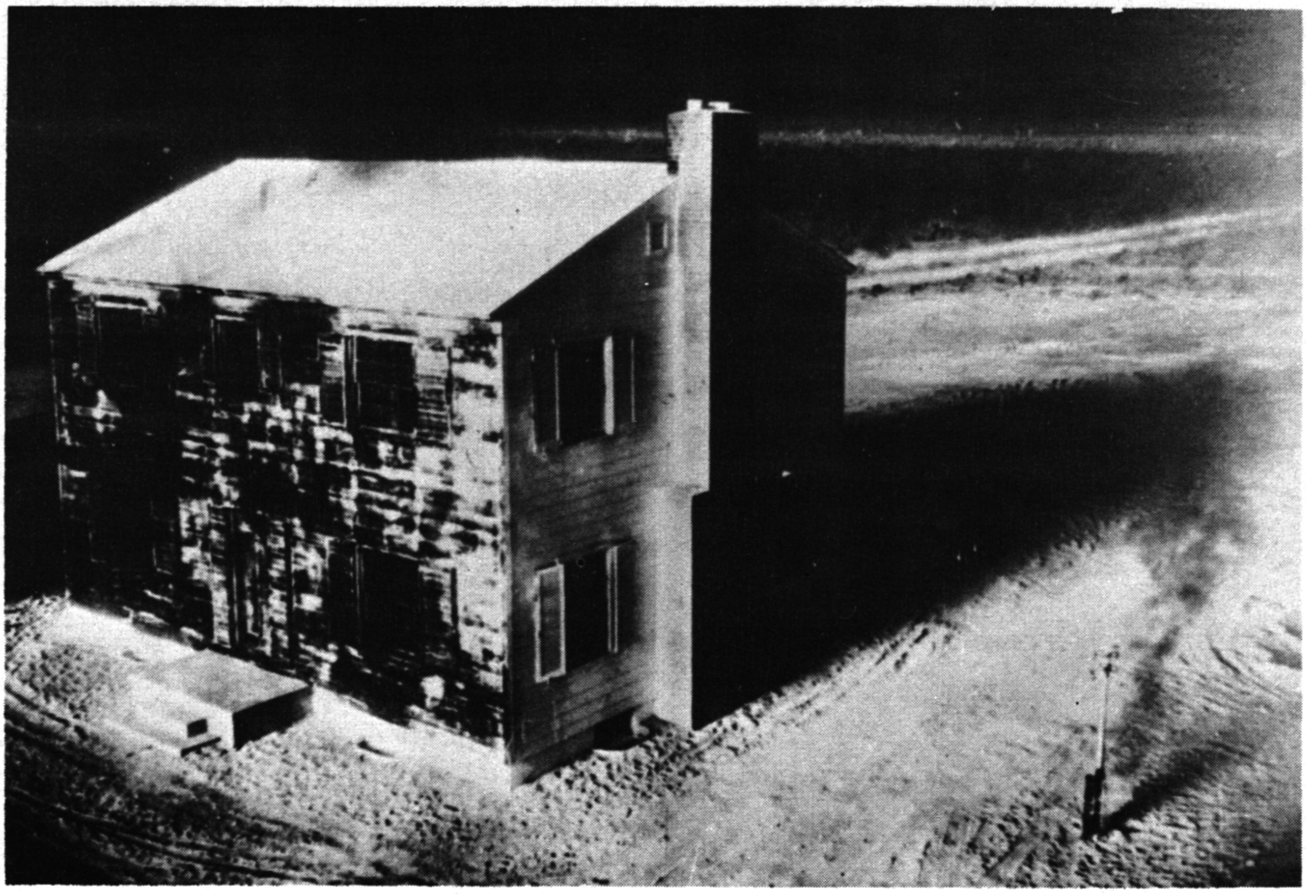

Figure 7.33b. Thermal effects on wood-frame house about ¾ second later.

In order to produce the same thermal effect in a given material, the total amount of thermal energy (per unit area) received must be larger for a nuclear explosion of high yield than for one of lower yield, because a given amount of energy is delivered over a longer period of time, i.e., more slowly, in the former case.

7.36 There is evidence that for thermal radiation pulses of very short duration, such as might arise from air bursts of low-yield weapons or from explosions of large yield at high altitudes, this trend is reversed. In other words, a given amount of energy may be less effective if delivered in a very short pulse, e.g., a fraction of second, than in one of moderate duration, e.g., one or two seconds. In some experiments in which certain materials were exposed to short pulses of thermal radiation, it was observed that the surfaces were rapidly degraded and vaporized. It appeared as if the surface had been "exploded" off the material, leaving the remainder with very little sign of damage. The thermal energy incident upon the material was apparently dissipated in the kinetic energy of the "exploding" surface molecules before the radiation could penetrate into the depth of the material.

Thermal Radiation Effects on Skin and Eyes

7.37 One of the most serious consequences of the thermal radiation from a nuclear explosion is the production of "flash burns" resulting from the absorption of radiant energy by the skin of exposed individuals. In addition, because of the focusing action of the lens of the eye, thermal radiation can cause permanent damage to the eyes of persons who happen to be looking directly at the burst; however, such direct viewing will be fortuitous and rare. What is expected to be a more frequent occurrence, and therefore much more important to defensive action, is the temporary loss of visual acuity (flash blindness or dazzle) resulting from the extreme brightness, particularly at night when the eyes have been adapted to the dark. This may be experienced no matter what the direction in which the individual is facing. The various effects of thermal radiation on human beings will be considered more fully in Chapter XI, which is concerned with the possible hazards to personnel that can arise from a nuclear detonation.

Thermal Radiation Damage to Fabrics, Wood, and Plastics

7.38 Some mention has already been made of the damage caused to fabrics by the high surface temperatures accompanying the absorpignitions may be started in newspaper as a direct result of the absorption of thermal radiation. Under hazy atmospheric conditions, or in the event of a surface burst, the distances obtained from Fig. 7.47 may be decreased. Similarly, in accordance with discussion in § 7.21 *et seq.*, a layer of dense cloud or smoke between the target and the point of burst will decrease the distance over which ignitions may occur.

Thermal Effects on Materials in Japan[3]

7.48 Apart from the actual ignition of combustible materials resulting in fires being started, which will be referred to later, a number of other phenomena observed in Japan testified to the intense heat due to the absorption of thermal radiation. Fabrics (Fig. 7.48a), utility poles (Fig. 7.48b), trees, and wooden posts, up to a radius of 11,000 feet (2.1 miles) from ground zero at Nagasaki, and 9,000 feet

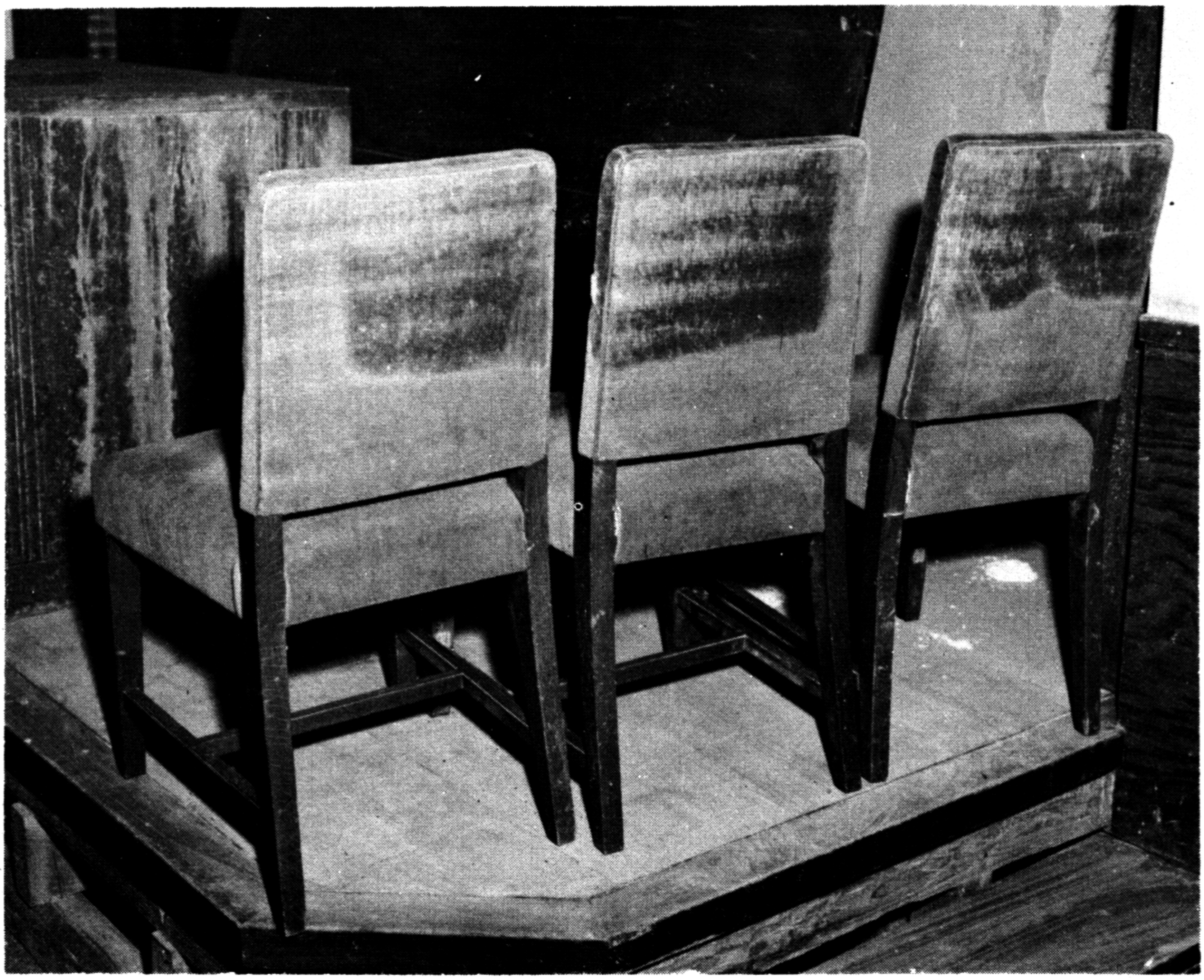

Figure 7.48a. Flash burns on upholstery of chairs exposed to bomb flash at window (1 mile from ground zero at Hiroshima).

[3] The effects of thermal radiations on human beings in Japan are described in Chapter XI.

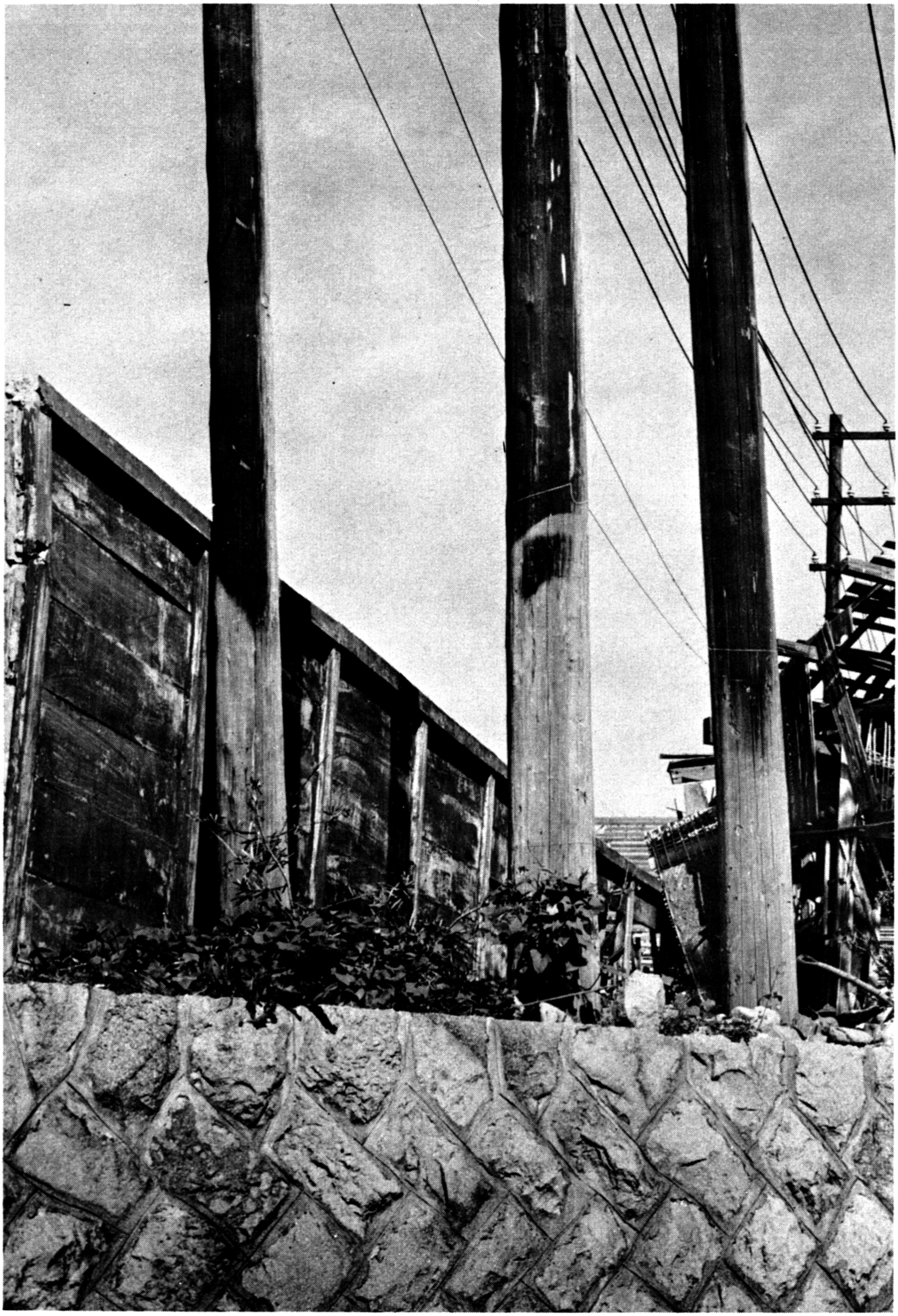

Figure 7.48b. Flash burns on wooden poles (1.7 miles from ground zero at Nagasaki). The uncharred portions were protected from thermal radiation by a fence.

(1.7 miles) at Hiroshima (3 to 4 calories per square centimeter), if not destroyed in the general conflagration, were charred and blackened, but only on the side facing the point of burst. Where there was protection by buildings, walls, hills, and other objects there was no evidence of thermal radiation effects.

7.49 An interesting case of shadowing of this kind was recorded at Nagasaki. The tops and upper parts of a row of wooden posts were heavily charred, but the charred area was sharply limited by the shadow of a wall. The wall was, however, completely demolished

Figure 7.50a. Flash marks produced by thermal radiation on asphalt of bridge in Hiroshima. Where the railings served as a protection from the radiation, there were no marks; the length and direction of the "shadows" indicate the point of the bomb explosion.

by the blast wave which arrived after the thermal radiation. This radiation travels with the speed of light, whereas the blast wave advances much more slowly (§ 3.14).

7.50 From observations of the shadows left by intervening objects where they shielded otherwise exposed surfaces (Figs. 7.50 a and b), the direction of the center of the explosion was located with considerable accuracy. Furthermore, by examining the shadow effects at various places around the explosion, a good indication was obtained of the height of burst. Occasionally, a distinct penumbra was found,

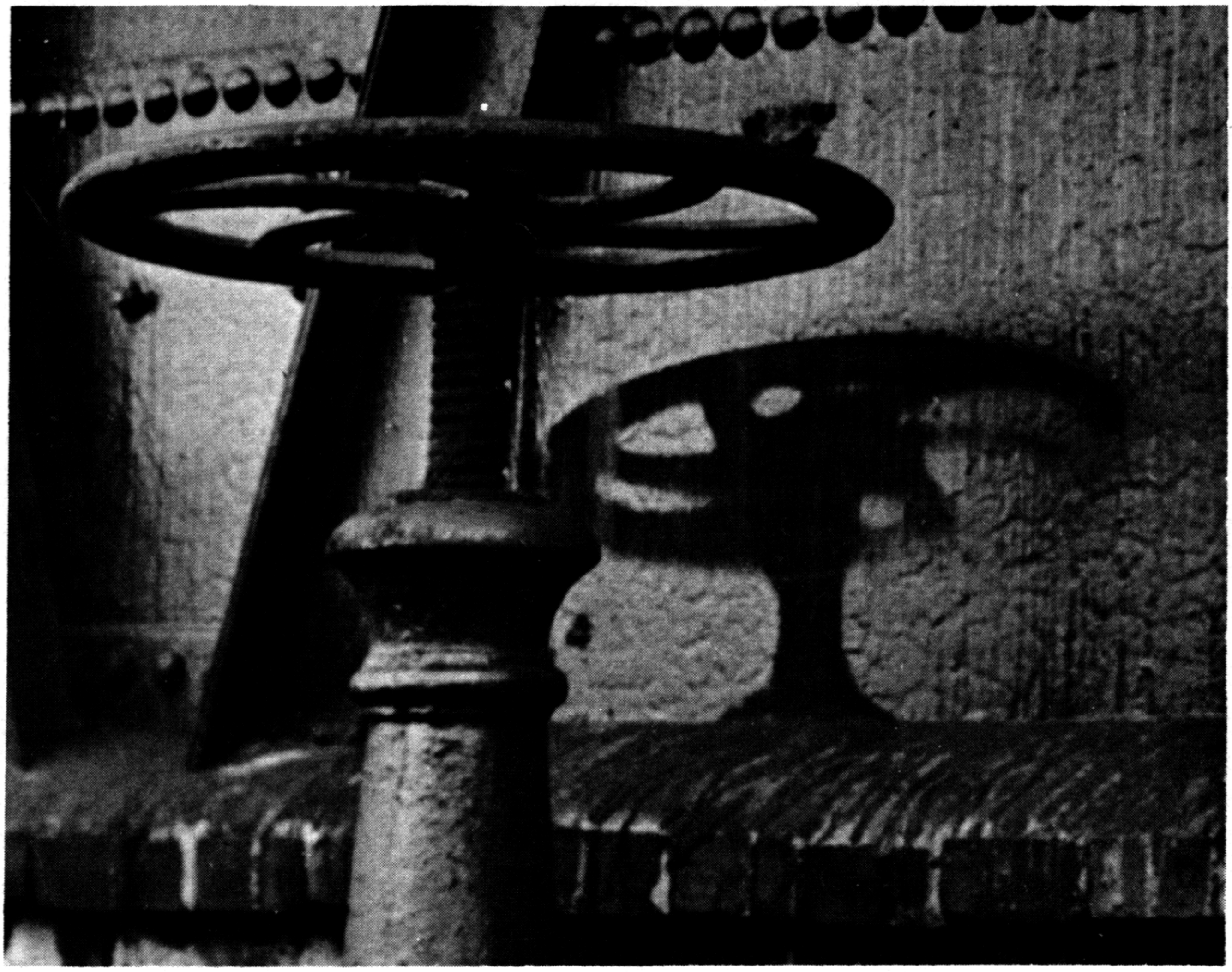

Figure 7.50b. Paint on gas holder scorched by the thermal radiation, except where protected by the valve (1.33 miles from ground zero at Hiroshima).

and from this it was possible to calculate the diameter of the fireball at the time the thermal radiation intensity was at a maximum.

7.51 One of the striking effects of the radiation was the roughening of the surface of polished granite where there was direct exposure. This roughening was attributed to the unequal expansion of the constituent crystals of the stone, and it is estimated that a temperature of at least 600° C (1,100° F) was necessary to produce the observed results. From the depth of the roughening and ultimate flaking of the granite surface, the depth to which this temperature was attained could be determined. These observations were used to calculate the maximum ground temperatures at the time of the explosion. As mentioned in § 7.31, they were extremely high, especially near ground zero.

7.52 Another thermal effect, which proved to be valuable in subsequent studies, was the bubbling or blistering of the dark green (almost black) tile with a porous surface which is widely used for roofing in Japan (Fig. 7.52). The phenomenon was observed out to 3,900 feet (0.75 mile) from the explosion center, where the radiant exposure was about 40 calories per square centimeter. The size of the bubbles and their extent increased with proximity to ground zero, and also with the directness with which the tile itself faced the

Figure 7.52. Blistered surface of roof tile; left portion of the tile was shielded by an overlapping one (0.37 mile from the explosion at Hiroshima).

explosion. In a laboratory test, using undamaged tile of the same kind, it was found that similar blistering could be obtained by heating to 1,800° C (3,270° F) for a period of 4 seconds, although the effect extended deeper into the tile than it did in Japan. From this result, it was concluded that in the nuclear explosion the tile attained a temperature of more than 1,800° C (3,270° F) for a period of less than 4 seconds.

7.53 The difference in behavior of light and dark fabrics exposed to thermal radiation in Japan is also of considerable interest. Light-colored fabrics either reflect or transmit most of the thermal radiation and absorb very little. Consequently, they will not reach such a high temperature and will suffer less damage than dark fabrics which absorb a large proportion of the radiation. In one case, a shirt con-

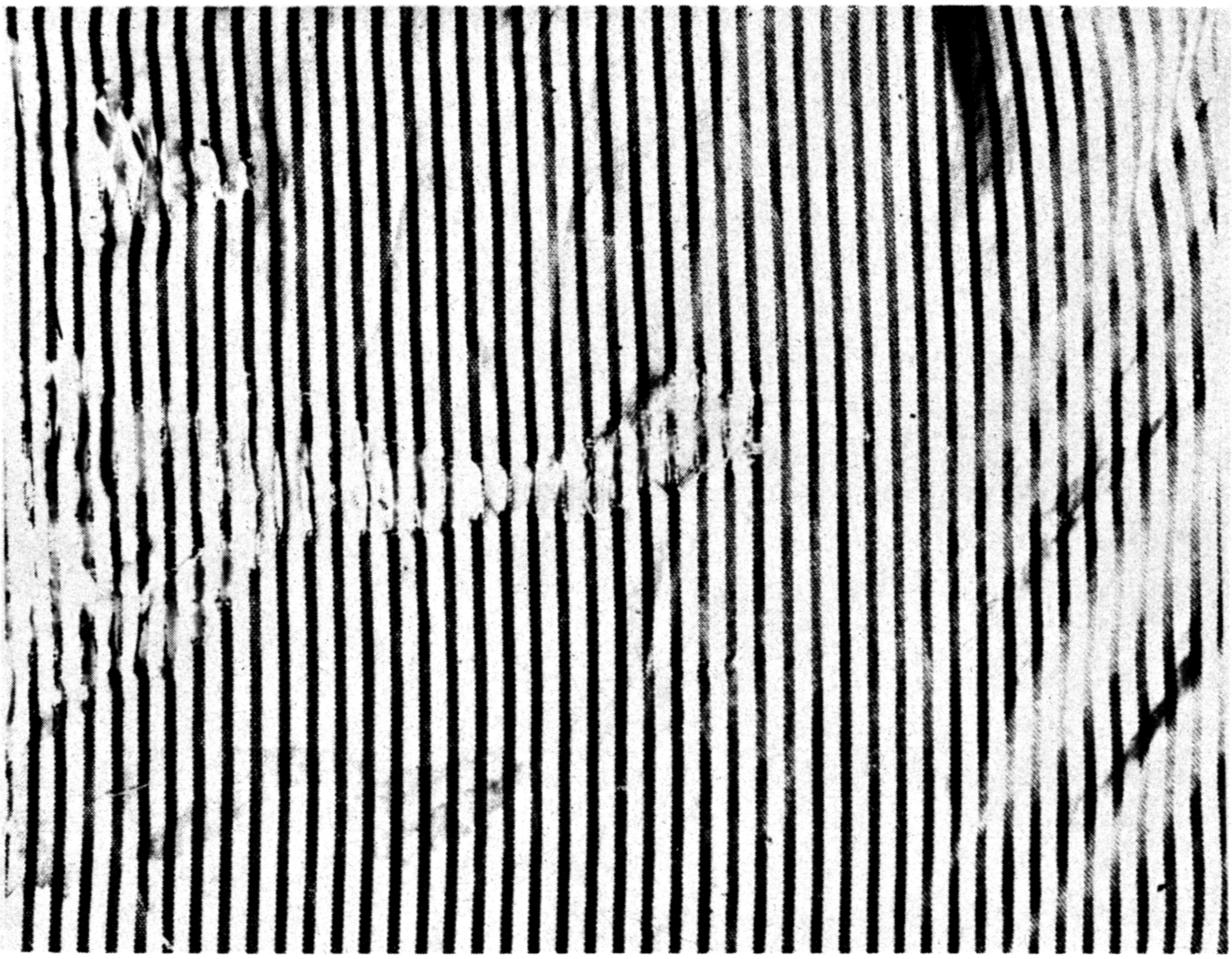

Figure 7.53. The light-colored portions of the material are intact, but some of the dark-colored stripes have been destroyed by the heat from the thermal radiation.

sisting of alternate narrow light and dark gray stripes had the dark stripes burned out, whereas the light-colored stripes were undamaged (Fig. 7.53). Similarly, a piece of paper, which had been exposed about 7,800 feet (1.5 miles) from ground zero (5 calories per square centimeter), had the characters, written in black ink, burned out, but the rest of the paper was not greatly affected.

INCENDIARY EFFECTS

Origin of Fires

7.54 There are two general ways in which fires can originate in a nuclear explosion. First, by the ignition of paper, trash, window curtains, awnings, excelsior, dry grass, and leaves, as a direct result of the absorption of thermal radiation. And second, as an indirect effect of the destruction caused by the blast wave, fires can be started by upset stoves and furnaces, electrical short-circuits, and broken gas lines. No matter how the fire originates, its subsequent spread will be determined by the amount and distribution of combustible materials in the vicinity. The manner whereby fires in cities grow and spread from ignition points is a complex matter which will be discussed later. In the meantime, two aspects of the problem of the development of fires accompanying a nuclear explosion will be considered, namely, (1) the number of points at which fires originate, and (2) the character of the surrounding area.

7.55 The initiation of secondary (or indirect) fires is difficult to analyze, but there are some aspects of direct ignition by thermal radiation which are reasonably clear. The most important appears to be what has been called the "density of ignition points." This is the number of points in a given area, e.g., an acre, where exterior combustible materials are present which will produce a primary ignition and may result in a fire. In general, these materials may be expected to ignite when exposed to at least the appropriate radiant energy values given in Tables 7.40 and 7.44. The data in Fig. 7.55 are based on surveys made in a number of large cities in the United States. It is seen that the density of ignition points is greatest in wholesale distribution and slum residential areas, and is least in good residential and large manufacturing areas.[4] Paper was the commonest ignitable material found everywhere except in downtown retail areas where awnings represented the major source of fire.

7.56 The density of ignition points provides some indication of the chance of fires being started under ideal weather conditions. But the results in Fig. 7.55 are by themselves not sufficient to permit an estimate to be made of the number of significant fires that will actually result. In the first place, at locations closer to ground zero where moderate to severe blast damage occurs, almost all ignitable materials will constitute a fire hazard. On the other hand, at greater distances, only those most easily ignitable will catch fire. Further,

[4] The area types are in accordance with the classification used by the U.S. Bureau of Census.

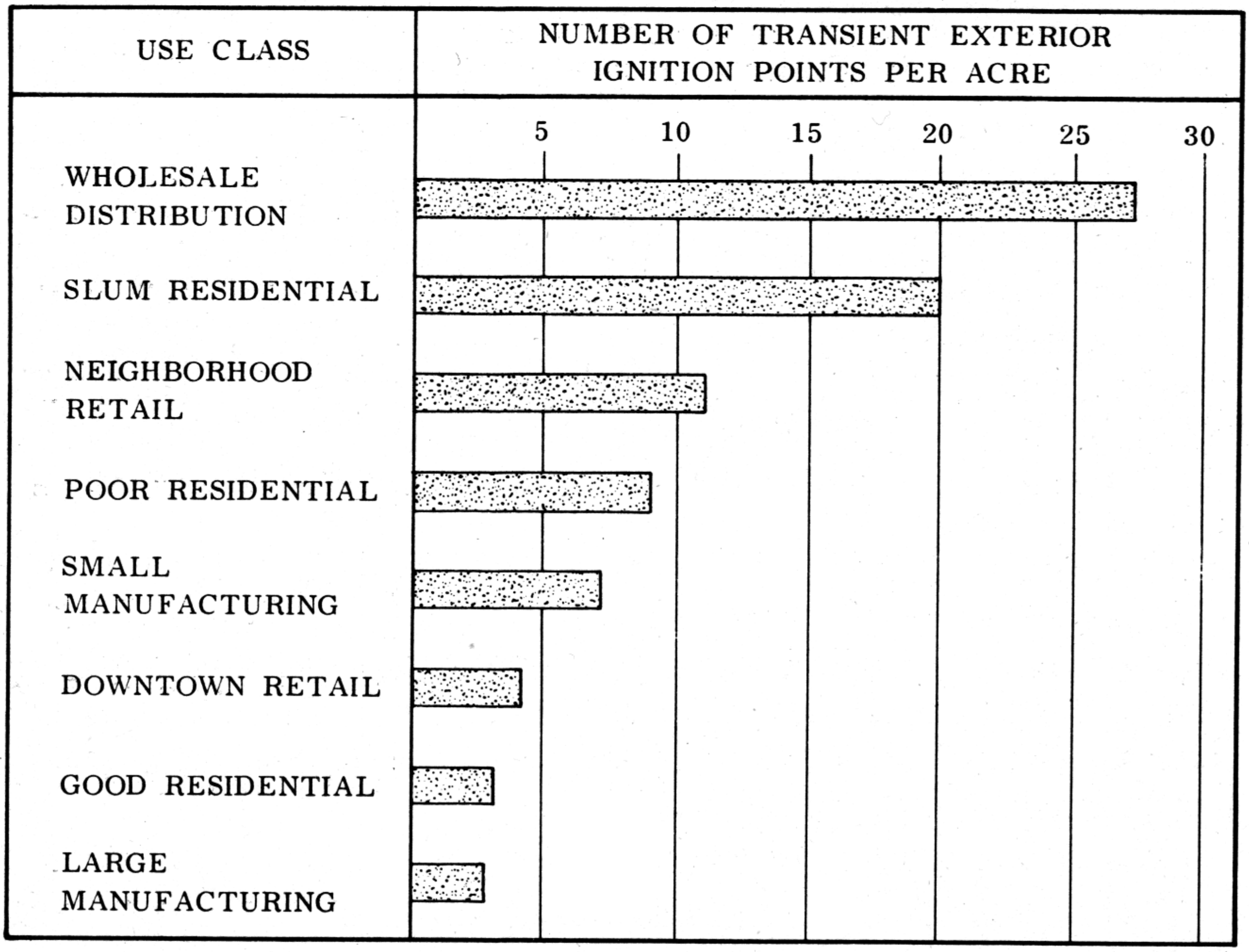

Figure 7.55. Frequency of exterior ignition points for various areas in a city

the formation of a significant fire, capable of spreading, will require appreciable quantities of combustible material close by, and this may not always be available.

7.57 The fact that accumulations of ignitable trash close to a wooden structure represent a real fire hazard was demonstrated at the nuclear tests carried out in Nevada in 1953. In these tests, three miniature wooden houses, each having a yard enclosed with a wooden fence, were exposed to 12 calories per square centimeter of thermal radiation. One house, at the left of Fig. 7.57, had weathered siding showing considerable decay, but the yard was free from trash. The next house also had a clean yard and in addition, the exterior siding was well maintained and painted. In the third house, at the right of the photograph, the siding, which was poorly maintained, was weathered, and the yard was littered with trash.

7.58 The state of the three houses after the explosion is seen in Fig. 7.58. The third house, at the right, soon burst into flame and was burned to the ground. The first house, on the left, did ignite but it did not burst into flame for 15 minutes. The well maintained house in the center with the clean yard suffered scorching only. It is of interest to recall that the wood of a newly erected white-painted

Figure 7.57. Wooden test houses before exposure to a nuclear explosion, Nevada Test Site.

Figure 7.58. Wooden test houses after exposure to a nuclear explosion.

house exposed to about 25 calories per square centimeter was badly charred but did not ignite (see Fig. 7.33b).

7.59 The value of fire-resistive furnishing in decreasing the number of ignition points was also demonstrated in the tests. Two identical, sturdily constructed houses, each having a window 4 feet by 6 feet facing the point of burst, were erected where the thermal radiation exposure was 17 calories per square centimeter. One of the houses contained rayon drapery, cotton rugs, and clothing, and, as was expected, it burst into flame immediately after the explosion and burned completely. In the other house, the draperies were of vinyl plastic, and rugs and clothing were made of wool. Although much ignition occurred, the recovery party, entering an hour after the explosion, was able to extinguish the fires.

7.60 There is another point in connection with the initiation of fires by thermal radiation that needs consideration. This is the possibility that the flame resulting from the ignition of a combustible material may be subsequently extinguished by the blast wind. It was thought that there was evidence for such an effect from an observation made in Japan (§ 7.67), but this may have been an exceptional case. The matter has been studied, both in connection with the effects in Japan and at various nuclear tests, and the general conclusion is that the blast wind has no significant effect in extinguishing fires (§ 7.68).

Spread of Fires

7.61 The spread of fires in a city, including the development of a "fire storm" to which reference is made in § 7.75, depends upon a variety of conditions, e.g., weather, terrain, and closeness and combustibility of the buildings. Information concerning the growth and spread of fires from a large number of ignition points, such as might follow a nuclear explosion, and their coalescence into large fires (or conflagrations) is limited to the experience of World War II incendiary raids and the two atomic bomb attacks. There is consequently some uncertainty concerning the validity of extrapolating from these limited experiences to the behavior to be expected in other cities. It appears, however, that if other circumstances are more-or-less the same, an important criterion of the probability of fire spread is the distance between buildings. It is evident, from general considerations, that the lower the building density or "built-upness" of an area, the less will be the probability that fire will spread from one structure to another. Furthermore, the larger the spaces between buildings the greater the chances that the fire can be extinguished.

7.62 The curve in Fig. 7.62 gives a rough idea of how the probability of fire spread, expressed as a percentage, depends upon the average distance between buildings in a city. The results will be dependent, to some extent, upon the types of structures involved, e.g., whether they are fire-resistive or not, as well as upon the damage caused by the blast wave. It should be noted that Fig. 7.62 applies to fire spread accompanying a nuclear explosion, when a large number of small fires are started directly by thermal radiation and indirectly in other ways.

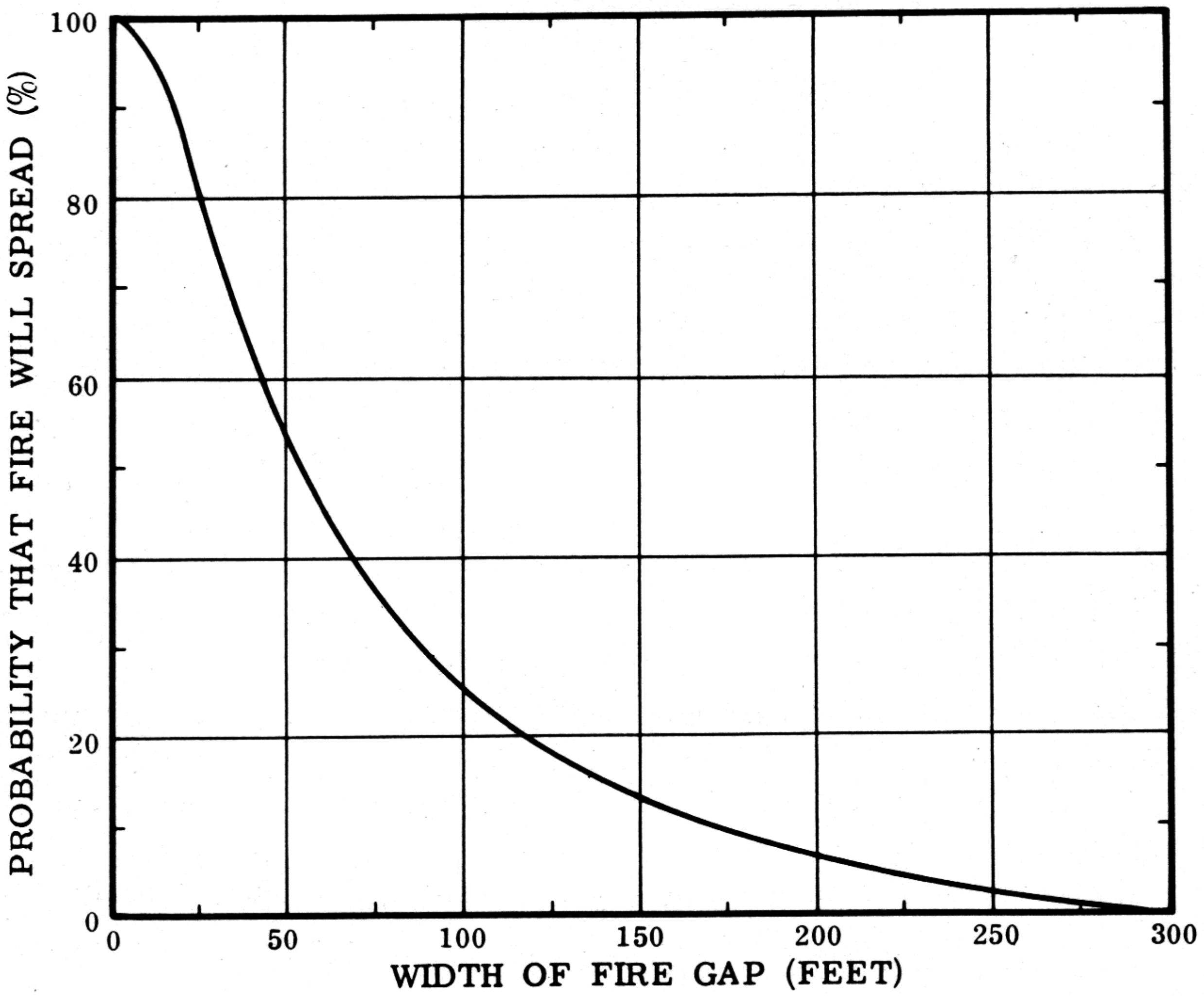

Figure 7.62. Width of gap and probability of fire spread.

7.63 Another aspect of fire spread is the development of mass fires in a forest following primary ignition of dried leaves, grass, and rotten wood by the thermal radiation. Some of the factors which will influence the growth of such fires are the moisture content of the trees, topography, and meteorological conditions. Low atmospheric humidity, strong winds, and steep terrain favor the development of forest fires. In general, a deciduous forest, particularly when in leaf, may be expected to burn less rapidly and with less intensity than a forest of coniferous trees. Green leaves and the trunks of trees would act as shields against thermal radiation, so that the number of points at which ignition occurs in a forest may well be less than would appear at first sight.

INCENDIARY EFFECTS IN JAPAN

The Nuclear Bomb as an Incendiary Weapon

7.64 The incendiary effects of a nuclear explosion do not present any especially characteristic features. In principle, the same overall result, as regards destruction by fire and blast, might be achieved by the use of conventional incendiary and high-explosive bombs. It has been estimated, for example, that the fire damage to buildings and other structures suffered at Hiroshima could have been produced by about 1,000 tons of incendiary bombs distributed over the city. It can be seen, however, that since this damage was caused by a single nuclear bomb of only 20 kilotons energy yield, nuclear weapons are capable of causing tremendous destruction by fire, as well as by blast.

7.65 Evidence was obtained from the nuclear explosions over Japan that the damage by fire is much more dependent upon local terrain and meteorological conditions than are blast effects. At both Hiroshima and Nagasaki the distances from ground zero at which particular types of blast damage were experienced were much the same. But the ranges of incendiary effects were quite different. In Hiroshima, for example, the total area severely damaged by fire, about 4.4 square miles, was roughly four times as great as in Nagasaki. One contributory cause was the irregular layout of Nagasaki as compared with Hiroshima; also greater destruction could probably have been achieved by a change in the point of burst. Nevertheless, an important factor was the difference in terrain, with its associated building density. Hiroshima was relatively flat and highly built up, whereas Nagasaki had hilly portions near ground zero that were bare of structures.

Origin and Spread of Fires in Japan

7.66 Definite evidence was obtained from Japanese observers that the thermal radiation caused thin, dark cotton cloth, such as the black-out curtains that were in common use during the war, thin paper, and dry, rotted wood to catch fire at distance up to 3,500 feet (0.66 mile) from ground zero (about 35 calories per square centimeter). It was reported that a cedar bark roof farther out was seen to burst into flame, apparently spontaneously, but this was not definitely confirmed. Abnormal enhanced amounts of radiation, due to re-

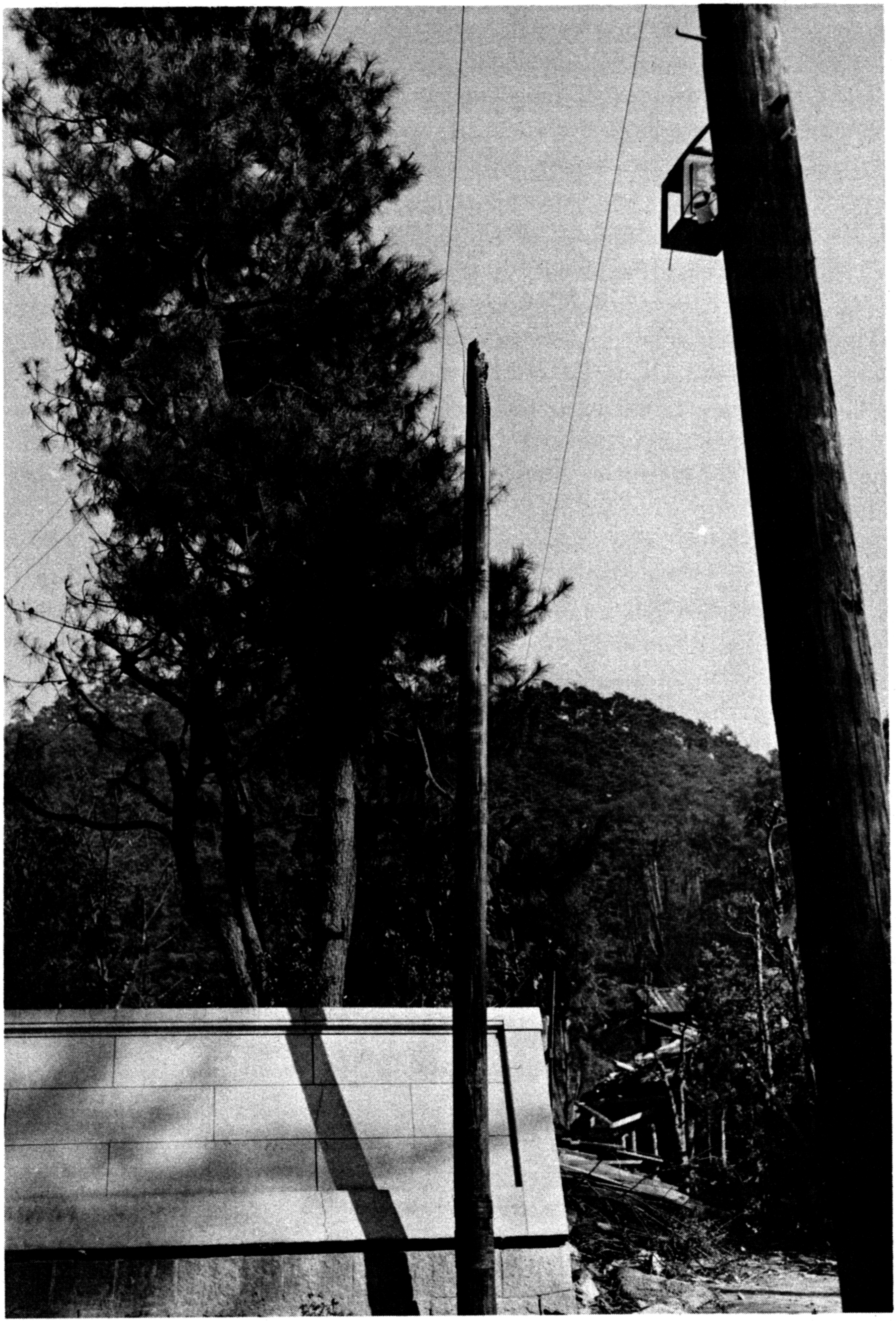

Figure 7.66. The top of a wood pole was reported as being ignited by the thermal radiation (1.25 miles from ground zero at Hiroshima). Note the unburned surroundings; the nearest burned building was 360 feet away.

flection, scattering, and focusing effects, might have caused fires to originate at isolated points (Fig. 7.66).

7.67 Interesting evidence of the ignition of sound wood was found about a mile from ground zero at Nagasaki, where the radiant exposure was approximately 15 calories per square centimeter. A light piece of wood, similar to the flat side of an orange crate, had its front surface charred. In addition, however, blackening was observed through cracks and nail holes, where the thermal radiation would not have penetrated, and also around the edges adjoining the charred surface. A possible explanation is that the exposed surface of the wood had actually ignited, due to the heat from the thermal radiation, and the flames had spread through the cracks and holes around the edges for several seconds, before they were extinguished by the blast wind.

7.68 From the evidence of charred wood found at both Hiroshima and Nagasaki, it was originally concluded that such wood had actually been ignited by thermal radiation and that the flames were subsequently extinguished by the blast. But it now seems more probable that, apart from some exceptional instances, such as that just described, there was no actual ignition of the wood. The absorption of the thermal radiation caused charring in sound wood but the temperatures were generally not high enough for ignition to occur (§ 7.33). Rotted and checked wood and excelsior, however, have been observed to burn completely, and the flame was not greatly affected by the blast wave.

7.69 It is not known to what extent thermal radiation contributed to the initiation of fires in the nuclear bombings in Japan. It is possible that, up to a mile or so from ground zero, some fires may have originated from secondary causes, such as upsetting of stoves, electrical short-circuits, broken gas lines, and so on, which were a direct effect of the blast wave. A number of fires in industrial plants were initiated by furnaces and boilers being overturned, and by the collapse of buildings on them.

7.70 Once the fires had started, there were several factors, directly related to the destruction caused by the nuclear explosion, that influenced their spreading. By breaking windows and blowing in or damaging fire shutters (Fig. 7.70), by stripping wall and roof sheathing, and collapsing walls and roofs, the blast made many buildings more vulnerable to fire. Noncombustible (fire-resistive) structures were often left in a condition favorable to the internal spread of fires by damage at stairways, elevators, and in firewall openings as well as by the rupture and collapse of floors and partitions (see Fig. 5.89d).

7.71 On the other hand, when combustible frame buildings were blown down, they did not burn as rapidly as they would have done had they remained standing. Moreover, the noncombustible debris produced by the blast frequently covered and prevented the burning of combustible material. There is some doubt, therefore, whether on the whole the effect of the blast was to facilitate or to hinder the development of fires at Hiroshima and Nagasaki.

Figure 7.70. Fire shutters in building blown in or damaged by the blast; shutter at center probably blown outward by blast passing through building (0.57 mile from ground zero at Hiroshima).

7.72 Although there were firebreaks, both natural, e.g., rivers and open spaces, and artificial, e.g., roads and cleared areas, in the Japanese cities, they were not very effective in preventing the fires from spreading. The reason was that fires often started simultaneously on both sides of the firebreaks, so that they could not serve their intended purpose. In addition, combustible materials were frequently strewn across the firebreaks and open spaces, such as yards and street areas, by the blast, so that they could not prevent the spread of fires. Nevertheless, there were a few instances where firebreaks assisted in preventing the burnout of some fire-resistive buildings.

7.73 One of the important aspects of the nuclear attacks on Japan was that, in the large area that suffered simultaneous blast damage, the fire departments were completely overwhelmed. It is true that the fire-fighting services and equipment were poor by American standards, but it is doubtful if much could have been achieved, under the circumstances, by more efficient fire departments. At Hiroshima, for example, 70 percent of the fire-fighting equipment was crushed in the collapse of fire houses, and 80 percent of the personnel were unable to respond. Even if men and machines had survived the blast, many fires would have been inaccessible because of the streets being blocked with debris. For this reason, and also because of the fear of being trapped, a fire company from an area which had escaped destruction was unable to approach closer than 6,600 feet (1.25 miles) from ground zero at Nagasaki. It was almost inevitable, therefore, that all buildings within this range would be destroyed.

7.74 Another contributory factor to the destruction by fire was the failure of the water supply in both Hiroshima and Nagasaki. The pumping stations were not largely affected, but serious damage was sustained by distribution pipes and mains, with a resulting leakage and drop in available water pressure. Most of the lines above ground were broken by collapsing buildings and by heat from the fires which melted the pipes. Some buried water mains were fractured and others were broken due to the collapse or distortion of bridges upon which they were supported (§ 5.117).

Fire Storm in Hiroshima

7.75 About 20 minutes after the detonation of the nuclear bomb at Hiroshima, there developed the phenomenon known as "fire storm." This consisted of a wind which blew toward the burning area of the city from all directions, reaching a maximum velocity of 30 to 40 miles per hour about 2 to 3 hours after the explosion, decreasing to light or moderate and variable in direction about 6 hours after. The wind was accompanied by intermittent rain, light over the center of the city and heavier about 3,500 to 5,000 feet (0.67 to 0.95 mile) to the north and west. Rain is often associated with a fire storm and is apparently due to the condensation of moisture on particles from the fire when they reach a cooler area. Because of the strong inward draft at ground level, the fire storm was a decisive factor in limiting the spread of fire beyond the initial ignited area. It accounts for the fact that the radius of the burned-out area was so uniform in Hiroshima and was not much greater than the range in which fires started soon after the explosion. However, virtually everything combustible within this region was destroyed.

7.76 It should be noted that the fire storm is by no means a special characteristic of nuclear weapons. Similar fire storms have been reported as accompanying large forest fires in the United States, and especially after incendiary bomb attacks in both Germany and Japan during World War II. The high winds are produced largely by the updraft of the heated air over an extensive burning area. They are thus the equivalent, on a very large scale, of the draft of a chimney under which a fire is burning. Because of limited experience, the conditions for the development of fire storms in cities are not well known. It appears, however, that some, although not necessarily all, of the essential requirements are the following: (1) thousands of nearly simultaneous ignitions over an area of at least a square mile, (2) heavy building density, e.g., more than 20 percent of the area is covered by buildings, and (3) little or no ground wind. Based on these criteria, only certain sections—usually the older and slum areas—of a very few cities in the United States would be susceptible to fire storm development.

7.77 It should be mentioned that no definite fire storm occurred at Nagasaki, although the velocity of the southwest wind, blowing between the hills, increased to 35 miles an hour when the conflagration had become well established, perhaps about 2 hours after the explosion. This wind tended to carry the fire up the valley in a direction where there was nothing to burn. Some 7 hours later, the wind had shifted to the east and its velocity had dropped to 10 to 15 miles per hour. These winds undoubtedly restricted the spread of fire in the respective directions from which they were blowing. The small number of dwellings exposed in the long narrow valley running through Nagasaki probably did not furnish sufficient fuel for the development of a fire storm as compared to the many buildings on the flat terrain at Hiroshima.

TECHNICAL ASPECTS OF THERMAL RADIATION [5]

Distribution and Absorption of Energy From the Fireball

7.78 Spectroscopic studies made in the course of weapons tests have shown that the fireball does not behave exactly like a black body, i.e., as a perfect radiator. Generally, the proportion of radiations of longer wave length (greater than 5,500 A)[6] corresponds to higher black body temperatures than does the shorter wave emission. The assumption of black body behavior for the fireball, however, serves as a reasonable approximation in interpreting the thermal

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

[6] The symbol "A" represents the "angstrom", i.e., 10^{-8} cm, the unit in which radiation wave lengths are commonly expressed.

radiation emission characteristics. For a black body, the distribution of radiant energy over the spectrum can be related to the surface temperature by Planck's radiation equation. If $E_\lambda d\lambda$ denotes the energy density, i.e., energy per unit volume, in the wave length interval λ to $\lambda+d\lambda$, then,

$$E_\lambda=\frac{8\pi hc}{\lambda^5}\cdot\frac{1}{e^{hc/\lambda kT}-1}, \tag{7.78.1}$$

where c is the velocity of light, h is Planck's quantum of action, k is Boltzmann's constant, i.e., the gas constant per molecule, and T is the absolute temperature. It will be noted that hc/λ is the energy of the photon of wave length λ (§ 1.70).

7.79 From the Planck equation it is possible to calculate the rate of energy emission (or radiant power) of a black body for a given wave length, i.e., J_λ, as a function of wave length for any specified temperature, since

$$J_\lambda=\frac{c}{4}E_\lambda, \tag{7.79.1}$$

where J_λ is in units of energy (ergs) per unit area (cm^2) per unit time (sec) per unit wave length (A). The results of such calculations for temperatures ranging from 100 million (10^8) degrees to 2,000° K are shown in Fig. 7.79. It is seen that the total radiant power, which is given by the area under each curve, decreases greatly as the temperature is decreased.

7.80 An important aspect of Fig. 7.79 is the change in location of the curves with temperature; in other words, the spectrum of the radiant energy varies with the temperature. At high temperatures, radiations of short wave length predominate, but at low temperatures those of long wave length make the major contribution. For example, in the exploding weapon, before the formation of the fireball, the temperature is several tens of million degrees Kelvin. Most of the (primary) thermal radiation is then in the wave length range from about 0.1 to 100 A, i.e., 120 to 0.12 kev energy, corresponding roughly to the soft X-ray region. This is the basis of the statement made earlier that the primary thermal radiation from a nuclear explosion consists largely of X-rays. These radiations are absorbed by the surrounding air to form the fireball from which the effective thermal radiation of present interest is emitted. Since the surface temperature of the fireball is generally below 10,000° K, the radiation is mainly in the ultraviolet, visible, and infrared regions of the spectrum. The dimensions of the fireball in which the thermal X-rays are absorbed depends on the ambient air density, as will be seen shortly.

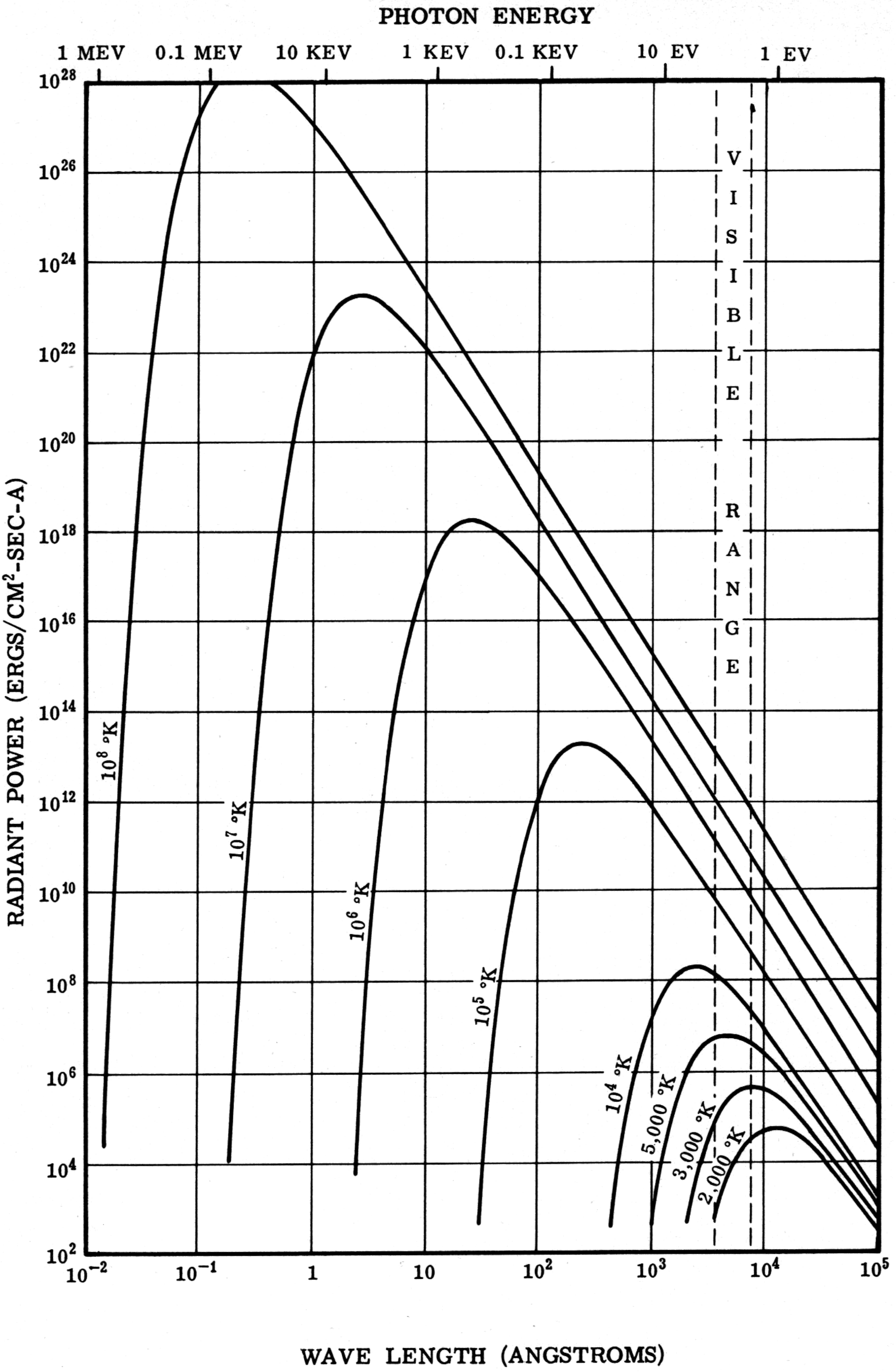

Figure 7.79. Radiant power of a black body as a function of wave length at various temperatures.

7.81 It will be recalled that the thermal radiation received at the earth's surface differs to some extent from that leaving the fireball. The reason is that the radiations of shorter wave length, i.e., in the ultraviolet, are more readily absorbed than the others by the atmosphere between the burst point and the earth's surface. The thermal radiation received at a distance from a nuclear explosion is fairly characteristic of a black body at a temperature of about 6,000 to 7,000° K, although somewhat depleted in the ultraviolet and other shorter wave lengths. Even if the detonation occurs at very high altitudes, the thermal radiation from the low-density fireball must pass through the denser atmosphere before reaching the ground. The effective thermal radiation received on the earth's surface is thus also composed of the longer wave lengths.

7.82 An expression for the wave length (λ_m) corresponding to the maximum in the radiant power as a function of the black body temperature can be obtained by differentiating equation (7.79.1) with respect to wave length and equating the result to zero. It is then found that

$$\lambda_m = \frac{C}{T}, \tag{7.82.1}$$

where C is a constant, equal to 2.90×10^7 angstroms-degrees K. This expression is known as Wien's displacement law.

7.83 The temperature at which the maximum in the radiant power distribution from a black body should just fall into the visible spectrum, i.e., wave length 3,850 A, is found from equation (7.82.1) to be about 7,500° K. This happens to be very close to the maximum surface temperature of the fireball after the minimum, i.e., during the second radiation pulse (Fig. 2.113). Since the apparent surface temperature generally does not exceed 8,000° K and the average is considerably less, it is evident that most of the thermal energy emitted in the second pulse should consist mainly of visible and infrared rays, with little in the ultraviolet region of the spectrum. This has been found to be the case in actual tests, even though the fireball deviates appreciably from black body behavior at this stage.

7.84 The mean free path (§ 2.104) in cold air, at sea-level density, of X-ray photons with energies from about 0.5 to 15 kev is given by the approximate relationship

$$\text{Mean free path} \approx \frac{E^3}{5} \text{ cm}, \tag{7.84.1}$$

where E is the photon energy in kilo-electron volts (kev). In order to make some order-of-magnitude calculations of the distances in which thermal X-rays from a nuclear explosion are absorbed in air, a convenient round-number temperature of 10^7 degrees Kelvin will be used for simplicity. According to equation (7.82.1), the wave length at which the rate of emission of radiation from a black body at this temperature is a maximum is 2.9 A. According to equation (1.70.2) this corresponds to a photon energy of 4.3 kev, and from equation (7.84.1) the mean free path of these photons in normal air is about 15 cm. In traversing a distance of one mean free path the energy of the radiations decreased by a factor of e, i.e., approximately 2.7; hence 90 percent of the energy will be deposited within a radius of 2.3 mean free paths. It is seen, therefore, that 4.3-kev radiation will be largely absorbed in a distance of about 35 cm, i.e., a little over 1 foot, in a sea-level atmosphere.

7.85 The primary thermal radiations from a nuclear explosion cover a wide range of wave lengths, as is evident from Fig. 7.79. However, for the present purpose, which is to obtain a rough indication of the initial size of the fireball, the wave length (or energy) at which the radiant power from a black body is a maximum may be taken as typical. It follows, therefore, from the results given above that the thermal X-rays from a nuclear explosion will be almost completely absorbed by about a foot of air at normal density. Because the oxygen and nitrogen in the air in the vicinity of the explosion are considerably ionized, they do not absorb as effectively as do neutral molecules. Nevertheless, in a nuclear explosion in the atmosphere where the air density does not differ greatly from the sea-level value, most of the X-rays, which constitute the primary thermal radiation, will be absorbed within a few feet of the explosion. It is in this manner that the initial fireball is formed in an air burst.

7.86 With increasing altitude, the air density decreases roughly by a factor of ten for every 10 miles (see § 10.75), so that at 150,000 feet (approximately 30 miles) the density is about 10^{-3} of the sea-level value. The mean free path of the photon varies inversely as the density, so that for nuclear explosions at an altitude of about 30 miles, the region of the air heated by X-rays, which is equivalent to the fireball, extends over a radius of some thousands of feet. In spite of the lower density, the mass of heated air in this large volume is much greater than in the fireball associated with a nuclear explosion at lower altitudes, and so the temperature attained by the air is lower.

7.87 At altitudes of about 100,000 to 350,000 feet (20 to 70 miles) the manner in which the thermal radiation is emitted from a nuclear detonation is somewhat different from that at lower altitudes. At the upper limit (350,000 feet), the heated (fireball) region can be about 0.5 to 6 miles in extent for yields of 1 kiloton to 1 megaton, respectively. The time required for a shock wave to form is of the order of 0.1 to 1 sec for these yields. For the reasons given in § 2.123, the thermal radiation is emitted from the fireball in a single pulse of relatively short duration. The limited data available indicate that the thermal radiation received on the ground from bursts at high altitudes is consistent with the statement (§ 7.25) that roughly 25 to 35 percent of the total yield of the weapon is converted into effective thermal radiation.

7.88 For altitudes in excess of 350,000 feet (above 70 miles) the air density is less than 10^{-7} of that at sea level. The mean free path of the dominant thermal X-rays produced in a nuclear explosion is then several hundred miles. In spite of the low density, the mass of air in which the thermal energy is deposited is many million tons, and so the temperature will not increase appreciably. At the low air temperatures, the thermal radiation emitted from an explosion in the megaton range is incapable of causing damage at the earth's surface.

Total Radiant Power From Fireball

7.89 According to the Stefan-Boltzmann law, the total amount of energy (of all wave lengths), J, radiated per square centimeter per second by a black body in all directions in one hemisphere is related to the absolute temperature, T, by the equation

$$J=\sigma T^4, \tag{7.89.1}$$

where σ is the Stefan-Boltzmann constant. The value of J can also be obtained by integration of equation (7.79.1) over all wave lengths from zero to infinity. It is then found that

$$\begin{aligned}\sigma&=2\pi^5k^4/15h^3c^2\\&=5.67\times10^{-5}\text{ erg/(cm}^2\text{) (sec) (deg}^4\text{)}\\&=1.38\times10^{-12}\text{ cal/(cm}^2\text{) (sec) (deg}^4\text{).}\end{aligned}$$

With σ known, the total radiant energy intensity from the fireball behaving as a black body can be readily calculated for any required temperature.

7.90 In accordance with the definition of J, given above, it follows that the total rate of emission of radiant energy from the fireball can be obtained upon multiplying the expression in equation

(7.89.1) by the area. If R is the radius of the fireball, its area is $4\pi R^2$, so that the total rate of thermal energy emission (or total radiant power) is $\sigma T^4 \times 4\pi R^2$. Representing this quantity by the symbol P, it follows that

$$P = 4\pi\sigma T^4 R^2$$
$$= 1.71 \times 10^{-11}\ T^4 R^2 \text{ calories per second,}$$

where T is in degrees Kelvin and R is in centimeters. Alternatively, if the radius, R, is expressed in feet, then,

$$P = 1.59 \times 10^{-8}\ T^4 R^2 \text{ calories per second.} \qquad (7.90.1)$$

7.91 The power, P, is measured directly as a function of time, t, for each explosion, but instead of plotting P versus t, a curve is drawn of the scaled power, i.e., P/P_{max}, versus the scaled time, i.e., t/t_{max}, where P_{max} is the maximum value of the thermal power, corresponding to the temperature maximum in the second pulse, and t_{max} is the time at which this maximum is attained. The resulting (left scale) curve, shown in Fig. 7.91 is then of general applicability, irrespective of the yield of the explosion. The zero of the scaled time axis is taken as the time of the first minimum; as seen in §2.116, this is approximately equal to $0.0025 W^{1/2}$ second, where W is the total explosion yield in kilotons. The first pulse is so short that the amount of thermal radiation energy received prior to the first minimum is only about 1 percent of the total.

7.92 In order to make the power-time curve specific for any particular explosion energy yield, it is necessary to know the appropriate values of P_{max} and t_{max}. These are related approximately to the yield, W kilotons, in the following manner for air bursts:

$$P_{max} \approx 4 W^{1/2} \text{ kilotons per second,}$$

and

$$t_{max} \approx 0.032\ W^{1/2} \text{ seconds.}$$

For air bursts in the megaton range, the value of t_{max} may be somewhat less than given by this expression. For a contact surface burst the fireball develops in a manner approaching that for an air burst of twice the yield, because the blast wave energy is reflected back from the surface into the fireball (§§ 2.117, 3.30). Hence, t_{max} may be expected to be larger than for an air burst of the same actual yield.

7.93 The amount of thermal energy, E, emitted by the fireball in an air burst up to any specified time can be obtained from the area

7.99 If there is no atmospheric attenuation, the thermal energy, E_{tot}, at a distance D from the explosion, may be regarded as being spread uniformly over the surface of a sphere of area $4\pi D^2$. The energy received per unit area of the sphere would thus be $E_{tot}/4\pi D^2$. If attenuation were due only to absorption in a uniform atmosphere, e.g., for an air burst, this quantity would be multiplied by the factor $e^{-\kappa D}$, where κ is an absorption coefficient averaged over the whole spectrum of wave lengths. Hence, in these circumstances, using the symbol Q to represent the radiant exposure, i.e., the energy received per unit area normal to the direction of propagation, at a distance D from the explosion, it follows that

$$Q=\frac{E_{tot}}{4\pi D^2}e^{-\kappa D}. \qquad (7.99.1)$$

7.100 When scattering of the radiation occurs, in addition to absorption, the coefficient κ is no longer a constant but is a function of distance, and it is then not convenient to express the attenuation by means of an exponential factor. A more useful formulation which has been developed is represented by

$$Q=\frac{E_{tot}T}{4\pi D^2}, \qquad (7.100.1)$$

where the transmittance, T, i.e., the fraction of the radiation (direct and scattered) which is transmitted, is a complex function of the visibility (scattering), absorption, and distance.[7]

7.101 The amount of thermal radiation energy, E_{tot}, emitted from a nuclear detonation can be related to the weapon yield W by the general expression

$$E_{tot}=fW, \qquad (7.101.1)$$

where f is the fraction of the total yield in the form of thermal radiation energy. Hence, the radiant exposure can be expressed as

$$Q=\frac{fTW}{4\pi D^2} \qquad (7.101.2)$$

by substituting fW for E_{tot} in equation (7.100.1).

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[7] Scattered radiation does not cause permanent damage to the retina of the eye. Hence, to determine the effective radiant exposure in this connection equation (7.99.1) should be used; κ is about 0.03 km^{-1} for a visibility of 80 km (50 miles), 0.1 km^{-1} for 40 km (25 miles), and 0.2 km^{-1} for 20 km (12.4 miles). Scattered radiation can, however, contribute to flash blindness, resulting from the dazzling effect of bright light.

7.102 In a weapons test, it is possible to measure Q and W, and since the distance D from the explosion is known the magnitude of the product fT can be determined from equation (7.101.2). To obtain f, the value of T for the atmosphere between the explosion and the observation point must be known. However, the atmospheric transmittance over a long distance varies with both time and direction, so that the value at the instant when Q is measured cannot be obtained with a precision better than about ± 20 percent. Consequently, average values of T, such as those given in Fig. 7.104 below, are employed. Using these data and analyzing values of the product fT from a large number of weapons tests, f is found to range from about 0.3 to 0.4, with a mean of about one-third, for air bursts.

7.103 By utilizing the fact that 1 kiloton of TNT is equivalent to 10^{12} calories and taking f as $\frac{1}{3}$, equation (7.101.2) for an air burst becomes

$$Q(\text{cal/sq cm}) = \frac{10^{12}WT}{12\pi D^2}, \tag{7.103.1}$$

where D is in centimeters. If the distance (or slant range) is expressed in miles, equation (7.103.1) reduces approximately to

$$Q(\text{cal/sq cm}) \approx \frac{1.04WT}{D^2}, \tag{7.103.2}$$

where D is now in miles.

7.104 The value of T, for any given atmospheric condition, depends on the solid angle over which scattered radiation can reach a particular exposed object. For the present purpose it will be assumed that the target is such, e.g., an appreciable flat area, that scattered radiation is received from all directions above, in addition to the direct thermal radiation from the source. The variation of the transmittance with distance from the explosion for the two different visibility ranges is shown in Fig. 7.104; one curve is for a visibility of 50 miles and 5 grams of water vapor per cubic meter of air and the other is for a visibility of 10 miles and 10 grams of water vapor per cubic meter. The data may be considered to be reliable up to distances of half the visibility in each case.

7.105 In order to simplify the use of equation (7.103.2), in conjunction with Fig. 7.104, the values of the thermal radiation exposure, Q, in calories per square centimeter, for various distances (slant ranges), D, from an air burst are plotted for $W=1$ kiloton in Fig. 7.105. The results are applicable provided D is less than half the appropriate visibility, between 10 and 50 miles. The thermal energy received from an explosion of *W* kilotons is then obtained upon multiplying the radiant exposure for the same distance in Fig. 7.105 by *W*. If the distances of interest are greater than half the visibility range, the thermal radiation exposures derived from Fig. 7.105 will be less reliable but in the majority of cases they will be conservative.

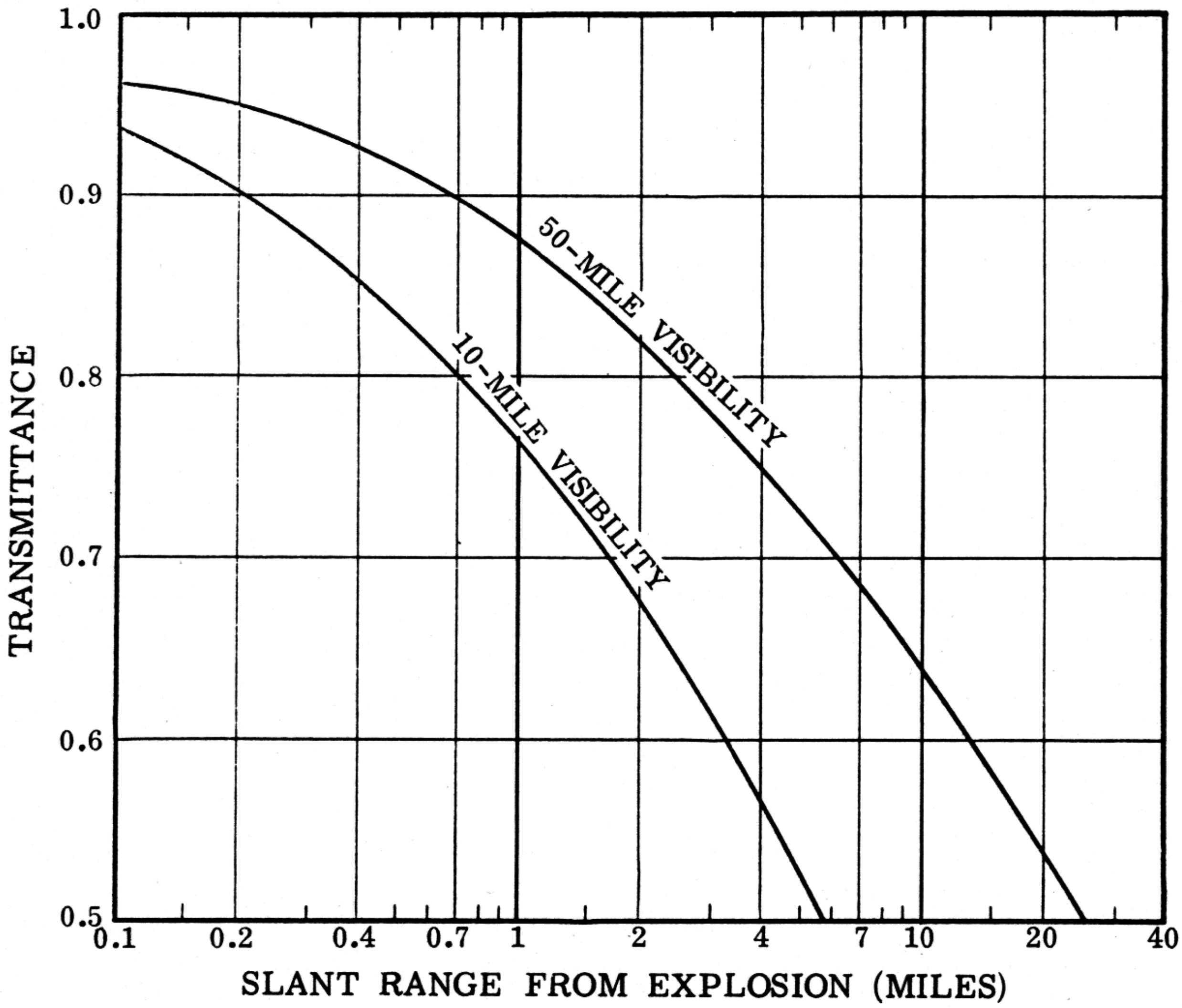

Figure 7.104. Atmospheric transmittance as a function of distance for visibilities of 10 miles and 50 miles.

7.106 For a surface burst, the radiant exposures along the earth's surface will be less than for equal distances from an air burst of the same total yield. This difference is partly due, as indicated in § 7.23, to the decreased transmittance of the intervening low air layer due to dust and water vapor produced by the explosion. Furthermore, the normal atmosphere close to the earth's surface transmits less than at higher altitudes. The thermal exposure from a surface burst thus ranges from about three-quarters at short distances to one-half at longer distances of the corresponding value for an air burst derived from equation (7.103.2) or from Fig. 7.105. In other words the *f*

The plot in Fig. 7.105, which is in two parts for convenience of representation, shows the amount of thermal energy (or radiant exposure) in calories per square centimeter received at various distances from a 1 KT air burst for atmospheric visibility between 10 and 50 miles.

Scaling. The radiant exposure at any specified distance from a W KT explosion is W times the value for the same distance from a 1 KT burst.

Example

Given: A 100 KT air burst and a visibility of between 10 and 50 miles.

Find: The radiant exposure received at a distance of 3 miles from the explosion.

Solution: From Fig. 7.104 the amount of thermal energy received at 3 miles from a 1 KT air burst is between 0.07 and 0.10 calorie per square centimeter. Consequently, the radiant exposure received at 3 miles from a 100 KT air burst is between

$$100 \times 0.07 = 7 \text{ calories per square centimeter.}$$

and

$$100 \times 0.10 = 10 \text{ calories per square centimeter.} \quad \textit{Answer.}$$

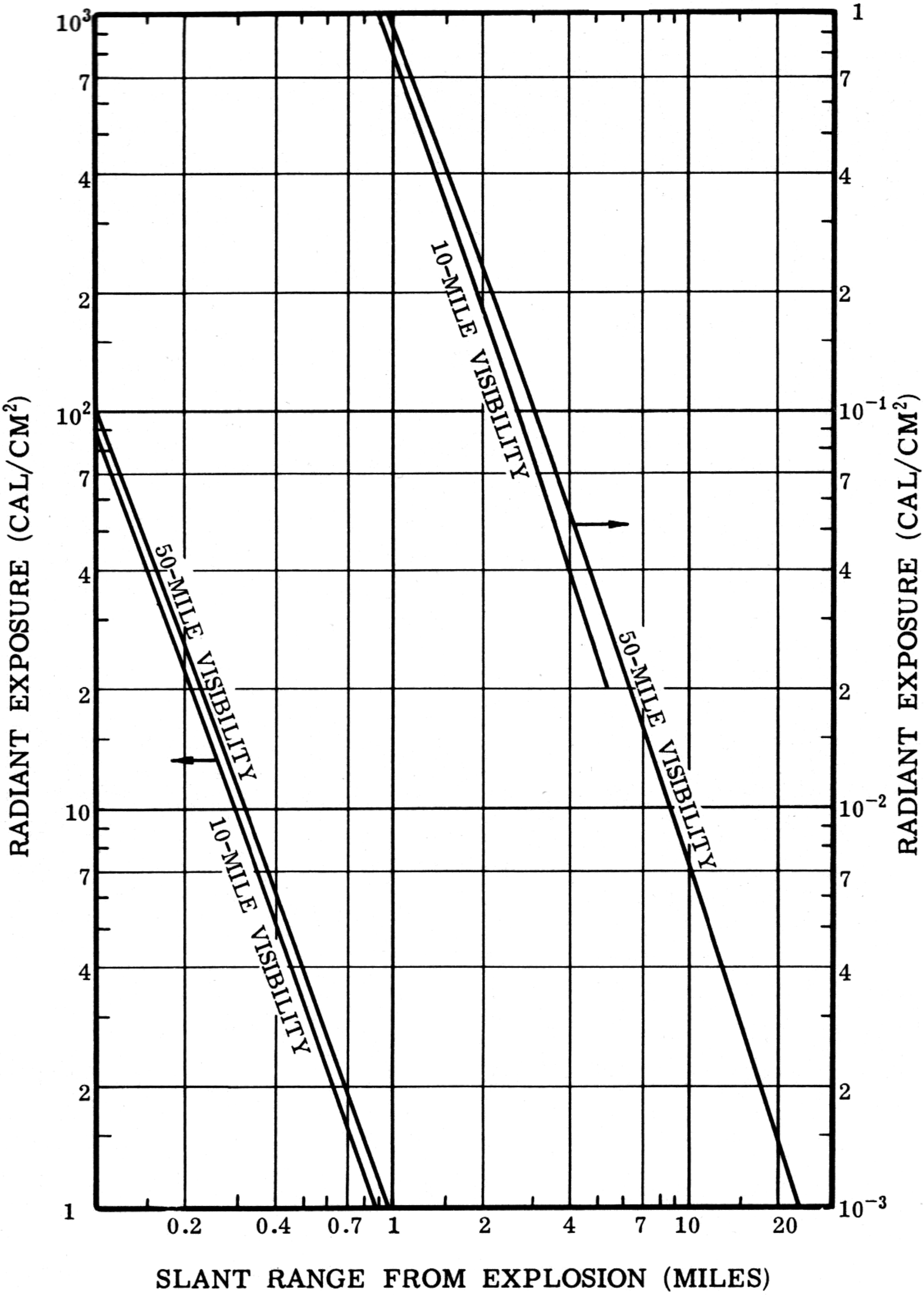

Figure 7.105. Radiant exposure as a function of slant range from a 1-kiloton air burst for visibilities of 10 miles and 50 miles.

factor of equation (7.101.2) has values which lie approximately between ¼ and ⅐. Thus, for a surface burst,

$$Q(\text{cal/sq cm}) \approx 0.8 \text{ to } 0.5 \frac{WT}{D^2}, \tag{7.106.1}$$

where D is the slant range in miles. It appears that as the yield increases the radiant exposure tends towards the larger limit of the values given by equation (7.106.1). DUE TO FIREBALL EXCEEDING CRATERING RADIUS

7.107 In the calculation of the thermal radiation exposure at some distance from a high-altitude nuclear explosion, e.g., at the earth's surface, equation (7.101.2), must be modified in two respects. First, the thermal energy capable of causing damage is approximately 25 to 35 percent of the total yield (§7.25), for detonations of altitudes from about 100,000 to 350,000 feet (20 to 70 miles). Correction for this difference can be made by taking E_{tot} to be roughly 0.25 W kilotons.

7.108 Second, in their passage from the burst point to the earth, the radiations pass through regions where the atmospheric density varies continuously and is considerably less than at sea level. The attenuation can be calculated in an approximate manner by utilizing the concept of the "reduced height of the atmosphere." This is equal to the total mass of air contained in a vertical column of unit cross section above the observer divided by the sea-level density of air. On the ground at sea level, the reduced height of the atmosphere is about 25,000 feet or roughly 5 miles. If an explosion occurs at an altitude of H miles, for example, it is assumed, for purposes of estimating the thermal attenuation, that, in arriving at a target on the ground vertically below the burst point, the radiation traverses $H-5$ miles of vacuum, in which there is no absorption or scattering, and 5 miles of sea-level atmosphere. If the explosion center is not immediately above the target, but makes an angle of elevation ϕ with the horizon, then the respective distances are $(H-5)/\sin\phi$ and $5/\sin\phi$, respectively.

7.109 On the basis of the foregoing argument, it can be shown that for a high-altitude explosion equation (7.103.2) can be written in the approximate general form

$$Q(\text{cal/sq cm}) \approx \frac{0.76WT}{H^2} \sin^2\phi \tag{7.109.1}$$

where T is the appropriate transmittance for the angle ϕ. If the shot is directly overhead, ϕ is 90° and $\sin^2\phi$ is unity. Values for the transmittance as a function of angle of elevation, for detonations at high altitude, are given in Fig. 7.109; with these data equation

(7.109.1) can be used to give results which are reliable within a factor of two or so. Observations of radiant exposure made on Johnston Island in connection with the TEAK shot, described in Chapter II, are in general agreement with equation (7.109.1).

7.110 For detonations at altitudes above about 70 miles, equation (7.109.1) is no longer applicable. As explained in §7.88, the volume of air heated by the thermal X-rays is so large that the temperatures attained are relatively low. Thermal radiation is then emitted at such a slow rate that, at distances of interest, the radiant energy capable of causing any kind of damage is less than for bursts of the same yield at lower altitudes.

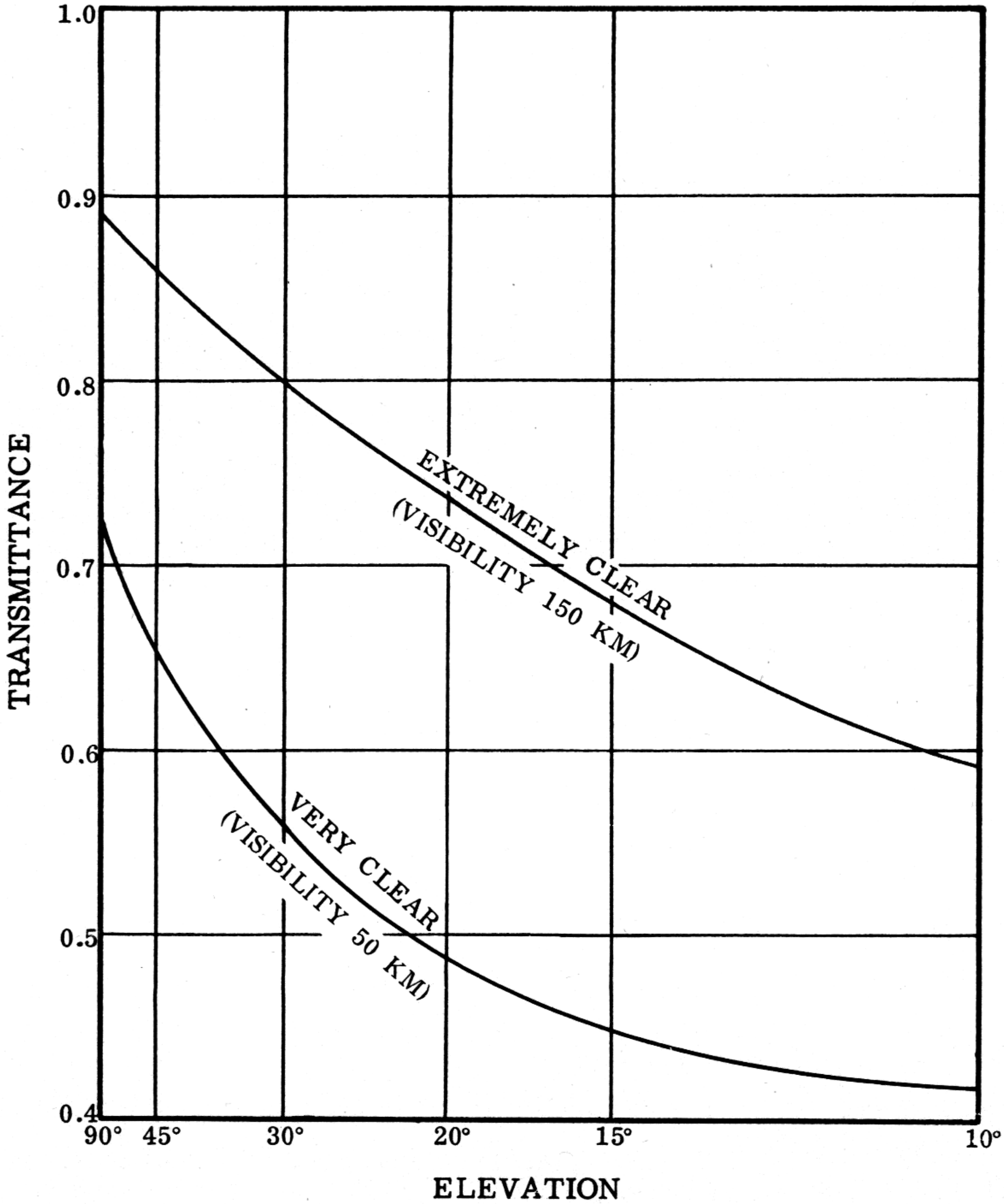

Figure 7.109. Atmospheric transmittance as a function of elevation for use in calculating radiant exposures from high-altitude explosions.

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

**These documents may be obtained from the Library of Congress, Washington 25, D.C.

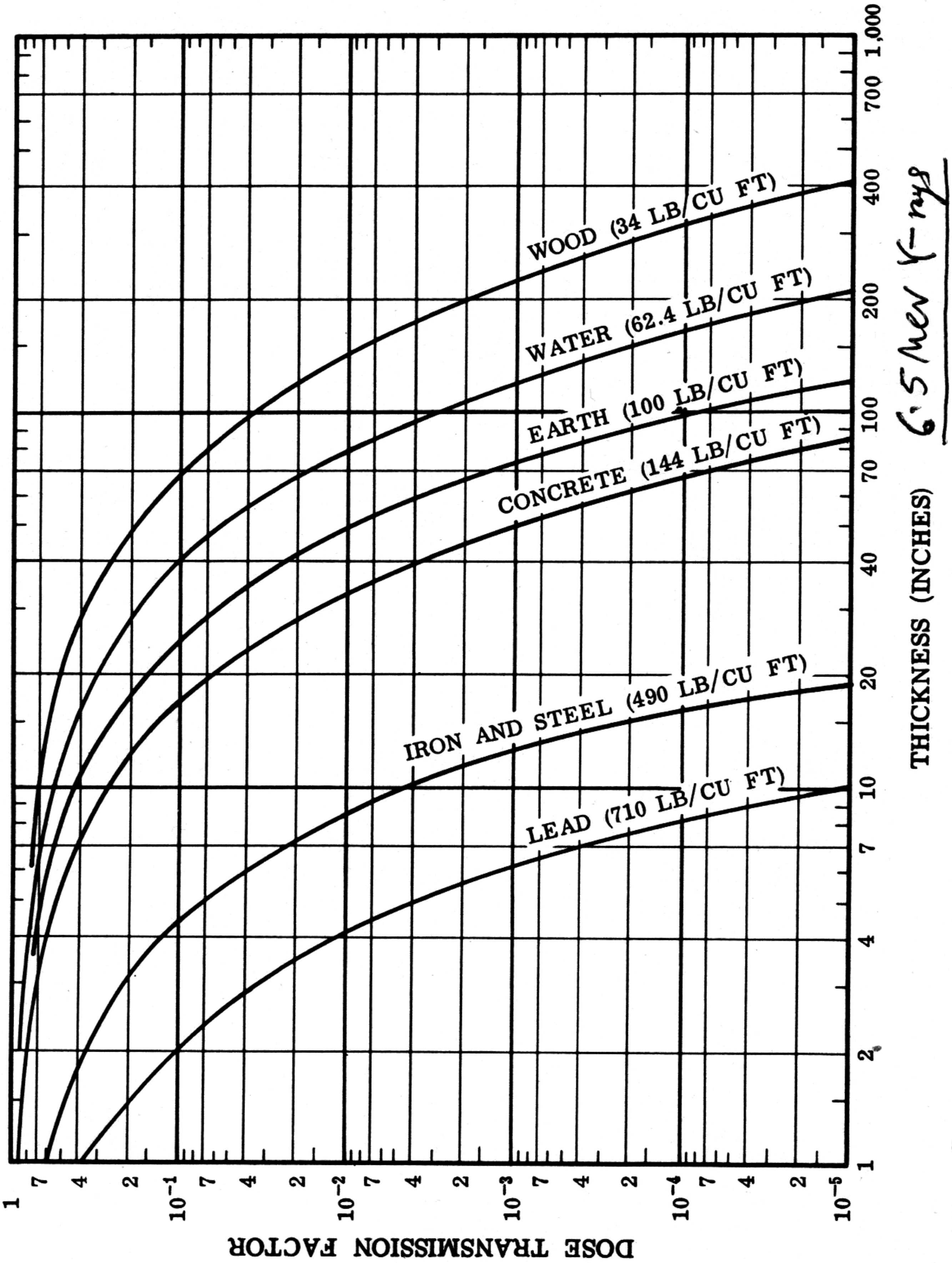

Figure 8.38. Dose transmission factors for initial gamma radiations of various materials as function of thickness.

PAGE 401 STATES EFFECTIVE ENERGY
OF GAMMA RAYS IS 6.5 MeV
(NEUTRON CAPTURE IN NITROGEN PRODUCES
THESE PENETRATING GAMMA RAYS)

Early Fallout

9.06 The radiological characteristics of the early fallout from a nuclear weapon are those of the fission products and any induced activity produced. The relative importance of these two sources of residual radiation depends upon the percentage of the total yield that is due to fission, and other factors mentioned in § 9.02. There are, however, two additional factors, namely, "fractionation" and "salting" which may affect the activity of the early fallout; these will be described below.

9.07 As the fireball cools, the fission products and other vapors are gradually condensed on such soil and other particles as are sucked up from below while the fireball rises in the air. For detonations over land, where the particles consist mainly of soil minerals, the fission product vapors condense onto both solid and molten soil particles and also onto other particles that may be present. In addition, the vapors of the fission products may condense with vapors of other substances to form mixed solid particles of small size. In these condensation processes the composition of the fission product mixture may be changed by the phenomenon known as "fractionation." The occurrence of fractionation is shown, for example, by the fact that in a land surface burst the larger particles, which fall out of the fireball at early times and are found near ground zero, have different radiological properties from the smaller particles that leave the radioactive cloud at later times and reach the ground some distance downwind.

9.08 The details of the fractionation process are not well understood, but the effect is related, in part at least, to the presence in the early stages of certain fission products which are inherently gaseous, e.g., krypton and xenon. Subsequently, these radioactive gases decay to form rubidium and cesium, respectively, which can condense onto solid particles. Consequently, the first solid particles to fall out, near ground zero, will be depleted not only in krypton and xenon, but also in their various decay (or daughter) products. On the other hand, small particles which have remained in the cloud for some time will have rubidium and cesium, and their daughters, strontium and barium, condensed upon them. Hence, the more distant fallout will be relatively richer in those elements in which the close fallout is depleted.

9.09 An additional phenomenon which contributes to the fractionation of fission product isotopes is the separation of the elements in the ascending fireball as they condense at different times, corresponding to their different boiling points. Thus the refractory elements can condense at early times in the fireball history, when its temperature is quite high, onto the relatively larger particles which are more abundant at these times. Conversely, volatile elements, with low boiling points, cannot condense until later, when the fireball has cooled and when the larger particle sizes will be depleted. Refractory elements are expected to be relatively more abundant in the close-in early fallout, representing the larger particles, and to be relatively depleted in the more distant portion of the early fallout deposited by smaller particles. The reverse will be true for the more volatile elements. Elements with intermediate boiling points will exhibit behavior between these two extremes.

9.10 For detonations of large energy yield at or near the surface of the sea, where the condensed particles consist of sea-water salts and water, fractionation of the fallout is usually very small. The reason is that the fireball must cool to 100° C (212° F) or less before the evaporated water condenses. The long cooling time and the presence of very small water droplets permit removal from the radioactive cloud of the daughters of the gaseous krypton and xenon along with the other fission products. In this event, there is little or no variation in composition of the radioactive fallout (or rainout) with distance from the explosion.

9.11 The composition of the fallout can also be changed by "salting" the weapon to be detonated. This consists in the inclusion of significant quantities of certain elements, possibly enriched in specific isotopes, for the purpose of producing induced radioactivity. There are several reasons why a weapon might be salted. For example, salting has been used in some weapons tests to provide radioactive tracers for various purposes, such as the study of the paths and relative compositions of the early and delayed stages of fallout. By the choice of elements, to give radioactive products of suitable half lives and radioactivity, the characteristics of the early fallout from a nuclear weapon could be modified for application in radiological warfare (§ 9.110).

Activity and Decay of Early Fallout

9.12 As stated in Chapter I, the fission products constitute a very complex mixture of over 200 different forms (isotopes) of 36 elements. Most of these isotopes are radioactive, decaying by the emission of beta particles, frequently accompanied by gamma radiation. About 2 ounces of fission products are formed for each kiloton (or 125 pounds per megaton) of fission energy yield. The total radioactivity of the fission products initially is extremely large but it falls off at a fairly rapid rate as the result of radioactive decay (§§ 1.23, 1.57).

9.13 At 1 minute after a nuclear explosion, when the residual nuclear radiation has been postulated as beginning, the gamma-ray activity of the 2 ounces of fission products from a 1-kiloton fission yield explosion is comparable with that of about 30,000 tons of radium in equilibrium with its decay products. It is seen, therefore, that for explosions in the megaton-energy range the amount of radioactivity produced is enormous. Even though there is a decrease from the 1-minute value by a factor of over 3,000 by the end of the day, the radiation intensity will still be large.

9.14 It has been calculated that if all the fission products from an explosion with a 1-megaton fission yield could be spread uniformly over a smooth area of 10,000 square miles, the radiation dose rate after 24 hours would be 6 roentgens per hour at a level of 3 feet above the ground. In actual practice, a uniform distribution would be improbable, since a larger proportion of the fission products would be deposited near ground zero than at farther distances. Hence, the radiation intensity will greatly exceed the average at points near the explosion center, whereas at much greater distances it will usually be less.

9.15 As stated in § 9.01, the early fallout consists mainly, but not entirely, of fission products. An indication of the manner in which the dose rate of the actual mixture decreases with time may be obtained from the following approximate rule: for every seven-fold increase in time after the explosion, the dose rate decreases by a factor of ten. For example, if the radiation dose rate at 1 hour after the explosion is taken as a reference point, then at 7 hours after the explosion the dose rate will have decreased to one-tenth; at $7 \times 7 = 49$ hours (or roughly 2 days) it will be one-hundreth; and at $7 \times 7 \times 7 = 343$ hours (or roughly 2 weeks) the dose rate will be one-thousandth of that at 1 hour after the burst. Another aspect of the rule is that at the end of 1 week (7 days), the radiation dose rate will be one-tenth of the value after 1 day. This rule is accurate to within about 25 percent up to 2 weeks or so and is applicable to within a factor of two up to roughly 6 months after the nuclear detonation. Subsequently, the dose rate decreases at a much more rapid rate than predicted by this rule.

9.16 Information concerning the decrease of dose rate in the early fallout can be obtained from the continuous curve in Figs. 9.16a and b, in which the ratio of the approximate exposure dose rate (in r/hr,

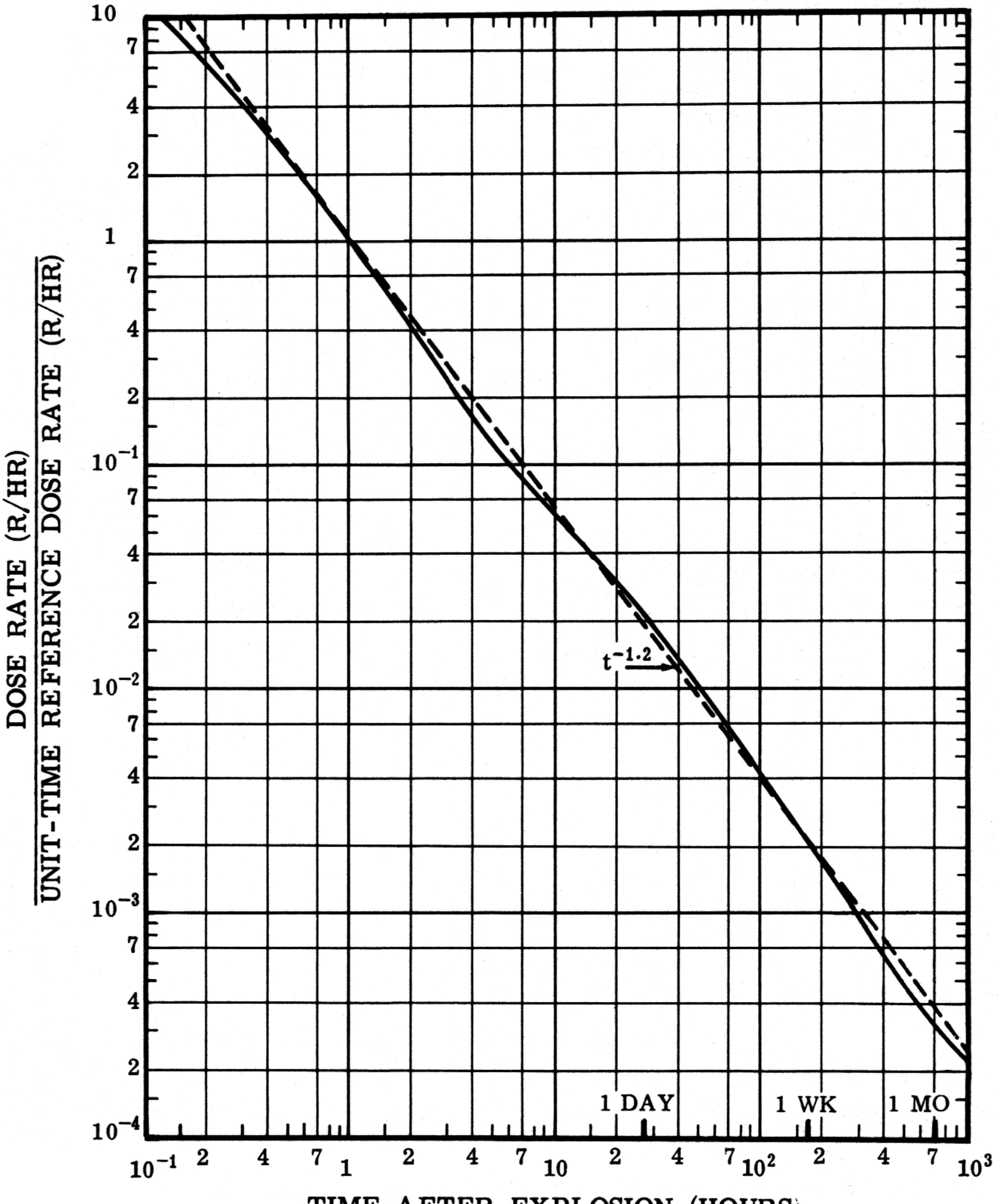

Figure 9.16a. Dependence of dose rate from early fallout upon time after explosion.

i.e., in roentgens per hour) at any time after the explosion to a convenient reference value, called the "unit-time reference dose rate," is plotted against time in hours.[1] The use of the reference dose rate simplifies the representation of the results and the calculations based on them, as will now be shown.

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[1] The significance of the dashed lines, marked "$t^{-1.2}$," will be described in § 9.170 *et seq.*, where the physical meaning of the unit-time reference dose rate will be explained. For the present, the dashed lines may be ignored.

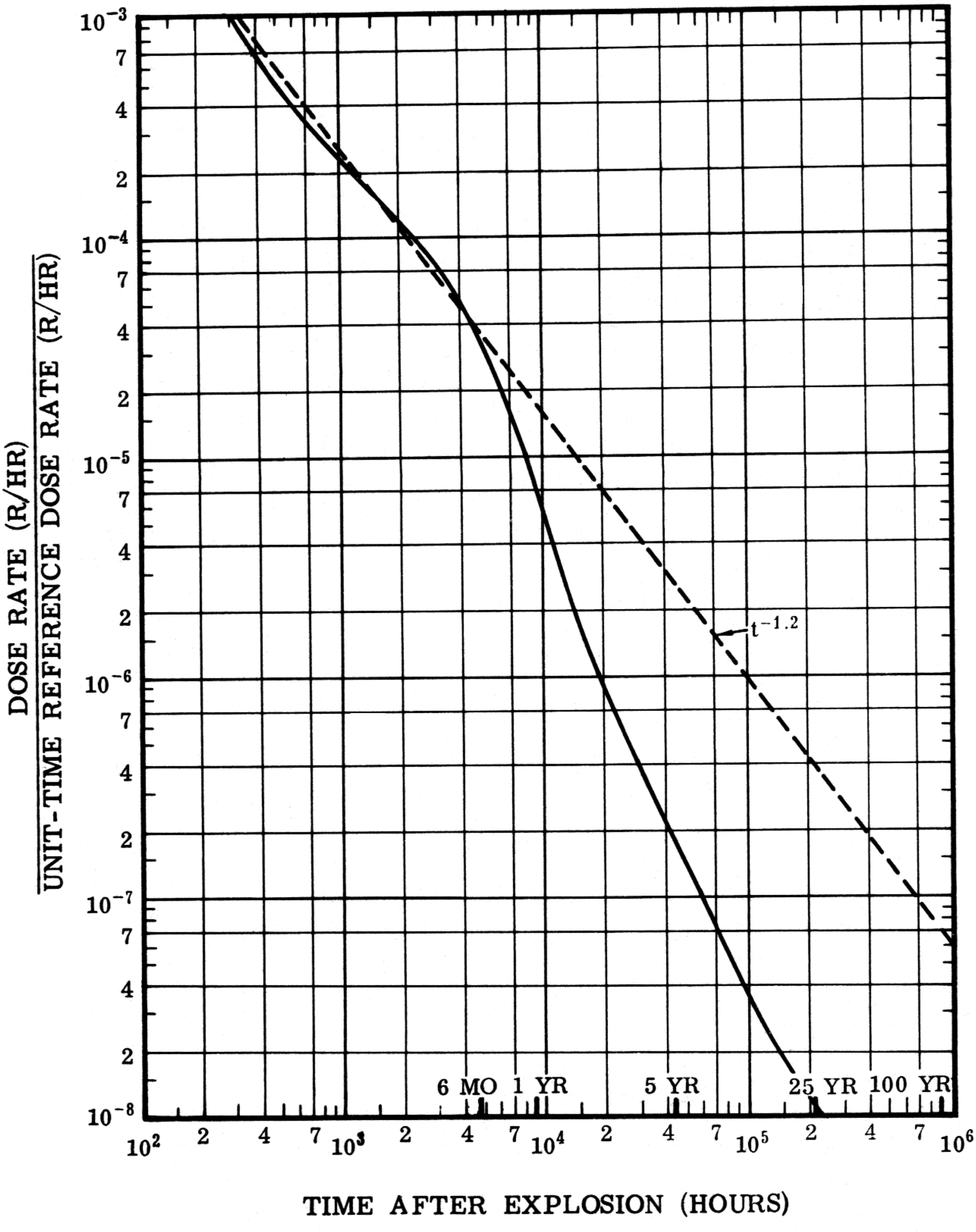

Figure 9.16b. Dependence of dose rate from early fallout upon time after explosion.

9.17 Suppose, for example, that at a given location, the fallout commences at 5 hours after the explosion, and that at 15 hours, when the fallout has ceased to descend, the observed dose rate is 4.0 roentgens per hour. From the curve in Fig. 9.16a (or the data in Table 9.19), it is seen that at 15 hours after the explosion, the ratio of the actual dose rate to the reference value is 0.040; hence, the reference dose rate must be 4.0/0.040 = 100 roentgens per hour. By means

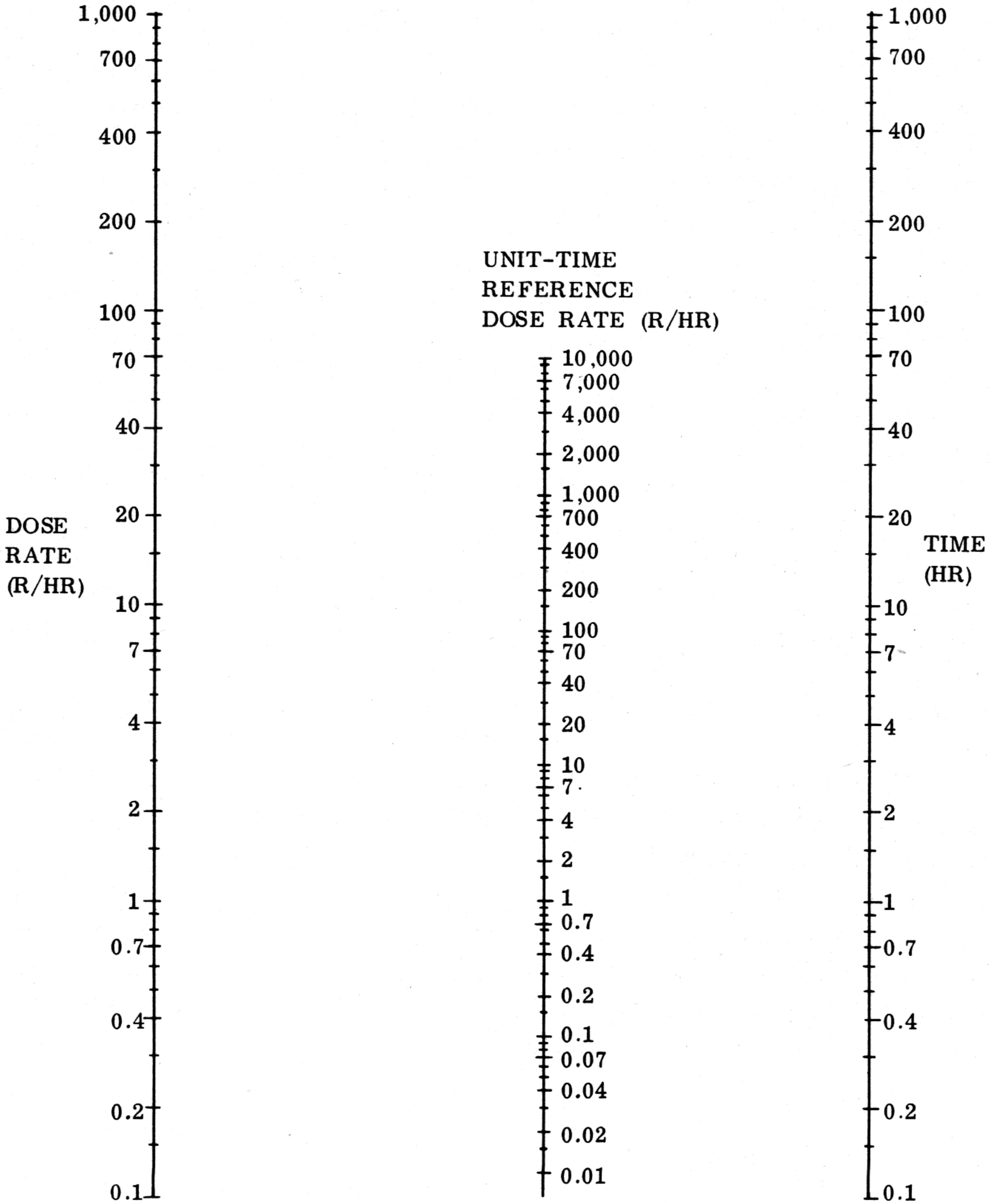

Figure 9.25. Nomograph for calculation of approximate dose rates from early fallout.

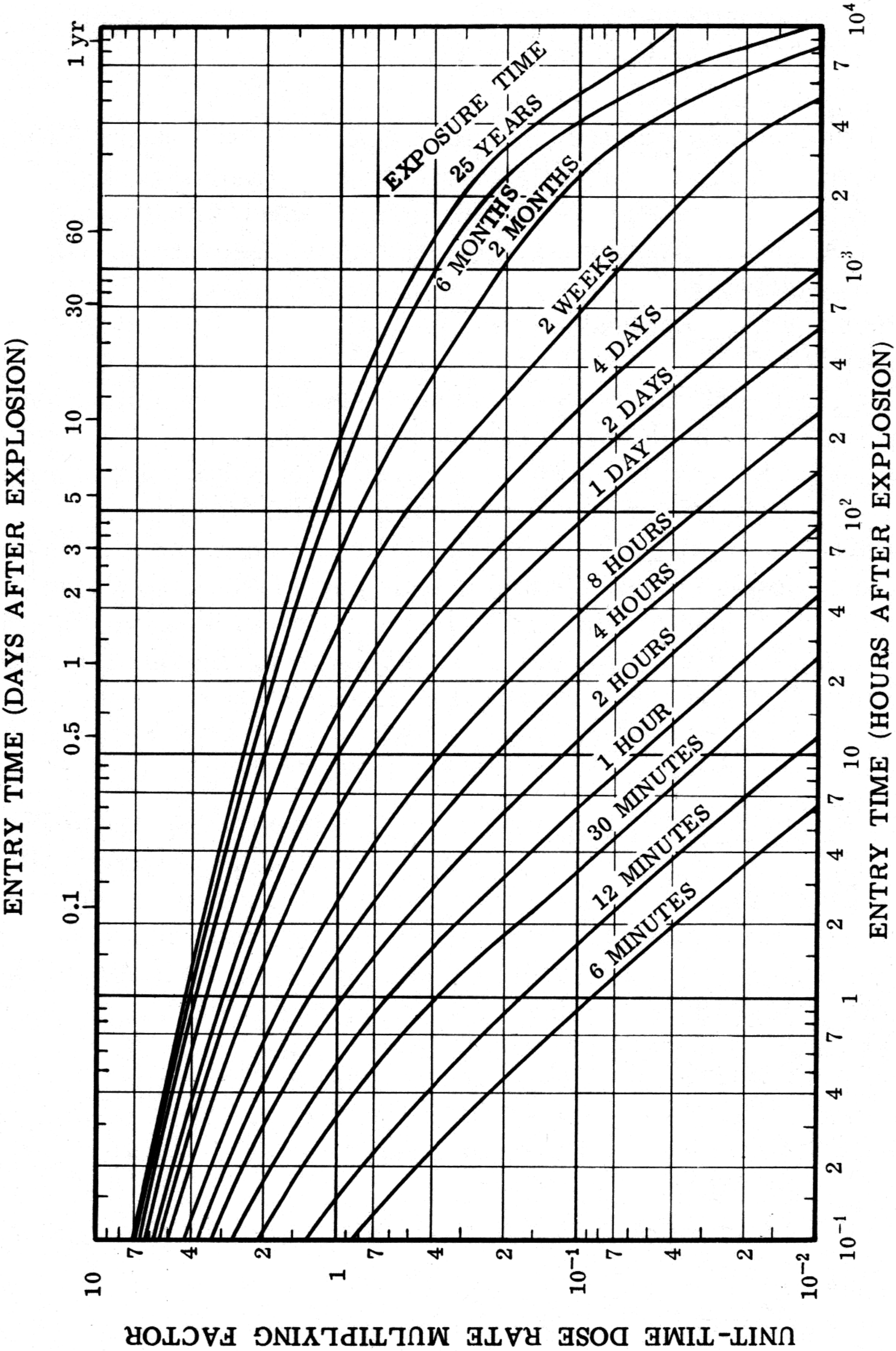

Figure 9.26. Total radiation dose from early fallout based on unit-time reference dose rate.

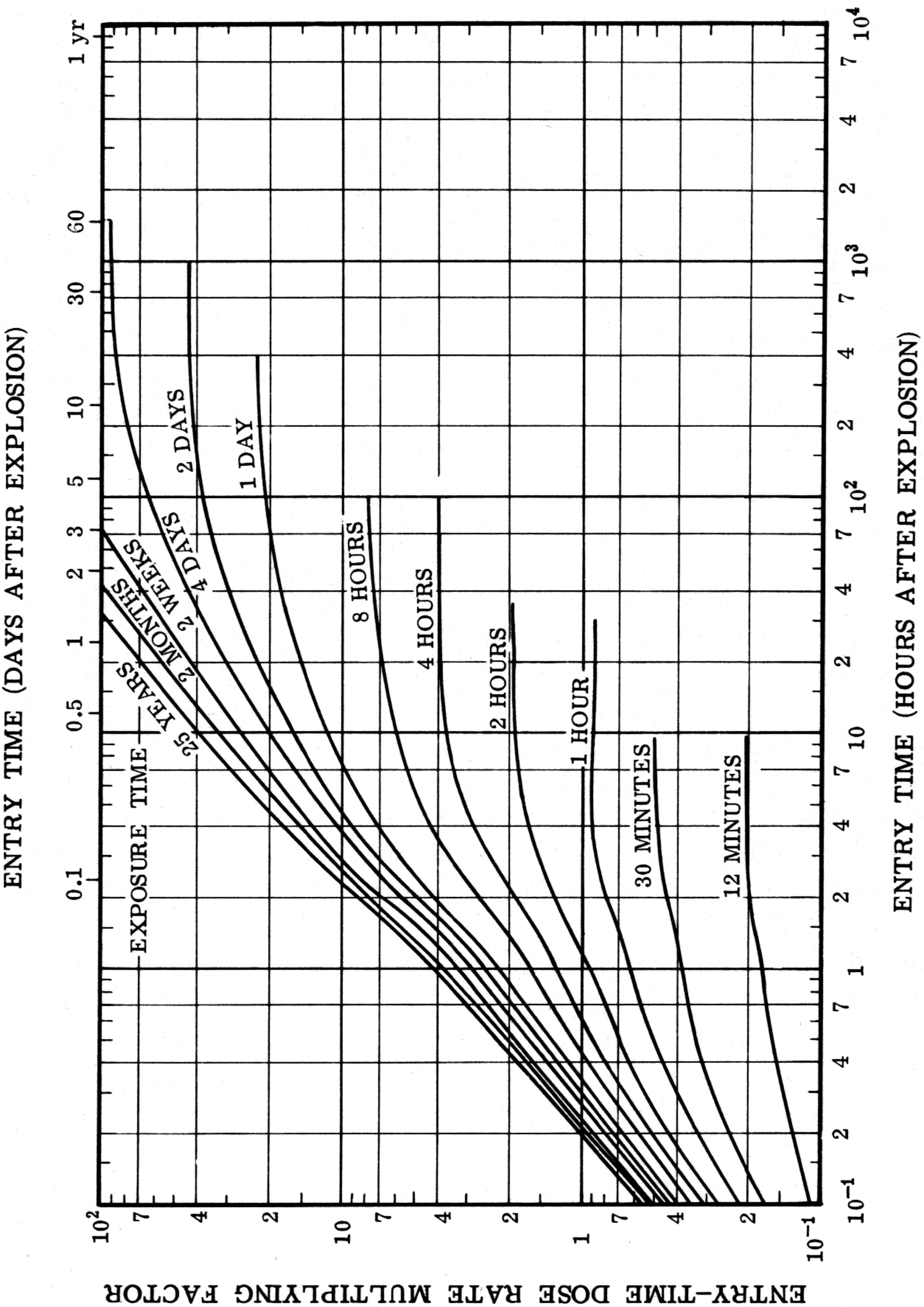

Figure 9.27. Total radiation dose from early fallout based on dose rate at time of entry.

(Text continued from p. 425.)

9.30 It is essential to understand that the tables and figures given above, and the calculations of radiation dose rates and doses in which they are used, are based on the assumption that an individual is exposed to a certain quantity of early fallout and remains exposed continuously (without protection) to this same quantity for a period of time. In an actual fallout situation, however, these conditions probably would not exist. For one thing, any shelter which attenuates the radiation will reduce the exposure dose rate (and dose) as given by the calculations. Furthermore, the action of wind and weather will generally tend to disperse the fallout particles in some areas and concentrate them in others. As a result, there may be a change in the quantity of early fallout at a given location during the time of exposure; the radiation dose rate (and dose) would then change correspondingly. The same would be true, of course, if there were additional fallout from another nuclear explosion.

Neutron-Induced Activity

9.31 The neutrons liberated in the fission process, but which are not involved in the propagation of the fission chain, are ultimately captured by the weapon materials through which they must pass before they can escape, by nitrogen (especially) and oxygen in the atmosphere, and by various elements present in the earth's surface. As a result of capturing neutrons many substances become radioactive. They, consequently, emit beta particles, frequently accompanied by gamma radiation, over an extended period of time following the explosion. Such neutron-induced activity, therefore, is part of the residual nuclear radiation.

9.32 The activity induced in the weapon materials is highly variable, since it is greatly dependent upon the design or structural characteristics of the weapon. Any radioactive isotopes produced by neutron capture in the residues will remain associated with the fission products. The curves and tables given above have been adjusted to include the contribution of such isotopes, e.g., uranium-237 and -239 and neptunium-239 and -240. In the period from 20 hours to 2 weeks after the burst, depending to some extent upon the weapon materials, these isotopes can contribute up to 40 percent of the total activity of the weapon residues. At other times, their activity is negligible in comparison with that of the fission products.

9.33 When neutrons are captured by oxygen and nitrogen nuclei present in the atmosphere, the resulting activity is of little or no significance, as far as the early residual radiation is concerned. Oxygen, for example, interacts to a slight extent with fast neutrons, but the product, an isotope of nitrogen, has a half-life of only 7 seconds. It will thus undergo almost complete decay within a minute or two.

9.34 The radioactive product of neutron capture by nitrogen is carbon-14 (§ 8.89) which emits beta particles of relatively low energy but no gamma rays. Although carbon-14 has a long half-life (5,760 years) and is not highly active, in the form of carbon dioxide it is readily incorporated by all forms of plant life and thus finds its way into the human body. The carbon in all living organisms contains a certain proportion of carbon-14 resulting from the capture by atmospheric nitrogen of neutrons from naturally occurring cosmic rays. The total reservoir of carbon-14 in nature, including oceans, atmosphere, and biosphere (living organisms), is known to be from 50 to 80 tons; of this amount, about 1 ton is in the atmosphere and 0.2 ton in the biosphere. It is estimated that before September 1961, weapons testing had produced 0.65 ton of carbon-14 and about half had dissolved in the oceans. Consequently, the carbon-14 content of the atmosphere had been increased by about 30 percent over the normal (1950) value. In the course of time, more and more of the carbon-14 will enter the oceans and, provided there is no great addition as a result of weapons tests, the level in the atmosphere will fall to less than 1 percent above normal in 50 to 100 years.

9.35 An important contribution to the residual nuclear radiation can arise from the activity induced by neutron capture in certain elements in the earth and in sea water. The extent of this radioactivity is highly variable. The element which probably deserves most attention, as far as environmental neutron-induced activity is concerned, is sodium. Although this is present only to a small extent in average soils, the amount of radioactive sodium-24 formed by neutron capture can be quite appreciable. This isotope has a half-life of 15 hours and emits both beta particles, and more important, gamma rays of relatively high energy.[3]

9.36 Another source of induced activity is manganese which, being an element that is essential for plant growth, is found in most soils, even though in small proportions. As a result of neutron capture, the radioisotope manganese-56, with a half-life of 2.6 hours, is formed. It gives off several gamma rays of high energy, in addition to beta particles, upon decay. Because its half-life is less than that of sodium-24, the manganese-56 loses its activity more rapidly. But, within the

[3] In each act of decay of sodium-24, there are produced two gamma-ray photons, with energies of 1.4 and 2.8 Mev, respectively. The mean energy per photon from fission products at 1 hour after formation is about 1 Mev.

first few hours after an explosion, the manganese may constitute a serious hazard, greater than that of sodium.

9.37 A major constituent of soil is silicon, and neutron capture leads to the formation of radioactive silicon-31. This isotope, with a half-life of 2.6 hours, gives off beta particles, but gamma rays are emitted in not more than about 0.07 percent of the disintegrations. It will be seen later that only in certain circumstances do beta particles themselves constitute a serious radiation hazard. Aluminum, another common constituent of soil, can form the radioisotope aulminum-28, with a half-life of only 2.3 minutes. Although isotopes such as this, with short half-lives, contribute greatly to the high initial activity, very little remains within an hour after the nuclear explosion.

9.38 When neutrons are captured by the hydrogen nuclei in water, the product is the nonradioactive (stable) isotope, deuterium, so that there is no resulting activity. As seen in § 9.33, the activity induced in oxygen can be ignored because of the very short half-life of the product. However, substances dissolved in the water, especially the salt (sodium chloride) in sea water, can be sources of considerable induced activity. The sodium produces sodium-24, as already mentioned, and the chlorine yields chlorine-38 which emits both beta particles and high-energy gamma rays. However, the half-life of chlorine-38 is only 37 minutes, so that within 4 to 5 hours its activity will have decayed to about 1 percent of its initial value.

9.39 Apart from the interaction of neutrons with elements present in soil and water, the neutrons from a nuclear explosion may be captured by other nuclei, such as those contained in structural and other materials. Among the metals, the chief sources of induced radioactivity are probably zinc, copper, and manganese, the latter being a constituent of many steels, and, to a lesser extent, iron. Wood and clothing are unlikely to develop appreciable activity as a result of neutron capture, but glass could become radioactive because of the large proportions of sodium and silicon. Foodstuffs can acquire induced activity, mainly as a result of neutron capture by sodium. However, at such distances from a nuclear explosion and under such conditions that this activity would be significant, the food would probably not be fit for consumption for other reasons, e.g., blast and fire damage. Some elements, e.g., boron, absorb neutrons without becoming radioactive, and their presence will decrease the induced activity.

Uranium and Plutonium

9.40 The uranium and plutonium which may have escaped fission in the nuclear weapon represent a further possible source of residual

9.65 For a detailed fallout prediction, the winds from the surface to all levels in the radioactive cloud must be considered. However, for the idealized patterns, the actual complex wind system is replaced by an approximately equivalent "effective wind." This is taken as the mean value of the wind speed and direction from the surface to some representative level in the cloud. The level chosen generally lies between the base and middle of the mushroom head, where the concentration of radioactivity is believed to be a maximum.

9.66 By assuming little or no wind shear, that is, essentially no change in wind direction at different altitudes, the idealized fallout patterns have a regular cigar-like shape, as will be seen shortly. But if the wind direction changes with altitude, the fallout will spread over a wider angle, as in Fig. 9.58a, and the activity (or radiation dose rate) at a given distance from surface zero will be decreased because the same amount of radioactive contamination will cover a larger area. Lower wind speeds will make the pattern shorter in the downwind direction because the particles will not travel so far before descending to earth; the activity at some distance from the burst point will be lower and the high dose rates immediately downwind of ground zero will be increased. If the wind speed is higher, the contaminated area will be greater, and the radioactivity will be higher at large distances from surface zero and lower immediately downwind of ground zero.

9.67 Before showing an idealized fallout pattern it is important to understand how such a pattern develops over a large area during a period of several hours following a 1-megaton fission yield surface burst. This may be illustrated by the diagrams in Figs. 9.67 a and b. The effective wind speed was taken as 15 miles per hour. Fig. 9.67a shows a number of "contours" (or "isodose-rate" lines) for certain (arbitrary) round-number values of the dose rate, as would be observed on the ground, at 1, 6, and 18 hours, respectively, after the explosion. A series of total (or accumulated) dose contours (or "isodose" lines) for the same times are given in Fig. 9.67b. It will be understood, of course, that the various dose rates and doses change gradually from one contour line to the next. Similarly, the last contour line shown does not represent the limit of the contamination, since the dose rate (and dose) will continue to fall off over a greater distance.

9.68 Consider, first, a location 22 miles downwind from ground zero. At 1 hour after the detonation, the observed dose rate is seen to be about 10 roentgens per hour but is rising very rapidly and will reach a value over 1,000 r/hr sometime between 1 and 2 hours and will

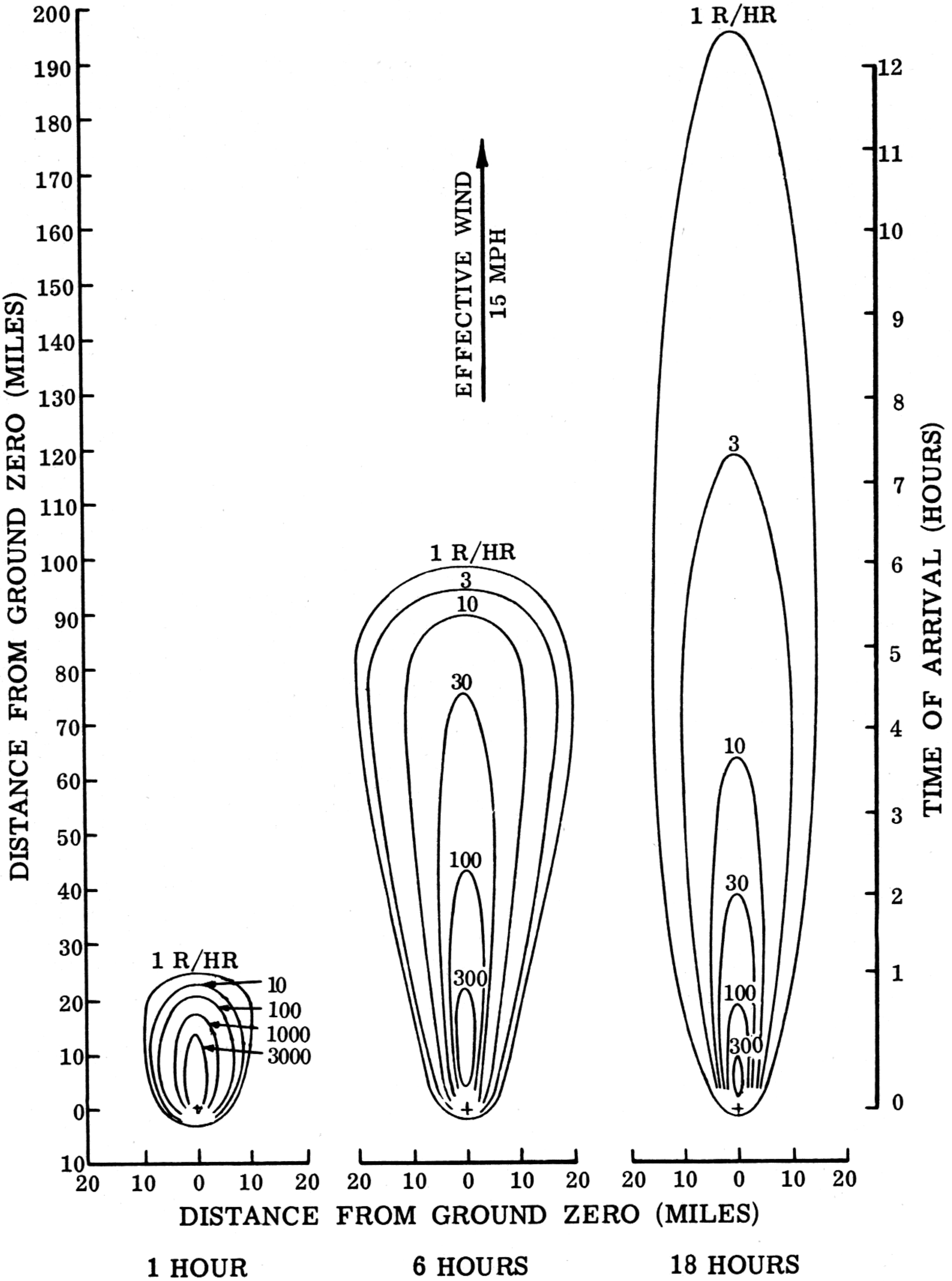

Figure 9.67a. Dose-rate contours from early fallout at 1, 6, and 18 hours after a surface burst with 1-megaton fission yield (15 mph effective wind speed).

then decay to about 300 r/hr at 6 hours. At 18 hours it is down to roughly 80 roentgens per hour. The increase in dose rate from 1 to 6 hours means that at the specified location the fallout was not complete at 1 hour after the detonation. The decrease from 6 to 18 hours

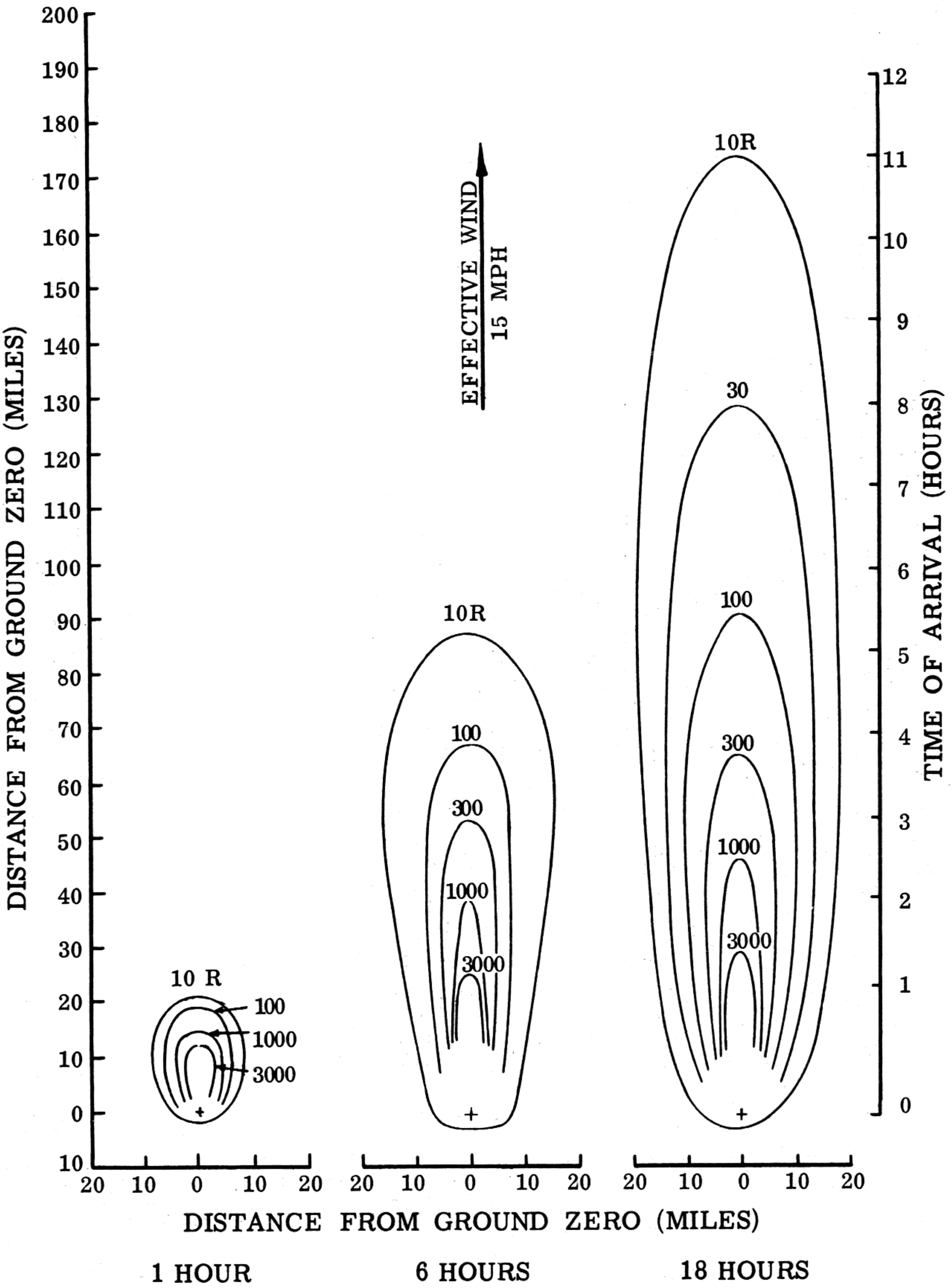

Figure 9.67b. Total-dose contours from early fallout at 1, 6, and 18 hours after surface burst with 1-megaton fission yield (15 mph effective wind speed).

is then due to the natural decay of the fission products. Turning to Fig. 9.67b, it is seen that the total radiation dose received at the given location by 1 hour after the explosion is small, because the fallout has only just started to arrive. By 6 hours, the total dose has reached over 3,000 roentgens and by 18 hours a total dose of some 4,800 roentgens will have been accumulated. Subsequently, the total dose will continue to increase, toward the infinity value, but at a slower rate (§ 9.22).

9.69 Next, consider a point 100 miles downwind from ground zero. At 1 hour after the explosion the dose rate, as indicated in Fig. 9.67a, is zero, since the fallout will not have reached the specified location. At 6 hours, the dose rate is about 1 roentgen per hour and at 18 hours about 5 roentgens per hour. The fallout commences at somewhat less than 6 hours after the detonation and it is essentially complete at 9 hours, although this cannot be determined directly from the contours given. The total accumulated dose, from Fig. 9.67b, is seen to be zero at 1 hour after the explosion, less than 1 roentgen at 6 hours, and about 80 roentgens at 18 hours. The total (infinity) dose will not be as great as at locations closer to ground zero, because the quantity of fission products reaching the ground decreases at increasing distances from the explosion.

9.70 In general, therefore, at any given location, at a distance from a surface burst, some time will elapse between the explosion and the arrival of the fallout. This time will depend on the distance from ground zero and the effective wind velocity. When the fallout first arrives, the dose rate is small, but it increases as more and more fallout descends. After the fallout is complete, the radioactive decay of the fission products will produce a steady decrease in the dose rate. Until the fallout commences, the total dose will, of course, be zero, but after its arrival the total (accumulated) radiation dose will increase continuously, at first rapidly and then somewhat more slowly, over a long period of time, extending for many months and even years.

9.71 The curves in Figs. 9.71 a and b illustrate this behavior; they show the variation with time of the dose rate and the dose from fallout at points 35 and 150 miles downwind from a 5-megaton surface burst. Both the dose rate and the accumulated dose are zero until the fallout particles reach the given locations at 1 and 10 hours after the burst, respectively. At these times the dose rate commences to increase, reaches a maximum, and subsequently decreases, rapidly at first as the radioisotopes of short half-life decay, and then more slowly. The total dose increases continuously from the time of arrival of the fallout toward the limiting (infinite time) value.

9.72 The representation of dose rate and accumulated dose curves, of the form of Figs. 9.67 a and b, for all times following a nuclear detonation would obviously be a highly complicated matter. Fortunately, the situation can be simplified by utilizing an idealized

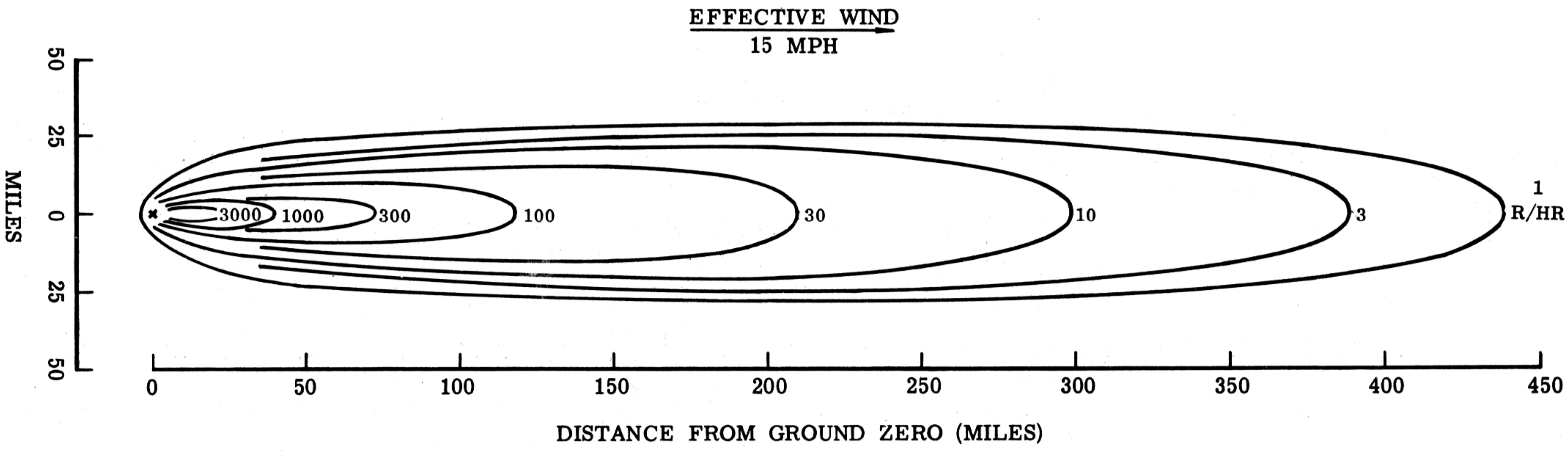

Figure 9.73. Idealized unit-time reference dose-rate pattern for early fallout from a 1-megaton fission yield surface burst (15 mph effective wind speed).

Table 9.73

DOWNWIND EXTENT OF UNIT-TIME REFERENCE DOSE-RATE CONTOURS FOR 1-MEGATON FISSION SURFACE BURST WITH 15 MPH WIND

Reference dose rate (roentgens/hour)	*Downwind distance (statute miles)*	*Maximum width (statute miles)*
3, 000	23	6
1, 000	42	10
300	74	12
100	120	18
30	210	30
10	300	42
3	390	50
1	440	56
0. 3	500	60
0. 1	530	62

Scaling

9.75 In order to obtain the idealized fallout pattern for a fission yield of F megatons, the values of the various contour lines in Fig. 9.73 may be multiplied by F. Thus, for a weapon having a total yield of M megatons with 50 percent of the energy derived from fission the factor would be 0.5 M. This scaling procedure, although highly simplified, gives reasonably good results for surface bursts from about 100 kilotons to 10 megatons fission yield. However, the higher values of dose rate (and dose) are probably overestimated for fission yields in excess of 1 megaton. Except for isolated points in the immediate vicinity of ground zero, observations indicate that unit-time reference dose rates greater than about 10,000 roentgens per hour are unlikely. A possible reason is that as the weapon yield increases so also does the initial volume of the radioactive cloud; hence, the maximum concentration of activity in the cloud does not change very much with the yield. The fallout contamination moderately near ground zero, where the dose rate is high, will thus not increase in proportion to the yield, as the simple scaling law given here implies. At greater distances downwind the law is much more reliable because, as a result of spreading by the wind, the initial cloud volume has relatively little influence on the concentration of fallout on the ground.

9.76 It should be noted that the proportional scaling procedure makes no allowance for the effect of the total, i.e., fission plus fusion, yield; thus it predicts the same fallout pattern for a 1-megaton all-fission detonation as for a 2-megaton 50-percent fission explosion. Actually, the unit-time reference dose rate near ground zero might be somewhat smaller in the latter case because the same amount of radioactivity would be spread through a larger volume of the initial cloud. At greater distances downwind from the burst point the effect of the initial cloud concentration is small, as indicated above. Furthermore, at such locations the dilution effect may be compensated by the fact that the cloud from the 2-megaton explosion will probably rise higher, thus increasing the distances at which particles from the same relative position in the cloud will reach the ground.

9.77 As stated in § 9.65, the effective wind speed and direction are the mean values from the ground up to a certain level in the radioactive cloud, depending on the total yield of the explosion. As a very rough approximation, the atmospheric layers over which the wind is to be averaged as a function of the weapon yield, are as follows:

Total yield	*Layer*
Less than 1 MT	Surface to 40,000 feet.
1 MT to 5 MT	Surface to 60,000 feet.
More than 5 MT	Surface to 80,000 feet.

These values should be adequate for the rough evaluation of hypothetical fallout situations based on the idealized patterns. More elaborate prediction schemes take into consideration the winds at different levels instead of a single average effective wind.

9.78 If there is no directional wind shear, then doubling the wind speed would cause the particles of a given size to reach the ground at twice the distance from ground zero, so that they are spread over roughly twice the area. Based on this conclusion, the following scaling laws may be used in connection with the idealized fallout pattern: (*a*) the unit-time reference dose-rate value for each contour in the 15-mile-per-hour wind velocity pattern in Fig. 9.73 is multiplied by $15/v$, where v is the actual effective wind velocity in miles per hour and (*b*) the downwind distances in Fig. 9.73 are multiplied by $v/15$. For a 30-mile-per-hour wind, for example, the contour values would be halved and the distances doubled.

9.79 It will be apparent that in scaling for either yield or wind speed the values of the dose-rate contours are changed. The scaled downwind extent for any given contour value may readily be obtained by plotting the scaled dose rates versus the scaled downwind distances on logarithmic graph paper and reading downwind distances corresponding to the desired contour value from the resulting smooth curve.

9.80 Both the idealized 15-mile-per-hour pattern in Fig. 9.73 and the wind scaling procedure tend to maximize the downwind extent of the dose-rate contours since they involve the postulate that there is very little (or no) wind shear. This is not an unreasonable assumption for the continental United States, since the wind shear is generally small at altitudes of interest from the standpoint of fallout. If there is considerable wind shear, e.g., 20° or more in the lower half of the mushroom head, the fallout pattern would be wider and shorter than that based on Fig. 9.73. The actual unit-time reference dose rate at a specified downwind distance from ground zero for a given effective wind speed would then be smaller than predicted. The crosswind values at certain distances might, however, be increased.

9.81 It may be noted that the method for wind scaling described in § 9.78 may be approximated by another procedure; the reference dose-rate contour values are left unchanged but the distances in Fig. 9.73 are multiplied by $(v/15)^{1/2}$. If considerable wind shear exists, a better approximation may be obtained by using the factor $(v/15)^{1/3}$. The results of this approximation are not reliable for dose rates greater than about 1,000 roentgens per hour for reasons similar to those given in § 9.75.

9.82 In order to emphasize the limitations of the idealized fallout patterns, Figs. 9.82 a and b are presented here. Figure 9.82a shows the idealized unit-time reference dose-rate contours for an 8-megaton, 50-percent fission surface burst and an effective wind speed of 40 miles per hour. Near ground zero the wind is from the southwest but the mean wind gradually changes to a westerly and then a northwesterly direction over a distance of a few hundred miles. In Fig. 9.82b an attempt is made to indicate what the actual situation might be like as a result of variations in local meteorological and surface conditions. The total contamination of the area is the same in both cases, but the details of the distribution, e.g., the occurrence of hot spots, which are shown shaded in Fig. 9.82b, is quite different. The pattern in Fig. 9.82b is hypothetical and not based on actual observations; its purpose is to call attention to the defects of the idealized fallout pattern. But since the factors causing deviations from the ideal vary from place to place and even from day to day, it is impossible to know them in advance. Consequently, the best that can be done here is to give an idealized pattern and show how it may be used to provide an overall picture of the contamination while, at the same time, indicating that in an actual situation there may be marked differences in the details of the distribution.

Upwind Fallout from Megaton-Range Explosions

9.83 A technique for predicting the ideal fallout contours in the upwind and crosswind directions has been developed from data obtained in connection with tests of devices in the megaton-energy range at the Eniwetok Proving Grounds. The treatment is based on the

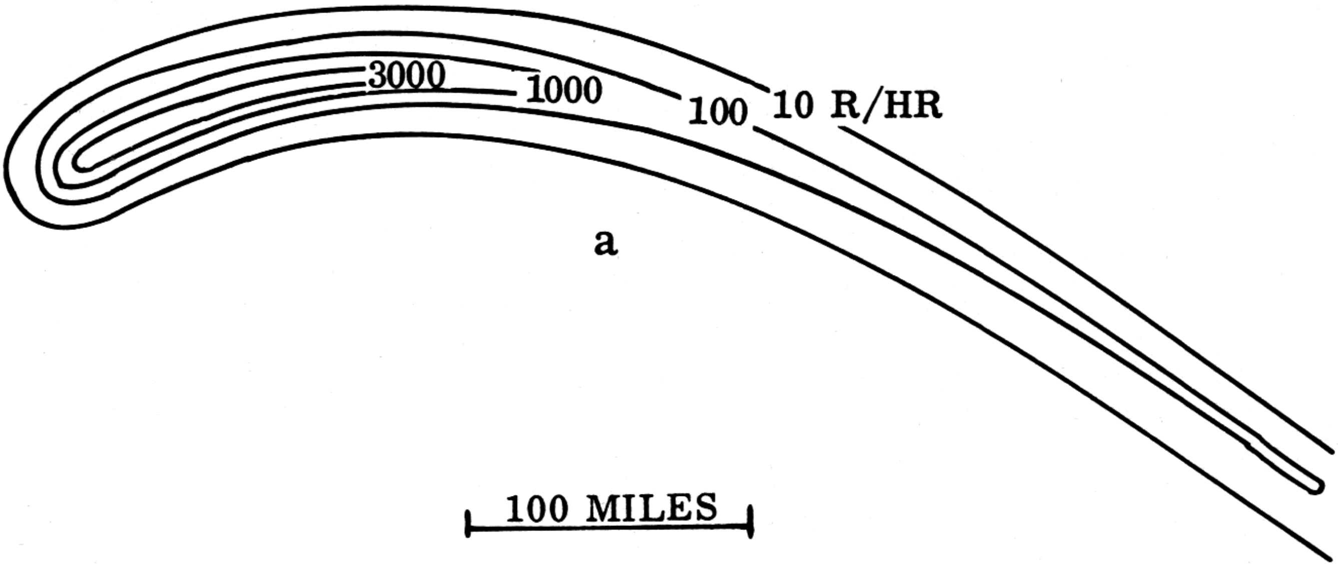

Figure 9.82a. Idealized unit-time reference dose-rate contours for an 8-megaton, 50-percent fission, surface burst (40 mph effective wind speed).

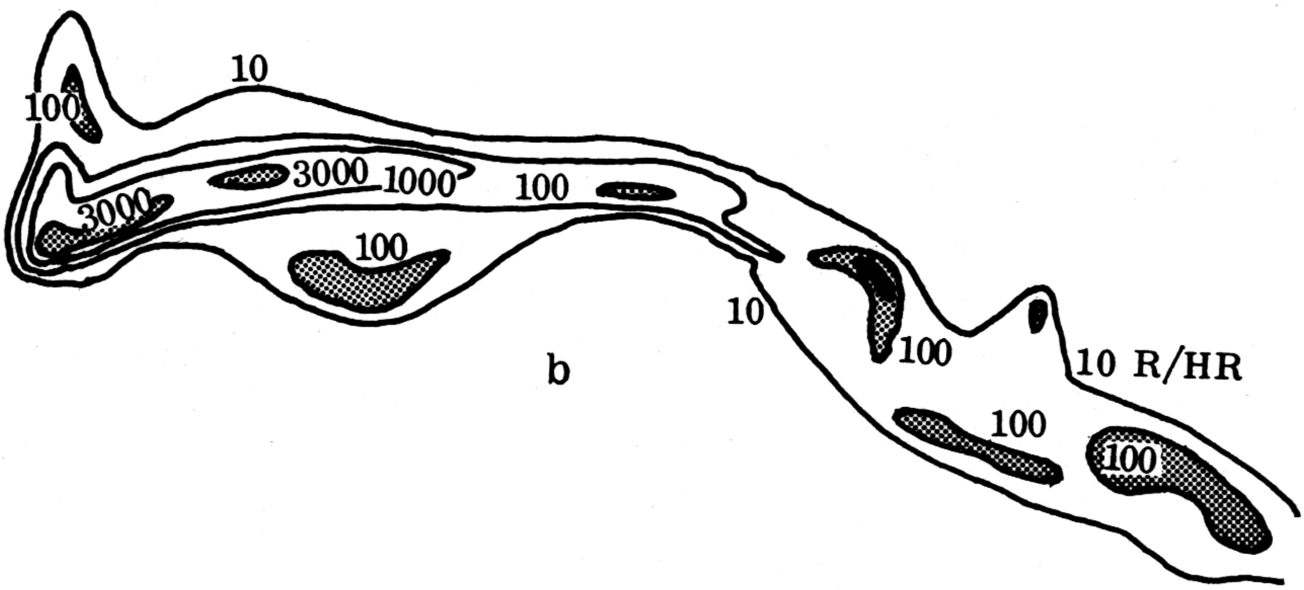

Figure 9.82b. Corresponding actual dose-rate contours (hypothetical).

expectation that the upwind extent of fallout will depend primarily on three factors: the maximum upwind extent of the radioactive cloud, the minimum time required for particles from the upwind edge of the cloud to reach the ground, and the mean effective wind from the ground to the altitude of the broadest part of the cloud.

9.84 Observations at Eniwetok have indicated that, for megaton-range detonations, the broad base of the cloud is generally stabilized at almost the altitude of the tropopause, which is about 55,000 feet in the test area. The mean arrival time on the ground for upwind fallout was found to be about 30 minutes (0.5 hour). In the continental United States, the height of the tropopause is less and the estimated time of arrival is roughly 24 minutes (0.4 hour). Hence, while falling, particles from the upwind edge of the cloud would be carried downwind, i.e., back toward ground zero, a distance (in miles) equal to 0.5 times the mean effective wind speed (in miles per hour) at the Eniwetok Proving Grounds or 0.4 times the wind speed in the United States. The same reasoning may be applied to specific dose-rate contours. It may be assumed that if there were no wind, all the contours would be circles centered at ground zero. The radius of each contour would be determined only by the total yield and the fission percentage. Presumably, the radius of a contour would not be appreciably affected by the wind, but the center of the circles would be displaced in the downwind direction by the same distance the particles are carried downwind from the edge of the cloud.

9.85 From the available data on upwind and crosswind fallout in tests made at Eniwetok, contours for unit-time reference dose rates of 1, 10, and 100 roentgens/hour have been derived. These have been adjusted to zero wind speed and the radii of the corresponding circles are shown in Fig. 9.85 as a function of the total yield of the surface burst, assuming 50 percent fission. If the fission percentage is different from this value, then the indicated dose rates in Fig. 9.85 should be multiplied by the ratio ot the actual fission percentage to 50 percent. The figure also gives the radius for a peak blast overpressure of 7 pounds per square inch, representing the area of almost total destruction, and the dimensions of the visible cloud at 10 minutes after the explosion, this being the average time at which the cloud becomes stabilized (§ 2.15).

9.86 To convert these results into the idealized contours for an actual situation, it is necessary to know the effective wind speed and direction. In view of the uncertainty of the height of the cloud base, it is recommended that the speeds for altitudes of both 40,000 and 60,000 feet be considered and the smaller one be taken for the present purpose. The wind direction, however, would be that for 40,000 feet.[4] Multiplication of the mean wind speed by 0.4 would then give the displacement from ground zero of the centers of the circular contours in the downwind direction in the United States.

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[4] Mean wind speeds and expected direction of fall of particles, for various elevations, can be obtained from the "UF" (Upper-air Fallout) wind data reported regularly by the U.S. Weather Bureau.

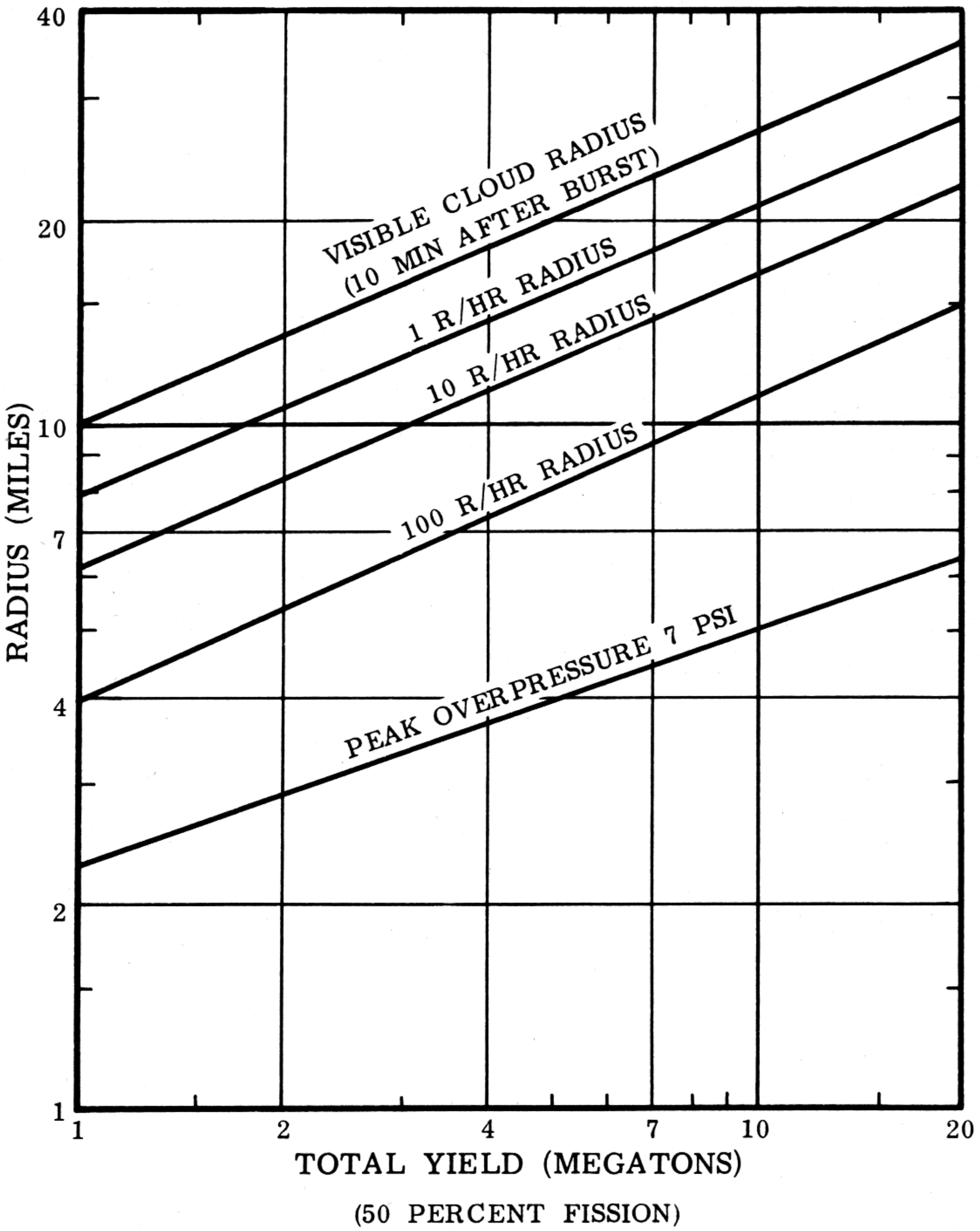

Figure 9.85. Radii for unit-time dose rates from early fallout, stabilized cloud, and 7-psi overpressure as function of total yield (50 percent fission) for surface bursts.

9.87 For purposes of illustration, consider a 10-megaton surface burst, with a 50-percent fission yield. Suppose that the mean wind from the surface to 40,000 feet is 25 miles per hour and its (downwind) direction is 30° east of north, and that the mean wind speed to 60,000 feet is 20 miles per hour. Hence, the effective wind to be used in constructing the upwind pattern is 20 miles per hour, but the direction is to be taken at 30° east of north. The displacement of the center of the contour circles is thus $0.4 \times 20 = 8$ miles, in the downwind direction.

From Fig. 9.85, the radii of the unit-time reference dose-rate contours for a 10-megaton burst are as follows:

1 roentgen/hour: 21 miles
10 roentgens/hour: 16.5 miles
100 roentgens/hour: 11 miles

Semicircles are now drawn having these radii with the point 8 miles downwind from ground zero as the center to give the actual upwind and crosswind contours, as shown in Fig. 9.87. Any contour, e.g., the one for 100 roentgens/hour, passing through the circle of severe blast damage (7 pounds per square inch overpressure), which has a radius of about 5 miles in the present case, may be regarded as uncertain. The area within the blast damage circle may be expected to be heavily contaminated by induced activity, stem fallout, and throwout, regardless of the wind speed.

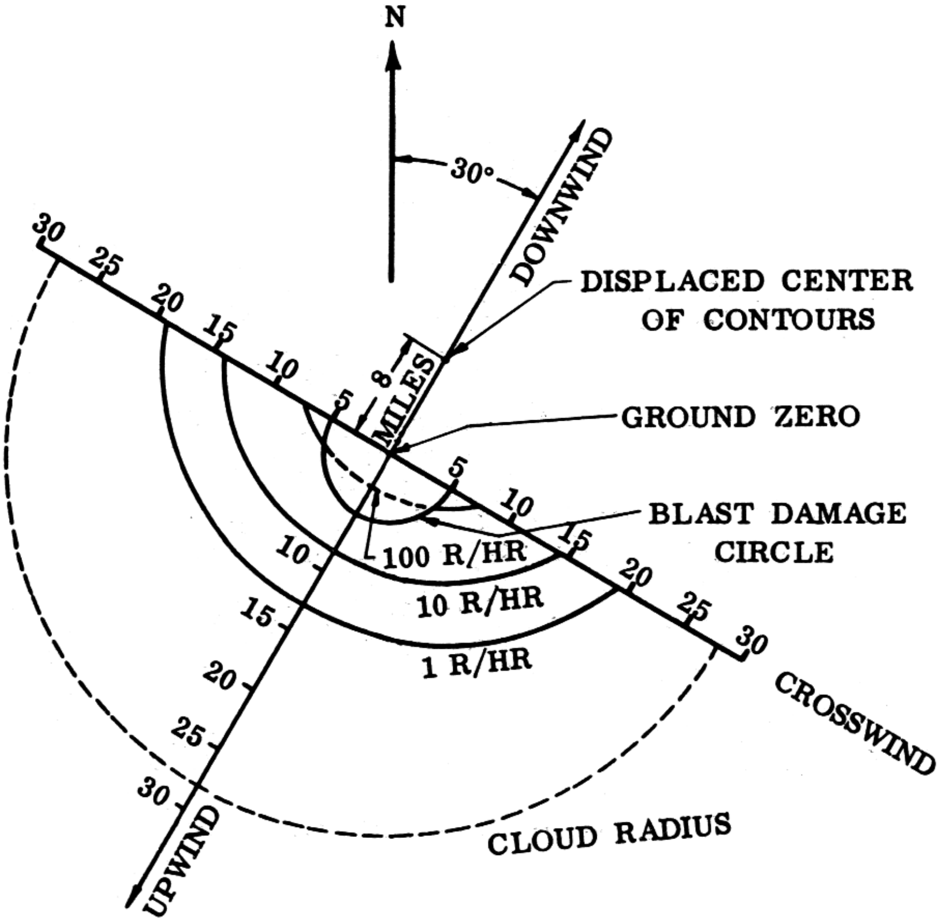

Figure 9.87. Illustration of calculation of upwind early fallout pattern.

9.88 The procedure described above is based on a number of assumptions, as are essentially all methods of fallout prediction. Nevertheless, it is felt that its shortcomings are outweighed by its simplicity and the fact that it can be used to provide a rapid, if approximate, estimate of the fallout contamination pattern in the upwind semicircle about ground zero.

Kiloton-Range Explosions

9.89 The basic fallout phenomena associated with a surface burst in the kiloton-energy range are essentially the same as for detonations of higher yield. The proportionately smaller quantity of fission products will, of course, mean that smaller areas are contaminated to a serious extent. Furthermore, the lower cloud height will result in fallout coming to earth sooner and at closer distances to the burst point. However, the peak dose rate at ground zero and for a short distance downwind may well be of the same order of magnitude as for explosions in the megaton range.

9.90 Representative dose-rate contour dimensions for a 20-kiloton surface burst, with a mean wind velocity of 15 miles per hour, and little wind shear, are recorded in Table 9.90. The downwind extent of a given contour may be scaled for yields from about 1 to 100 kilotons and for any effective wind speed in the same manner as described above for 1-megaton fission yield contours. However, the prediction method for upwind fallout from megaton-range detonations is not applicable to the kiloton-energy range. The upwind fallout associated with these lower yields will be much less extensive because of the smaller cloud radius, e.g., 3 miles or less. Dose rates in the region around ground zero will still be very high because of induced activity, stem fallout, throwout from the crater, and the fallout of larger particles from the cloud.

Table 9.90

DOWNWIND EXTENT OF UNIT-TIME REFERENCE DOSE-RATE CONTOURS FOR 20-KILOTON SURFACE BURST WITH 15 MPH WIND

Reference dose rate (roentgens/hour)	*Downwind distance (statute miles)*	*Maximum width (statute miles)*
3, 000	1	<0. 5
1, 000	3	<1. 0
300	7	1
100	14	2
30	32	4
10	60	6
3	100	11
1	150	16

9.91 On the average, fallout patterns from kiloton-range detonations will be more affected by wind shear than for megaton explosions because the particles spend a larger fraction of their fall times in the turbulent lower atmosphere. The effect of wind shear will be to reduce the areas enclosed by the high dose-rate contours, making them shorter and wider. In addition, very large areas may be covered by contamination of a low order.

Uncertainties in Fallout Predictions

9.92 Although the procedures described above for developing idealized fallout patterns under various conditions are probably as good as can be expected, it must be emphasized that they are intended only for overall planning. There are several factors which will affect the details of the distribution of the early fallout and also the rate of decrease of the radioactivity. Near ground zero, activity induced by neutrons in the soil will be significant, apart from that due to the fallout. However, the extent of the induced activity is difficult to estimate, since it will depend on the type of weapon, e.g., the actual amounts of fission and fusion energy, the height of burst, and the nature of the soil. The existence of unpredictable hot spots will also affect the local radiation intensity. These are dependent upon a variety of conditions not all of which are fully understood. There is a possibility that the formation of a hot spot some distance downwind from ground zero is characteristic of high-yield explosions (§ 9.59). The nature of the terrain may also influence the dose rate at a given location as a result of incidential shielding. The data in Fig. 9.73 are applicable to moderately flat, uninhabited areas, such as those in which weapons tests are carried out. In a city, buildings, trees etc., might well reduce the average radiation intensity above the ground to 70 or 75 percent of this open-terrain value.

9.93 The rate of decay of the early fallout radioactivity, and hence the total dose accumulated over a period of time, will be affected by weathering. Wind may transfer the fallout from one location to another, thus causing local variations. Rain, on the other hand, may wash the fallout into the soil and this will tend to decrease the dose rate at a level a few feet above the ground. The extent of this decrease will, of course, depend on the climatic and surface conditions, but it has been estimated that, in temperate regions, the weathering effect will probably be negligible during the first month after the explosion, but that over a period of years the fallout dose rate would decrease to about half that which would otherwise be expected. If rain should occur at the time of the detonation, the fallout pattern might be changed considerably, as will be seen in § 9.95 *et seq.*

9.94 In attempting to predict the time that must elapse, after a nuclear explosion, for the radiation dose rate to decrease to a level that will permit reentry of a city or the resumption of agricultural operations, use may be made of the (continuous) decay curves in Figs. 9.16a and b or of equivalent data. However, it is inadvisable to depend entirely on these estimates because of the uncertainties mentioned above. Moreover, even if the decay curve could be relied upon completely, which is by no means certain, the actual composition of the fallout is known to vary with distance from ground zero (§ 9.08) and the decay rate will vary accordingly. At 3 months after a nuclear explosion, the radiation intensity will have fallen to about 0.01 percent, i.e., one ten-thousandth part, of its value at 1 hour, so that almost any contaminated area will be safe enough to enter for the purposes of taking a measurement with a dose-rate meter, provided there has been no additional contamination in the interim.

Rainout of Radioactive Debris

9.95 If the airborne debris from a nuclear explosion should encounter a region where precipitation is occuring, a large proportion of the radioactive particles may be brought to earth with the rain. It should be noted, however, that the tops of rain-bearing clouds are generally below the 20,000-foot level, whereas the bulk of the radioactivity for detonations in excess of about 5-kilotons energy yield very soon attains a greater altitude. Hence, early fallout particles from a high-yield surface burst will spend only a fraction of their fallout time in the rain layer and the total amount of early fallout should not be significantly affected by the precipitation. The distribution of the fallout will probably be more irregular than in the absence of rain, with heavy showers producing local hot spots scattered within the contaminated area. Fallout from the cloud stem in an explosion of high yield should not be greatly influenced by precipitation since the particles in the stem will fall to earth in a relatively short time, regardless of whether there is precipitation or not.

9.96 In the surface detonation of a low-yield nuclear weapon in a rainy situation, the whole of the radioactive cloud might be within the rain layer. This would probably result in deposition on the ground of very nearly 100 percent of the fission product activity within a few hours after the explosion. The fallout (or rainout) pattern might cover a smaller area and the peak dose rates would be higher than in the absence of rain, but the difference would probably be less than an order of magnitude.

9.97 The fallout situation following an air burst of low total yield would be greatly altered by precipitation. If there were no precipitation, then this type of burst would produce virtually no local fallout.

Detonation in heavy rain, however, could result in almost as much early fallout (or rainout) as for a surface burst of the same fission yield.

9.98 In a high-yield air burst, essentially all the radioactive debris would generally be carried above the rain-bearing layer and there would be little or no early fallout. An important exception could arise if the airborne debris were to encounter thunderstorms, since precipitation may then originate as high as 60,000 feet. Should such an encounter take place within a few hours after the burst, localized hot spots of very high intensity might develop due to rainout. Although radioactive decay, wind shear, and diffusion all tend to reduce the concentration of activity in the cloud, thunderstorm scavenging of the weapon residues could still conceivably produce serious contamination of the ground many hours after detonation and hundreds of miles downwind from the point at which the air burst occurred.

9.99 It must be admitted that much of what has been stated above concerning the possible effects of rain on fallout from both surface and air bursts is based largely on theoretical considerations. Nuclear test operations have been conducted in such a manner as to avoid the danger of rainout. The few recorded cases of rainout which have occurred have involved very low levels of contamination and the possibility of severe contamination under suitable conditions has not been verified.

The High-Yield Explosion of March 1, 1954

9.100 The foregoing discussion of the distribution of the early fallout may be supplemented by a description of the observations made of the contamination of the Marshall Islands area following the high-yield test explosion (BRAVO) at Bikini Atoll on March 1, 1954.[5] The total yield of this explosion was approximately 15-megatons TNT equivalent. The device was detonated on a coral reef and the resulting fallout, consisting of radioactive particles ranging from about one-thousandth to one-fiftieth of an inch in diameter, contaminated an elongated area extending over 330 (statute) miles downwind and varying in width to over 60 miles. In addition, there was a severely contaminated region upwind extending some 20 miles from the point of detonation. A total area of over 7,000 square miles was contaminated to such an extent that avoidance of death or radiation

[5] "The Effects of High-Yield Nuclear Explosions." A report by the U.S. Atomic Energy Commission, Government Printing Office, February 1955.

injury would have depended upon evacuation of the area or taking protective measures.

9.101 The BRAVO shot is of particular interest because the predicted fallout patterns for megaton-range explosions, such as those given in §9.67 and §9.73, are largely based on inferences drawn from measurements made after this detonation. The available data, for the estimated total doses received at various locations at 96 hours after the explosion, are shown by the points in Fig. 9.101. Through these points there have been drawn a series of contour lines which appear to be in reasonably good agreement with the data. However, other patterns are possible; one, for example, ascribes the large radiation doses on the northern islands of Rongelap Atoll to a hot spot and brings the 3,000-roentgen contour line in much closer to Bikini Atoll. Because of the absence of observations from large areas of ocean, the choice of the fallout pattern, such as the one in Fig. 9.101, is largely a matter of guesswork. Nevertheless, one fact is certain: there was appreciable radioactive contamination at distances downwind of 300 miles or more from the explosion.

9.102 It should be noted that the doses to which the contours in Fig. 9.101 refer are values calculated from instrument records. They represent the maximum possible exposure and would be received only by those individuals who remained in the open, with no protection against the radiation, for the whole time. Any kind of shelter, e.g., within a building, or evacuation of the area would have reduced the dose received. On the other hand, persons remaining in the area for a period longer than 96 hours after the explosion would have received larger doses of the residual radiation.

9.103 A radiation dose of 700 roentgens spread over a period of 96 hours would probably prove fatal in the great majority of cases. It would appear, therefore, that following the test explosion of March 1, 1954, there was sufficient radioactivity from the fallout in a downwind belt about 170 miles long and up to 35 miles wide to have seriously threatened the lives of nearly all persons who remained in the area for at least 96 hours following the detonation without taking protective measures of any kind. At distances of 300 miles or more downwind, the number of deaths due to short-term radiation effects would have been negligible, although there would probably have been many cases of sickness resulting in temporary incapacity.

9.104 The period of 96 hours after the explosion, for which Fig. 9.101 gives the accumulated radiation exposures, was chosen somewhat arbitrarily. It should be understood, however, as has been frequently stated earlier in this chapter, that the radiations from the

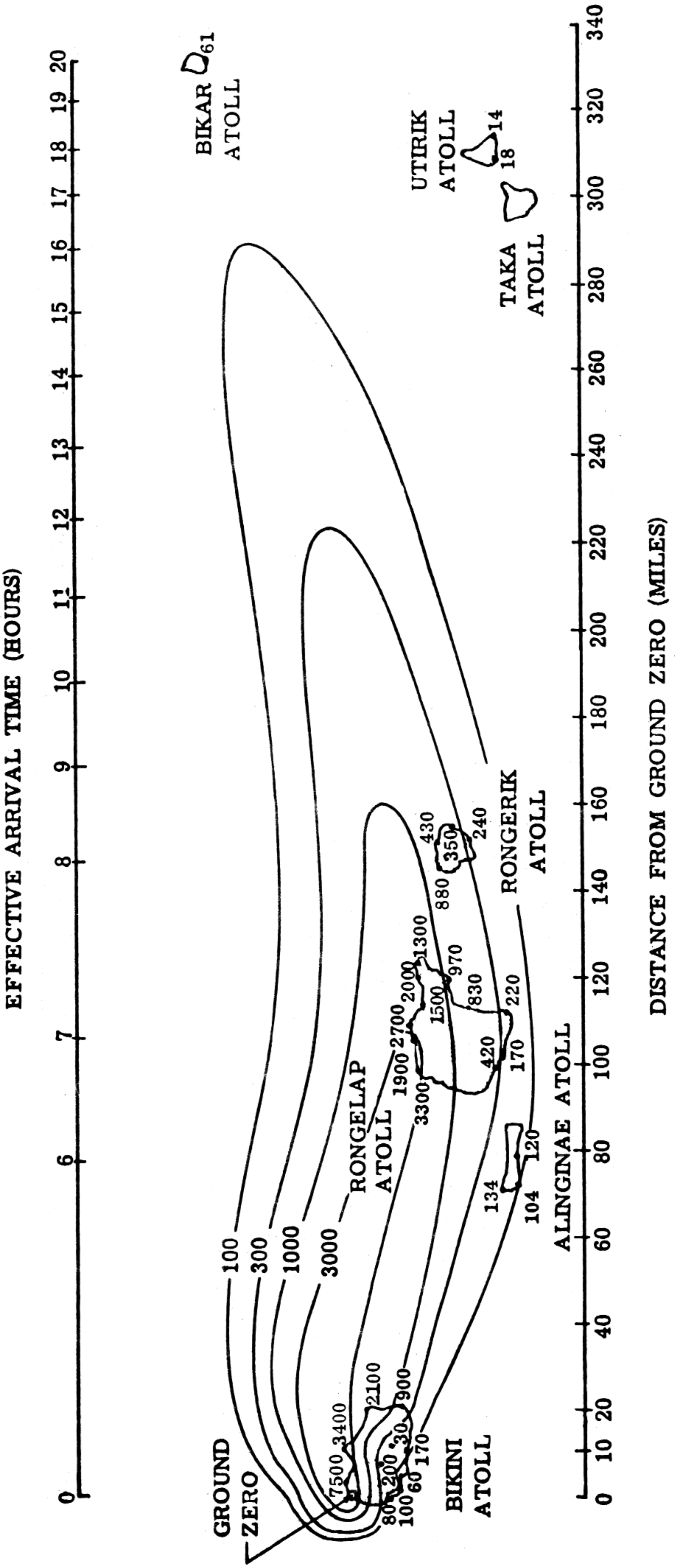

Figure 9.101. Estimated total-dose contours in roentgens at 96 hours after the BRAVO test explosion.

fallout will continue to be emitted for a long time, although at a gradually decreasing rate. The persistence of the external gamma radiation may be illustrated in connection with the BRAVO test by considering the situation at two different locations in Rongelap Atoll. Fallout began about 4 to 6 hours after the explosion and continued for several hours.

9.105 The northwestern tip of the atoll, 100 miles from the point of detonation, received 3,300 roentgens during the first 96 hours after the fallout started. This was the heaviest fallout recorded at the same distance from the explosion and may possibly have represented a hot spot, as mentioned above. About 25 miles south, and 115 miles from ground zero, the dose over the same period was only 220 roentgens. The inhabitants of Rongelap Atoll were in this area, and were exposed to radiation dosages up to 175 roentgens before they were evacuated some 44 hours after the fallout began (see § 11.126). The maximum theoretical exposures in these two areas of the atoll for various time intervals after the explosion, calculated from the decay curves given earlier in this chapter, are recorded in Table 9.105.

TABLE 9.105

CALCULATED RADIATION DOSES AT TWO LOCATIONS IN RONGELAP ATOLL FROM FALLOUT FOLLOWING THE MARCH 1, 1954 TEST AT BIKINI

	Accumulated dose in this period (roentgens)	
Exposure period after the explosion	*Inhabited location*	*Uninhabited location*
First 96 hours	220	3, 300
96 hours to 1 week	35	530
1 week to 1 month	75	1, 080
1 month to 1 year	75	1, 100
Total to 1 year	405	6, 010
1 year to infinity	About 8	About 115

9.106 It must be emphasized that the calculated values in Table 9.105 represent the maximum doses at the given locations, since they are based on the assumption that exposed persons remain out-of-doors for 24 hours each day and that no measures are taken to remove radioactive contamination. Furthermore, no allowance is made for weathering or the possible dispersal of the particles by winds. For example, the dose rates measured on parts of the Marshall Islands on the 25th day following the explosion were found to be about 40 percent of the expected values. Rains were known to have occurred during the second week, and these were probably responsible for the major decrease in the contamination.

9.107 In concluding the present discussion of fallout contamination, it may be noted that the 96-hour dose contours shown in Fig. 9.101, representing the fallout pattern in the vicinity of Bikini Atoll after the high-yield explosion of March 1, 1954, as well as the unit-time reference dose-rate contours in Fig. 9.73, can be regarded as more-or-less typical, so that they may be used for planning purposes. Nevertheless, it should be realized that they cannot be taken as an absolute guide. The particular situation which developed in the Marshall Islands was the result of a combination of circumstances involving the energy yield of the explosion, the height of burst, the nature of the surface below the point of burst, the wind system over a large area and to a great height, and other meteorological conditions. A change in any one of these factors could have affected considerably the details of the fallout pattern.

9.108 In other words, it should be understood that the fallout situation described above is one that *can* happen, but is not necessarily one that *will* happen, following the surface burst of a high fission-yield weapon. The general direction in which the fallout will move can be estimated fairly well if the wind pattern is known. However, the fission yield of the explosion and the height of burst, in the event of a nuclear attack, are unpredictable. Consequently, it is impossible to determine in advance how far the seriously contaminated area will extend, although the time at which the fallout will commence at any point could be calculated if the effective wind velocity and direction were known.

9.109 In spite of the uncertainties concerning the exact fallout pattern, there are highly important conclusions to be drawn from the results described above. One is that the residual nuclear radiation can, under some conditions, represent a serious hazard at great distances from a nuclear explosion, well beyond the range of blast, shock, thermal radiation, and the initial nuclear radiation. Another is that plans can be made to minimize the hazard, but such plans must be flexible, so that they can be adapted to the particular situation which develops after the attack.

RADIOACTIVE CONTAMINATION FROM NUCLEAR EXPLOSIONS

Radiological Warfare

9.110 For some time, consideration has been given to the possibility of using radioactive material deliberately as an offensive weapon in what is called "radiological warfare." The basic idea is that radioactive contamination of areas, factories, or equipment would make their use either impossible or very hazardous without any accompanying material destruction. To be effective, a radiological warfare agent should emit gamma radiations and it should have a half-life of a few weeks or months. Radioisotopes of long half-life give off their radiations too slowly to be effective unless large quantities are used, and those of short half-life decay too rapidly to provide an extended hazard.

9.111 Even if a radioisotope with suitable properties and which could be readily manufactured were selected as a radiological warfare agent, the problems of production, handling, and delivery of the weapon emitting intense gamma radiation would not be easily solved. In addition, stockpiling the radioactive material would present a difficulty. Other weapons can be prepared in advance, ready for an emergency. They can be kept for a long time without suffering deterioration. This is not true for radiological warfare agents, for natural decay would result in a continuous loss of active material. The production of a specific radioisotope is a slow process, at best, and so the continual and unavoidable loss would be a serious drawback.

9.112 The situation has undergone a change with the development of weapons having high fission energy yields. The explosion of such devices at low altitudes can cause radioactive contamination over large areas that are beyond the range of physical damage. Consequently, they are, in effect, weapons of radiological warfare. Instead of preparing and stockpiling the contaminating agent in advance, with its attendant difficulties, the radioactive substances are produced by fission at the time of the explosion. Radiological warfare has thus become an automatic extension of the offensive use of nuclear weapons of high fission yield. WORD "FISSION" INSERTED INTO 1962/4 EDITIONS (NOT IN 1957 EDITION, PAGE 428), TO ALLOW FOR HIGH-FUSION, RELATIVELY CLEAN BOMBS!

SHOULD SAY "FOR SURFACE BURSTS"!

CONTAMINATION OF AREAS

9.113 It was suggested in § 9.110 that radioactive contamination could deny the use of considerable areas for an appreciable period of time. There are two aspects of this situation which merit consideration. First, the direct effect of the radiation exposure on human beings who might have to live or work in a contaminated region, and second, the indirect effect due to the consumption of food grown (and animals raised) in such an area. The methods for calculating exposure doses from fallout, assuming no protection, have been given earlier in this chapter. The time that may be spent at a given location can thus be determined, provided some limit has been set concerning the total exposure dose. The value of such an emergency dose will vary, depending on the radiation history of the individual and the degree of hazard that he is willing to risk incurring under the existing conditions.

9.114 In contaminated agricultural areas, the hazard to workers could be reduced by turning over the earth, so as to bury the fallout particles. But there still remains the matter of absorption of radioisotopes from the soil by plants and their ultimate entry into the human system in food. It is known that some elements are taken up more easily than others, but the actual behavior depends on the nature of the soil and other factors. Some aspects of this subject are considered further in § 11.174 *et seq.*

Contamination in Subsurface Bursts

9.115 The extent of the contamination due to residual nuclear radiation following a subsurface explosion will depend primarily on the depth of the burst. If the explosion occurs at a sufficient depth below the surface, essentially none of the weapon residues and neutron-induced radioactive materials will escape into the atmosphere. There will then be no appreciable fallout. On the other hand, if the burst is near the surface, so that the fireball actually breaks through, the consequences, as regards fallout, will not be very greatly different from those following a surface burst.

9.116 There will, in fact, be a gradual transition in behavior from a high air burst, at one extreme, where all the radioactive residues are dissipated in the atmosphere, to a deep subsurface burst, at the other exteme, where the radioactive materials remain below the surface. In neither case will there be any significant local fallout. Between these two extremes are surface bursts or low air bursts which will be accompanied by extensive contamination due to early fallout. These merge into shallow subsurface bursts, for which the behavior is similar. With increasing depth of explosion, more of the radioactive residues remain in the vicinity of the burst point, i.e., in and around the crater, and proportionately less goes into the upper atmosphere to descend at a distance as fallout.

9.117 Since a shallow subsurface burst, in which the fireball emerges from the ground, is essentially similar to a surface burst, in which a large part of the fireball touches the earth, this type of nuclear explosion need not be discussed further. The case of interest, however, is that of a subsurface burst at such a depth that the fireball does not emerge, yet a considerable amount of dirt (or water) is thrown up as a column into the air.

9.118 It may be noted that some contribution to the residual nuclear radiations following a subsurface detonation is made by the radioisotopes, e.g., sodium-24 (§ 9.35), formed by neutron capture. However, as with a surface burst, this is so small in comparison with the radiations from the fission products that it may be ignored.

9.119 In the case of an underground explosion at a moderate depth there will be considerable crater formation. Much of the radioactive material will remain in the crater area, partly because it does not escape and partly because the larger pieces of contaminated rock, soil, and debris thrown up into the air will descend in the vicinity of the explosion. The finer particles produced directly or in the form of a base surge (§ 2.89) will remain suspended in the air and will descend as a fallout at some distance from ground zero.

9.120 The early fallout contour pattern will be dependent upon the fission energy yield, the depth of burst, the nature of the soil, and also upon wind and weather conditions. Other circumstances being more or less equal, the contamination in the crater area following a subsurface burst will be about the same as for a surface explosion of equal fission yield. However, the total contaminated area will be greater for the shallow subsurface burst because a larger amount of fission products is present in the early fallout.

Underwater Explosions

9.121 In a shallow underwater explosion, radioactive contamination will arise from the visible and invisible base surge, which remains near the water surface, and from the radioactive, airborne cloud, which is produced by condensation of the vented weapon residues (Chapter II). The radioactive cloud does not ascend as high as it would for a surface (or low air) burst of the same yield and so a large proportion of the fission product activity rains out in a short time within a radius of a few thousand yards of surface zero. In the Bikini BAKER test (§ 2.61), the contaminated fallout (or rain-out) consisted of both solid particles and of a slurry of salt crystals in drops of water. This contamination was difficult to dislodge and had there been personnel on board the ships used in the test, they would have been subjected to considerable doses of radiation if the fallout were not removed immediately.[6] Since the BAKER

[6] The technique of washdown of ships, by continuous flow of water over exposed surfaces to remove fall-out as it settles, was developed as a result of the Bikini BAKER observations.

shot was fired in shallow water, the bottom material may have helped in the scavenging of the radioactive cloud, thus adding to the contamination. It is expected that for shallow bursts in very deep water the fallout from the cloud will be less than observed at the test in Bikini lagoon, and in some cases there may be no cloud at all.

9.122 The base surge, both visible and invisible, created by the water from the plume as it falls back on the surface, will carry radioactive particles outward rapidly, enveloping nearby ships and land stations. The dose rate of the "transient" radiation, i.e., radiation from a source which is moving past a given location, from the base surge can be very high, e.g., of the order of 100,000 roentgens per hour, at early times. However, the radiation intensity declines rapidly as the concentration of the activity decreases as a result of radial expansion of the base surge ring and decay of the fission products. The total radiation dose delivered at a given distance from surface zero will depend on the direction and velocity of the wind which carries the base surge with it; for ships close to the explosion, the dose can be lethal.

9.123 The relative contributions of the base surge and the fallout (and rainout) from the cloud will depend upon the distance from surface zero, the depth of burst, and the environment. It is possible that shots at slightly greater depths than Bikini BAKER may produce no radioactive cloud and then all the contamination will come from the base surge. The nearness of the bottom may have an important bearing upon whether a detonation at a certain depth will create an airborne cloud or not. Furthermore, atmospheric conditions may also affect the rainout. For these reasons, the BAKER shot may not necessarily be entirely typical of a shallow underwater burst.

9.124 For a deep underwater shot there will generally be no airborne cloud (§ 2.82) and consequently no fallout and rainout. The radiation hazard will then arise only from the base surge, the characteristics of which are similar to those for a shallow underwater detonation. Whether the base surge from a deeper shot will be more or less radioactive than from one at a shallower depth, will depend on the scavenging action of the water on the fission debris in the interior of the underwater steam bubble created by the explosion. If all the debris is injected into the base surge, it will be considerably more radioactive than from a shallow shot, when much of the fission product residues goes into the airborne cloud. On the other hand, if the detonation takes place at a sufficiently great depth, it is possible that most of the fission debris will remain in the water and little will go into the base surge. In any event, the exact behavior of the fission products is believed to depend to a great extent on the precise condition of the bubble of gas and steam as it vents at the surface (§ 2.84).

9.125 There will always be some gaseous products of the fission process that are more or less insoluble in water. These radioactive gases may jet out of the plume and drift skyward, for shots fired at a moderate depth. Hence, even in the absence of a regular cloud, they will constitute a radioactive hazard in addition to the base surge.

9.126 The phenomena associated with nuclear explosions on the surface of the water will probably be similar to those at shallow depth; however, the probability of creating a base surge has not been established. The fallout and rainout from the cloud will also be subject to many variations dependent upon atmospheric conditions.

9.127 Most of the radioactivity remaining in the water and on the bottom after an underwater or water surface burst will be found initially in the vicinity of the shot. For detonations occurring in deep water, activity will be left behind at layers where the hot gas and steam bubble was in a contraction phase during the course of its rise through the water (§ 2.84). Fallback from the plume and venting of the bubble will leave considerable amounts of contamination on the surface near the burst point. This will rapidly diffuse downward and outward, thus reducing the activity level to safe limits for ships' personnel within 15 minutes to an hour.

9.128 An indication of the rate of spread of the active material and the decrease in the dose rate following a shallow underwater burst is provided by the data in Table 9.128, obtained after the Bikini BAKER test. Although the dose rate in the water was still fairly high after 4 hours, there would be considerable attenuation in the interior of a ship, so that during the time required to cross the contaminated area the total dose received would be small. Within 2 or 3 days after the BAKER test the radioactivity had spread over an area of about 50 square miles, but the radiation dose rate in the water was so low that the region could be traversed in safety.

9.129 The radioactivity falling back on the sea from the high airborne cloud will extend downwind much farther than the base surge or that transported by the water. However, it will be much less significant than other sources of contamination, the level of activity seldom being such as to prohibit operation of modern ships. The fallout debris quickly mixes with the water and since the water absorbs (or attenuates) the radiation to a considerable extent, the hazard is much less than would result from the same fallout on land. The radioactive water will gradually be transported to other locations by the prevailing currents, and if these are known, the path of the contaminated water can be predicted.

TABLE 9.128

DIMENSIONS AND DOSE RATE OF CONTAMINATED WATER AFTER THE 20-KILOTON UNDERWATER EXPLOSION AT BIKINI

Time after explosion (hours)	*Contaminated area (square miles)*	*Mean diameter (miles)*	*Maximum dose rate (roentgens per hour)*
4	16. 6	4. 6	3. 1
38	18. 4	4. 8	0. 42
62	48. 6	7. 9	0. 21
86	61. 8	8. 9	0. 042
100	70. 6	9. 5	0. 025
130	107	11. 7	0. 008
200	160	14. 3	0. 0004

ATTENUATION OF RESIDUAL NUCLEAR RADIATION

ALPHA AND BETA PARTICLES

9.130 In their passage through matter, alpha particles produce considerable direct ionization and thereby rapidly lose their energy. After traveling a certain distance, called the "range," an alpha particle ceases to exist as such.[7] The range of an alpha particle depends upon its initial energy, but even those from plutonium, which have a fairly high energy, have an average range of only just over 1½ inches in air. In more dense media, such as water or body tissue, the range is less, being about a one-thousandth part of the range in air. Consequently, alpha particles from radioactive sources are unable to penetrate even the outer layer of the skin (epidermis). It is seen, therefore, that as far as alpha particles arising from sources outside the body are concerned, attenuation is no problem.

9.131 Beta particles, like alpha particles, are able to cause direct ionization in their passage through matter. But the beta particles dissipate their energy less rapidly and so have a greater range in air and in other materials. Many of the beta particles emitted by the fission products traverse a total distance of 10 feet (or more) in the air before they are absorbed. However, because the particles are continually deflected by electrons and nuclei of the medium, they follow a tortuous path, and so their effective (or net) range is somewhat less.

9.132 The range of a beta particle is shorter in more dense media, and the average net distance a particle of given energy can travel in

[7] An alpha particle is identical with a nucleus of the element helium (§ 1.62). When it has lost most of its (kinetic) energy, it captures two electrons and becomes a harmless (neutral) helium atom.

water, wood, or body tissue is roughly one-thousandth of that in air. Persons in the interior of a house would thus be protected from beta radiation arising from fission products on the outside. It appears that even moderate clothing provides substantial attenuation of beta radiation, the exact amount varying, for example, with the weight and number of layers. Only beta radiation from material ingested or in contact with the skin poses a hazard (§ 11.148).

Gamma Radiation

9.133 The residual gamma radiations present a different situation. These gamma rays, like those which form part of the initial nuclear radiation, can penetrate considerable distances through air and into the body. Shielding will be required in most fallout situations to reduce the radiation dose to an acceptable level. Incidentally, any method used to decrease the gamma radiation will also result in a much greater attenuation of both alpha and beta particles.

9.134 The absorption of the residual gamma radiation from fission products and from radioisotopes produced by neutron capture, e.g., in sodium, manganese, and in the weapon residues, is based upon exactly the same principles as were described in Chapter VIII in connection with the initial gamma radiation. Except for the earliest stages of decay, however, the gamma rays from fallout have much less energy, on the average, than do those emitted in the first minute after a nuclear explosion. This means that the residual gamma rays are more easily attenuated; in other words, compared with the initial gamma radiation, a smaller thickness of a given material will produce the same degree of attenuation.

9.135 Calculation of the attenuation of the gamma radiation from fallout is different and in some ways more complicated than for the initial radiations. The latter emanate from the explosion point, but the residual radiations arise from contamination which is widely distributed on the ground, on roofs, trees, etc. The complication stems from the fact that the effectiveness of a given thickness of material is influenced by the fallout distribution (or geometry) and hence depends on the degree of contamination and its location relative to the position where protection is desired. Estimates of the attenuation of residual radiation in typical residential structures have been made, based partly on calculations and partly on measurements with simulated fallout.

9.136 Some of the results obtained for various locations are given in Table 9.136 for one- and two-story, brick-veneer and wood-frame houses, respectively. The "protection factor" is the ratio of the dose which would be received outdoors, without any protection, to that received at the indicated location in the structure. It should be emphasized that, while the values in the table are considered to be fairly representative, they must not be regarded as being exact. Deviations are to be expected because of differences in constructional details and environment, e.g., effect of nearby buildings.

TABLE 9.136

PROTECTION FACTORS AT VARIOUS LOCATIONS IN TYPICAL RESIDENTIAL STRUCTURES

	Type of structure			
	One-story brick veneer		One-story frame	
	Location			
First floor area (*sq ft*)	Center of ground floor	Center of basement	Center of ground floor	Center of basement
1,000	3.4	22	2.3	20
1,200	3.1	18	2.2	17
1,500	3.1	16	2.3	15
2,000	3.0	14	2.2	13
	Type of structure			
	Two-story brick veneer		Two-story frame	
	Location			
First floor area (*sq ft*)	Center of ground floor	Center of basement	Center of ground floor	Center of basement
1,000	4.4	54	2.3	44
1,200	4.4	41	2.4	37
1,500	4.4	37	2.4	34
2,000	4.1	34	2.4	29

9.137 The data in the table show that the heavier type of construction (brick veneer) provides better protection than a frame dwelling. It will be noted, too, that the protection factors in the middle of the ground floor of a wood-frame house are approximately the same for one- and two-story structures, but are appreciably different for brick-veneer houses. The reason is that in the latter case the fallout on the roof contributes a larger fraction of the overall dose than for the lighter walled construction. Consequently, reducing the radiation from the roof by increasing the separation distance, in the two-story house, produces a greater change in the dose (and protection factor) in the case of the brick-veneer house. In each type of dwelling the protection factor expected at the center of the ground floor does not change very much as the floor area is increased. This is because there is a compensation between the increase in dose received from fallout on the roof and the decrease due to the greater distance from the outside.

9.138 The advantages of a basement location in providing protection against fallout radiation in any type of house are obvious from Table 9.136. The values given apply only if no part of the basement wall is exposed; in other words, it must be completely covered by earth and there must be no window openings. Under these circumstances, greater protection can be obtained near the exterior wall than in the center of the basement, because there is a decrease in the radiation from fallout on the roof. This is one reason why it is generally recommended that fallout shelters be constructed in the basement adjacent to an outer wall which is not exposed in any way (§12.55).

9.139 Typical protection factor ranges for a wide variety of structures of different types are summarized in Table 9.139. All the structures are assumed to be isolated, so that the effects, if any, of adjacent buildings have been neglected. From these values, rough estimates can be made of the shielding from fallout radiation that might be expected under various conditions.

9.140 It is of interest to mention that a simple one-man foxhole, 3 feet in diameter and 4 feet deep, can provide a protection factor of about 40 if fallout is present up to the edge, but not inside. If an area 3 or 4 feet wide around the foxhole is kept free of fallout material, a protection factor of 100 or more is possible.

DELAYED FALLOUT

Introduction

9.141 Before proceeding to a description of delayed fallout, a general comparison may be made between the two types of fallout. In addition to corresponding to different physical situations, with regard to space and time, the early and delayed fallout represent different biological hazards. The principal hazard from early fallout

Table 9.139

PROTECTION FACTOR RANGES FOR VARIOUS STRUCTURES

Type of structure	*Protection factor range*
Underground shelters (3 ft earth cover or equivalent). Sub-basements of multistory buildings.*	1,000 or greater
Basement fallout shelters (heavy masonry residences). Basements without exposed walls of multistory masonry buildings. Central areas of upper floors (excluding top 3 floors) of high-rise buildings † with heavy floors and exterior walls.	250 to 1,000
Basement fallout shelters (frame and brick veneer residences). Central areas of basements with partially exposed walls in multistory buildings. Central areas of upper floors (excluding top floor) of multistory buildings with heavy floors and exterior walls.	50 to 250
Basements without exposed walls of small 1- or 2-story buildings. Central areas of upper floors (excluding top floor) of multistory buildings with light floors and exterior walls.	10 to 50
Basements (partially exposed) of small 1- or 2-story buildings. Central areas on ground floor in 1- or 2-story buildings with heavy masonry walls.	2 to 10
Above ground areas of light residential structures.	2 or less

* Multistory buildings are those having from 3 to about 10 stories.
† High-rise buildings have more than about 10 stories.

arises from the possible exposure to gamma rays from sources outside the body, with the effect of beta particles from fallout material in direct contact with the skin as secondary. Because most of the radioisotopes in the early fallout have relatively short half-lives, the activity decays fairly rapidly and will have decreased by a factor of several thousand after 6 months (or less). The delayed fallout hazard, on the other hand, is due to radioactive material, particularly strontium-90, which is ingested as food. The strontium-90 accumulates in the bone and part may remain there for many years, representing a prolonged internal hazard. Both early and delayed fallout can have long-term genetic effects, but they are probably of less significance than other deleterious effects to be expected. These and related aspects of fallout are discussed more fully in Chapter XI.

9.142 The very fine particles present in the radioactive cloud, with radii of a few microns or less (§ 9.47), fall extremely slowly under the influence of gravity. Consequently, they remain suspended in the

CHAPTER X

RADIO AND RADAR EFFECTS

INTRODUCTION

10.01 A nuclear explosion is accompanied by two principal types of electromagnetic effects.[1] These are entirely different from each other in nature, but both involve the whole spectral region of wavelengths longer than infrared, i.e., from about 1 millimeter on up to very large values. One involves the actual emission of an electromagnetic pulse of short duration from the explosion itself (or from the disturbed region in its vicinity), whereas the other, through alterations to the electrical properties of the atmosphere, can result in serious disturbance of electromagnetic waves, such as are used in communications and for radar, passing in the vicinity of the nuclear detonation. This disturbance may be caused by debris or water vapor introduced into the atmosphere by the burst, or by the unusual conditions created by the ionizing radiations from the exploding device. The latter mechanism may cause some radio and radar systems to be "blacked out" for several hours following the explosion. What little is known about the origin and characteristics of the electromagnetic pulse will be described first; the bulk of this chapter will then be concerned with a discussion of the changes in the normal ionization of the atmosphere brought about by a nuclear explosion and of the consequences of these changes.

THE ELECTROMAGNETIC PULSE

Origin of the Electromagnetic Pulse

10.02 The electromagnetic pulse or "radioflash" which is produced at the time of a nuclear detonation is of considerable interest. It is fairly well known that even small detonations of ordinary chemical

[1] The term "electromagnetic" as used in this chapter applies to radiations of the longer wavelengths and not to the entire spectrum described in § 1.69 *et seq.*, which is strictly included in the term.

explosives can produce electromagnetic signals, so it is not surprising that substantial pulses of this type accompany nuclear explosions.

10.03 There appear to be at least two different mechanisms whereby an electromagnetic pulse may be produced by a nuclear explosion. The first is associated with the creation by radiations from the burst of some kind of asymmetry in the electric charge distribution in the region surrounding the detonation; the second is the result of the rapid expansion of the essentially perfectly-conducting plasma of weapon residues in the earth's magnetic field. The first mechanism, often called the "Compton-electron model" for reasons which will be seen below, is believed to be the principal means for generation of electromagnetic pulses by detonations on or slightly above the earth's surface and by those near the "top" of the sensible atmosphere. The other, called the "field displacement" model, might be responsible for electromagnetic signals from underground bursts where the expansion is restrained in a more or less spherically symmetrical manner by the surrounding material, or from those at such great altitudes that the only immediate interaction of the explosion is with the geomagnetic field.

10.04 In the Compton-electron model the photons of the initial gamma radiation leave the exploding weapon with high energies, very soon collide with electrons in the atoms and molecules of the surrounding air, and transfer to them most of their energy. These Compton electrons (§ 8.68) move rapidly away, on the average, from the center of the burst. Provided some kind of asymmetry exists, this motion is apparently one of the main sources of the electromagnetic pulse. If the explosion were perfectly symmetrical, in a uniform atmosphere, the effects would be equal in all directions; the opposite components would then compensate each other exactly and there would be no electromagnetic signal. However, there are invariably a number of unrelated factors associated with a nuclear explosion which insures the presence of an asymmetry and, hence, of an electromagnetic pulse.

10.05 The most obvious asymmetric situation is that arising from a surface or near-surface (within 350 feet or so) burst, where the presence of the earth itself confines expansion of the weapon residues and radiation emission to the upward hemisphere. At the other extreme, where the explosion takes place high in the atmosphere, there will be very little interaction by upward-moving gamma rays because of the low air density, whereas those going downward will produce Compton electrons within a moderate distance. In both these cases, though their detailed behavior is probably different and their directions are opposite, the effective Compton-electron pulse is essentially vertical. Moreover, no matter where the burst occurs, there is inevitably some asymmetry in the emission and interaction of the photons. For example, the gamma-ray flux from an exploding weapon is itself never fully symmetric because of the presence of auxiliary apparatus, external structure, or the carrying vehicle. It should be noted that, while the "natural" asymmetries tend to be vertical, the other type may be oriented in any direction.

10.06 The Compton electrons created by the initial gamma radiation thus move away asymmetrically, at high velocity, from the exploding weapon. Since the remaining symmetrical components still compensate each other's effects, this motion appears from a distance to be a practically instantaneously accelerated pulse of current in one direction; it is, in other words, something like an "electric dipole" radiator of classical electrodynamics. The current pulse in the air radiates electromagnetic energy just as it would if it were flowing in a wire transmitting antenna, and this radiation constitutes the first part of the characteristic signal of the explosion.

10.07 When the Compton electrons move away from the explosion they leave behind the much slower moving positive ions, which are the other component of the ion pairs (§ 8.16). This relative displacement of positive and negative charges produces a radial electric field. In addition, in its passage through the air each Compton electron itself produces a large number of electron-ion pairs, perhaps 30,000, mostly toward the end of its path of 10 to 15 feet. Under the influence of the radial electric field, the large number of electrons now present will be driven back toward the burst point. This initiates a second pulse of current, but it is rapidly terminated by recombination of electrons with ions and by attachment of the electrons to neutral atoms and molecules in the air, even before the electric field is neutralized. The negative ions produced in the attachment process, and a corresponding number of positive ions, remain free a while longer because the ions, being heavier and less mobile than electrons, collide less frequently. This large volume of ionized gas (or "plasma") undergoes oscillations at characteristic frequencies similar to those observed in experimental plasmas in the laboratory. The oscillations damp out in a short time, as the negative particles (ions and electrons) combine with positive ions, but while they last they produce electromagnetic waves in the radiofrequency range.

Characteristics of the Compton-Electron Signal

10.08 The effective rise-time of the main part of the initial signal pulse (produced by the Compton electrons) from surface or near-surface bursts is of the order of 10^{-8} second, so that oscillation frequencies as high as 100 megacycles (10^8 cycles) per second may be expected. However, only a very small part of the total electromagnetic energy radiated is carried at such high frequencies. In addition, the higher frequencies are attenuated much more rapidly than the lower ones in normal propagation through the atmosphere. The frequencies of the plasma oscillations, which continue for several milliseconds and radiate considerably more energy, are much lower. These frequencies are attenuated hardly at all in normal propagation. At the lower end of the spectrum are the extremely low frequencies (in the very low kilocycle region) which might be detected very close to any such excited radiating dipole; they would exist principally in the "induction" and "quasi-static" fields and not be radiated at all.

10.09 The electromagnetic signal, as detected at a range of a hundred miles or so, thus consists of a continuous spectrum with most of its energy distributed about a median frequency (10 to 15 kilocycles per second) which is related inversely to the yield. At much longer distances, of many hundreds or thousands of miles, the form and spectrum of the pulse are determined largely by the characteristics of the medium of propagation, i.e., the "duct" between the surface of the earth and the D- or E-region of the ionosphere (see § 10.16).

10.10 A somewhat similar explosively-excited vertical dipole radiator which is frequently encountered in nature is lightning, and the electromagnetic signal (or static) associated with lightning also has a peak in the region of 10 kilocycles. This must not be taken, however, to mean that there is a detailed similarity in the modes of generation of the electromagnetic signals from lightning discharges and from nuclear explosions. The transmission path largely obliterates the characteristics of the original signal in both cases.

The Field-Displacement Mechanism

10.11 The second possibility which has been mentioned for the generation of radiofrequency signals by a nuclear explosion is considered to be of particular significance for extremely-high-altitude bursts. Immediately after the detonation has occurred, the hot weapon debris is essentially a highly ionized vapor (or plasma) which is expanding rapidly. A property possessed by all plasmas is a tendency to exclude a magnetic field, such as that of the earth, from its interior. The expanding plasma of weapon residues thus

IONIZATION PRODUCED BY NUCLEAR EXPLOSIONS

Introduction

10.23 Both nuclear and thermal radiations from a nuclear explosion can produce ionization in the air, and anywhere from 10 to 75 percent of the total energy yield, depending on the height of burst, may be expended in this respect. Utilizing the value of 34 ev as the amount of energy required to produce one ion pair in air, it is found that if only 10 percent of the energy of a megaton weapon were utilized for this purpose, a total of about 10^{32} free electrons would be formed. This is approximately equal to the number of free electrons in the entire normal ionosphere. Since many communications systems are profoundly affected by, or are even dependent upon, the ionospheric ionization, it is apparent that major consequences to such systems are possible as the result of a nuclear explosion.

10.24 In the subsequent treatment of the manner in which the electron density in the ionosphere can be affected by nuclear detonations, various burst height ranges, associated with different mechanisms, will be considered. It should be understood, however, that these ranges are somewhat arbitrary and are chosen for convenience in bringing out the changes in behavior that occur with burst height. Actually, there are no lines of demarcation between the various altitude ranges; the changes are continuous, but one type of mechanism gradually supersedes another and becomes the dominating one in each of the indicated regions.

10.25 For electromagnetic waves in the radio and radar range, circumstances are such that the maximum attenuation effects occur mainly within a 10-mile range centered around an altitude of about 45 miles. Hence most of the subsequent discussions pertain to this relatively narrow altitude region, which coincides with the D-region of the normal ionosphere.

Detonations Below 10 Miles Altitude

10.26 For nuclear detonations at altitudes below about 10 miles, much of the ionization produced in the surrounding air by the initial gamma radiation and neutrons and also by the thermal X-rays will be contained within a few hundred yards of the fireball. These free electrons will attach themselves almost immediately to neutral particles in the atmosphere, so that they will have a very short lifetime.

Within the fireball, the high temperature, of the order of a million degrees or so, will produce considerable ionization for a small fraction of a second. During this short period the free electron density in the fireball region will be sufficient to cause some attenuation of electromagnetic signals in the immediate vicinity of the burst. This effect will, however, disappear in a matter of seconds.

10.27 As the fireball rises, the residual nuclear radiation, mainly beta particles and gamma rays from the fission products and other weapon debris, will produce ionization in the immediate vicinity. Since the air density is quite appreciable, the free electrons will be rapidly removed by attachment to neutral particles and so their density will remain low. Consequently, unless the radioactive cloud rises to considerable heights, e.g., 20 miles or more, there will be little effect on radiofrequency wave propagation, in spite of the continuous emission of beta particles and gamma rays.

10.28 For explosions with yields in the megaton range, the radioactive cloud may rise to heights of more than 20 miles. The gamma radiation is emitted in all directions and although that going downward is of little consequence, as stated above, the situation is different for the rays traveling upward, into regions of low air density. The tenth-value thickness (§ 8.34) for absorption of the residual gamma radiation at altitudes of over 20 miles is more than 12 miles. Consequently, an appreciable proportion of the gamma rays will reach the D-region of the ionosphere and free electrons produced there will persist for several minutes. The continued emission of gamma radiation from the weapon residues in the radioactive cloud will then result in the build-up of a considerable concentration of electrons. Hence, a large-yield explosion at a fairly low altitude can cause abnormally high electron densities in the D-region that persist for several hours after the burst.

Detonations at 10 to 40 Miles Altitude

10.29 If the burst occurs in the altitude range of roughly 10 to 40 miles, where the air density is low, some of the initial nuclear radiations (gamma ray and neutrons) and, to a minor extent, the thermal X-rays will reach the D-region and cause significant amounts of ionization there. The approximate calculated electron densities at an altitude of 45 miles, where the densities are expected to be maximal (§ 10.77), resulting from a 1-megaton fission yield explosion at various burst heights, are shown in Fig. 10.29 as a function of

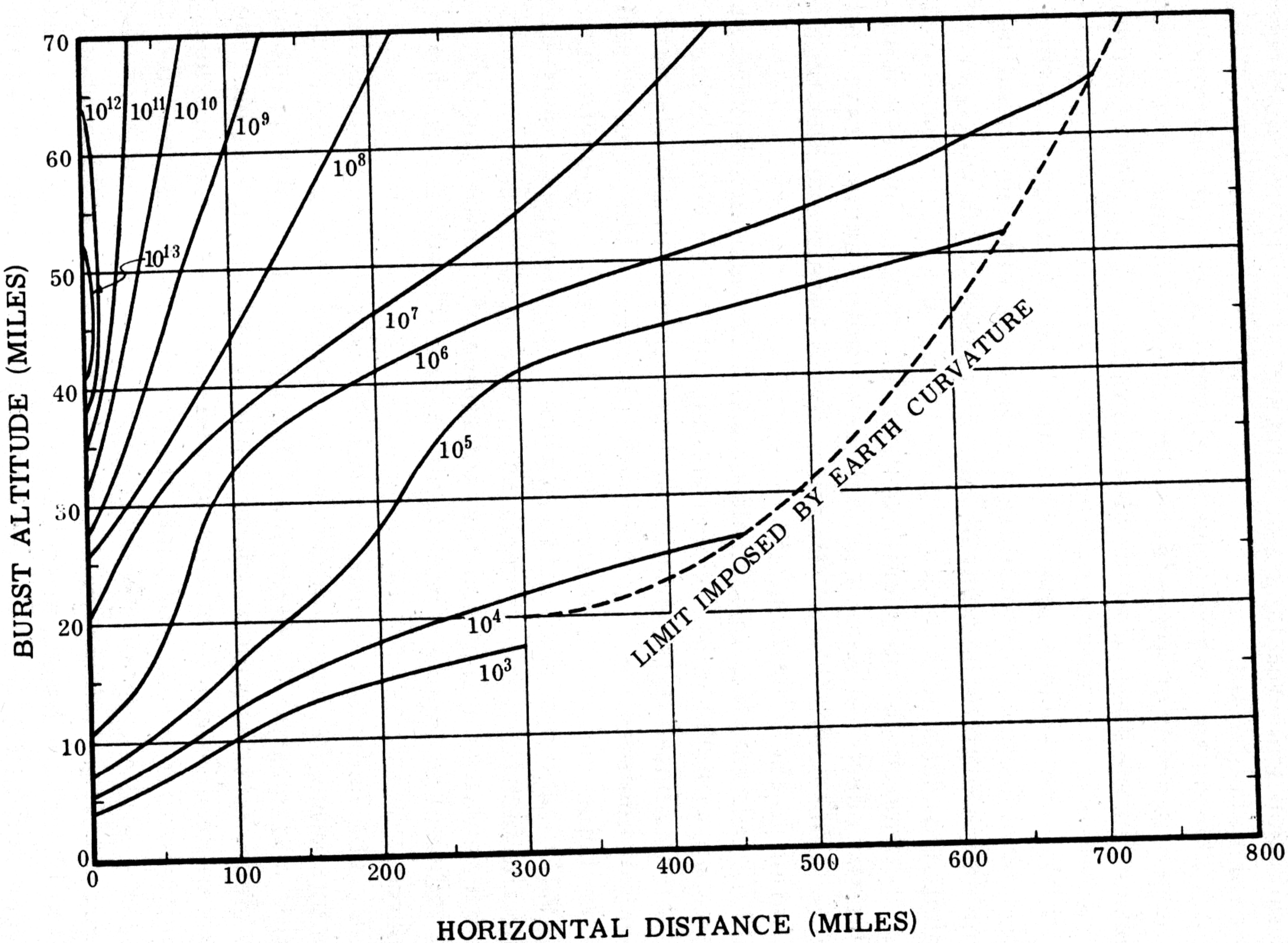

Figure 10.29. Calculated electron densities at an altitude of 45 miles produced by 1-megaton fission yield explosion at various burst heights as a function of horizontal distance.

BURSTS AT 40–70 MILES ALTITUDE: X-RAY HEATING OF AIR —

~~ity.~~ The sudden increase in the temperature of the air causes a proportional increase in the pressure; hence, the air pressure is no longer in balance with the gravitational force. This unbalance of forces causes the fireball to be hurled upward at high velocity, possibly as much as a mile per second. Consequently, the weapon debris reaches altitudes of several hundred miles, which are much higher than those to be expected if the rise were caused by buoyancy forces alone. Since the density of the air is extremely low, the particles will fall rapidly from these heights and within an hour will have reached an altitude of about 85 miles. Further fall will be much slower because of the increasing atmospheric density. The upward motion of the debris carries the radioactive particles into the regions where the gamma radiation has extremely long ranges. Thus, the gamma rays from fission residues will produce widespread ionization, although the electron concentration will be low because of the large volume involved. From a height of 300 miles, for example, the gamma rays will produce appreciable ionization in the D-region as far out as 3,000 miles, which is as far as the curvature of the earth will permit.

10.38 For the beta particles emitted by the radioisotopes in the weapon residues, a new situation arises for detonations at high altitudes. Because they carry an electrical charge, these particles follow a spiral path along the earth's magnetic field lines. As the radioactive debris from the burst rises and spreads, the beta particles will travel along the earth's magnetic field lines, about half moving toward the conjugate point in one hemisphere and the other half toward the corresponding point in the other hemisphere (§ 2.127). The particles will travel freely along the field lines at high altitudes, but will suffer collisions with atoms and molecules when they reach the denser air of lower altitudes. At about the D-region (45 miles altitude), the beta particles encounter air at a sufficient density to permit their absorption with accompanying ionization. There will thus be produced two (conjugate) volumes of ionization, one in each hemisphere, where the earth's magnetic field lines passing through the radioactive cloud encounter the D-region (see Fig. 2.127). Each of the volumes will be of roughly the same extent as the cloud and its effective vertical thickness will be about 10 miles, centered at an altitude of 45 miles. The electron density in each ionization volume will be approximately half that to be expected if the radioactive cloud were actually present at that particular location.

Detonations Above 70 Miles Altitude

10.39 If the burst altitude is from 70 miles up to a few hundred miles, still another behavior pattern can be expected. The initial nuclear radiation and thermal ultraviolet and X-rays traveling downward will cause ionization over a large extent of the D-region, in the manner described above. The radiations going upward, however, will not encounter enough air molecules (or atoms) to be absorbed and most will escape the earth's atmosphere completely. Some widespread ionization of low intensity will be caused, however, by neutrons which decay in the earth's magnetic field, as described in § 10.35.

10.40 The effect of the residual beta and gamma radiation will be determined, as in other cases, by the location of the radioactive debris. The motion of these residues is difficult to predict exactly, but a qualitative picture can be presented. Immediately after the explosion, the weapon debris travels radially outward from the burst point at high velocity, most of the material consisting of fission product (and other) ions and free electrons because of the very high temperatures. At the lower altitudes, the radial motion is quickly stopped by the surrounding atmosphere and the ions and electrons soon re-combine to form neutral atoms. But at the extreme altitudes under consideration, the air density is too low, i.e., collisions between debris and ambient air atoms are too infrequent, to cause any appreciable deceleration of the outward motion of the radioactive particles. However, since the material consists largely of free ions and electrons, i.e., a plasma, the earth's magnetic field plays a significant part in stopping the radial expansion.

10.41 As stated earlier (§ 10.11), a plasma in a magnetic field always tends to exclude the field lines from its interior. Hence, when the weapon debris expands it will cause the earth's field lines to be "stretched" in such a way that they remain outside the conducting volume. This stretching of the lines of force requires that work be done on the field by the expanding debris and the expansion stops when the pressure has decreased to such a point that it is equal to the magnetic pressure (or energy density) of the field. For a 1-megaton fission explosion it is estimated that this would occur at a radius of 600 miles, whereas for a 1-kiloton weapon the radius would be 60 miles.

10.42 If the burst point is not too high, the weapon residues in moving downward will reach a region of appreciable air density, at an altitude of about 85 miles, before the earth's magnetic field halts the expansion; part of the debris will then be stopped and neutralized.

FALLING ALONG EARTH'S MAGNETIC FIELD LINES!!

Because of the heating of the air by the thermal X-rays (§ 2.100), the radioactive material will probably be carried upward a short distance by the rising heated air. But it will settle again to an altitude of about 85 miles and be deposited in a circular layer, the radius of which is determined by the fission yield and altitude of the burst. This sheet will irradiate the D-region, the gamma rays producing widespread ionization of low intensity and the beta particles two regions of more intense ionization at locations on the magnetic field lines passing through the radioactive layer (§ 10.38).

10.43 The behavior of that part of the weapon debris which has been stopped by the magnetic field is somewhat uncertain. The distorted magnetic field will begin to recover and, in returning to their normal position, the field lines will probably cause turbulence and will tend to mix ambient air into the debris. Part of the debris will become electrically neutral, by recombination of the ions and electrons, and will no longer be affected by the magnetic field, so that it escapes from the region of confinement; the remainder, which is still charged, will be recompressed. Neutral particles of radioactive debris with sufficient energy and proper direction of motion will escape from the earth's gravitational field. The others will eventually settle to an altitude of about 85 miles and irradiate the D-region with the residual beta and gamma radiation, as described earlier.

10.44 The part of the debris which retains its charge for a longer time, and is confined by the magnetic field, will be in a position to release beta particles in locations and directions suitable for trapping in the earth's magnetic field. These particles, traveling back and forth, as described in § 2.129, and drifting eastward in longitude around the earth, will, within a few hours, spread to form a shell of high-energy beta particles, i.e., electrons, completely around the earth. In the ARGUS experiments, in which the bursts occurred at altitudes of about 300 miles (§ 2.54), well-defined shells, about 60 miles in thickness, were established and remained in place with measurable electron densities for many days. This has become known as the "Argus effect."

Time History of Ionization

10.45 After the ionization in the D-region has increased as the result of a nuclear detonation, the electron density will decay toward the normal value by electron-ion recombination and by electron-neutral particle attachment. If the electron density in the D-region exceeds about 10^6 electrons per cubic centimeter, recombination will be the dominant process for electron removal both day and night; but if the density is below this value, recombination will predominate in the daytime and attachment at night (§ 10.85 *et seq.*).

10.46 The times required for various electron densities in the D-region to be decreased by a factor of 10 have been calculated and the results are summarized in Table 10.46. The significance of these times is as follows: after 1 second, day or night, all electron densities

TABLE 10.46

CALCULATED RECOVERY TIMES IN D-REGION OF IONOSPHERE

Electron Density (electrons/cm³)	*Time for density to decrease by factor of 10*	
	Day (sec)	*Night (sec)*
10^8 or greater decreased to 10^7	less than 1	less than 1
10^7	10	10
10^6	100	15
10^5	1, 000	15
10^4	10, 000	15

of 10^8 or more will have decreased to 10^7; densities of 10^7 or less will remain essentially unchanged. At 10 seconds later, day or night, the density of 10^7 will have dropped to 10^6, but densities of 10^6 or less will not be appreciably affected. Below a density of about 10^6, the recovery times for day and night are different; during the day, it takes 100 seconds for the electron density to decrease from 10^6 to 10^5, whereas at night the same change requires only 15 seconds. Densities below 10^5 will decrease relatively slowly in the daytime. Since the normal electron density in the D-region is 10^3 in the daytime and almost zero at night, the data in Table 10.46 show that it would take about 3 hours in the day and about 100 seconds at night for this region to recover completely from a sudden increase in the electron density.

10.47 By using the recovery times in Table 10.46 in connection with the curves in Fig. 10.29, it is possible to determine the time history of the ionization produced by the initial nuclear radiation and the thermal radiation from a 1-megaton fission explosion taking place at various altitudes. However, because of simplifications made in the calculations, the results, at best, represent orders of magnitude only. Furthermore, in regions where the ionosphere has been severely disturbed by the nuclear burst, electron densities may remain above 10^7 electrons per cubic centimeter for much longer than the 1 second indicated in Table 10.46.

10.48 The density of electrons produced by the residual beta and gamma radiations decreases at a rate which is somewhat more difficult to estimate, because the ionization continues over an extended period of time. However, by combining the rates of removal of electrons by recombination and attachment with the rate of decay of the activity of the weapon residues, the results in Figs. 10.48 a and b have been obtained; they refer to 1-megaton fission detonations at altitude ranges of 10 to 40 miles and 40 to 70 miles, respectively. Two quantities are displayed on each figure: the radius to which the debris has expanded (which determines the region in which enhanced electron concentrations occur), and the associated D-region electron densities.

10.49 It is seen, for example, that at 1 hour after a 1-megaton burst in the 10- to 40-mile altitude range, an electron density of about 10^6 will extend over a region of radius 100 miles around the burst point, day or night. At 3 hours after the explosion, a density of 2×10^5 will be found out to a radius of 300 miles in the daytime, but at night the electron density out to this distance would be about 3×10^4 electrons per cubic centimeter.

EFFECTS ON RADIO AND RADAR SIGNALS

Introduction

10.50 The effects on radio communications systems of the atmospheric ionization produced by nuclear explosions at various altitudes depend on the type of system and in the particular manner in which the ionosphere is involved in transmitting the signals. The latter is determined, in turn, by the operating frequency of the system. It is convenient, therefore, to divide the discussion into sections corresponding to the conventional division of the communications spectrum into various decade frequency ranges. These ranges, with associated frequencies and wavelengths, are enumerated in Table 10.50.

Table 10.50

COMMUNICATIONS SPECTRUM

Name of Range	*Frequency Range**	*Wavelength Range*
Very-Low-Frequency (VLF)	3–30 kc	10^7–10^6 cm.
Low-Frequency (LF)	30–300 kc	10^6–10^5 cm.
Medium-Frequency (MF)	300 kc–3 Mc	10^5–10^4 cm.
High-Frequency (HF)	3–30 Mc	10^4–10^3 cm.
Very-High-Frequency (VHF)	30–300 Mc	10^3–10^2 cm.
Ultra-High-Frequency (UHF)	300 Mc–3 kMc	10^2–10 cm.

*The abbreviations kc, Mc and kMc refer to kilocycles (10^3 cycles/sec), megacycles (10^6 cycles/sec), and kilomegacycles (10^9 cycles/sec), respectively. 1 cycle/second = 1 Hertz = 1 Hz.

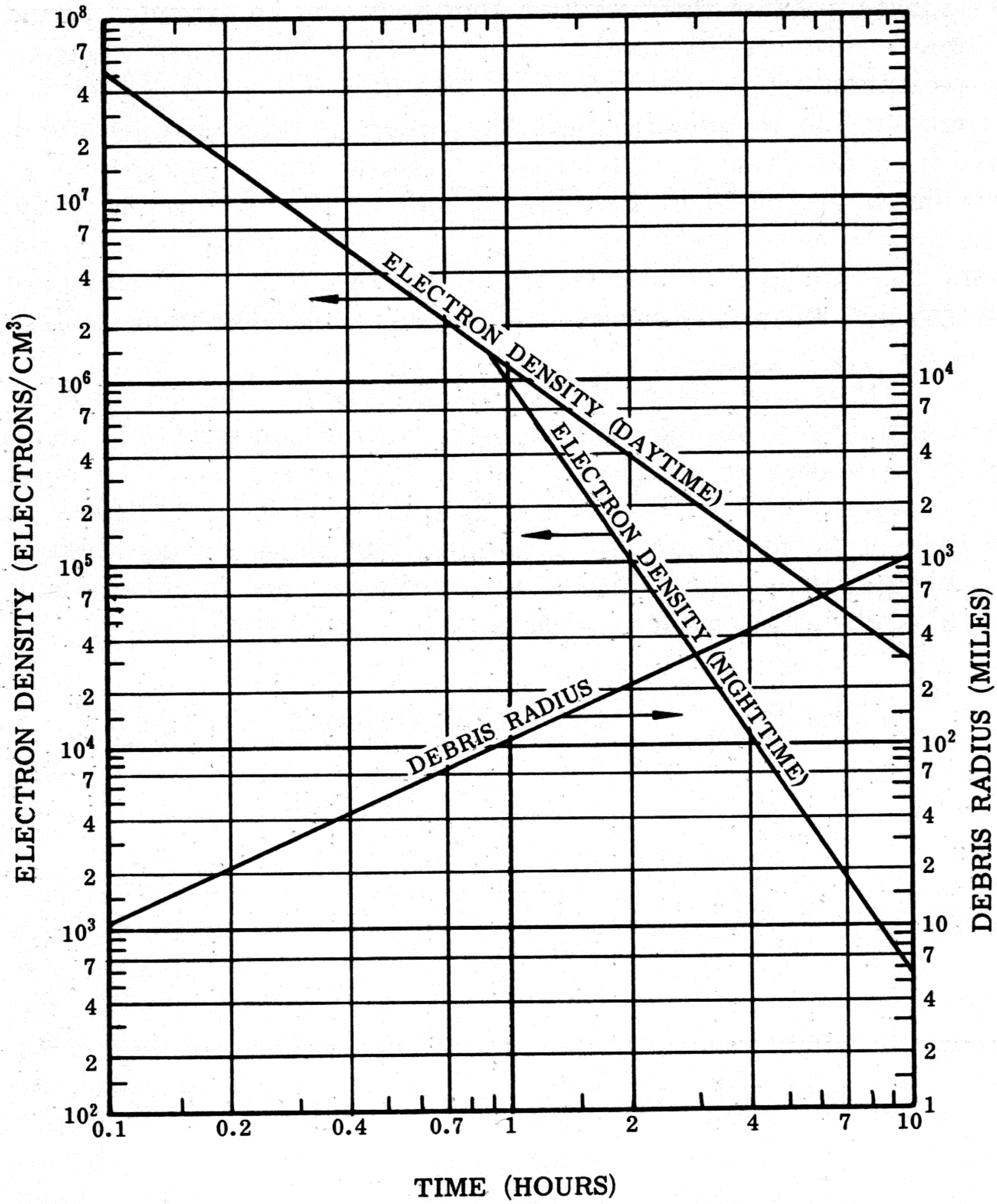

Figure 10.48a. Radius of debris expansion and corresponding D-region electron density as functions of time for a 1-megaton fission detonation in the altitude range of 10 to 40 miles.

Radar systems, which normally employ the frequency range of VHF or higher, are treated separately in § 10.64 *et seq.*

Very-Low-Frequency Range

10.51 Signals in the VLF range are transmitted by reflection

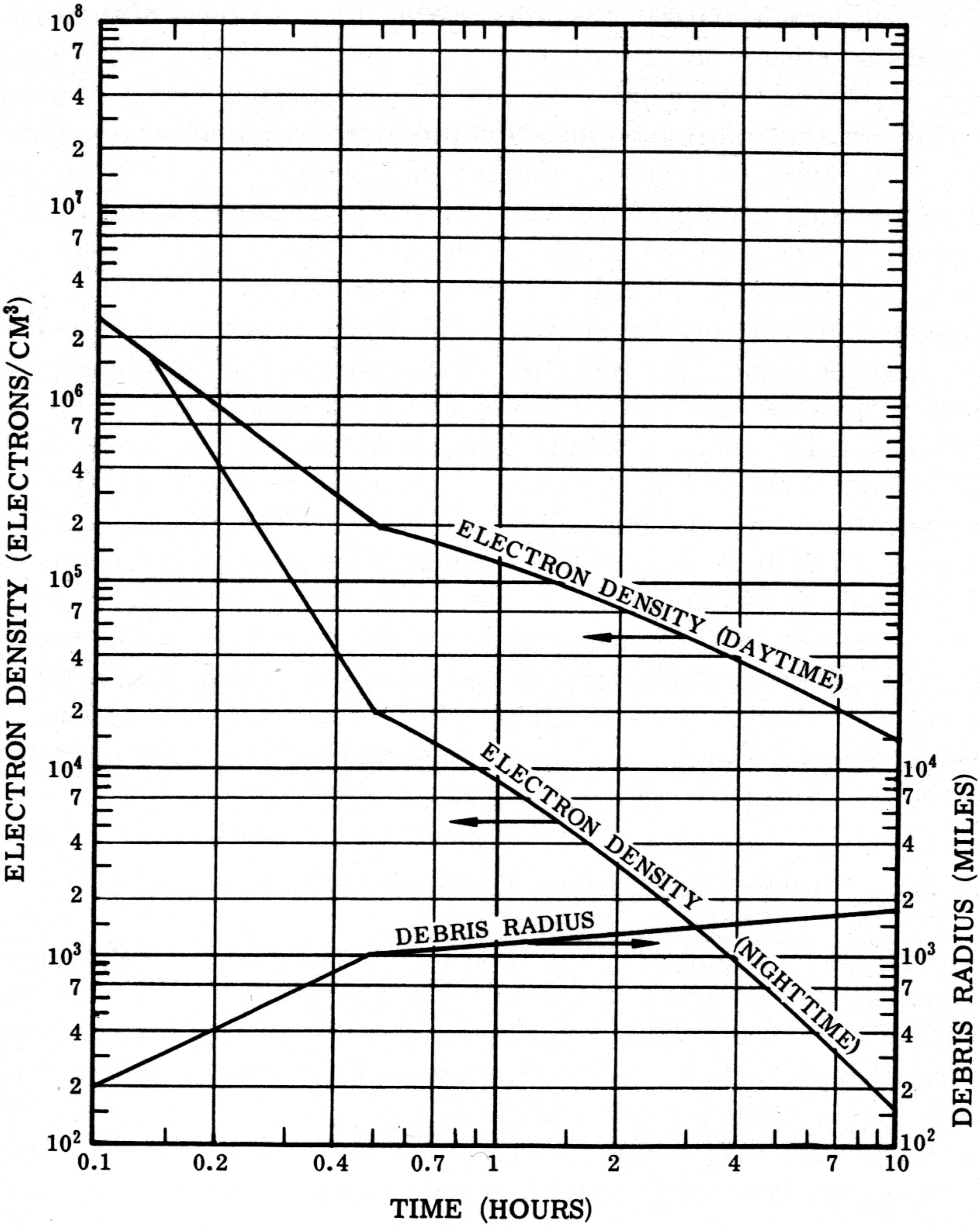

Figure 10.48b. Radius of debris expansion and corresponding D-region electron density as functions of time for a 1-megaton fission detonation in the altitude range of 40 to 70 miles.

between the surface of the earth and the extreme lower boundary of the ionosphere. At these frequencies, signals are reflected by such a slight change in electron density that they do not ordinarily penetrate into the ionosphere past the point where the electron density reaches 10^3 electrons per cubic centimeter. The wave may be regarded as traveling down a duct (or guide) whose boundaries are the earth and that level in the atmosphere at which the electron density is about

10^3 per cubic centimeter. Communication over distances of thousands of miles is possible by this mode.

10.52 Since the signal does not penetrate appreciably into the ionosphere, the additional ionization produced by a nuclear detonation does not cause any serious amount of attenuation. However, the actual distance the signal will travel between transmitter and receiver depends on the height at which the signal is reflected. If the electron density is rapidly increased, the waves will be reflected from a lower altitude and will travel a shorter total distance between transmitter and receiver; hence, the wave will arrive with a shift in phase. The most noticeable effect of a nuclear explosion on a VLF system will thus be a sudden phase shift of the signal at the time the ionosphere is disturbed. This will be followed by gradual recovery as the ionosphere returns to its normal state. Long-range gamma ray and neutron-decay beta ionization may alter VLF propagation conditions at very large distances from the detonation. In fact, after the TEAK and ORANGE high-altitude shots described in Chapter II, the 18.6-kilocycle signal transmitted from the Naval Radio Station at Seattle, Washington, to Gambridge, Massachusetts, suffered an abrupt 40° phase shift. The entire path was at least 3,000 miles from the burst point.

Low- and Medium-Frequency Ranges

10.53 For communications systems operating in the LF and MF regions of the spectrum, a different mode of propagation is normally utilized. Although there is a sky-wave mode, in which the signal is reflected repeatedly by the ionosphere and the ground, it is not normally relied upon for communication because of strong absorption. In the ground-wave mode, the signal is transmitted along the surface of the earth; it tends to bend and follow the curvature of the earth, particularly in regions where the surface is a good conductor of electricity. With reasonable amounts of transmitter power, it is possible to use this method for communication over distances of a few hundred miles. Thus, a high-altitude nuclear burst which changes the conditions in the ionosphere might have drastic effects on the sky-wave transmission but would not be expected to have any appreciable influence on the normally used ground-wave mode, in the LF and MF ranges of the radio spectrum.

zero at which there was 50-percent survival (for at least 20 days) among the occupants of a number of buildings in Hiroshima. School personnel who were indoors had a much higher survival probability than those who were outdoors at the times of the explosions.

TABLE 11.17

AVERAGE DISTANCES FOR 50-PERCENT SURVIVAL AFTER 20 DAYS IN HIROSHIMA

Conditions	*Approximate distance (miles)*
Overall	0. 8
Concrete buildings	0. 12
School personnel:	
Indoors	0. 45
Outdoors	1. 3

CAUSES OF INJURIES AMONG SURVIVORS

11.18 From surveys made of a large number of Japanese, a fairly good idea has been obtained of the distribution of the three types of injuries among those who became casualties but survived the nuclear attacks. The results are quoted in Table 11.18. It will be observed that the totals add up to more than 100 percent, since many individuals suffered multiple injuries.

TABLE 11.18

DISTRIBUTION OF TYPES OF INJURY AMONG SURVIVORS

Injury	*Percent of survivors*
Blast (mechanical)	70
Burns (flash and flame)	65
Nuclear radiation (initial)	30

11.19 Among survivors the proportion of indirect blast (mechanical) injuries due to flying missiles and movement of other debris was smallest outdoors and largest in certain types of industrial buildings. Patients were treated for lacerations received out to 10,500 feet (2 miles) from ground zero in Hiroshima and out to 12,500 feet (2.2 miles) in Nagasaki. These distances correspond roughly to those at which moderate damage occurred to wood-frame houses, including the shattering of window glass.

11.20 An interesting observation made among the Japanese survivors was the relatively low incidence of serious mechanical injuries.

For example, fractures were found in only about 4 percent of survivors. In one hospital among 675 patients, there were no cases of fracture of the skull or back and only one fractured femur although many injuries must have undoubtedly occurred. This was attributed to the fact that persons who suffered severe concussion or fractures were rendered helpless, particularly if leg injuries occurred, and, along with those who were pinned beneath the wreckage, were trapped by the flames. Such individuals, of course, did not survive.

BLAST INJURIES

Direct Blast Injuries: Biological Factors

11.21 Blast injuries are of two main types, namely, direct (or primary) injuries associated with exposure of the body to the environmental pressure variations accompanying a blast wave, and indirect injuries resulting from impact of missiles on the body or as the consequences of displacement of the body as a whole. There are also miscellaneous blast injuries, such as burns from the gases and debris, and irritation, and possibly suffocation, caused by airborne dust. The present section will treat direct injuries, and indirect blast effects will be discussed later.

11.22 The general interactions of a human body with a blast wave are somewhat similar to that of a structure as described in Chapter IV. Because of the relatively small size of the body, the diffraction process is quickly over, the body being rapidly engulfed and subjected to severe compression. This continues with decreasing intensity for the duration of the positive phase of the blast wave. At the same time the blast wind exerts a drag force of considerable magnitude which contributes to the displacement hazard to be discussed subsequently.

11.23 Due to the compression and subsequent decompression of the body and the transmission of pressure waves through the organism, damage occurs mainly at junctions between tissues and air-containing organs and at areas of union between tissues of different density, such as where cartilage and bone join soft tissue. The chief consequences are hemorrhage and occasional rupture of abdominal and thoracic organs. The lungs are particularly prone to hemorrhage and edema (liquid extrusion), and if the injury is severe, air reaches the veins of the lungs and hence the heart and arterial circulation. Death occurs in a few minutes from air embolic obstruction of the vessels of the heart or brain, but may also ensue from suffocation

Displacement Velocity of Missiles [5]

11.35 Because the effects of both missiles and body displacement depend on the velocity attained before impact, it is convenient to consider the relationships between displacement velocity and the blast parameters for objects as small as tiny pieces of glass and as large as man. The significant physical factors in all cases are the magnitude and duration of the blast overpressure and the accompanying winds, the acceleration coefficient of the displaced object,[6] ground shock, gravity, and the distance traveled by the object. The latter is important because, as a result of the action of the blast wave, the velocity of the object increases with the time and distance of travel until it attains that of the blast wind. Subsequently, the velocity falls because of negative winds or impact with the ground or other material.

11.36 As a result of the interaction of the various factors, small and light objects reach their maximum velocity fairly quickly, often after only a small portion of the blast wave has passed over them. The maximum velocity is thus not too sensitive to the duration of the overpressure and winds. Large, heavy objects, on the other hand, gain velocity more slowly and attain their maximum only after most of the blast wave has passed. The velocity is consequently influenced by the duration of the winds and overpressure.

11.37 The variations of the overpressure and dynamic pressure with time (see § 3.51 *et seq.*) at the location of interest also have a bearing on the behavior of a displaced object. The results given here were obtained at nuclear weapons tests under such conditions that the blast wave was approximately ideal in behavior. Some of the median velocities, masses, and spatial densities (number of fragments per square foot) of window glass, from houses exposed to the blast, and of natural stones are summarized in Table 11.37. For glass, the velocities refer to those attained after 10 feet of travel; for the stones the distances are unknown, but the velocities given in the table may be regarded as applicable to optimum distances of missile travel.

11.38 Studies have also been made of the displacement produced by the blast from a nuclear explosion on anthropomorphic dummies weighing 165 pounds. A dummy standing with its back to the blast

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[5] I. G. Bowen, *et al.*, "A Model Designed to Predict the Motion of Objects Translated by Classical Blast Waves," Civil Effects Test Operations, U.S. AEC Report CEX-58.9, 1961; E. R. Fletcher, *et al.*, "Determination of Aerodynamic Drag Parameters of Small Irregular Objects," Civil Effects Test Operations, U.S. AEC Report CEX-59.14, 1961.

[6] The acceleration coefficient is the product of the projected area presented to the blast wave and the drag coefficient (§ 4.69) divided by the mass of the object.

Table 11.37

VELOCITIES, MASSES, AND DENSITIES OF MISSILES

Missile	*Peak overpressure (psi)*	*Median velocity (ft/sec)*	*Median mass (grams)*	*Maximum number per sq ft*
Glass	1. 9	108	1. 45	4. 3
Glass	3. 8	168	0. 58	159
Glass	3. 9	140	0. 32	108
Glass	5. 0	170	0. 13	388
Stones	8. 5	286	0. 22	40

attained its maximum velocity, which was about 21 feet per second, after a displacement of 9 feet within 0.5 second after the arrival of the blast wave. The free-field overpressure at the test location was 5.3 pounds per square inch. The dummy traveled 13 feet before striking the ground and then slid or rolled a further 9 feet. It is of interest to note that a prone dummy did not move under the same conditions. The foregoing results were obtained in a situation where the blast wave was nearly ideal, but in another test, at a peak overpressure of 6.6 pounds per square inch, where the blast wave was nonideal (§ 3.43), both standing and prone dummies suffered considerably greater displacements. Even in these circumstances, however, the displacement of the prone dummy was less than that of the standing one.

Missile and Displacement Injury Criteria [7]

11.39 Velocity criteria for the production of skin lacerations by penetrating missiles, e.g., glass fragments, are not known with certainty. However, some reliable information is available concerning the probability of penetration of the abdominal cavity by glass. The impact velocities, for glass fragments of different masses, corresponding to 1, 50, and 99 percent probability are recorded in Table 11.39. Any wound involving a serous cavity can have dangerous consequences; the threshold for such injury can be taken to be about 100 feet per second for a 10-gram glass missile. For smaller fragments, the threshold velocity is higher.

11.40 Little is known concerning the relationship between missile mass and velocity of nonpenetrating missiles that will cause injury after impact with the body wall near the liver and spleen. It appears, however, that a missile with a mass of 10 pounds striking the head at

[7] D. R. Richmond, I. G. Bowen, and C. S. White, "Tertiary Blast Effects: The Effect of Impact on Mice, Rats, Guinea Pigs, and Rabbits," *Aerospace Medicine*, **32**, 789 (1961).

TABLE 11.39

PROBABILITIES OF GLASS FRAGMENTS PENETRATING ABDOMINAL CAVITY

Mass of glass fragments (grams)	*Probability of penetration (percent)*		
	1	50	99
	Impact velocity (ft/sec)		
0. 1	235	410	730
0. 5	160	275	485
1. 0	140	245	430
10. 0	115	180	355

a velocity of 12 to 13 feet per second or more can cause skull fracture. For such missiles it is unlikely that a significant number of dangerous injuries will occur at impact velocities of less than 10 feet per second.

11.41 Although there may be some hazard associated with the accelerative phase of body displacement by a blast wave, the deceleration, particularly if impact with a solid object is involved, is by far the more significant. Since a hard surface will cause more serious injury than a soft one, the damage criteria given below refer to impact of the displaced body with a hard object. From various data, it is concluded that an impact velocity of 10 feet per second is unlikely to be associated with a significant number of serious injuries; between 10 and 20 feet per second some fatalities may occur; and above 20 feet per second the probability of fatal injury increases rapidly with increasing displacement velocity.

11. 42 From the results of field work and laboratory studies it is possible to predict the ranges at which missiles (and man) will attain specified velocities for different nuclear explosion yields and burst conditions. The values are dependent upon the acceleration coefficient (§ 11.35) of the moving object, and two special cases of interest have been chosen for representation in Fig. 11.42: one is for glass missiles ranging in mass from 0.1 to 10 grams (acceleration coefficient 0.72 sq ft/lb), and the other is for man in random orientation (average acceleration coefficient 0.03 sq ft/lb); in both cases the displacement is arbitrarily fixed at the reasonable value of 10 feet. The curves in Fig. 11.42 give the velocities as a function of range for a 1-kiloton explosion assuming (1) a surface burst and (2) air burst conditions which yield the maximum range for each velocity. In order to determine the velocities for any specified energy yield, the scaling expressions given on the page facing the figure are to be used.

The curves in Fig. 11.42 give the velocity attained after 10 feet displacement of (*a*) 0.1- to 10-gram pieces of double-strength window glass (acceleration coefficient 0.72 sq ft/lb) and (*b*) a 165-pound man standing in an open area (acceleration coefficient 0.03 sq ft/lb), as a function of distance from ground zero in air and surface bursts of a 1-kiloton weapon. (The burst heights for the air burst are such as to maximize the range for each velocity.)

Scaling. The respective distances scale approximately as follows:

$$(a)\ R \approx R_1 W^{0.35} \text{ and } (b)\ R \approx R_1 W^{0.4},$$

where R_1 is the range for a 1-kiloton explosion, as given in Fig. 11.42, and R is the range for the same velocity for a W-kiloton burst.

Example

Given: A 1 MT air burst.

Find: (*a*) The distance from ground zero at which a small piece of double-strength window glass will attain a velocity of 100 feet per second at a location 10 feet from the window.

(*b*) The velocity of a 165-pound man, standing in the open 5 miles from ground zero, after a displacement of 10 feet.

Solution: (*a*) For a 1 KT air burst, the range for a 100-ft/sec velocity for glass fragments is found from Fig. 11.42 to be 0.68 mile; hence, for 1 MT, i.e., 1,000 KT, the corresponding range from ground zero is

$$R = R_1 W^{0.35} = 0.68 \times (1{,}000)^{0.35} = 7.5 \text{ miles.} \quad \textit{Answer}$$

(*b*) The range R_1 for 1 KT which is equivalent to 5 miles for 1 MT for the velocity of a man is given by

$$R_1 = \frac{R}{W^{0.4}} = \frac{5}{(1{,}000)^{0.4}} = 0.31 \text{ mile.}$$

For a 1 KT air burst at this range, the velocity is found from Fig. 11.42 to be 21 feet per second; this is consequently the value for 5 miles from a 5 MT air burst. *Answer*.

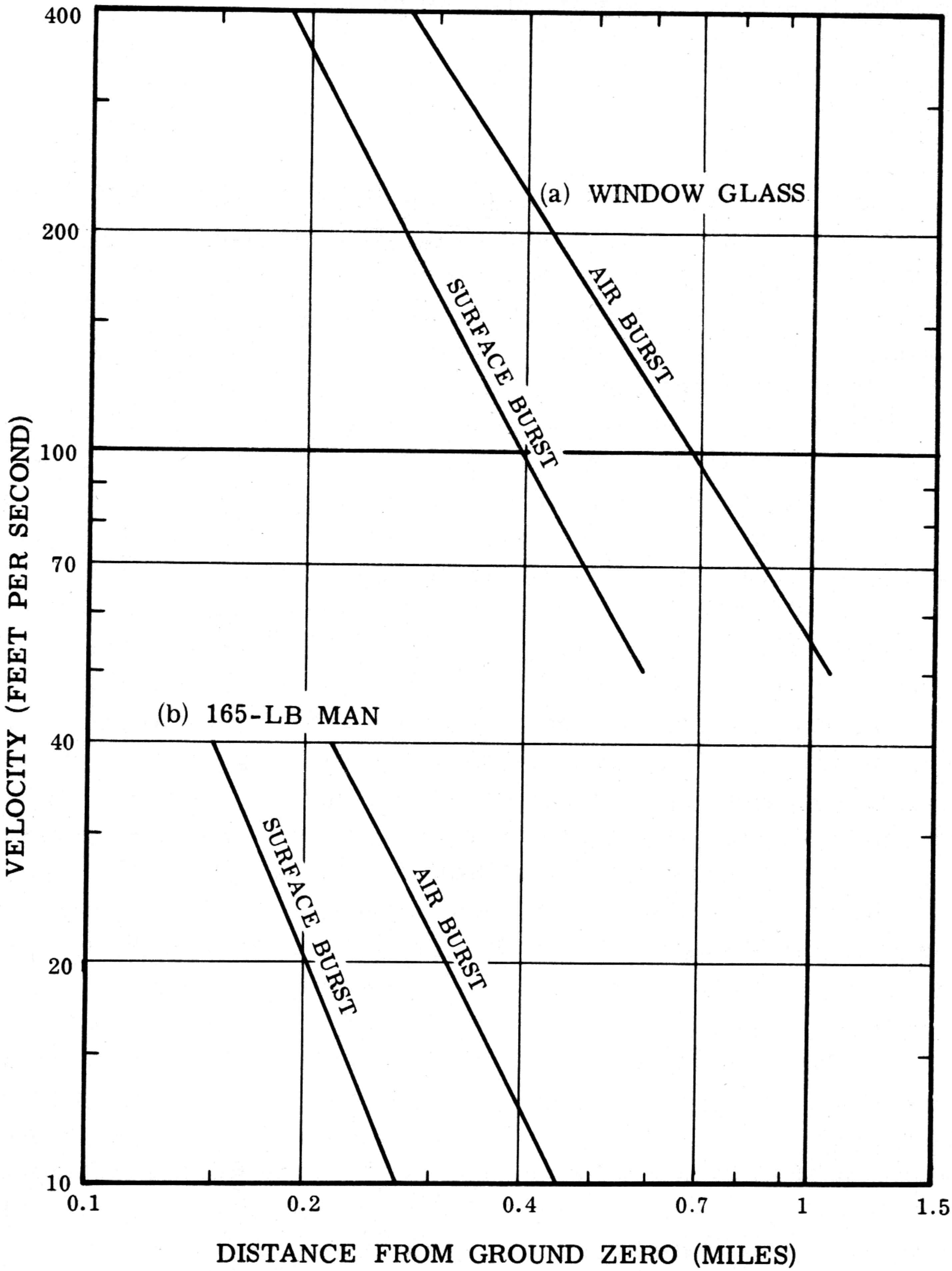

Figure 11.42. Velocities attained after 10 feet displacement by (*a*) 0.1- to 10-gram pieces of window glass, and (*b*) a 165-pound man in 1-kiloton surface and optimized air bursts.

11.62 It will be seen from Fig. 11.61 that the radiant exposure required to produce a burn of any particular degree of severity increases with the total energy yield of the explosion. The reason for this difference lies in the fact that with air bursts of lower energy yield the thermal energy is received in a short time, e.g., not more than a few tenths of a second, but with high energy yields, the effective delivery time may extend to several seconds (see Fig. 7.95). The greater the exposure time, the larger, in general, is the amount of thermal energy required to produce a particular effect (§ 7.35).

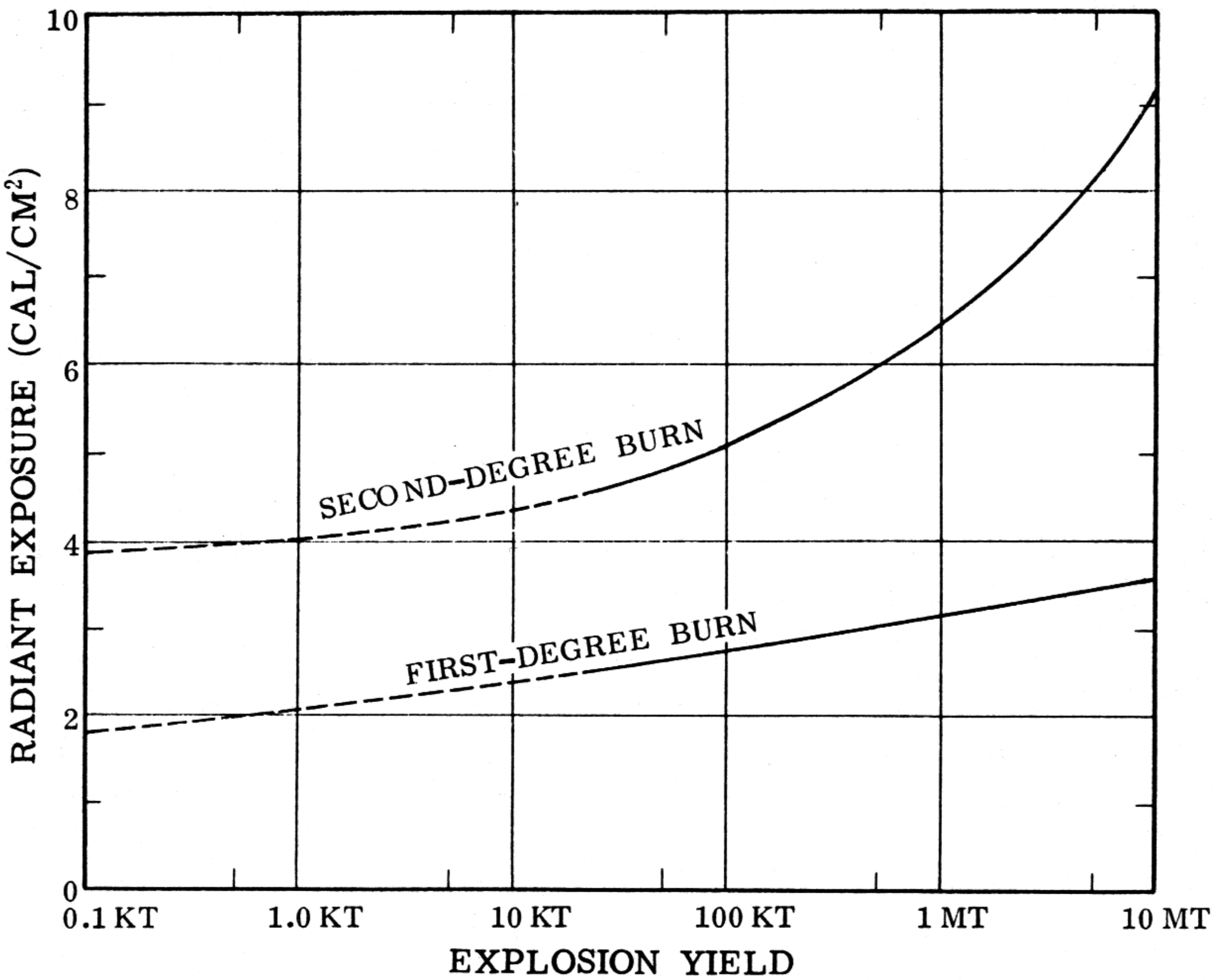

Figure 11.61. Radiant exposures required to produce first- and second-degree burns as a function of total energy yield.

11.63 Taking into consideration the variation of the thermal energy requirement with the energy yield of the explosion, Fig. 11.63 has been prepared to show the ranges for moderate first- and second-degree burns for nuclear explosions from 1 kiloton to 10 megatons total energy yield. In deriving the curves, two particular assumptions have been made. First, it is supposed that the explosion occurs in the air at such a height that the atmospheric pressure is not very greatly different from that at sea level. For a surface burst, the distances would be scaled down to about 80 percent of those in the figure. If the detonation takes place at a high altitude, i.e., above 100,000 feet, where the air pressure is quite low, the situation is different. Second, it is assumed that reasonably clear atmospheric conditions prevail, so that the attenuation is essentially independent of the visibility range as far out as 10 miles or more from ground zero. If the atmosphere is hazy, the distances predicted in Fig. 11.63, especially for the higher energy yields, may be somewhat in excess of the actual distances. They will certainly be too large if there is a substantial layer of cloud or smoke below the point of burst. On the other hand, the distances may be too small if clouds above the burst point or snow on the ground reflect the thermal radiation.

11.64 The application of Fig. 11.63 may be illustrated by using it to estimate the approximate limiting range for burns of the second degree in the event of an air burst of 100-kilotons energy. The figure is entered at the point where the vertical scale indicates 100 kilotons; the horizontal line is followed until it encounters the curve representing the second-degree burn formation. The value on the horizontal (distance) scale corresponding to this point is seen to be 4 miles. Hence, it may be expected that, for a 100-kiloton explosion, moderate second-degree (or more severe) burns will be experienced as far out as about 4 miles from the burst point, under average atmospheric conditions.

Effects of Thermal Radiation on the Eyes

11.65 It is an interesting fact that among the survivors in Hiroshima and Nagasaki, eye injuries directly attributable to thermal radiation appeared to be relatively unimportant. There were many instances of temporary blindness, occasionally lasting up to 2 or 3 hours, but only one case of retinal injury was reported.

11.66 The eye injury known as keratitis (an inflammation of the cornea) occurred in some instances. The symptoms, including pain caused by light, foreign-body sensation, lachrymation, and redness, lasted for periods ranging from a few hours to several days. Among 1,000 cases, chosen at random, of individuals who were in the open, within some 6,600 feet (1.25 miles) of ground zero at the time of the explosions, only 42 gave a history of keratitis coming on within the first day. Delayed keratitis was reported in 14 additional cases, with symptoms appearing at various times up to a month or more after the explosion. It is possible that nuclear radiation injury, which is associated with delayed symptoms, as will be seen below, may have been a factor in these patients.

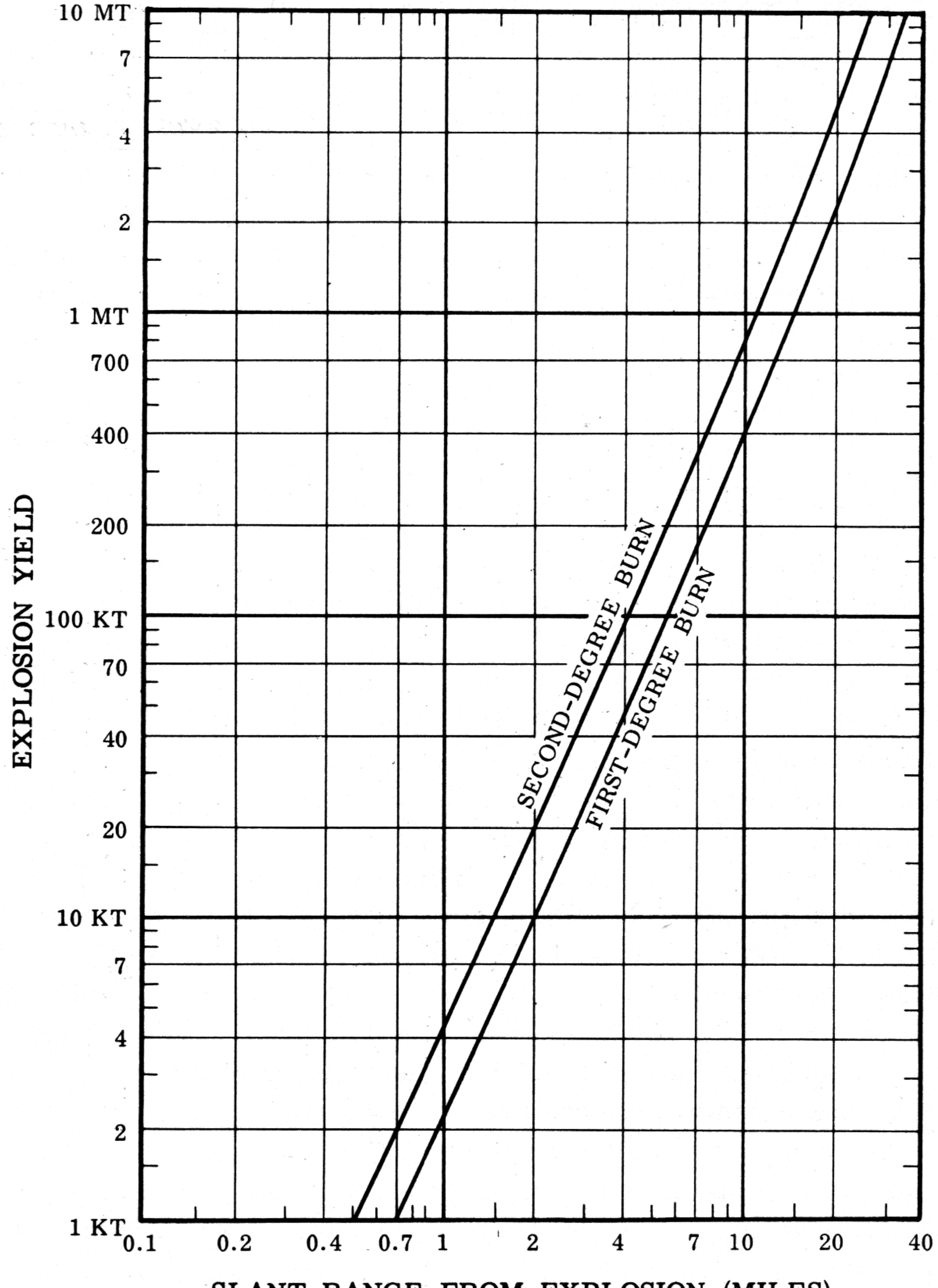

Figure 11.63. Ranges for first- and second-degree burns as a function of the total energy yield.

11.67 Investigators have reported that in no case, among 1,400 examined, was the thermal radiation exposure of the eyes apparently sufficient to produce permanent opacity of the cornea. This observation is not surprising since the cornea is transparent to the major portion of the thermal energy which is received in the visible and longer wavelength (infrared) parts of the spectrum. In approximately one-quarter of the cases studied there had been facial burns and often singeing of the eyebrows and eyelashes. Nevertheless, some 3 years later the corneas were found to be normal. ← NO EYES BURNED OUT.

11.68 Several reasons have been suggested for the scarcity of severe eye injuries in Japan. For example, the detonations occurred in the morning in broad daylight when the eye pupil would be expected to be small. Another possible explanation is that the recessed position of the eyes and, in particular, the overhanging upper lids served to decrease the direct exposure to thermal radiation. Furthermore, on the basis of probability, it is likely that only a small proportion of individuals would be facing the explosions in such a way that the fireball would actually be in their field of vision.

11.69 The effects of thermal radiation on the eyes fall into two main categories: (1) permanent (chorioretinal burns) and (2) temporary (flash blindness). Concentration of sufficient direct thermal energy, due to the focusing action of the eye lens, can cause the permanent damage. The focusing occurs, however, only if the fireball is in the individual's field of view. When this happens, chorioretinal burns may be experienced at distances from the explosion which exceed those where the thermal radiation produces skin burns. As a result of accidental exposures at nuclear weapons tests, a few burns of this type have been received at distances up to 10 miles from explosions of approximately 20-kilotons energy yield.

11.70 Experiments have been made with rabbits in an attempt to estimate the susceptibility of the human eye to thermal radiation. Although the rabbit eye is smaller, it is similar to the human eye in many respects including pupillary opening. However, under the same exposure conditions, the rabbit retina receives a larger amount of radiant energy per unit area because the rabbit eye, being smaller and having a shorter focal length, produces a smaller image. Estimates of the limiting distances are given in Table 11.70 for chorioretinal burns associated with a 20-kiloton low air burst, based on tests with rabbits and the assumption that, in humans, an exposure of 0.1 calorie per square centimeter for a period of about 0.15 second would produce a minimal eye burn. It should be noted, however, that research suggests this assumption may not be entirely correct. The distances are given for various degrees of atmospheric visibility, as defined in § 7.12, and for different pupil diameters. The importance of the air visibility and the brightness to which the eye is adapted are apparent.

TABLE 11.70

ESTIMATED LIMITING DISTANCES FOR CHORIORETINAL BURNS IN HUMANS FOR A 20-KILOTON LOW AIR BURST

	Pupil Opening Diameter		
	2 mm (Bright sunlight adapted	*4 mm (Cloudy day)*	*8 mm (Completely dark adapted)*
Visibility (miles)		*Distance (miles)*	
25	23	31	40
12	11	16	20
6	6	8	10
2	2	3	4

11.71 The size of the eye lesion produced is uncertain since it depends on the distance from the explosion and severity of the damage. The lesions contain areas of different types and degrees of damage; their relations to yield depend on a variety of factors and cannot be established with the information available at present. In all instances, however, there will be some temporary loss of visual acuity, at least, but the ultimate effect will depend upon the severity of the exposure and, to a greater extent, upon its location. If a chorioretinal burn is mild, or on the periphery of the visual field, the acuity may hardly be affected, but in more serious or centrally located cases there may be considerable loss of vision.

11.72 In a high-altitude detonation, the thermal radiation will generally traverse less of the atmosphere than for an air burst at the same slant range. Consequently, the atmospheric attenuation will be less in the former case in the absence of clouds, and chorioretinal burns may be expected at greater distances from the point of burst for similar energy yields. In order to obtain data concerning the possibility of eye injury, rabbits were exposed to the radiation from the TEAK shot of a megaton-range weapon at an altitude of 252,000 feet (§§ 2.53, 2.123 *et seq.*). Under nighttime conditions, chorioretinal burns occurred at slant distances up to about 345 miles; however, no measurements were made at greater distances and so this cannot be considered as a threshold range for eye damage.

11.73 Although extrapolation of the rabbit data to man is uncertain for high-altitude shots, it is felt that there would be some danger to human beings at distances greater than 200 miles under similar circumstances, and possibly as far as the eye can see at high altitude. It may be concluded from the Japanese situations that the number of individuals who will be looking directly at the fireball in the event of an unexpected air burst will not be large. High-altitude detonations will be visible over greater distances and so it is probable that more people would actually observe an explosion of this type.

11.74 The size of the fireball image on the retina decreases with increasing slant range from the burst point and hence the radiant energy is received on a smaller area of the retina. The decrease in area largely compensates for the decrease in thermal energy, which varies inversely as the square of the distance from the explosion. In these circumstances, therefore, the thermal energy received per unit area of the retina decreases only as the atmospheric transmittance decreases with increasing distance (§ 7.104). However, because of chromatic aberration, the image on the retina does not become much less than about 10 microns (0.001 cm) in diameter. Consequently, beyond a certain distance from the explosion, the image of the fireball does not decrease further. The radiant exposure then decreases rapidly with increasing distance since it is dependent on both the inverse square of the distance and the atmospheric transmittance.

11.75 Temporary "flash blindness" or "dazzle" can occur in persons who are too far from the explosion to suffer chorioretinal injury or who do not view the fireball directly. Flash blindness results when more thermal energy is received on the retina than is necessary for image perception, but less than is required for burn. The effect is a localized bleaching of the visual elements, with image persistence, after-image formation, halo, etc. From a few seconds to several days may be required for the eye to recover its functions. Dazzle is essentially the same as flash blindness although some authorities reserve the term dazzle for the effect of scattered light reaching the eye in which recovery is much more rapid than with "line of sight" flash blindness. Flash blindness occurs at greater ranges at night, when the eye is dark adapted, than in daylight; however, the range of these effects is highly dependent on atmospheric conditions prevailing at the time of detonation.

11.76 Much of the thermal radiation responsible for chorioretinal burns and flash blindness would arrive so soon after the explosion of a weapon in the kiloton energy range that reflex actions, such as blinking and contraction of the eye pupil, can give only limited protection. The same holds true for high-altitude, kiloton and megaton yield detonations, in which most of the thermal energy is emitted in very short times (§ 7.96). In certain situations with air bursts of high yield, however, the thermal pulse is long enough to permit some protection by the blink reflex.

LATE EFFECTS OF IONIZING RADIATION

Introduction

11.135 There are a number of consequences of nuclear radiation which may not appear for some years after exposure. Among them, apart from genetic effects, are the formation of cataracts, non-specific life shortening, leukemia, other forms of malignant disease, and retarded development of children *in utero* at the time of the exposure. Information concerning these late effects has been obtained from continued studies of various types, including those in Japan made chiefly under the direction of the Atomic Bomb Casualty Commission.[14]

11.136 The effects which occur later in life, like the acute reactions observed within a few weeks or months after irradiation, arise from changes in cells and tissues at the time of exposure. If an exposed individual survives the acute reaction, cell replacement may be complete, but the cells may not necessarily be quite normal; however, the causes for the late effects are largely unknown although many theories have been proposed.

Cataracts

11.137 An examination for the incidence of cataracts among the survivors of the bombings of Hiroshima and Nagasaki has revealed about 100 cases of non-vision-disturbing lens opacities in persons who were within about 3,000 feet (0.6 mile) from ground zero at the times of the respective explosions. Only in a small proportion of the patients was the opacity serious enough to require an operation. The cataracts are similar to those which have been previously associated with overexposure to X-rays or gamma rays, and so they were probably due to the initial nuclear radiation from the explosions. Because of the relatively high biological effectiveness of fast neutrons for the formation of lens opacities, as compared with gamma rays (§ 11.88), it is probable that this radiation was largely responsible for the Japanese cases.

11.138 Most persons in the same zone, with respect to the center of the explosion, died either from thermal or mechanical injuries or from radiation illness. Consequently, it is probable that all (or nearly all) the survivors who later developed cataracts must have received at

[14] The Atomic Bomb Casualty Commission of the U.S. National Academy of Sciences-National Research Council is sponsored by the Atomic Energy Commission and administered in cooperation with the Japanese National Institute of Health. One of its purposes is to study the long-term effects of exposure to nuclear radiation.

and future reports may shed more light on the incidence of neoplastic disease following exposure to ionizing radiation.

Retarded Development of Children

11.146 Among the mothers who were pregnant at the time of the nuclear explosions in Japan, and who received sufficiently large doses to show the usual radiation symptoms, there was a marked increase over normal in the number of still-births and in the deaths of newly born and infant children. A study of the surviving children made 4 or 5 years later showed a slightly increased frequency of mental retardation. Nearly all the mothers of these children, then *in utero*, were so close to ground zero that they must have been exposed to at least 450 rems of nuclear radiation. Maldevelopment of the teeth, attributed to injury of the roots, was also noted in many of the children.

11.147 A comparison made about 1952 of exposed children, whose ages ranged from less than 1 to about 14 years at the time of the explosions, with unexposed children of the same age, showed that the former had somewhat lower average body weight and were less advanced in stature and sexual maturity. On the other hand, no significant differences were observed in various neuromuscular coordination and muscular tests. It should be mentioned that those who were conceived in Japan after the nuclear attacks, even by irradiated parents, appear, for the most part, to be normal. The fear expressed at one time that there would be a sharp increase in the frequency of abnormalities has not been substantiated.

EFFECTS OF EARLY FALLOUT

External Hazard: Beta Burns

11.148 Injury to the body from external sources of beta particles can arise in two general ways. If the beta-particle emitters, e.g., fission products in the fallout, come into actual contact with the skin and remain for an appreciable time, a form of radiation damage, sometimes referred to as "beta burn," will result. In addition, in an area of extensive early fallout, the whole surface of the body will be exposed to beta particles coming from many directions. It is true that clothing will attenuate this radiation to a considerable extent; nevertheless, the whole body could receive a large dose from beta particles which might be significant.

11.149 Valuable information concerning the development and healing of beta burns has been obtained from observations of the Marshall Islanders who were exposed to fallout in March 1954. Within about 5 hours of the burst, radioactive material commenced to fall on some of the islands. Although the fallout was observed as a white powder, consisting largely of particles of lime (calcium oxide) resulting from the decomposition of coral (calcium carbonate) by heat, the island inhabitants did not realize its significance. Because the weather was hot and damp, the Marshallese remained outdoors; their bodies were moist and they wore relatively little clothing. As a result, appreciable amounts of fission products fell upon the hair and skin and remained there for a considerable time. Moreover, since the islanders, as a rule, did not wear shoes, their bare feet were continually subjected to contamination from fallout on the ground.

11.150 During the first 24 to 48 hours, a number of individuals in the more highly contaminated groups experienced itching and a burning sensation of the skin. These symptoms were less marked among those who were less contaminated with early fallout. Within a day or two all skin symptoms subsided and disappeared, but after the lapse of about 2 to 3 weeks, epilation and skin lesions were apparent on the areas of the body which had been contaminated by fallout particles. There was apparently no erythema, either in the early stages (primary) or later (secondary), as might have been expected, but this may have been obscured by the natural coloration of the skin.

11.151 The first evidence of skin damage was increased pigmentation, in the form of dark colored patches and raised areas (macules, papules, and raised plaques). These lesions developed on the exposed parts of the body not protected by clothing, and occurred usually in the following order: scalp (with epilation), neck, shoulders, depressions in the forearm, feet, limbs, and trunk. Epilation and lesions of the scalp, neck, and foot were most frequently observed (Figs. 11.151 a and b).

11.152 In addition, a bluish-brown pigmentation of the fingernails was very common among the Marshallese and also among American Negroes. The phenomenon appears to be a radiation response peculiar to the dark-skinned races, since it was not apparent in any of the white Americans who were exposed at the same time. The nail pigmentation occurred in a number of individuals who did not have skin lesions. It is probable that this was caused by gamma rays, rather than by beta particles, as the same effect has been observed in dark-skinned patients undergoing X-ray treatment in clinical practice.

11.153 Most of the lesions were superficial without blistering. Microscopic examination at 3 to 6 weeks showed that the damage

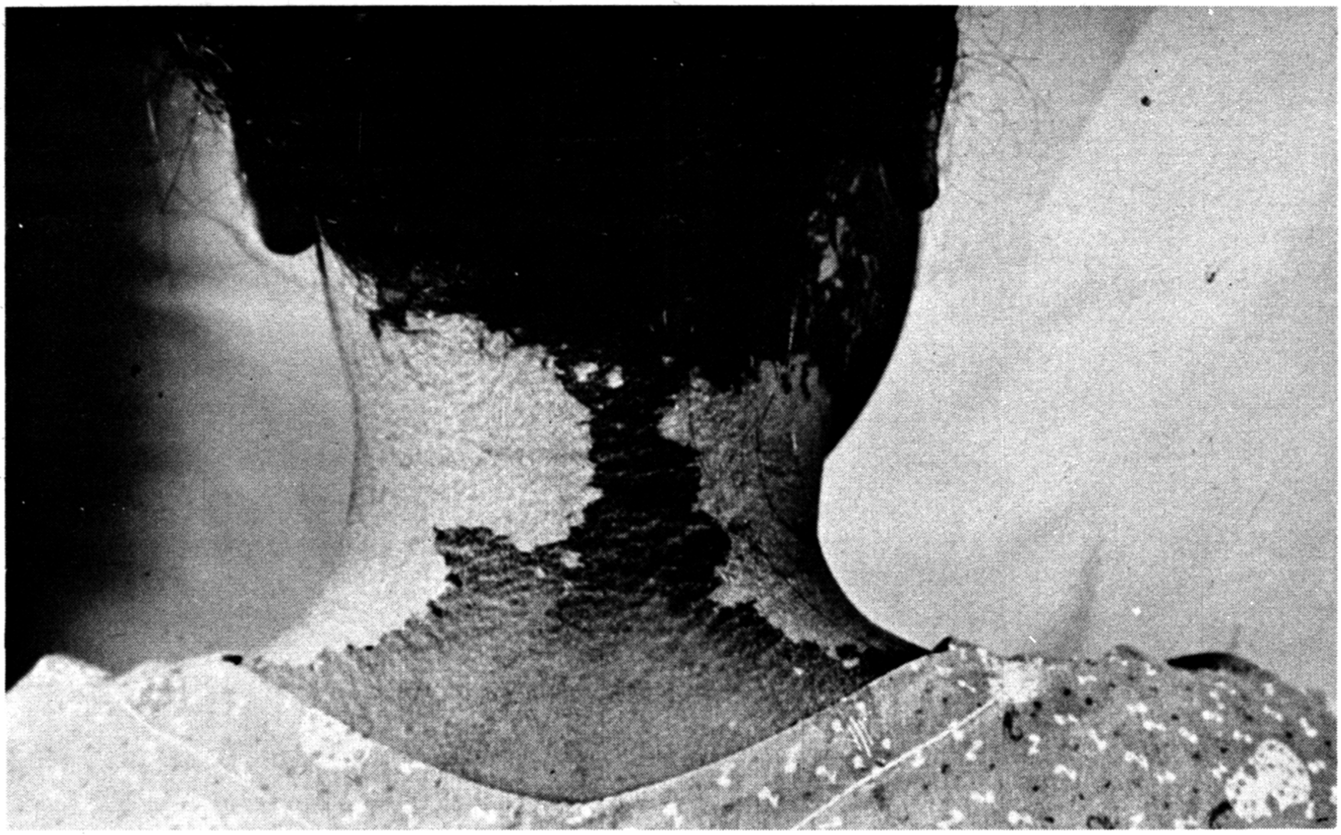

Figure 11.151a. Beta burn on neck 1 month after exposure.

was most marked in the outer layers of the skin (epidermis), whereas damage to the deeper tissue was much less severe. This is consistent with the short range of beta particles in animal tissue. After formation of dry scab, the lesions healed rapidly leaving a central depigmented area, surrounded by an irregular zone of increased pigmentation. Normal pigmentation gradually spread outward in the course of a few weeks.

11.154 Individuals who had been more highly contaminated developed deeper lesions, usually on the feet or neck, accompanied by mild burning, itching, and pain. These lesions were wet, weeping, and ulcerated, becoming covered by a hard, dry scab; however, the majority healed readily with the regular treatment generally employed for other skin lesions not connected with radiation. Abnormal pigmentation effects persisted for some time, and in several cases about a year elapsed before the normal (darkish) skin coloration was restored (Figs. 11.154 a and b).

11.155 Regrowth of hair, of the usual color (in contrast to the skin pigmentation) and texture, began about 9 weeks after contamination and was complete in 6 months. By the same time, nail discoloration had grown out in all but a few individuals. Seven years later, there were only 10 cases which continued to show any effects of beta burns, and there was no evidence of malignant changes.

Figure 11.151b. Beta burn on feet 1 month after exposure.

Blood studies of platelets and red blood cells indicated levels lower than average at 5 years after exposure; at 7 years after exposure the platelets continued to be slightly depressed. It thus appears that repair of bone marrow injury was not complete at this time. In the 1961 examination of the Marshallese people there was a possible indication of bone growth retardation in children who were babies at the time of the explosion.

Internal Hazard

11.156 Wherever fallout occurs there is a chance that radioactive material will enter the body through the digestive tract (due to the

Figure 11.154a. Beta burn on neck 1 year after exposure (see Fig. 11.151a).

consumption of food and water contaminated with fission products), through the lungs (by breathing air containing fallout particles), or through wounds or abrasions. It should be noted that even a very small quantity of radioactive material present in the body can produce considerable injury. Radiation exposure of various organs and tissues from internal sources is continuous, subject only to depletion of the quantity of active material in the body as a result of physical (radioactive decay) and biological (elimination) processes. Furthermore, internal sources of alpha emitters, e.g., plutonium, or of beta

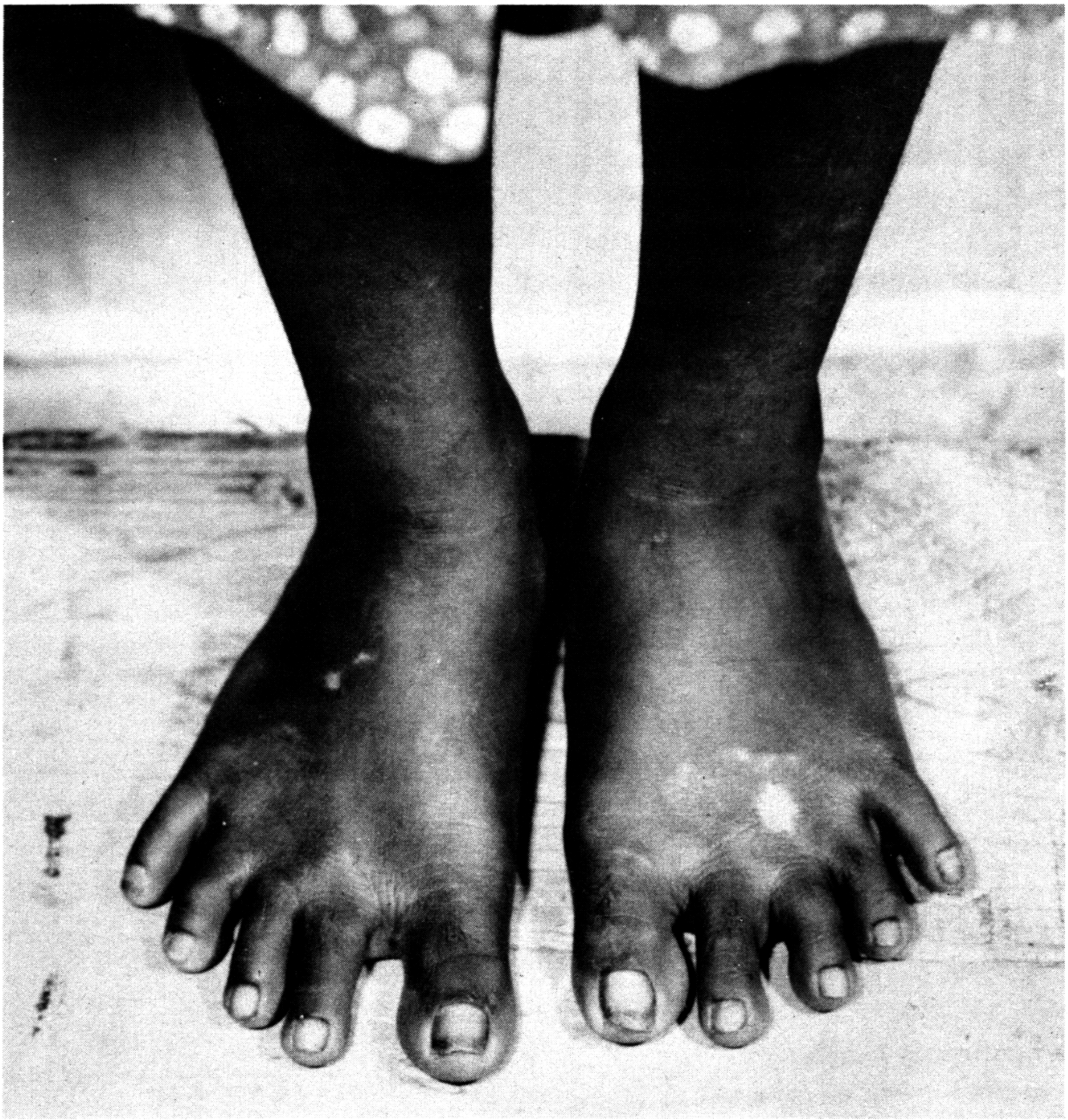

Figure 11.154b. Beta burn on feet 6 months after exposure (see Fig. 11.151b).

particles, or soft (low-energy) gamma-ray emitters, can dissipate their entire energy within a small, possibly sensitive, volume of body tissue, thus causing considerable damage.

11.157 The situation just described is sometimes aggravated by the fact that certain chemical elements tend to concentrate in specific cells or tissues, some of which are highly sensitive to nuclear radiation. The fate of a given radioactive element which has entered the blood stream will depend upon its chemical nature. Radioisotopes of an element which is a normal constituent of the body will follow the same metabolic processes as the naturally occurring, inactive (stable) isotopes of the same element. This is the case, for example, with iodine which tends to concentrate in the thyroid gland.

11.158 An element not usually found in the body, except perhaps in minute traces, will behave like one with similar chemical properties that is normally present. Thus, among the absorbed fission products, strontium and barium, which are similar chemically to calcium, are largely deposited in the calcifying tissue of bone. The radioisotopes of the rare earth elements, e.g., cerium, which constitute a considerable proportion of the fission products, and plutonium, which may be present to some extent in the fallout, are also "bone-seekers." Since they are not chemical analogues of calcium, however, they are deposited to a smaller extent and in other parts of the bone than are strontium and barium. Bone-seekers, are, nevertheless, potentially very hazardous because they can injure the sensitive bone marrow where many blood cells are produced. The damage to the blood-forming tissue thus results in a reduction in the number of blood cells and so affects the entire body adversely.

11.159 The extent to which early fallout contamination can get into the blood stream will depend upon two main factors: (1) the size of the particles, and (2) their solubility in the body fluids. Whether the material is subsequently deposited in some specific tissue or not will be determined by the chemical properties of the elements present, as indicated previously. Elements which do not tend to concentrate in a particular part of the body are eliminated fairly rapidly by natural processes.

11.160 The amount of radioactive material absorbed from early fallout by inhalation appears to be relatively small. The reason is that the nose can filter out almost all particles over 10 microns (0.001 centimeter) in diameter, and about 95 percent of those exceeding 5 microns (0.0005 centimeter). Most of the particles descending in the fallout during the critical period of highest activity, e.g., within 24 hours of the explosion, will be considerably more than 10 microns in diameter (§ 9.186 *et seq*). Consequently, only a small proportion of the early fallout particles present in the air will succeed in reaching the lungs. Furthermore, the optimum size for passage from the alveolar (air) space of the lungs to the blood stream is as small as 1 to 2 microns. The probability of entry into the circulating blood of fission products and other weapon residues present in the early fallout, as a result of inhalation, is thus low. Any very small particles reaching the alveolar spaces may be retained there or they may be removed either by physical means, e.g., by coughing, or by the lymphatic system to lymph nodes in the mediastinal (middle chest) area, where they may accumulate.

11.161 The extent of absorption of fission products and other radioactive materials through the intestine is largely dependent upon the solubility of the particles. In the early fallout, the fission products as well as uranium and plutonium are chiefly present as oxides, many of which do not dissolve to any great extent in body fluids. The oxides of strontium and barium, however, are soluble, so that these elements enter the blood stream more readily and find their way into the bones.[15] The element iodine is also chiefly present in a soluble form and so it soon enters the blood and is concentrated in the thyroid gland.

11.162 In addition to the tendency of a particular element to be taken up by a specific organ, the main consideration in determining the hazard from a given radioactive isotope inside the body is the total radiation dose delivered while it is in the body (or specific organ). The most important factors in determining this dose are the mass and half-life (§ 1.60) of the radioisotope, the nature and energy of the radiations emitted, and the length of time it stays in the body. This time is dependent upon the "biological half-time" which is the time taken for the amount of a particular element in the body to decrease to half of its initial value due to elimination by natural (biological) processes. Combination of the radioactive half-life and biological half-time gives rise to the "effective half-life," defined as the time required for the amount of a specified radioactive isotope in the body to fall to half of its original value as a result of both radioactive decay and natural elimination. In most cases of interest, the effective half-life in the body as a whole is essentially the same as that in the principal tissue (or organ) in which the element tends to concentrate. For some isotopes it is difficult to express the behavior in terms of a single effective half-life because of their complicated metabolic mechanisms in the human body (see § 11.178, footnote).

11.163 The isotopes representing the greatest potential internal hazard are those with relatively short radioactive half-lives and comparatively long biological half-times. A certain mass of an isotope of short radioactive half-life will emit particles at a greater rate than the same mass of another isotope, possibly of the same element, having a longer half-life. Moreover, the long biological half-time means that the active material will not be readily eliminated from the body by natural processes. For example, the element iodine has a fairly long biological half-time in many individuals. The actual value varies over a wide range, from a few days in some people to many

[15] Even under these conditions, only about 10 percent of the strontium or barium is actually absorbed.

years in others, but on the average it is about 90 days. Iodine is quickly taken up by the thyroid gland from which it is generally eliminated slowly. The radioisotope iodine-131, a fairly common fission product, has a radioactive half-life of only 8 days. Consequently, if a sufficient quantity of this isotope enters the blood stream it is capable of causing serious damage to the thyroid gland, because it remains there during essentially the whole of its radioactive life.

11.164 At short times after a detonation, other radioisotopes of iodine, e.g., iodine-133 and -135, would contribute materially to the total dose to the thyroid gland. However, their radioactive half-lives are measured in hours, and so they decay to insignificant levels within a few days of their formation. It should be mentioned that, apart from immediate injury, any radioactive material that enters the body, even if it has a short effective half-life, may contribute to damage which does not become apparent for some time.

11.165 In addition to radioiodine, the most important potentially hazardous fission products, assuming sufficient amounts get into the body, fall into two groups. The first, and more significant, contains strontium-89, strontium-90, cesium-137, and barium-140, whereas the second consists of a group of rare earth and related elements, particularly cerium-144 and the chemically similar yttrium-91.

11.166 Another potentially hazardous element, which may be present to some extent in the early fallout, is plutonium, in the form of the alpha-particle emitting isotope plutonium-239. This isotope has a long radioactive half-life (24,000 years) as well as a long biological half-time (about 200 years). Consequently, once it is deposited in the body, mainly on certain surfaces of the bone, the amount of plutonium present and its activity decrease at a very slow rate. In spite of their short range in the body, the continued action of alpha particles over a period of years can cause significant injury. In sufficient amounts, radium, which is very similar to plutonium in these respects, is known to cause necrosis and tumors of the bone, and anemia resulting in death.

11.167 Experimental evidence indicates that nearly all, if not all, inhaled plutonium deposits in the lungs where a certain portion, less than 10 percent, remains. Some of this is found in the bronchial lymph nodes. For this reason, the primary hazard from inhaled plutonium is to the lungs and bronchial lymph nodes. It is of interest to note that despite the large amounts of radioactive material which may pass through the kidneys in the process of elimination, these organs ordinarily are not greatly affected. By contrast, uranium causes damage to the kidneys, but as a chemical poison rather than because of its radioactivity.

11.168 Early fallout accompanying the nuclear air bursts over Japan was so insignificant that it was not observed. Consequently, no information was available concerning the potentialities of fission products and other weapon residues as internal sources of radiation. Following the incident in the Marshall Islands in March 1954, however, data of great interest were obtained. Because they were not aware of the significance of the fallout, many of the inhabitants ate contaminated food and drank contaminated water from open containers for periods up to 2 days.

11.169 Internal deposition of fission products resulted mainly from ingestion rather than inhalation for, in addition to the reasons given above, the radioactive particles in the air settled out fairly rapidly, but contaminated food, water, and utensils were used all the time. The belief that ingestion was the chief source of internal contamination was supported by the observations on chickens and pigs made soon after the explosion. The gastrointestinal tract, its contents, and the liver were found to be more highly contaminated than lung tissue.

11.170 From radiochemical analysis of the urine of the Marshallese subjected to the early fallout, it was possible to estimate the body burden, i.e., the amounts deposited in the tissues, of various isotopes. It was found that iodine-131 made the major contribution to the activity at the beginning, but it soon disappeared because of its relatively short radioactive half-life (8 days). Somewhat the same was true for barium-140 (12.8 days half-life), but the activity levels of the strontium isotopes were more persistent. Not only do these isotopes have longer radioactive half-lives, but the biological half-time of the element is also relatively long.

11.171 No elements other than iodine, strontium, barium, and the rare earth group were found to be retained in appreciable amounts in the body. Essentially all other fission product and weapon residue activities were rapidly eliminated, because of either the short effective half-lives of the radioisotopes, the sparing solubility of the oxides, or the relatively large size of the fallout particles.

11.172 The body burden of radioactive material among the more highly contaminated inhabitants of the Marshall Islands was never very large and it decreased fairly rapidly in the course of 2 or 3 months. The activity of the strontium isotopes fell off somewhat more slowly than that of the other radioisotopes, because of the longer radioactive half-lives and greater retention in the bone. Nevertheless, even strontium could not be regarded as a dangerous source of internal radiation in the cases studied. At 6 months after the explosion, the urine of most individuals contained only barely detectable quantities of radioactive material.

11.173 In spite of the fact that the Marshallese people lived approximately 2 days under conditions where maximum probability of contamination of food and water supplies existed, and that they took few steps to protect themselves, the amount of internally deposited radioactivity from early fallout was small. There seems to be little doubt, therefore, that, at least as far as short term effects are concerned, the radiation injury by early fallout due to internal sources can be quite minor in comparison with that due to the external radiation. If reasonable precautions are taken, the short-term, internal hazard can probably be greatly reduced.

LONG-TERM HAZARD FROM DELAYED FALLOUT [16]

CESIUM-137

11.174 Of the fission products which present a potential long-term hazard, from either the testing of nuclear weapons in peacetime or their use in warfare, the most important are probably the radioactive isotopes cesium-137 and strontium-90. Since both of these isotopes are fairly abundant among the fission products and have relatively long half-lives, they will constitute a large percentage of any delayed fallout. The process of fractionation will tend to increase the proportions of strontium and cesium still further, as explained in § 9.08. Of course, the activity level due to these isotopes at late times in the early fallout pattern in the area close to a surface or subsurface burst will be considerably larger than in the delayed fallout from a given explosion. However, the special interest in the delayed fallout arises from the fact that it may occur in significant amounts in many parts of the globe remote from the point of the nuclear detonation, as explained in Chapter IX, as well as in close by areas.

11.175 Cesium-137 has a radioactive half-life of 30.5 years and is of particular interest in fallout that is more than a year old because it is the principal constituent whose radioactive decay is accompanied by the emission of gamma rays.[17] The chemical and biochemical

[16] Much valuable information on delayed fallout and related problems is to be found in the published Hearings before the Special Committee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States: "The Nature of Radioactive Fallout and its Effects on Man," May 27 to June 7, 1957; "Fallout from Nuclear Weapons Tests," May 5 to 8, 1959; and "Biological and Environmental Effects of Nuclear War," June 22 to 26, 1959 (U.S. Government Printing Office).

[17] The gamma rays are actually emitted, within a very short time, by a high-energy state of the decay product, barium-137.

properties of cesium resemble those of potassium. The compounds of these elements are generally more soluble than the corresponding compounds of strontium and calcium and the details of the transfer of these two pairs of elements from the soil to the human body are quite different. The element cesium is relatively rare in nature and the body normally contains only small traces. Consequently, the biochemistry of cesium has not been studied as extensively as that of some of the more common elements. It has been determined, however, that cesium distributes itself within living cells in a way similar to potassium, so that it is found mostly in muscle.

11.176 Based on one experiment with several human subjects, the current estimate of the biological half-time of cesium is 140 days. Because of the penetrating properties of the gamma rays from the decay of cesium-137, the radiation is distributed more or less uniformly to all parts of the body. In spite of the gamma-ray emission, the biological half-time of cesium is so relatively short that, for the same amount of delayed fallout, the residual cesium-137 is less of a general biological hazard than the residual strontium-90.

11.177 The amount of internal exposure to cesium-137 is determined by the quantity of this isotope in the diet. If the major mechanism for its incorporation into the diet is through the root systems of plants, then the dose will be more or less proportional to the total amount of cesium-137 accumulated on the ground. On the other hand, if this isotope enters the diet mainly through material deposited directly on the leaves of plants, the internal dose will be more nearly proportional to the rate of descent of delayed fallout. It has been calculated that if the former mechanism prevails, the internal 30-year dose to the gonads, which is of interest in connection with possible genetic effects (§ 11.191), would be much higher than if the alternative mechanism were of major importance. The best data presently available on cesium-137 levels in food suggest that, up to the present time, the fallout rate has been the dominant factor; but in the future a larger proportion of the cesium may get into food via the soil, provided no considerable amounts of cesium-137 are added to the atmosphere.

Strontium-90

11.178 Strontium-90, because of its relatively long radioactive half-life of 27.7 years and its appreciable yield in the fission process, accounts for a considerable fraction of the total activity of fission products which are several years old. Strontium is chemically similar to calcium, an element essential to both plant and animal life; an adult human being, for example, contains over 2 pounds of calcium, mainly in bone. However, the relationship between strontium and calcium is not a simple one as will be seen in subsequent sections and, because of its complex metabolism in the body, the behavior of strontium-90 cannot be stated in terms of a single effective half-life.[18]

11.179 The probability of serious pathological change in the body of a particular individual, due to the effects of internal radiation material, depends upon the intensity and energy of the radioactivity and upon the length of time the source remains in the body. Although strontium-90 emits only beta particles of fairly low energy, a sufficient amount of this isotope can produce damage because once it gets into the skeleton it will stay there for a long time.[19] Experiments with animals indicate that the pathological effects which result from damaging quantities (§ 11.184) of strontium-90 may be anemia, bone necrosis, cancer, and possibly leukemia.

11.180 Most of the strontium-90 in the delayed fallout is ultimately brought to earth by rain or snow, and it makes its way into the human body primarily through plants. At first thought, it might appear that the ratio of strontium to calcium in man would be equal to that in the soil from which he obtains his food. Fortunately, however, a number of processes in the chain of biological transfer of these elements to the human body operate collectively to decrease the relative quantity of strontium that is stored in man by an overall factor of two to ten. The processes which influence the strontium-90 which gets into the human body include availability and proximity of strontium to the root system of the plant, strontium-90 uptake by the plant, transfer from plant to animal, and transfer (where relevant) from animal to man.

11.181 Greenhouse experiments show a slight discrimination in favor of calcium and against strontium when these elements are taken up by most plants from homogeneous soils. However, several factors make it difficult to generalize concerning the ratio of strontium to calcium in the plant compared to that in field soils. First, plants

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[18] Data from strontium-90 excretion by the Marshallese people and studies in a case of accidental inhalation indicate that for an acute intake the major portion of the absorbed strontium-90 is excreted with a biological half-time of 40 days during the first year. During the next 2 years, at least, a smaller fraction is excreted with a biological half-time of 500 days. The remaining portion (less than 10 percent) is tightly bound to bone and is excreted very slowly with a long biological half-time of about 50 years. In this latter case, the effective half-life would be about 18 years. The situation for a chronic intake, e.g., from delayed fallout, although not the same, would be similar.

[19] The energy of the strontium-90 beta particles is 0.54 Mev. However, its daughter isotope, yttrium-90, which has the short half-life of only 64 hours, emits 2.27-Mev beta particles (no gamma rays); the decay product is stable zirconium-90. Thus, both 0.54- and 2.27-Mev beta particles (and the associated bremsstrahlung or secondary X-radiation) accompany the decay of strontium-90.

obtain most of their minerals through their root systems, but such systems vary from plant to plant, some having deep roots and others shallow roots. Most of the strontium-90 deposited in undisturbed soil has been found close to the surface, so that the uptake of this isotope may be expected to vary with the root habit of the plant. Second, although strontium and calcium, because of their chemical similarity, may be thought of as competing for entry into the root system of plants, not all of the calcium in soil is available for assimilation. Some natural calcium compounds in soil are insoluble and are not available as plant food until they have been converted into soluble compounds. Most of the strontium-90 in the delayed fallout, however, is in a water-soluble form. Third, in addition to the strontium-90 which plants derive from the soil, growing plants retain a certain amount of strontium-90 from fallout deposited directly on the surface of the plant.

11.182 As the next link in the chain, animals consume plants as food, thereby introducing strontium-90 into their bodies. Once again, the evidence indicates that natural discrimination factors result in a strontium-90/calcium ratio in the edible animal products that is less than in the animal's feed. Very little strontium is retained in the soft tissue, so that the amount of strontium-90 in the edible parts of the animal is negligible. It is of particular interest, too, that the strontium-90/calcium ratio in cow's milk is much lower than that in the cow's feed, since this is an important barrier to the consumption of strontium-90 by man. This barrier does not operate, of course, when plant food is consumed directly by human beings. However, it appears that about three-fourths of the calcium, and hence a large fraction of the strontium-90, in the average diet in the United States is obtained from milk and milk products. The situation may be different in areas where a greater or lesser dependence is placed upon milk and milk products in the diet.

11.183 Not all of the strontium-90 that enters the body in food is deposited in the human skeleton. An appreciable fraction of the strontium-90 is eliminated, just as is most of the daily intake of calcium. However, there is always some fresh deposition of calcium taking place in the skeletal structure of healthy individuals, so that strontium-90 is incorporated at the same time. The rate of deposition of both calcium and strontium-90 is, of course, greater in growing children than in adults. In addition to the fact that the human metabolism discriminates against strontium, it will be noted that, in each link of the food chain, the amount of strontium-90 retained is somewhat less than in the previous link. Thus, a series of safeguards reduce deposition of strontium in human bone.

11.184 As there has been no experience with appreciable quantities of strontium-90 in the human body, the relationship between the probability of serious biological effect and the body burden of this isotope is not known with certainty. Tentative conclusions have been based on a comparison of the effects of strontium-90 with radium on experimental animals, and on the known effects of radium on human beings. From these comparisons it has been estimated that a body content of 10 microcuries (1 microcurie is a one-millionth part of a curie, as defined in § 9.163) of strontium-90 in a large proportion of the population would produce a noticeable increase in the occurrence of bone cancer. On this basis, the Radioactivity Concentration Guide (RCG) recommendation is that the maximum amount of strontium-90 in the body of any individual who is exposed in the course of his occupation be taken as 2 microcuries. Since the average amount of calcium in the skeleton of an adult human is about 1 kilogram (or a little over 2 pounds), this corresponds to a concentration in the skeleton of 2 microcuries of strontium-90 per kilogram of calcium. Moreover, the limit generally considered to be acceptable for any member of the general population is 0.2 microcurie of strontium-90 per kilogram of calcium. This is in accord with the recommendations made in 1960 by the U.S. National Academy of Sciences. The International Commission on Radiological Protection has suggested, further, that the concentration of strontium-90 averaged over the whole population should not exceed 0.067 microcurie per kilogram of calcium.

11.185 As a result of nuclear test explosions in various countries, there has been an increase in the strontium-90 content of the soil, plants, and the bones of animals and man. This increase is worldwide and is not restricted to areas in the vicinity of the test sites, although it is naturally somewhat higher in these regions because of the more localized (early) fallout.[20] As the fine particles descend from the stratosphere over a period of years, and are brought down by rain and snow in the troposphere, the amount of strontium-90 falling to the earth each year had reached a maximum in the summer of 1961 and had started to decline (§ 9.167). However, the subsequent addition of strontium-90 to the stratospheric reservoir may be expected to cause a temporary increase.

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[20] It is to be expected that areas near the explosion will be more highly contaminated in strontium-90 than are more distant regions, to an extent dependent upon such factors as the height (or depth) of burst, the total and fission yields of the explosion, and the prevailing atmospheric conditions. Because of the phenomenon of fractionation, the proportion of strontium-90 in the local (early) fallout will generally be less than that in the worldwide (delayed) fallout (§ 9.08). It is of interest to mention, too, that the strontium-90 in early fallout appears to be in a less soluble form, and hence probably less readily accessible to plants, than that present in the delayed fallout.

11.186. In the event that nuclear weapons with high fission yields were to be used extensively in warfare, calculations, based on somewhat uncertain premises, suggest that debris from many thousands of megatons of fission would have to be added to the stratosphere before the delayed fallout from these weapons would lead to an average concentration equal to the RCG value, for occupationally exposed persons, of 2 microcuries of strontium-90 per kilogram of calcium in human beings.

Carbon-14 and Other Isotopes

11.187 In addition to the effects of internal cesium-137 and strontium-90 considered above, consideration must be given to whole-body exposure from ingested carbon-14,[21] which is a beta-particle emitter, and from the gamma rays emitted by cesium-137 and isotopes of shorter half-life, such as zirconium-90, ruthenium-103 and -106, and cerium-141 and -144, deposited on the ground.

11.188 Weapons testing through the year 1958 had increased the amount of carbon-14 in the troposphere by about 30 percent (§ 9.34). If there had been no more nuclear explosions in the atmosphere, the additional carbon-14 would have dropped to 1 percent of the natural level in 50 to 100 years. Calculations indicate that the total dose from carbon-14 over the next two generations (50 years) will be a small fraction of that received from internal cesium-137. After a few hundred years, essentially all of the cesium-137 will have decayed, but the carbon-14, with its radioactive half-life of 5,760 years, will have diminished very little.

11.189 It has been estimated that, from the standpoint of the genetic impact of weapons tests upon the next 200 generations of mankind, the total dose from carbon-14 may be about equal to that from cesium-137, but the former will be delivered at an extremely low level during the whole 200 generations whereas that from cesium-137 will be received almost entirely within the first few generations. It should be noted, however, that the calculations for carbon-14 take into account only the ionization produced by the beta particles emitted during decay. An additional genetic effect can result from the detrimental biochemical consequences of the replacement of all the carbon-14 incorporated into genetic material by its decay product nitrogen-14. Present estimates suggest that the genetic damage from the transmutation of carbon-14 into nitrogen-14 might be as much as that caused by the emitted beta particles.

[21] Carbon-14 is not strictly a component of fallout but it is convenient to include it here since it is a possible long-term hazard arising from nuclear explosions.

11.190 The amounts of radiation, expressed in millirems, received from weapons tests through the year 1958 are summarized in Table 11.190. The first column gives the total dose for the year 1959, the second is an estimate for the 30 years between 1955 and 1985, and the third column for 70 years between 1955 and 2025. The reasons for choosing these two periods is that evaluation of the genetic effects of radiation on human beings (§ 11.191 *et seq.*) is generally based on the amount received by the gonads (or the whole body if uniformly irradiated) during the first 30 years of life, whereas the somatic effects are determined by the exposure during the whole lifetime (70 years). In most cases, the values listed in the table are conservative and are probably higher than would be received by the average person in the United States. It should be noted that both the 30-year whole-body (genetic) dose of 75 millirems and the 70-year whole-body (somatic) plus strontium-90 (bone marrow) dose of 201 millirems are less than 3 percent of the accumulated natural background doses over the same periods.

TABLE 11.190

ACCUMULATED DOSES FROM DELAYED FALLOUT FROM WEAPONS TESTS THROUGH 1958*

	Whole-body dose (millirems)		
Source	*1959*	*1955 to 1985*	*1955 to 2025*
Internal carbon-14	0. 3	5	8
Internal cesium-137	2	20	30
External cesium-137	1	20	30
External short half-life	20	30	30
Total	23	75	98
Bone marrow dose from strontium-90	7	75	103
Natural background radiation (sea level)	100	3, 000	7, 000

*Additional doses from weapons tests which have been carried out subsequent to September 1, 1961 are not included.

GENETIC EFFECTS OF NUCLEAR RADIATIONS

SPONTANEOUS AND INDUCED MUTATIONS

11.191 The genetic effects of nuclear radiation consist of changes produced in the hereditary components of the reproductive cells; they are accompanied by no visible injury in the exposed individual but they may have notable consequences in future generations.

Although genetic damage is cumulative, it is now recognized that the rate at which changes result from exposure to radiation is somewhat dependent on the dose rate. Prompt, high dose rate exposures (greater than 25 rads per minute) may be at least four times as effective as are continuous exposures at low dose rates (1 rad or less per minute), for the same total dose. Thus, the protracted exposure that could result from a low-dose fallout field would presumably not carry the same threat of genetic change as would exposure to a single high-intensity dose, e.g., from the initial nuclear radiation, although the total dose delivered may be the same in both cases.

11.192 The mechanism of heredity, which is basically similar in sexually reproducing plants and animals, including man, is somewhat as follows. The nuclei of dividing cells contain a definite number of thread-like entities called "chromosomes" which are visible under the microscope. These chromosomes are believed to be differentiated along their length into thousands of distinctive units, referred to as "genes." The chromosomes (and genes) exist in every cell of the body, but from the point of view of genetics (or heredity), it is only those in the germ cells, present in the reproductive organs, that are important.

11.193 Human body cells normally contain 46 chromosomes, made up of two similar (but not identical) sets of 23 chromosomes each. One of these sets was inherited from the mother, for the egg cell (produced in the ovaries) carries a set of 23 chromosomes, whereas the other set came from the father, for the sperm cell (produced in the testes) carries a set of 23 similar (but not identical) chromosomes. As the individual develops, following upon the fusion of the original egg and sperm cells, the chromosomes and genes are, in general, duplicated without change.

11.194 In rare instances, however, a deviation from normal behavior occurs and instead of a chromosome duplicating itself in every respect, there is a change in one or more of the genes. This change, called a "mutation," is essentially permanent, for the mutant gene is reproduced in its altered form. If this mutation occurs in a body cell, there may be some effect on the individual, but the change is not passed on. However, if the mutation occurs in a germ cell of either parent, a new characteristic may appear in a later generation. The mutations which occur naturally, without any definitely assignable cause or human intervention, are called "spontaneous mutations."

11.195 The matter of immediate interest is that the frequency with which mutations occur can be increased in various ways, one being by exposure of the sex glands (or "gonads"), i.e., testes or ovasuch infections are caused by bacteria which, under normal circumstances, are harmless.

11.220 Very often in whole-body irradiation the outward signs of severe damage to the bone marrow, lymphatic organs, and epithelial linings are gangrenous ulcerations of the tonsils and pharynx. This condition (agranulocytic anemia) is also found in cases of chemical poisoning of the bone marrow that resemble the effect of radiation exposure. Such ulcerations and the pneumonia that often accompanies them are unusual in that very little suppuration is found because of the paucity of leucocyte cells. Although most of the bacteria in such ulcerations can usually be controlled by antibiotic drugs, the viruses and fungi which also invade such damaged tissues are not affected by treatment, and fatal septicemia is common.

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

CHAPTER XII

PRINCIPLES OF PROTECTION

BASIS FOR PROTECTIVE ACTION

INTRODUCTION

12.01 In the preceding chapters the phenomena and the destructive effects of nuclear explosions have been described in terms that are reasonably exact. In addition, the best available assessment of these effects on man have been presented. But in planning protection from the consequences of a nuclear explosion, so many uncertainties are encountered that precise analysis of a particular situation is impractical. For example, it is impossible to know in advance where or when a weapon will be detonated and what will be the explosive energy or the kind of burst. Nevertheless, there are some basic principles which, if properly understood and applied, could provide a measure of protection to a large proportion of the population in the event of a nuclear attack.

12.02 The most fruitful application of the principles of protection requires considerable preplanning on the part of individuals; however, some protection may be possible even in certain emergency situations if the principles are understood beforehand. It is the purpose of this chapter to present the quantitative aspects of weapons effects in a simplified form and to use them to explain the principles of protection. The information provided should be helpful in indicating the nature of the protection required and what steps must be taken in advance to achieve such protection. However, details of specific measures are not included since they are described in other publications.[1]

12.03 In the following sections the various effects of a nuclear explosion will be reviewed, with special reference to their ranges, and the principles of protection against each of these effects will be examined. At the same time, it will be shown how the measures used to provide protection from one particular effect can furnish protection against

[1] See the bibliography at the end of the chapter.

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others, so that the problem is less complicated than it might at first appear. Finally, a brief discussion will be presented of the planning needed to implement the principles of protection so as to make them effective.

IMMEDIATE AND DELAYED EFFECTS

12.04 The effects of a nuclear explosion may be divided into two broad categories, namely, immediate and delayed. The immediate effects are those which occur within a few minutes of the actual explosion. These include air blast and ground shock, thermal radiation (light and heat), and initial nuclear radiation.

12.05 The delayed effects are associated with the radioactivity present in fallout and neutron-induced radioactivity. The early fallout from a surface burst will begin to reach the ground within a few minutes after the explosion at close-in locations, and at increasingly later times at greater distances from ground zero, depending on the effective wind speed and direction. At distances of several hundred miles from the explosion, the fallout may not commence until as late as 24 hours after the burst time. Furthermore, several hours may elapse between the time of arrival of the fallout at any point and the time when deposition is essentially complete. A significant early fallout is associated with a surface burst or a subsurface burst which vents to the atmosphere, but not with an air burst or with a completely contained underground burst. Neutron-induced radioactivity, apart from that in the weapons residues, extends only a short distance from ground zero and it decays more rapidly than fallout.

12.06 Except for a contained burst, all presently known nuclear weapons produce delayed (world-wide) fallout. However, this part of the fallout is generally not apparent until several weeks or months have elapsed; it will not be treated here, since the present discussion refers to protection which is effective at the time of, and soon after, an explosion.

RANGES OF VARIOUS IMMEDIATE EFFECTS

12.07 When a nuclear weapon of known yield is detonated on the surface, at a particular height in the air, or at a particular depth below the surface, the ranges of the immediate effects are fairly well defined. For example, there will be an area surrounding ground zero within which the destruction due to blast and shock, and accompanying fires, will be so great that the survival of inhabitants in conventional structures is improbable. At considerably greater distances the immediate effects will be weaker and damage to structures will be minor, e.g., broken windows and damage to window frames and doors. The radiation from fallout may be significant in this region, but this is a delayed effect which will be considered later (§12.48 *et seq.*). Between the zone of total destruction and the area at which damage is not significant, there is a region in which protective measures can determine whether inhabitants survive, with little or no injury, or whether they become serious casualties.

12.08 The distances from ground zero within which various degrees of destruction may be expected depend primarily upon the energy yield of the explosion and the conditions of the burst, i.e., air, surface, etc. The topography and weather also influence these distances. By using the data presented in the earlier chapters, it is possible to draw a series of circles, as depicted in Fig. 12.08, representing areas within which effects of different types are to be expected for air bursts of various yields from 10 kilotons to 10 megatons TNT equivalent. The height of burst is such as to maximize the distance to which each effect extends; in other words, the radii of the circles give the greatest ranges at which the indicated thermal radiation, initial nuclear radiation, and overpressure levels will occur for any air burst of the given energy yield. It should be mentioned that the circular areas depict an idealized situation. Actually, as was the case in Japan, the pattern would be distorted by the conditions of the terrain, weather, etc. Two or more weapons detonated within a short distance can, of course, change the situation considerably.

12.09 Within the ring at which the blast overpressure is 5 pounds per square inch (5 psi), nearly all conventional houses will be damaged beyond repair. Even strong buildings, such as reinforced concrete and steel structures, will suffer damage and, without protective measures, the casualties to the inhabitants of this area will be high. In the central zone of heavy damage, there will alsa be a great fire hazard. Individuals in this area will be exposed not only to the effects of blast, but also to nuclear and thermal radiation. Apart from fortuitous circumstances, few persons will survive who have not sought protection in strong structures or shelters which will withstand the fire, blast, and shock and which will attenuate the radiation.

12.10 At distances from the burst where the blast overpreseure is 1 psi, the destructive effect of the air blast wave is minor. Window frames, doors, and plaster will suffer light damage. Window panes will be broken at much greater distances. The initial nuclear radiation dose will be so small that its immediate consequences are negligible, but thermal radiation may still be a significant source of

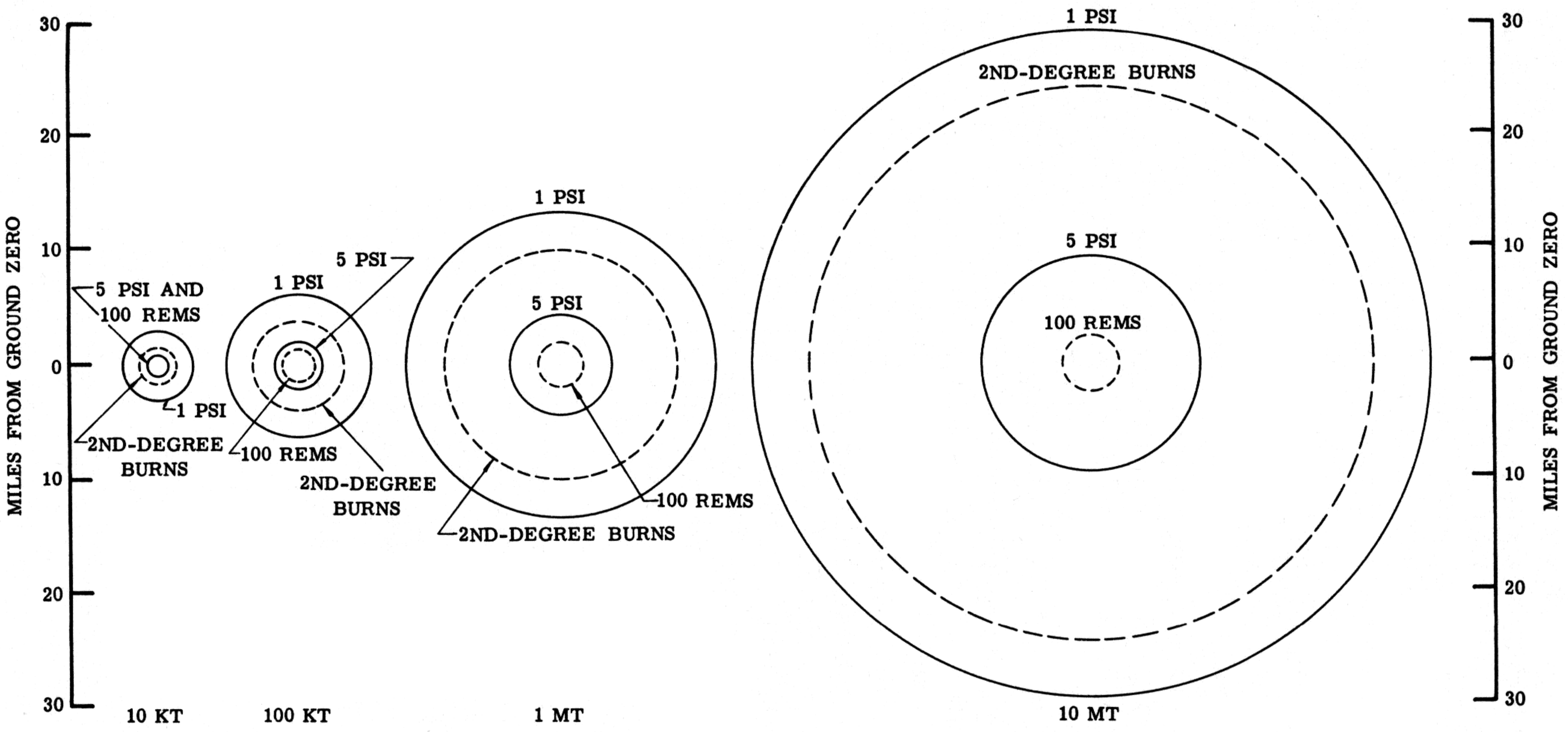

Figure 12.08. Idealized ranges for effects of air burst with the heights of burst optimized to give the maximum range for each individual effect.

casualties. Second-degree burns may be experienced at distances approaching those for 1 psi overpressure and less severe burns may be suffered at much greater distances from ground zero. Eye injury may also occur at even greater ranges and for high-altitude bursts of megaton weapons, this distance may be as much as several hundred miles. Furthermore, in dry, clear weather, many small fires would probably be ignited in newspapers and other thin combustible materials both within and outside of buildings.

Effective Protection Areas

12.11 In Japan, where little evasive action was taken, the survival probability depended upon whether the individual was outdoors or inside a building and, in the latter case, upon the type of structure. At distances between 0.3 and 0.4 mile (530 and 700 yards) from ground zero in Hiroshima the average survival rate, for at least 20 days after the nuclear explosion, was less than 20 percent. Yet in two reinforced-concrete office buildings, at these distances, almost 90 percent of the nearly 800 occupants survived more than 20 days, although some died later from radiation injury. Furthermore, of approximately 3,000 school students who were in the open and unshielded within a mile of ground zero at Hiroshima, about 90 percent were dead or missing after the explosion. But of nearly 5,000 students in the same zone who were shielded in one way or another, only 26 percent were fatalities. These facts bring out clearly the greatly improved chances of survival from a nuclear explosion that could result from the adoption of suitable warning and protective measures.

12.12 As a rough guide, the inner range at which protection in conventional structures could be achieved may be supposed to be that where the overpressure is 5 pounds per square inch and the outer range, beyond which casualties will be small *for an air burst*, is at 1 pound per square inch (or the limit for second-degree burns). As seen above, survival in Hiroshima was possible in buildings at such distances that the overpressure in the open was 15 to 20 pounds per square inch. The somewhat arbitrary choice of an overpressure of 5 pounds per square inch, which was experienced at a little over a mile from ground zero in Japan, is thus very conservative. In any case, it is evident from the circles in Fig. 12.08 that the area over which protection could be effective in saving lives is roughly eight to ten times as great as that in which the chances of survival are small. It may be concluded, therefore, that a considerable proportion of the population "at risk" from a nuclear explosion would be in an area in which the casualty rate from the immediate effects may be significantly reduced provided protective measures are employed.

12.13 The various circles in Fig. 12.08 refer to an air burst, in which case there is essentially no early fallout. In the event of a burst at or near the surface, the situation would be different. The overpressure ranges would be reduced to roughly three-fourths and the second-degree burn range to about four-fifths of those shown in Fig. 12.08. However, there would be early fallout which might cover very extensive areas, from about 7 square miles for a 1-kiloton explosion to several thousand square miles for a 10-megaton yield (§9.100). Data that can be used for planning purposes are given in Chapter IX, but the conclusions concerning the extent of the hazard from early fallout cannot be expressed in simple diagrammatic form. However, it can be stated quite definitely that, following a surface burst of a high-yield weapon, a very large region extending possibly to three or four hundred miles downwind from the explosion center may become contaminated by the early radioactive fallout. The area affected will be influenced both by the total energy yield of the nuclear weapon and the proportion that is due to fission. The distance at which significant fallout will descend depends on the direction and speed of the wind at all levels from the radioactive cloud down to the ground.

12.14 From the standpoint of the present discussion, it cannot be too strongly emphasized that it is within this possibly large area of early fallout that preplanning of protective measures is of the utmost importance. At locations far from the point of attack, where the immediate effects of the nuclear explosion, i.e., blast, shock, initial nuclear radiation, and thermal radiation, are of absolutely no consequence, the delayed effect of fallout can be extremely serious unless steps are taken, in advance, to achieve protection when the emergency arises.

Relative Importance and Time Scale of Effects

12.15 It is not possible to arrange a single burst which maximizes the potential damage from each of the various immediate and delayed effects of a nuclear explosion. Thus, in a surface burst, the areas affected by blast, thermal radiation, and the initial nuclear radiation are appreciably less than for an air burst of similar energy yield. But, on the other hand, the surface burst is accompanied by early fallout whereas the air burst is not. Even with air bursts, the relative importance of the various effects depends on the height of burst.

12.16 In the following analysis an attempt is made to indicate the relative hazards associated with the various effects, as experienced by a ground observer, under different burst conditions for a given energy yield. The phenomena are given roughly in the order of their appearance. First, there is the flash of brilliant light accompanied and followed by heat, both of which are part of the thermal radiation. The initial nuclear radiation starts at the same time but may continue after the thermal radiation has ceased. Then ground and water shock, if any, will arrive, followed very soon by the air blast (and sound) wave; then will come the early fallout, if any, which may continue for several hours. The general conclusions are summarized in Table 12.16, the degree (or severity) of a particular effect being indicated by the number of asterisks. The various degrees are relative to each other for a given burst type, and are best interpreted in terms of the descriptions given below.

HIGH-ALTITUDE BURST

Light: Very intense.
Heat: Moderate, decreases with increasing burst altitude.
Initial nuclear radiation: Negligible.
Shock: Negligible.
Air blast: Small on the ground, decreasing with increasing burst altitude.
Early fallout: None.

Summary: The most significant effect will be flash blindness over a very large area; eye burns will occur in persons looking directly at the explosion. Other effects will be relatively unimportant.

AIR BURST

Light: Fairly intense, but much less than for high-altitude burst.
Heat: Intense out to considerable distances.
Initial nuclear radiation: Intense, but generally hazardous out to shorter distance than heat.
Shock: Negligible except for very low air bursts.
Air blast: Considerable out to distances similar to heat effects.
Early fallout: Negligible.

Summary: Blast will cause considerable structural damage; burns to exposed skin are possible over a large area and eye effects over a still larger area; initial nuclear radiation will be a hazard at closer distances; but the early fallout hazard will be negligible.

GROUND SURFACE BURST

Light: Less than for an air burst, but still appreciable.
Heat: Less than for an air burst, but significant.
Initial nuclear radiation: Less than for an air burst.

Shock: Will cause damage within about three crater radii, but little beyond.

Air blast: Greater than for an air burst at close-in distances, but considerably less at farther distances.

Early fallout: May be considerable (for a high-yield weapon) and extend over a large area.

Summary: Except in the region close to ground zero, where destruction would be virtually complete, the effects of blast, thermal radiation, and initial nuclear radiation will be less extensive than for an air burst; however, early fallout may be a very serious hazard over a large area which is unaffected by blast, etc.

SHALLOW UNDERGROUND BURST

Light, heat, and initial nuclear radiation: Less than for a ground surface burst, depending on the extent to which the fireball breaks through the surface.

Shock: Ground shock will cause damage within about three crater radii, but little beyond.

Air blast: Less than for surface burst, depending upon depth of burst.

Early fallout: May be considerable, if the depth of burst is not too large, and in addition there may be a highly radioactive base surge.

Summary: Light, heat, and initial nuclear radiation will be less than for a ground surface burst; early fallout can be significant, and at distances not too far from the explosion the base surge will be an important hazard.

WATER SURFACE BURST

Light: Somewhat more intense than for a ground surface burst.

Heat: Similar to ground surface burst.

Initial nuclear radiation: Similar to ground surface burst.

Shock: Water shock can cause damage to ships and underwater structures to a considerable distance.

Air blast: Similar to ground surface burst.

Early fallout: May be considerable.

Summary: The general effects of a water surface burst are similar to those for a ground surface burst, except that the effect of the shock wave in water will extend farther than ground shock. In addition, water waves can cause damage on a nearby shore by the force of the waves and by inundation.

SHALLOW UNDERWATER BURST

Light, heat, and initial nuclear radiation: Less than for a water surface burst, depending upon how much of the fireball breaks through the surface.

Shock: Water shock will extend farther than for a water surface burst.

Air blast: Less than for a surface burst, depending on the depth of burst.

Early fallout: May be considerable, if the depth of burst is not too large, and in addition there may be a highly radioactive base surge.

Summary: Light, heat, initial nuclear radiation, and blast effects will be less than for a surface burst; early fallout can be significant, but at distances not too far from the explosion the radioactive base surge will be an important hazard. Water waves can also cause damage, as in the case of a water surface burst.

CONFINED SUBSURFACE BURSTS

Light, heat, and initial nuclear radiation: Negligible or none.

Shock: Severe, especially at fairly close distances from the burst point.

Air blast: Negligible or none.

Early fallout: None.

Summary: If the burst does not penetrate the surface, either of the ground or water, the only hazard will be from ground or water shock. No other effects will be significant.

TABLE 12.16

RELATIVE DEGREES OF WEAPON EFFECTS FOR VARIOUS BURST CONDITIONS†

Burst conditions	Thermal radiation		Initial nuclear radiation	Ground or water shock	Air blast	Early fallout
	Light	Heat				
High altitude	****	**	*		*	
Air	***	****	****	*	****	
Ground surface	**	***	***	**	***	****
Water surface	***	***	***	**	***	****
Confined subsurface				****		

†The number of asterisks provides a rough indication of the relative importance of the indicated effect to a ground observer. Four asterisks imply that the effect is the most extensive for the given burst type; a blank space means that the effect is negligible or absent. For a more complete interpretation, see the accompanying text.

12.17 The time sequence referred to in § 12.16 brings up another aspect of nuclear weapons effects that has a bearing on protection. Except very close to ground zero, even the immediate effects do not occur simultaneously. The first, almost instantaneous, indication of a nuclear explosion in the air or on the earth's surface is a brilliant flash of light. In many circumstances, it may be feasible, after observing the flash, to take some appropriate protective action that could greatly minimize the degree of injury suffered. At distances beyond those at which the immediate blast, thermal, and initial nuclear effects of the explosion are significant, there may be some time to make final preparations to decrease the early fallout.

12.18 As a general guide for planning purposes, it is useful to know the magnitudes of the respective immediate effects at a range of distances from an explosion of given yield. This information can be obtained from various figures and tables given in earlier chapters and can be identified from the list in the table of contents at the beginning of the book. A tabular summary of part of the data for air bursts, which may be more convenient for some purposes, is given in Table 12.18. The heights of burst are such as to maximize the various effects. An asterisk indicates that the particular distance is within the fireball; otherwise a blank space implies that the value is too small to be significant. The initial nuclear radiation doses are not given for distances of 5 miles or more for they are extremely small even for a 10-megaton explosion.

BLAST EFFECTS

Effects on Structures

12.19 Injury to individuals both inside and outside a structure may occur because of the blast damage to that structure. Persons in the interior of the building can be injured and trapped by collapse and fire, and those outside can be hurt by flying debris. For these and other reasons, an important aspect of protection is an understanding of the relative ability of different structures to withstand damage from air blast. Both the peak overpressure and the peak dynamic (or wind) pressure determine the amount of the damage, but for certain structures one or the other of these pressures has the dominant effect. For most office-type and residential buildings, including ordinary houses, the extent of destruction is mainly dependent on the peak overpressure, and an approximate correlation between the overpressure and the expected physical damage is given in Table 12.19.

TABLE 12.18

WEAPON EFFECTS FOR AIR BURSTS WITH MAXIMIZED RANGES

Distances from ground zero	Explosion yield				
	1 KT	10 KT	100 KT	1 MT	10 MT
½ mile				(*)	(*)
Overpressure (psi)	4.1	13	46		
Thermal radiation (cal/cm²)	3.8	38	380		
Initial nuclear radiation (rems)	670	6.7×10^{3}	7.6×10^{4}		
1 mile				(*)	(*)
Overpressure (psi)	1.5	4.5	14		
Thermal radiation (cal/cm²)	0.9	9.1	91		
Initial nuclear radiation (rems)	9.1	91	1100		
2 miles					(*)
Overpressure (psi)	<1.0	1.7	5.0	16	
Thermal radiation (cal/cm²)	0.2	2.1	21	210	
Initial nuclear radiation (rems)		0.2	1.9	35	
3 miles					
Overpressure (psi)		1.0	2.8	8.6	29
Thermal radiation (cal/cm²)		0.9	9.0	90	900
Initial nuclear radiation (rems)				<1.0	2.6
5 miles					
Overpressure (psi)		<1.0	1.4	4.1	13
Thermal radiation (cal/cm²)		<1.0	3.0	30	300
10 miles					
Overpressure (psi)			<1.0	1.5	4.5
Thermal radiation (cal/cm²)			<1.0	6.6	66
20 miles					
Overpressure (psi)				<1.0	1.7
Thermal radiation (cal/cm²)				1.4	14
50 miles					
Overpressure (psi)					<1.0
Thermal radiation (cal/cm²)				<1.0	1.7

*Inside or close to fireball.

TABLE 12.19

RELATION BETWEEN PEAK OVERPRESSURE AND DAMAGE TO STRUCTURES

Structure type	*Damage*	*Overpressure (psi)*
Wood-frame building, residential type.	Moderate	2 to 3
	Severe	3 to 4
Wall-bearing, masonry building, apartment-house type.	Moderate	3 to 4
	Severe	5 to 6
Multistory, wall-bearing building, monumental type.	Moderate	6 to 7
	Severe	8 to 11
Reinforced-concrete (not earthquake-resistant) building, concrete walls, small window area.	Moderate	8 to 10
	Severe	11 to 15

12.20 This information can be utilized, in conjunction with the overpressure-distance data in Table 12.18, or with the curves in Chapter III, to determine approximately how far from ground zero the respective degrees of damage would be experienced for air bursts of various yields. The height of burst is assumed to be such as to maximize the area of structural damage. For example, it is seen from Table 12.18 that for a 1-megaton air burst a peak overpressure of 3 to 4 pounds per square inch is attained at about 5 miles from ground zero. This is consequently the approximate limit of moderate damage to brick, apartment-house type buildings and of severe damage to wood-frame dwellings.

12.21 The results of a more detailed analysis, based on the nomograph in Fig. 4.58a, are given in Table 12.21. The maximum distances from ground zero for moderate and severe damage to the four types of structures referred to above are recorded for air bursts (at optimum heights) of weapons with yields from 1 kiloton to 10 megatons. For a surface burst, the damage range is three-quarters that for an air burst of the same yield.

TABLE 12.21

MAXIMUM RANGES FROM GROUND ZERO FOR STRUCTURAL DAMAGE FROM AIR BURSTS*

		Explosion yield				
		1 KT	*10 KT*	*100 KT*	*1 MT*	*10 MT*
Structure type	*Damage*	*(Distance in miles)*				
Wood-frame building, residential type.	Moderate	0.66	1.5	3.2	6.6	14
	Severe	0.47	1.1	2.4	5.5	12
Wall-bearing, masonry building, apartment-house type.	Moderate	0.53	1.1	2.4	4.7	10
	Severe	0.34	0.76	1.7	3.5	8.7
Multistory, wall-bearing building, monumental type.	Moderate	0.36	0.76	1.6	3.5	7.4
	Severe	0.23	0.55	1.3	2.8	6.1
Reinforced-concrete (not earthquake-resistant) building, concrete walls, small window area.	Moderate	0.28	0.61	1.5	3.4	7.2
	Severe	0.19	0.44	1.1	2.5	5.9

*For a surface burst the respective distances are three-quarters of those for an air burst of the same yield.

12.22 Information on the effects of 20-kiloton and 1-megaton air bursts on a variety of structures, including many which are damaged by dynamic loading, is given in Tables 12.22 a and b. These refer to "typical" air bursts at heights of 1,850 and 6,800 feet, respectively,

TABLE 12.22a

DAMAGE RANGES FOR 20-KT TYPICAL AIR BURST

Peak Wind Velocity (mph)	Positive Phase Duration (sec)	Peak Dynamic Pressure (psi)	Peak Over-Pressure (psi)	Range from Ground Zero (MILES)	Range from Ground Zero (1000 FT)	
						Light damage to window frames and doors, moderate plaster damage out to about 4 miles; glass breakage possible out to 8 miles.
				2		
70	0.95	0.09	2.0		10	
				1.8		Fine kindling fuels: ignited.
79	0.94	0.12	2.3		9	Wood-frame buildings: moderate damage. Smoke stacks: slight damage.
				1.6		
93	0.92	0.17	2.7		8	
				1.4		
112	0.90	0.27	3.2		7	Wood-frame buildings: severe damage. Radio and TV transmitting towers: moderate damage. Wall-bearing, brick building (apartment house type): moderate damage.
				1.2		
139	0.86	0.42	4.2		6	
						Wall-bearing, brick buildings (apartment house type): severe damage.
				1.0		Telephone & power lines: limit of significant damage.
190	0.80	0.80	6.0		5	Multistory, wall-bearing buildings (monumental type): moderate damage. Light steel-frame, industrial buildings: moderate damage.
				0.8		
291	0.72	1.50	10.0		4	
						Multistory, wall-bearing buildings (monumental type): severe damage. Light steel-frame industrial buildings: severe damage. Highway and RR truss bridges: moderate damage.
				0.6		
431	0.63	3.90	16.3		3	
						Multistory, steel-frame building (office type): severe damage. Transportation vehicles: moderate damage. Multistory, blast-resistant designed, reinforced-concrete building: moderate damage.
				0.4		
459	0.54	7.50	22.5		2	Multistory, reinforced-concrete, frame building (office type): severe damage. Multistory, blast-resistant designed, reinforced-concrete buildings: severe damage. All other (above ground) structures: severely damaged or destroyed.
260	0.44	2.70	30.0	0.2	1	
				0	0	Ground zero for 20 KT air burst.

Table 12.22b

DAMAGE RANGES FOR 1-MT TYPICAL AIR BURST

Peak Wind Velocity (mph)	Positive Phase Duration (sec)	Peak Dynamic Pressure (psi)	Peak Over-Pressure (psi)	Range from Ground Zero (miles)	Range from Ground Zero (1000 ft)	Damage
				↑		Light damage to window frames and doors, moderate plaster damage out to about 15 miles; glass breakage possible out to 30 miles.
				10		
44	3.45	0.036	1.2		50	
				9		
51	3.45	0.049	1.4		45	Fine kindling fuels: ignited.
				8		
60	3.44	0.072	1.7		40	
				7		Smokestacks: slight damage.
72	3.43	0.11	2.1		35	
				6		Wood-frame buildings: moderate damage.
89	3.40	0.16	2.6		30	Radio and TV transmitting towers: moderate damage.
				5		Wood-frame buildings: severe damage. Telephone & power lines: limit of significant damage.
117	3.24	0.28	3.5		25	Wall-bearing, brick buildings (apartment house type): moderate damage.
				4		Wall-bearing, brick buildings (apartment house type): severe damage.
177	3.02	0.60	5.5		20	Light steel-frame, industrial buildings: moderate damage. Light steel-frame, industrial buildings: severe damage. Multistory, wall-bearing buildings (monumental type): moderate damage.
				3		
278	2.69	1.40	9.4		15	Multistory, wall-bearing buildings (monumental type): severe damage. Highway and RR truss bridges: moderate damage. Multistory, steel-frame building (office type): severe damage. Transportation vehicles: moderate damage.
				2		
464	2.25	5.22	18.0		10	Multistory, reinforced-concrete frame buildings (office type): severe damage.
						Multistory, blast-resistant designed, reinforced-concrete buildings: moderate.
307	1.75	3.60	27.0	1	5	Multistory, blast-resistant designed, reinforced-concrete buildings: severe. All other (above ground) structures: severely damaged or destroyed.
				0	0	Ground zero for 1 MT air burst.

whereas the results in Table 12.21 and in Figs. 4.58 a and b are for heights of burst which produce a maximum area of damage for each type of structure.

Effects on Personnel

12.23 For ease of understanding, the effects of air blast on personnel are referred to as either direct or indirect. Among the direct effects are those due to overpressure, such as damage to the ear drums and the lungs (§§ 11.29, 11.31). These occur at close-in distances. An indirect type of injury can arise from displacement of the body as a whole by dynamic (or wind) pressure and its resulting impact with a hard surface (§ 11.33 *et seq.*). This can be experienced at distances where the overpressure (and dynamic pressure) are relatively low, because the maximum wind velocities in the open can still be quite high (Tables 12.22 a and b). Indirect blast injuries can also arise from broken glass and flying debris of various kinds produced by the destruction of buildings. These injuries could be quite numerous over the area in which the overpressure is about 2 pounds per square inch or more.

Protective Construction and Evasive Action

12.24 It is impractical to construct an aboveground conventional building, e.g., office, apartment, or warehouse, that will resist overpressures greater than 25 psi or more, but by taking certain precautions the blast resistance of any structure can be increased somewhat without adding seriously to its cost. The building should be designed for a prescribed overpressure of a certain duration in order that the structure may have essentially uniform strength in different parts. In this connection, it should be borne in mind that the reflected pressure on a wall facing the blast wave will be more than twice as great as on a side wall (§ 3.71). Sturdy connections between beams and columns, such as are commonly used in earthquake-resistant design, and the extensive use of bracing will generally increase the strength of the structure.

12.25 For large buildings, walls of reinforced concrete, which also contain the frame, will give a structure having maximum blast resistance. Such buildings withstood the blast from a nuclear bomb in Japan (Chapter V), although the interiors were badly damaged by fire. Unreinforced block construction, with brick, concrete, or glass, is not only much less able to withstand blast than is a reinforced-concrete structure, but produces more flying debris when it is damaged.

12.26 In industrial-type structures, e.g., for housing machine tools, which have walls made of a frangible material, such as asbestos sheet, rather than of metal, the blast wave will destroy the siding with the result that the loading on the frame will be reduced mainly to that from wind drag. The lightweight debris produced will cause little damage to the machines inside the building. However, shelters are necessary to protect personnel in such buildings from flying pieces of frangible material.

12.27 Blast resistant personnel shelters have been tested at nuclear weapon tests at overpressure levels up to 200 pounds per square inch. Animals exposed at overpressures up to 90 pounds per square inch in such shelters have survived. Similar or more modest shelters can be constructed at relatively low cost if they are planned and built concurrently with new construction. Essential features of blast-resistant shelters are structural strength to resist blast loads to the selected overpressure level, an access door of corresponding strength, a protected ventilation system to permit occupancy of the shelter until fires have subsided, and adequate nuclear radiation shielding.

12.28 Where a blast-resistant shelter is not available, protection should be sought in the strongest building that is accessible. Protection against flying debris can be obtained by taking refuge in a location, preferably selected in advance, that is least likely to be entered by blast debris. In addition, individuals should stay away from windows and easily breakable materials, such as plaster walls or ceilings. In the collapse of buildings as a result of blast, heavy members and pieces of structural materials and contents will fall or be hurled about. There is a dual hazard of being hit and trapped; therefore, positions next to walls in basements offer the best protection. Above ground, however, the safest locations are generally near, but not against, walls and away from doors and windows.

12.29 Even if there is no prior warning of a nuclear attack and the first indication is the flash of light, there may still be the opportunity to take some protective action against the effects of blast. In Table 12.29 are given some approximate values of the times which elapse between the instant of the explosion and the arrival of the blast wave front at various distances from ground zero for air bursts of energy yields from 1 kiloton to 10 megatons TNT equivalent. For distances at which the peak overpressure is small, e.g., 1 pound per square inch or less, the times are not included.

TABLE 12.29—ARRIVAL TIME FOR PEAK OVERPRESSURE

Distance (miles)	Explosion yield 1 KT	10 KT	100 KT	1 MT	10 MT
	(Time in seconds)				
1	4. 3	3. 6	3. 7	2. 5	1. 5
2	>9	8. 1	7. 4	6. 5	5. 0
3	--------	>13	12	11	9. 5
5	--------	--------	21	20	16
7	--------	--------	>30	28	26
10	--------	--------	--------	42	37
20	--------	--------	--------	>90	83
30	--------	--------	--------	--------	>130

12.30 It is seen that at 10 miles from a 10-megaton air burst, which is within the area where protection against blast could be effective, some 37 seconds would elapse before arrival of the blast wave. If prompt action is taken, a person in a building could reach a position of the type indicated above. In the open, some protection against the blast may be obtained by falling prone, and remaining in that position until the wave has passed. In the prone position, with the head directly toward or directly away from the explosion, the area of the body exposed to the onrushing blast wave is relatively small and the danger of displacement is thereby decreased (cf. § 11.38).

THERMAL RADIATION EFFECTS

EFFECTS ON PERSONNEL

12.31 The main direct effects of thermal radiation on human beings are skin burns, generally called flash burns to distinguish them from flame burns, and permanent or temporary eye damage. Burns are classified by "degree"; first-degree burns being mild in nature, roughly similar to moderate sunburn; they should heal without special treatment. Second-degree burns are associated with blister formation and if a significant area of the body is involved, medical attention is necessary (§ 11.44 *et seq.*). The approximate limiting distances from air bursts of various total yields at which first- and second-degree burns of exposed (light-colored) skin may be expected are given in Table 12.31. Third-degree burns, which involve the entire thickness of the skin, can occur at shorter ranges. For a surface burst, the respective distances are decreased to about four-fifths of the values in the table. The ranges shown are actually from the burst point rather than from ground zero, but at the heights of burst that maximize the distances over which burns are experienced, the differences are small.

TABLE 12.31

RANGES FROM GROUND ZERO FOR BURNS TO BARE SKIN FROM AIR BURSTS*

	Explosion yield				
	1 KT	*10 KT*	*100 KT*	*1 MT*	*10 MT*
	(Distance in miles)				
First-degree burn	0. 7	1. 9	5. 3	14	>30
Second-degree burn	0. 5	1. 5	4. 0	11	24

*For a surface burst the distances are about four-fifths those for an air burst of the same yield.

12.32 The data presented in Table 12.31 are applicable to reasonably clear atmospheric conditions. Fog or mist near the ground or a layer of cloud between the point of the explosion and the ground would attenuate the thermal radiation and thus decrease the ranges at which flash burns may be experienced by exposed persons. However, snow on the ground or cloud layers above the explosion provide reflecting surfaces which increase these ranges.

12.33 Eye injuries are of two main types: temporary (flash blindness) and permanent (chorioretinal burns), as described in § 11.69 *et seq.* Both kinds of injury can occur at great distances from the explosion, considerably greater even than those for first-degree burns given in Table 12.31. The nature and extent of the eye injury depends on the yield and type of burst, on the orientation of the observer to the burst, on the clarity of the atmosphere, and on the size of the pupil opening. As a general rule, permanent eye injury would be expected only in those persons who were looking directly at the fireball. Flash blindness, on the other hand, could be quite general over a large area.

PROTECTIVE MEASURES

12.34 In an air or surface burst, the thermal radiation is received in two pulses, in each of which there is a maximum of intensity followed by a decrease. If an individual is caught in the open or is near a window in a building at the time of a nuclear explosion, evasive action to minimize flash burn injury should be taken, if possible, before the maximum in the second pulse. At this time only 20 percent of the thermal energy will have been received, so that a large proportion can be avoided if shelter is obtained before or soon after the second thermal maximum. The elapsed times between the instant of the explosion and the second thermal maximum for air and surface bursts of various energy yields are recorded in Table 12.34. From this table it is seen that the prospects of being able to take evasive action are not good for air or surface bursts of low energy yield, but some possibility may exist for explosions in the megaton range.

TABLE 12.34

TIME TO SECOND THERMAL MAXIMUM

	Explosion yield				
	1 KT	*10 KT*	*100 KT*	*1 MT*	*10 MT*
Time (seconds)	0. 03	0. 1	0. 3	1. 0	3. 2

12.35. The major part of the thermal radiation travels in straight lines, and so any opaque object interposed between the fireball and the exposed skin will give some protection. This is true even if the object is subsequently destroyed by the blast, since the main thermal radiation pulse is over before the arrival of the blast wave.

12.36 At the first indication of a nuclear explosion, by a sudden increase in the general illumination, a person inside a building should immediately fall prone, as described in § 12.30, and, if possible, crawl behind or beneath a table or desk or to a planned vantage point. Even if this action is not taken soon enough to reduce the thermal radiation exposure greatly, it will minimize the displacement effect of the blast wave and provide a partial shield against splintered glass and other flying debris. An individual caught in the open should fall prone to the ground in the same way, while making an effort to shade exposed parts of the body. Getting behind a tree, building, fence, ditch, bank, or any structure which prevents a direct line of sight between the person and the fireball, if possible, will give a major degree of protection. If no substantial object is at hand, the clothed parts of the body should be used to shield parts which are exposed. There will still be some hazard from scattered thermal radiation, especially from high-yield weapons at long range, but the decrease in the direct radiation will be substantial.

12.37 Clothing of the proper kind provides good protection against flash burns. Materials of light color are usually preferable to dark materials because the former reflect the radiation. Clothing of dark shades absorbs the thermal radiation and may become hot enough to ignite, so that severe flame burns, which are more serious that the flash burns, may result. Woolen materials give better protection than those of cotton of the same color, and the heavier the fabric the greater the protection. An air space between two layers of clothing is very effective in reducing the danger of flash burns.

12.38 Protection against eye injury is difficult, especially for those persons who happen to be facing the burst point. The blink reflex, i.e., the automatic blinking of the eye, which requires 0.15 second, may be helpful in providing some protection from air and surface bursts in the megaton range. It is doubtful, however, if much can be done at those distances where the same total amount of thermal energy is received from weapons of lower energy. In a nuclear explosion at high altitude, that is, at heights above 20 miles, the thermal radiation is emitted in a single rapid pulse. Assuming the total thermal energy received by a person at a particular location is sufficient to cause flash burns or eye injury, it seems improbable that any evasive action will be effective, as even the involuntary blink will not be in time to help very much. Ordinary sunglasses will provide little or no protection against eye damage, since much more opaque material would be required to decrease the radiation intensity. In all cases individuals should make every effort to avoid looking toward the fireball.

Fire Protection

12.39 After a nuclear attack on an urban area, extensive fires may develop as they did in Japan. Such fires were started both directly by thermal radiation and by secondary blast effects, i.e., overturning of stoves, short circuiting of electrical wires, etc. (§ 7.69). Appropriate fire control action may be directed along three lines, namely, (1) reduction of potential ignition points, (2) provision for isolation or rapid extinction of ignitions to prevent formation of large fires, and (3) minimization of the consequences should large-scale fires develop.

12.40 Since the elimination of wood as a construction material for houses is virtually impossible, potential ignition points can be decreased by continuous upkeep of existing wood structures and by taking steps to keep yards free from all combustible trash. As stated in § 7.57 *et seq.*, it was clearly demonstrated at the 1953 tests in Nevada that a well-maintained house, with a yard free from trash, is much more capable of withstanding the thermal effects of a nuclear explosion than is a poorly-maintained house or one with an unkept yard. Fire-resistive furnishings, e.g., draperies, rugs, etc., made of vinyl plastic or wool, also proved to be advantageous in these tests.

12.41 The second aspect of fire control action is to plan and train for the elimination of small fires before they can grow into serious ones.

In Japan the fires were so numerous and spread so rapidly that it would have been beyond the capability of regular fire departments to deal with them even if the latter had survived the bombings. The training of private individuals in emergency methods of firefighting, such as were developed in Europe during World War II, is therefore desirable. By extinguishing small fires soon enough, the number of serious fires may be sufficiently small to be dealt with by professional firefighters.

12.42 Conventional methods for preventing the spread of large fires, by the use of natural and artificial fire breaks, were not too successful in Japan, for the reasons mentioned in § 7.72. Nevertheless, consideration should be given to the provision of adequate fire breaks and to the zoning and planning of urban areas. As seen in § 7.55, the potential for the development and spread of fires is greatest in wholesale distribution and slum residential areas. Dispersal and protection of utilities and emergency services should be included in such planning.

INITIAL NUCLEAR RADIATION

Effects on Personnel

12.43 The initial nuclear radiation consists of gamma rays and neutrons received during the first minute after the explosion. Doses of this radiation up to 100 rems, over the whole body, would have little or no immediate observable effects on exposed individuals. The only effect expected might be a slight feeling of fatigue in some people. Many persons receiving larger doses, up to 200 rems, would not be greatly affected by the radiation, except for blood changes. For the present purpose, however, it will be supposed that a whole-body dose of 100 rems will cause few, if any, casualties requiring medical attention. At the other extreme, it is probable that every person receiving 1,000 rems over the whole body will become sick within 4 hours (or less) of exposure and will die in 2 or 3 weeks. Between these extremes there is a great deal of variation in the expected effects on personnel, but at an exposure of around 400 to 500 rems, all will be nauseated and vomit on the first day, and most will require medical care. However at this exposure, at least one-half of the people will probably recover.

12.44 The actual distances from air bursts of various yields at which the initial nuclear radiation will produce doses of 100, 500, and 1,000 rems, respectively, to completely unprotected individuals are shown in Table 12.44. However, the heights of burst which maximize these distances are such that the latter are not very different from the ground zero ranges. For purposes of comparison, the distances for an overpressure of 5 pounds per square inch and for second-degree flash burns of exposed skin are included. It is seen that the hazards from blast and thermal radiation extend to much greater distances than do those from initial nuclear radiation, especially for weapons of yields in excess of 10 kilotons. For example, an individual 2 miles from a 1-megaton burst probably would show no significant symptoms of nuclear radiation sickness, but the thermal radiation exposure would be 210 calories per square centimeter (see Table 12.18). Less than 7 calories per square centimeter are sufficient to produce a second-degree skin burn from an explosion of 1 megaton. The corresponding blast wave overpressure of 18 pounds per square inch would cause severe damage to the strongest conventional structures (cf. Table 12.19).

TABLE 12.44

RANGES FROM GROUND ZERO FOR VARIOUS INITIAL NUCLEAR RADIATION DOSES FROM AIR BURSTS*

	Explosion yield				
	1 KT	*10 KT*	*100 KT*	*1 MT*	*10 MT*
	(Distances in miles)				
Radiation Dose					
100 rems	0. 7	1. 0	1. 3	1. 8	2. 4
500 rems	0. 6	0. 8	1. 1	1. 5	2. 1
1,000 rems	0. 5	0. 7	1. 0	1. 4	2. 0
Other Effects					
5 psi	0. 4	0. 9	2. 0	4. 3	9. 2
Second-degree burns	0. 5	1. 5	4. 0	11	22

*The distances for a specified radiation dose are slightly less for a surface burst.

PROTECTION FROM INITIAL NUCLEAR RADIATION

12.45 It is apparent that for weapons with yields greater than 10 kilotons, the regions in which large doses of initial nuclear radiation could be received are those of high blast pressure and intense thermal radiation. Protection against all three effects would be provided by a massive reinforced, fire-resistant building. An 18-inch thickness of concrete, for example, would reduce the fatal dose of 1,000 rems to the tolerable one of about 100 rems. Thus, aboveground buildings of massive construction would provide some protection against the initial nuclear radiation. Additional protection may be obtained in basements beneath substantial concrete floor slabs. The surrounding earth also helps in this connection; a 26-inch thickness of earth attenuates the radiation by a factor of about ten and 3 feet by about thirty.

12.46 The immediate evasive action suggested earlier for limiting the effects of thermal radiation and blast to a person in the open may assist, to a lesser extent, in reducing the dose of initial nuclear radiation. From high-yield weapons, in particular, a second or two elapses before much of the nuclear radiation is delivered at distances where survival is possible (§ 8.43). Table 12.46 gives the percentage of the total initial gamma-radiation dose received at given distances from 20-kiloton and 5-megaton explosions as a function of time. The total unshielded dose would be about 4,500 roentgens in each case.

TABLE 12.46

INITIAL GAMMA-RADIATION DOSE AS A FUNCTION OF TIME

		Time (seconds)						
		1	*2*	*4*	*7*	*10*	*15*	*20*
Explosion yield	*Distance (miles)*	*Percentage of initial gamma-radiation dose delivered*						
20 KT	0. 5	67	78	88	95	97	100	-----
5 MT	1. 5	5	17	43	76	90	98	100

12.47 As shown by the table, there is some possibility of reducing the radiation dose by immediate evasive action. However, from the numbers given above for the attenuation by concrete and earth, it is obvious that a nuclear radiation shield must be very massive if it is to be effective. Normal clothing, for example, will do little to attenuate initial nuclear radiation, although it may provide complete protection from thermal radiation. Another difficulty in connection with obtaining shelter in the open is the scattering of nuclear radiation, so that it may reach a person from many directions and not just along a direct line from the point of explosion.

RESIDUAL NUCLEAR RADIATION

FALLOUT HAZARD

12.48 The principal effects on personnel from residual radiation are similar to those from comparable doses of initial nuclear radiation as described in the preceding section. However, the hazards of exposure to residual radiation are entirely different from exposure to initial radiation and these hazards are described in this section.

12.49 Protection against residual nuclear radiation occupies a position of special significance. Because the early fallout can cover an area much larger than that over which blast, thermal radiation, and initial nuclear radiation are significant, it is possible for people to become casualties at such distances from the explosion that the immediate effects are negligible or completely absent. As noted earlier, it is not feasible to state the degree of hazard from residual radiation in a reasonably accurate manner because it is so highly dependent upon conditions, especially wind speeds and directions over a considerable height. It is certain, however, that a surface burst in the megaton range will lead to contamination of very large areas by early fallout. This fallout will reach the ground very soon after the explosion at near distances, but at distances of several hundred miles, up to 24 hours may elapse before the fallout starts to arrive.

12.50 The early fallout hazard is of two main kinds: one results from the actual contact of the radioactive material with the skin, causing what are called "beta burns" produced by the action of the beta particles, and the second is due to the continuous exposure of the body to gamma rays, both direct and scattered, from fallout particles. It is with the second of these hazards that the discussion here will be mainly concerned. The protective measures for use against beta burns are chiefly associated with keeping the dust-like particles off the skin. If the fallout dust does get on the skin, it should be immediately washed off with soap and water. The possible hazard from entry of radioactive material into the body by ingestion will be considered later (§ 12.66 *et seq.*).

Induced Radioactivity

12.51 In addition to the radioactive fallout, there may be a residual radiation hazard near ground zero caused by induced activity resulting from the capture of neutrons by various elements in the soil, especially sodium and manganese. The induced-activity hazard may exist on the ground after an air burst when the initial fallout is virtually absent. However, this activity not only decays much more rapidly than does that from fallout, but it extends only a short distance (1 mile or less) from ground zero. Since the destruction in this area would be considerable, the only persons entering it for some time after the explosion should be rescue teams and others performing urgent missions. Such teams would be equipped with instruments to inform them of the radiation hazard.

Protective Measures

12.52 Assuming the population is to remain in the fallout area, and not be evacuated, it is necessary to obtain protection which attenuates the gamma radiation. The basic principle to be borne in mind is that any massive or thick material will decrease the nuclear radiation level to some extent, whereas lighter construction, e.g., window areas, hollow, thin, or light walls, etc., permits the radiation to penetrate. A layer of concrete 8 inches thick or of earth 12 inches thick will yield an attenuation factor of 10; [2] doubling these thicknesses will increase the factor to 100. Thus, each extra foot of earth between an individual and the fallout will increase the protection factor tenfold. It should be remembered that scattered radiation will come from many directions, and so protection is necessary from all directions, either by the use of a mass of material or by distance.

12.53 Information has been published that describes procedures and standards for evaluating the potential of existing structures as fallout shelters and for modifying such structures to improve their effectiveness in this respect. The recommended procedures and standards may also be utilized in the design of new structures. Furthermore, instructions for building simple and effective fallout shelters are readily available. Basically, a fallout shelter is a structure with massive walls and ceiling. Practical materials of construction are earth, concrete, or solid masonry. Attenuation of the gamma radiation is provided by absorption in these materials and by the distance separating the fallout particles from the people in the shelter.

12.54 Since a shelter may have to be occupied continuously for periods as long as 2 weeks, until the natural decay of the radioactivity outside will allow the people to emerge, stocks of food and other supplies will be required. Where fallout arrives soon after the explosion, the early radiation dose rate will be high. It may then be necessary to wait several days before it is possible to come out of the shelter for more than a limited period without risking a radiation dose of sufficient magnitude to cause serious illness. In the path of the fallout, the early radiation levels will be lower at more distant points from the explosion, and the time necessary to occupy the shelter will be shorter, unless "hot spots" are present (§ 9.55). However, in any area where contamination is at all significant, it will probably be necessary to spend the first day or two after the burst sheltered from the residual gamma radiation. It is during the period immediately following the nuclear explosion, when the radiation level is at its highest, that protection is most important.

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[2] It should be noted that more than twice these thicknesses of concrete (18 inches) and of earth (26 inches) are required to attenuate the initial nuclear radiation to the same extent (§ 12.45) because the energy of the initial gamma rays is greater than in the residual (fallout) radiation.

12.55 A fallout shelter of the kind referred to in §12.53 will provide a protection factor of about 200 from the residual radioactivity; in other words, the dose rate in the shelter will be only ½ percent of that measured outside at a height of 3 feet above the ground. Where a shelter is not available, a similar protection factor from radiation can be obtained in the following manner in a small area of the basement of a two-story house. A sturdy table is placed in a corner adjacent to an unexposed outer wall and covered with 10 to 12 inches of soil, sandbags, solid concrete block, etc., according to what is available. If there are no heavy partitions or walls near the corner of the basement chosen, a layer of sandbags or concrete blocks should be stacked along the walls up to the height of the material on top of the table. Within the area under the table, there will be a protective factor of at least 100 from fallout radiation. The disadvantage of this type of protection is that it is unlikely that stocks of food and water would be available within the shelter, so that it could not be occupied continuously for an extended period, as could the more permanent type outlined previously. In almost any house with a buried basement, having uniformly thick exterior walls, a protection factor of 20 to 40 is possible. The maximum protection can be obtained near the floor and in the corners of the basement adjacent to an unexposed outer wall.

12.56 Before leaving a shelter, either temporarily or permanently, it is highly desirable that the radiation dose rate, both in the immediate area of the shelter and in the surrounding vicinity, be known. Marked variations in fallout patterns have been observed in weapons tests, with unexpected areas (hot spots) of exceptionally high activity. Hence, it is not sufficient to know merely that a nearby location is relatively safe. Communications equipment, e.g., battery-powered radios, and radiation measuring instruments should be in shelters. Otherwise it will not be possible to obtain information on radiation dose rates in the locality and in the immediate vicinity of the shelter, particularly at early times when high radiation levels will prevent radiation monitors from moving safely and freely about the community. As a rough rule-of-thumb, it may be stated that for every sevenfold increase in time, the radiation level will decrease by a factor of 10, provided the fallout is complete. For example, the radiation level at the end of 7 days will have fallen to roughly one-tenth of that at the end of 1 day. At the end of 49 days, it will have decreased by a factor of 100, etc.[3]

12.57 It is appropriate to mention here that whether or not fallout is visible to the eye, its measurement requires the use of suitable

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[3] The rule is applicable to any unit of time; thus at 7 hours the residual radiation level will be one-tenth of that at 1 hour, at 14 hours it will be one-tenth of that at 2 hours, and so on, provided the fallout is complete at both times.

instruments sensitive to nuclear radiations. Some, although perhaps not all, of the fallout in the Marshall Islands, after the test explosion of March 1, 1954 (§ 9.100 *et seq.*), could be seen as a white powder or dust. This was due, partly at least, to the light color of the calcium oxide or carbonate of which the particles were mainly composed. It is probable that whenever there is sufficient fallout to constitute a hazard, the dust will be visible. Nevertheless, continuous monitoring with instruments for radioactive contamination would appear to be essential in all areas in the vicinity of the burst.

Radiological Surveys

12.58 As soon after a nuclear explosion as conditions permit, radiological monitoring surveys will have to be initiated for the purpose of developing information on the extent and levels of the contamination. At early times in heavily contaminated areas, where dose rates will be very high, only the most limited amount of monitoring can be accomplished by individuals with hand-carried instruments. In these circumstances, some kind of remote radiation monitoring equipment may be necessary. This will permit the monitor to remain within the shelter while taking readings of the dose rate outside.

12.59 The most rapid method for obtaining radiation levels in a large area is by aerial survey. Because of their long range in air, gamma rays can be detected by sensitive instruments at a height of a few thousand feet. Low-flying airplanes or helicopters, carrying suitable radiation instruments for measuring dose rates, can survey large areas unimpeded by damage on the surface and by impassable streets and roads. Moreover, by making initial flights at an altitude of 1,600 feet or so, the dose rates are only about 1 percent of those on the ground, so that the hazard to the monitor is decreased accordingly.

12.60 The dose rates measured at an altitude must be multipled by an appropriate factor to give the approximate dose rates near the ground. This factor will depend primarily on the height above the ground and nature of the terrain. In the absence of more specific information, the data in Fig. 9.181 may be used to estimate the attenuation factor at a known altitude with reference to that at a height 3 feet above the ground.

12.61 The aerial survey is important because it can be made readily and can provide information which might be impossible to obtain in any other way at the time of interest. Nevertheless, such a survey can serve only as a rough guide and should be made only after all the early fallout is out of the air and on the ground. For points of special interest, the aerial survey must be supplemented by measurements made on the ground when it is safe to do so. The information obtained from the aerial survey will help, however, in planning the ground survey. In this way, the first appreciation of the broad aspects of the radiological situation will lead to the determination of conditions at critical points, to the establishment of dose-rate contours, and to the location of contaminated hot spots as well as the safest areas.

Radiation Doses and Times in Contaminated Areas

12.62 For the planning of defensive actions in connection with the residual activity from fallout or for carrying out survey operations in an area contaminated by the residues from a nuclear explosion, it is necessary either to make some estimate of the permissible time of stay for a prescribed gamma-radiation dose (in roentgens or rems) or to determine the dose which would be received in a certain period of time. The basic data are presented in the form of graphs in Chapter IX, but the same results may be expressed, in a somewhat more limited form, in tables that are more convenient for some purposes.

12.63 If the radiation dose rate (in roentgens or rems per hour) is known at a certain time at a given location, Table 12.63 may be used to determine the dose rate at any other time at the same location, *assuming that the fallout has descended completely and there has been no change other than that resulting from natural radioactive decay.* The same table can be utilized to determine the time after the explosion at which the dose rate will have attained a specific value. Suppose, for example, that at 5 hours after the explosion the measured dose rate is 6 roentgens per hour; when will it have decreased to 1 roentgen per hour? To obtain the answer, find the line in the left-hand column indicating "5 hours," and follow this horizontally until the value nearest to 6 is reached; this is 5.8, which is lower than the actual dose rate. Now proceed vertically down this column until the indicated value is somewhat less than 1.0; it is seen to be roughly 25 hours.

12.64 To determine the allowable time of stay in a contaminated area before a specified total dose is received, Table 12.64 may be employed if the dose rate at the time of entry is known. Suppose that upon entering a contaminated area at 8 hours after the explosion, the dose rate (R) is found to be 45 roentgens per hour. A competent authority has decided that exposed persons in the area may receive a total dose (D) of 25 roentgens, without endangering themselves, in order to perform an important mission; how long can they stay?

TABLE 12.63

FALLOUT ACTIVITIES AT VARIOUS TIMES AFTER A NUCLEAR EXPLOSION

Time after explosion	Dose rate																			
6 min	16	32	66	95	127	159	318	477	636	795	954	1,272	1,590	----	----	----	----	----	----	----
12 min	7	14	28	41	55	69	138	207	276	345	414	552	691	1,380	----	----	----	----	----	----
18 min	4.3	8.6	17	25	34	43	86	129	172	216	259	344	431	862	1,290	----	----	----	----	----
30 min	2.3	4.5	9.1	13	18	23	45	68	91	114	136	182	227	456	681	908	1,140	----	----	----
42 min	1.5	3.0	6.0	9.1	12	15	30	46	61	76	91	122	152	304	456	608	760	912	1,220	----
1 hr	1.0	2.0	4.0	6.0	8.0	10	20	30	40	50	60	80	100	200	300	400	500	600	800	1,000
1 hr 30 min	0.6	1.2	2.4	3.7	4.9	6.1	12	18	24	31	37	48	61	122	183	244	305	366	488	610
2 hr	0.4	0.9	1.8	2.6	3.5	4.4	8.7	13	18	22	26	35	44	87	131	175	219	262	350	437
3 hr	0.3	0.5	1.1	1.6	2.1	2.7	5.4	8.0	11	13	16	21	27	54	80	107	134	161	214	268
5 hr	----	0.3	0.6	0.9	1.2	1.5	2.9	4.4	5.8	7.3	8.7	12	15	29	44	58	73	87	116	145
7 hr	----	----	0.4	0.6	0.8	1.0	1.9	2.9	3.9	4.9	5.8	8	10	19	29	39	49	58	78	97
10 hr	----	----	----	0.4	0.5	0.6	1.3	1.9	2.5	3.2	3.8	5.1	6.4	13	19	25	32	38	51	64
15 hr	----	----	----	----	0.3	0.4	0.8	1.2	1.6	1.9	2.3	3.2	3.9	7.8	12	16	19	23	31	39
1 day	----	----	----	----	----	----	0.5	0.7	0.9	1.2	1.3	1.8	2.3	4.5	6.8	9.0	12	13	18	23
1 d 12 hr	----	----	----	----	----	----	0.3	0.4	0.6	0.7	0.9	1.2	1.5	2.9	4.4	5.8	7.3	8.7	12	15
2 d	----	----	----	----	----	----	----	----	0.4	0.5	0.6	0.8	1.0	1.9	2.9	3.9	4.9	5.8	7.8	10
4 d	----	----	----	----	----	----	----	----	----	----	----	0.3	0.4	0.8	1.3	1.7	2.1	2.5	3.3	4.2
1 wk	----	----	----	----	----	----	----	----	----	----	----	----	----	0.5	0.7	0.9	1.2	1.4	1.8	2.3
2 wk	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	0.3	0.4	0.5	0.6	0.8
4 wk	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	0.3	0.4

Table 12.64

ALLOWABLE STAY TIME IN AREA CONTAMINATED BY FALLOUT FROM A NUCLEAR EXPLOSION

	Time of entry in hours after the explosion																		
	0.1	0.2	0.5	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40
D/R	Duration of exposure (in hours and minutes) required to produce specified values of D/R for various times of entry after the explosion.																		
0.2	1–11	0–25	0–15	0–14	0–13	0–12	0–12	0–12	0–12	0–12	0–12	0–12	0–12	0–12	0–12	0–12	0–12	0–12	0–12
0.3	9–40	1–00	0–22	0–22	0–20	0–19	0–19	0–19	0–19	0–18	0–18	0–18	0–18	0–18	0–18	0–18	0–18	0–18	0–18
0.4	312–24	2–22	0–42	0–31	0–27	0–26	0–26	0–25	0–25	0–25	0–25	0–25	0–25	0–24	0–24	0–24	0–24	0–24	0–24
0.5	∞	6–12	1–02	0–42	0–35	0–34	0–32	0–32	0–32	0–31	0–31	0–31	0–31	0–31	0–31	0–30	0–30	0–30	0–30
0.6	------	19–20	1–26	0–54	0–44	0–41	0–39	0–39	0–38	0–38	0–38	0–37	0–37	0–37	0–37	0–37	0–37	0–36	0–36
0.7	------	82–06	2–05	1–08	0–52	0–49	0–47	0–46	0–45	0–45	0–44	0–44	0–44	0–44	0–43	0–43	0–43	0–43	0–42
0.8	------	624–48	2–56	1–23	1–02	0–57	0–54	0–53	0–52	0–51	0–51	0–51	0–50	0–50	0–49	0–49	0–49	0–49	0–49
0.9	------	2,000–00	4–09	1–42	1–12	1–05	1–02	1–00	0–59	0–58	0–58	0–57	0–57	0–57	0–56	0–55	0–55	0–55	0–55
1.0	------	∞	5–56	2–03	1–23	1–14	1–10	1–08	1–06	1–05	1–05	0–04	1–04	1–03	1–02	1–02	1–02	1–01	1–01
1.25	------	--------	15–30	3–13	1–54	1–38	1–31	1–28	1–25	1–24	1–23	1–22	1–21	1–20	1–19	1–18	1–17	1–17	1–16
1.5	------	--------	48–20	4–57	2–30	2–05	1–54	1–49	1–45	1–43	1–41	1–40	1–39	1–37	1–36	1–34	1–33	1–33	1–32
2.0	------	--------	1,562–00	11–52	4–06	3–13	2–46	2–35	2–29	2–24	2–20	2–18	2–16	2–13	2–10	2–08	2–06	2–05	2–04
2.5	------	--------	∞	31–00	6–26	4–28	3–48	3–28	3–16	3–08	3–03	2–59	2–55	2–51	2–46	2–45	2–40	2–38	2–36
3.0	------	--------	--------	96–39	9–54	6–09	5–01	4–28	4–10	3–58	3–49	3–43	3–38	3–30	3–24	3–17	3–14	3–11	3–08
4.0	------	--------	--------	3,124–00	23–43	11–05	8–12	6–57	6–16	5–50	5–33	5–19	5–10	4–58	4–44	4–32	4–26	4–20	4–15
6.0	------	--------	--------	∞	193–19	35–35	19–48	14–43	12–19	10–55	10–02	9–24	8–57	8–19	7–46	7–15	7–01	6–48	6–34
10.0	------	--------	--------	--------	∞	728–49	124–00	59–18	39–34	30–39	25–42	22–35	21–32	17–52	15–41	13–57	13–05	12–24	11–42

D/R=Allowable dose in roentgens divided by dose rate in roentgens per hour at time of entry.

The allowable dose (D) is divided by the dose rate (R) at the time of entry to give D/R, i.e., $25/45=0.55$. This result falls between two values in the left-hand column of Table 12.64, and the smaller one is taken. Follow the $D/R=0.5$ line horizontally until the column headed "8 hours" after the detonation is reached. The allowable stay time is seen to be 31 minutes; for $D/R=0.6$, the corresponding time is 38 minutes, and so the actual permissible stay time would be about 34 minutes. By using both Tables 12.63 and 12.64, a variety of other estimates can be made.

12.65 There are two important reservations which must be kept in mind in using Tables 12.63 and 12.64. First, if there is any change in the situation, either by further contamination or by decontamination in the period between the two times concerned, the results will not be valid. Second, even if the conditions under which the tables are applicable are fulfilled, the estimates should be used for *planning purposes only*, and to provide a guide for any action that may be required. Changes in dose rates and total accumulated doses over a period of time must always be checked by instruments.

FOOD AND WATER

12.66 After a nuclear attack, in addition to protection from external residual radiation exposure, it is important that personnel in the fallout area also be protected from internal radiation exposure due to ingestion of radioactive fallout material along with food and water. Food and water are not adversely affected by exposure to the residual radioactivity. The principle of protection to be understood is that fallout material must be removed from food and water prior to consumption to prevent this material from getting inside the body. Relative to that which could be taken into the body by eating and drinking, it appears that the amount of radioactive material taken in by inhalation may be small (see §11.160). Nevertheless, air which contains fallout particles should not be directly inhaled without a protective respiratory device (such as a dust-filter respirator) until it is established by monitoring procedures that the air is free from radioactive contamination.

12.67 The contamination of emergency food and water supplies by residual radiation can be prevented by storing them in dust-tight containers. Although the outside of a container may become contaminated by fallout, most of the radioactive substance can be removed by washing the container before it is opened. The foods or fluids can then be removed and consumed without significant contamination.

12.68 If emergency food supplies do become contaminated, or if it is necessary to resort to contaminated sources after emergency supplies are exhausted, many types of food can be treated to remove the radioactive material. Fresh fruits and vegetables can be washed or peeled to remove the outer skin or leaves. Food products of the absorbent type cannot be decontaminated in this manner and should be disposed of by burial. Boiling or cooking of the food has no effect in removing the fallout material. Milk, from cows which survive in a heavily contaminated area, may not be safe to drink because of the radioiodine content and this condition may persist for weeks or months.

12.69 Domestic water supplies from underground sources will usually remain free from radioactive contamination. Water supplies from surface sources may become contaminated if watersheds and open reservoirs are in areas of heavy fallout. However, most of the radioactive fallout material would be removed by regular water treatment which includes coagulation, sedimentation, and filtration. If a surface water supply is not treated in this manner, but merely chlorinated, it may be unfit for consumption for several days after an attack. As a result of dilution and natural decay the contamination will decrease with time.

12.70 If the regular water supply is not usually subjected to any treatment other than chlorination, and an alternative source is not available, consideration should be given in advance planning to the provision of ion-exchange columns or beds for emergency decontamination use. Home water softeners might serve the same purpose on a small scale. The water contained in a residential hot-water heater would serve as an emergency supply, provided it can be removed without admitting contaminated water. Water may also be distilled to make it safe for drinking purposes. *It should be emphasized that mere boiling of water contaminated with fallout is of absolutely no value in removal of the radioactivity.*

Decontamination

12.71 Decontamination is the process of removing radioactive material from a location where it is a hazard to one in which it can do little or no harm. It is one of the means which are available for reducing the radiation dose that would be received from fallout. Preferably it should be accomplished under the supervision of personnel trained in decontamination procedures. Radiation measuring instruments should be used not only to determine the effectiveness of the decontamination but also to make sure that the contaminated material is disposed of in a safe manner.

12.72 Because of its particulate nature, fallout will tend to collect on horizontal surfaces, e.g., roofs, streets, tops of vehicles, and the ground. In the preliminary decontamination, therefore, the main effort should be directed toward cleaning such surfaces. The simplest way of achieving this is by water washing, if an adequate supply of water is available. The addition of a commercial wetting agent (detergent) will make the washing more efficient. The radioactive material is thus tranferred to storm sewers where it is less of a hazard. Covering the ground around a building with uncontaminated earth or removing the top layer of the ground to a distance, by means of earth-moving equipment, are methods for reducing the dose rate inside a building. Inasmuch as decontamination of streets, buildings, and other large items requires substantial manpower and resources, the effectiveness of these operations will benefit from sound planning and skilled supervision.

12.73 It is important to note, in connection with removal of contaminated earth for the purpose described above or to provide a means of transit, that the gamma rays from fission products can travel considerable distances through air. For example, at 3 feet above the ground, roughly 50 percent of the dose rate received in the center of a large, flat, uniformly contaminated area comes from distances greater than 50 feet away, and about 25 percent from distances more than 200 feet away. Thus, complete removal of the contaminated surface from a circle 200 feet in radius would reduce the dose rate in the center to about one-fourth of its original value. However, if the contaminated earth were not completely removed, but just pushed to the outside of the circle, the dose rate would be considerably greater than one-fourth the initial value.

12.74 It is apparent, therefore, that if facilities are to be provided across open country which is contaminated over a large area, bulldozing the top few inches of contaminated soil to the sides will be satisfactory only if a wide strip is cleared. Thus, if the strip is 250 feet in width, the radiation dose rate in the middle will be reduced to one-tenth of the value before clearing. A similar result may be achieved by scraping off the top layer of soil and burying it under fresh soil. Something like a foot of earth cover would be required to decrease the dose rate by a factor of ten.

12.75 Badly contaminated clothing, as well as rugs, curtains, and upholstered furniture, would have to be discarded and buried or stored in an isolated location. When the radioactivity has decayed to a sufficient extent, or if the initial contamination is not too serious, laundering may be effective in reducing the activity of clothing and fabrics, to permit their recovery. Thorough vacuum cleaning of furniture might be adequate in some cases, but an instrument check would be necessary before further use.

SUMMARY

Planning Protection

12.76 In planning protection against the hazards associated with a nuclear attack, it must be recognized that the amount of protection that will be available to individuals is, in a large degree, directly related to the extent of public knowledge concerning nuclear weapons effects and associated protective measures, and to the steps taken prior to the attack to put these measures into a state of readiness. There are certain actions which can be taken by the unprepared in extreme emergencies, but the protection achieved is minor when compared to that which would be available to those who had made adequate preparations. Moreover, following an attack there are certain procedures that can tend to minimize the remaining hazards and these also will be made more effective by sufficient concern beforehand as to their implementation.

12.77 A massive, reinforced, fireproof shelter structure is required at close distances to protect individuals against the severe immediate effects (blast, thermal, and initial nuclear radiation) of a nuclear explosion. This type of protection is the most comprehensive and requires the greatest amount of preplanning effort and knowledge of the effects hazards. Conventional buildings may also be designed to be blast and fire resistant. Measures to minimize the thermal and fire hazard (§ 12.39 *et seq.*) may also be effected. In those areas where early fallout is expected to be a hazard, shelters may be constructed and provision made for occupying them for considerable lengths of time. Knowledge of warning systems and evacuation procedures will also minimize confusion. Moreover, possession of battery operated communications systems and of radiation monitoring equipment will make it possible to obtain information on the condition of the occupied area following an attack.

12.78 In the event that shelters are not available, certain evasive actions may prove helpful at distances where the immediate effects are least severe. By instantly falling prone and covering exposed portions of the body or getting behind opaque objects, much of the thermal radiation may be avoided, especially in the case of large-yield weapons. Under no circumstances should an individual look in the direction of the fireball. Staying behind thick walls or lying in a deep ditch may help to avoid initial nuclear radiation. All of the above actions will also help to decrease the possible danger from the blast wave. Moreover, persons should avoid areas which have frangible materials, such as window glass, plaster, etc., which may become flying debris by the action of the blast.

12.79 After the immediate effects of the nuclear explosion are over, certain acts are required to minimize the hazards of the early fallout and from the fires which may result from thermal radiation and secondary blast effects. First, if small fires can be quickly extinguished, extensive conflagrations may be prevented. This must be accomplished before the arrival of the fallout or in areas of low radioactivity levels. Some protection from the fallout may be secured in the basements of buildings or in a quickly constructed shelter, such as is described in § 12.55. It is important to keep from coming into physical contact with the fallout particles, and to prevent contamination of food and water sources. Monitoring equipment should be used to determine areas which have safe radiation levels and decontamination efforts can proceed to recover necessary equipment, buildings, and areas.

Conclusion

12.80 Much of the discussion presented in earlier sections of this chapter have been based, for simplicity, on the effects of a single weapon. It must not be overlooked that in a nuclear attack some areas may be subjected to several bursts. The basic principles of protection would remain unchanged, but protective action against *all* the effects of a nuclear explosion—blast, thermal radiation, initial nuclear radiation, and fallout—would become even more important. There is a good possibility that many people would survive a nuclear attack and this possibility would be greatly enhanced by utilizing the principles of protection in preattack preparations and planning, in taking evasive action at the time of an attack, and in determining what should be done in the recovery phase after the attack.

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APPENDIX A

NUCLEAR WEAPONS SAFETY AND ACCIDENT HAZARDS

INTRODUCTION

A.1 Nuclear weapons are designed with great care to explode only when deliberately armed and fired. Nevertheless, there is always a possibility that, as a result of accidental circumstances, an explosion will take place inadvertently. Although all conceivable precautions are taken to prevent them, such accidents might occur in areas where the weapons are assembled and stored, during the course of loading and transportation on the ground, or when actually in the delivery vehicle, e.g., an airplane or a missile.

A.2 In general, nuclear weapons contain varying amounts of high explosive (§ 1.54), in addition to the fissionable material, i.e., the nuclear explosive. The chances that the latter alone will detonate are so remote that they can be ruled out completely. It is the high-explosive component which comprises the main possible hazard, just as it does with conventional weapons. The spontaneous detonation of this material, without external cause, is highly improbable, but an explosion might occur if the weapon were dropped from a height or if it were involved in a fire. Both aircraft and missiles contain fuel or propellant which is combustible and so in an accident to these vehicles a serious fire could develop which might possibly, although by no means certainly, cause the detonation of the high explosive in a nuclear weapon.

A.3 Even if such an explosion did occur, the nuclear component would not necessarily be affected. A nuclear weapon is a complex system and all of its components must function almost perfectly if it is to produce an energy release that even approaches the design value. Any nuclear energy contribution resulting from the accidental detonation of the high-explosive component will, therefore, be either completely absent or very small. During more than 16 years (from 1945 through 1961) of storing, transporting, flying, overhauling, modifying, inspecting, and otherwise working on and with nuclear weapons, the nuclear part of the weapon has not contributed to the cause or the effect of an accident. Although any accident is to be deplored, the fact that none has been more serious than from a conventional high-explosive weapon of moderate power, is a tribute to the extreme care devoted to the design of nuclear weapons and to the development of safe procedures for handling and transporting them.

A.4 Before discussing the various hazards which might be associated with an accident to a nuclear weapon, mention may be made of the possibility of a nuclear explosion being produced deliberately by sabotage or by the action of a psychotic individual who has access to a weapon. To eliminate or, at least, to minimize the probability of such an occurrence, there are positive physical and procedural measures which prevent deliberate or inadvertent arming, launching, firing, or release of a nuclear weapon. Among the precautions taken mention may be made of the use of launch or release controls which are locked or sealed in the safe position, the employment of two or more separate controls, and procedures requiring the presence of two or more properly informed and authorized persons.

A.5 Since accidents, by their very nature, are completely unpredictable, consideration must be given to all conceivable hazards that might arise in the storage or transportation of nuclear weapons. These hazards may be due to (*a*) fire and detonation of the high explosive, (*b*) fissionable material, i.e., uranium and plutonium, (*c*) tritium, which is radioactive, and (*d*) fission products in the unlikely event that there is an appreciable nuclear yield. These aspects of accidents to nuclear weapons will be considered in turn.

Fire and Detonation

A.6 If a nuclear weapon is exposed to the flames from a gasoline or similar fire, arising from the fuel or propellant of the carrying vehicle, the high explosive will probably ignite and burn. Fires resulting from large quantities of burning high explosives are very difficult to extinguish. At the same time, acrid, suffocating, and toxic gases are produced, and a poisonous residue may remain. If the high explosive is confined, as in an intact weapon, detonation may occur at any time. In addition, high explosives melt at relatively low temperatures; the heat of the fire may thus cause the molten explosive to flow out of the weapon and then resolidify. In this state, the material is extremely sensitive to shock, and may detonate if stepped on.

A.7 In any accident involving a nuclear weapon, such as dropping or exposure to fire, there is a possibility that detonation of the high explosive may occur. However, one of the characteristics of TNT and similar explosives is the unpredictability of their response to a given stimulus. Thus, impact or a fire may or may not cause a detonation. If a detonation does occur, it can range from a very small to a large chemical explosion or it may be a series of small explosions. The breakage of a weapon due to impact or to a small explosion will probably result in scattering of small pieces of high explosive; these may burn and possibly explode.

A.8 Rough handling of high explosives as well as accidents can lead to the formation of powdered explosive. Under these conditions, most explosive materials are more unstable than in bulk form and are more apt to be detonated by shock or change in temperature. Exposure to sunlight also increases the sensitivity of high explosives; at the same time there is a change in color which makes small pieces and powder difficult to distinguish from their surroundings. The danger of an explosion is thereby increased.

A.9 The detonation of high explosives can cause injury to personnel by direct and indirect blast effects, as described in Chapter XI. The greatest danger is probably from flying debris, falling objects, fragments of glass, etc. It is recommended that, in the event of a nuclear weapon becoming involved in a fire, all persons not essential for damage control or recovery operation withdraw to a distance of at least 1,500 feet. This will minimize the injury potential of the blast that would result from the detonation of the high explosive.

A.10 Because of the formation of noxious fumes, etc., as stated above, produced by the burning explosive, and by any vehicle fuel that may be present, only those individuals properly protected with respiratory equipment should be permitted to remain in the downwind path of a fire or potential detonation. Smoke may be tolerated for a short period of time if necessary in the interest of saving lives. When the fire has subsided and a check has been made by instruments that no radiation hazard exists, trained experts may approach the scene of the accident in order to clear the area of scattered pieces of high explosive.

Fissionable Material

A.11 All nuclear weapons contain a certain amount of fissionable material, either uranium or plutonium (or both); these substances are radioactive, emitting alpha particles (§ 9.40). Following an accident to a nuclear weapon, the fissionable material could, in some circumstances, be spread over a large area. However, because alpha particles cannot penetrate even the dead surface layer of the unbroken skin, the only possible hazard that could arise would be the entry of uranium or plutonium into the body. The danger from plutonium lies in the tendency of this element to concentrate in the bone, where the continuous emission of alpha particles may cause significant injury. Uranium, on the other hand, acts mainly as a chemical poison, and fairly large amounts would have to be absorbed to produce any serious effect. Both uranium and plutonium can be detected as surface contamination by instruments which indicate the presence of alpha particles; the particles from plutonium have the higher energies.

A.12 Plutonium and uranium react readily with oxygen from the air and so they may become dispersed as small particles of oxide if the fissionable material is exposed. This may occur if the nuclear weapon is broken by impact or by the detonation of the high explosive. In the event of a fire, very fine particles of the oxides may be carried in the smoke. In the few instances in which aircraft containing nuclear weapons have burned, the fissionable material melted and was left on the ground as a slag. In this condition, oxides will form on the surface and may become airborne if disturbed, e.g., by the wind, to become an inhalation hazard.

A.13 As is the case with fallout particles (§ 11.156), significant entry of plutonium and uranium oxides into the body can occur through the respiratory tract; even then, the nose and lungs act as effective filters. Because of their small solubility, absorption of the oxides by the gastrointestinal system is very low. Furthermore, pentration of intact skin is impossible and although the material may enter where the skin is broken, it will be localized at the point of access. It may then be cleansed away, even at some later time, without appreciable translocation to the blood stream or other body tissues having occurred.

A.14 The results of observations made at the Nevada Test Site indicate that, at distances greater than 1,500 feet from the incident, the amounts of plutonium that might be received either from a contaminated smoke cloud or in other ways would not exceed the accepted Radioactivity Concentration Guide values (§ 11.100). For undisturbed surfaces, initial concentrations up to 100 micrograms of plutonium per square foot appear to be tolerable; for uranium the tolerance value is somewhat higher. The general conclusion drawn from the tests is that, even though the Radioactivity Concentration Guide for the body burden of plutonium is small (approximately half a microgram), it is difficult to acquire this amount as a result of a weapon accident outside the exclusion radius given above. The permissible concentration of uranium in the body is larger than for plutonium, and is not likely to be attained in the same circumstances.

Tritium

A.15 Tritium is another radioactive isotope used in weapons which could be hazardous in a confined area. In air tritium becomes an analogue of water, i.e., T_2O or HTO. In an enclosed space where the tritium water vapor can concentrate in the air, it can be easily absorbed through the unbroken skin, the lungs, and the gastrointestinal system, constituting an exposure problem to the entire body. Should it enter the body, tritium water dissolves in the body water and is eliminated at the same rate as ordinary water since it does not tend to concentrate in bone or in any organ as do some of the more hazardous radioactive materials.

A.16 From the point of view of the general public, the possibility of confrontation with a tritium hazard is negligible, for only selected military personnel can gain access to areas of enclosure which contain nuclear weapons. Because the existence of tritium in air can be detected by instruments sensitive to beta particles, monitoring systems are installed wherever necessary. The precautionary procedures employed to protect against the possible hazards from other radioactive materials in weapons provide more than adequate safeguards against tritium. The accepted Radioactivity Concentration Guide for this isotope is 3 millicuries distributed throughout the body. To accumulate such a dose it would be necessary to breathe for an hour air containing a concentration of 21 millicuries per cubic foot.

Fission Products

A.17 Fission products would be produced in an accident with a nuclear weapon only if there were a nuclear (fission) contribution to the energy released in a fire or explosion. The probability that there will be any nuclear yield at all is extremely small, but the possibility must, of course, be kept in mind. In no accident, to date, has there been any fission product release, although in some cases the weapon has become hot enough to cause the fissionable material to melt, as noted earlier.

A.18 If there should be any nuclear yield, the hazard would be mainly due to the beta particles and gamma rays emitted by the radioactive fission products. The effects would be similar to those arising from the residual nuclear radiation, as described in Chapter IX, but scaled down to the actual fission yield in the accident. In addition, neutrons released in the fission process may be captured by materials close to the explosion and so produce induced activity (§ 9.31), consisting of either beta particles alone or in conjunction with gamma rays. Both beta and gamma radiation are easily detected with the proper instruments, so that survey of an accident area will readily indicate if a fission energy release has occurred. If it has, then proper precautions must be taken in cleaning up the area. Incidentally, if the beta-gamma survey meter shows the presence of contamination, it may be taken for granted, without further test, that fissionable material (uranium or plutonium) is also present. As a general rule, it is expected that the radiation dose from fission products and induced activity delivered at a distance of 1,500 feet from the scene of the accident will be negligible.

PROTECTIVE MEASURES

A.19 The Department of Defense and the Atomic Energy Commission have several hundred teams of men, in various parts of the United States, who are trained to deal with accidents involving nuclear weapons. Since such an accident may occur anywhere, for example, as the result of the crash of an airplane carrying a weapon, it is imperative that fire, police, civil defense, public health authorities, and other emergency services should take appropriate action. If it appears at all practicable, the first step should be to rescue and assist injured personnel. Next, the nearest military installation or AEC office should be notified of the accident, so that a special team may be dispatched to the scene. At the same time advice may be obtained concerning further action. Meanwhile, the area surrounding the accident should be cleared of all non-essential personnel to a distance of at least 1,500 feet.

A.20 If there is a fire and it is apparent that the weapon is not burning or engulfed in flames, an attempt should be made to extinguish the fire with water, in the normal manner, from the upwind side only. If the water seems to accelerate the burning, then it must be stopped. The weapon should be kept cool by means of a water spray, since it is expected that the high explosive will not detonate if its temperature is maintained below 300° F. In cases where the weapon is not in the fire, the foam used for extinguishing fuel fires can be spread over the weapon to protect it from radiated heat from flames. The breaking down of a foam blanket on fuel with water streams must be avoided.

A.21 If the weapon is engulfed in flames or it is believed that the high explosive is burning, no attempt should be made to put out the fire. All personnel should then evacuate the area of 1,500 feet radius around the site of the accident because of the danger of detonation occurring. It may be mentioned that burning high explosive may sometimes be detected by jets of white flame coming out of the weapon ("torching"), but this is not always observed. Consequently, if the flames, such as those produced by burning fuel, appear to be growing in intensity and extending toward or actually enveloping the weapon, all personnel should be removed from the scene.

A.22 The area downwind from the accident should be kept clear in order to avoid the toxic, and possibly radioactive, smoke from a burning weapon. If exposure to dense smoke is necessary for any length of time, dust-filtering masks and goggles, or special breathing apparatus, should be used. But the lack of such equipment should not hold up rescue efforts which require a short stay in the smoke area. Personnel who have been exposed to smoke must be monitored for radioactivity and, if necessary, decontaminated by members of the special team trained for the work. In fact, such action is advisable for all personnel who may have been contaminated in any way. They should be prevented from wandering about, since this would spread the radioactivity and make it more difficult to clear up.

A.23 If the special team has not arrived by the time the fire has subsided or been extinguished, no attempt should be made to clean up the scene of the accident. It may be highly radioactive and could represent a serious radiation hazard. For the same reason, the area of the accident should be roped off so as to prevent access by anyone, other than members of the survey teams. After they have made a careful examination of the area, they will either undertake its decontamination or will advise on what should be done in the interests of safety and security.

ANNOUNCED UNITED STATES NUCLEAR DETONATIONS

Name	Date (GCT)	Time (GCT)	Location of Shot	Height of Burst (Feet)	Type of Burst	Mean Sea Level (Feet) Cloud Top	Mean Sea Level (Feet) Cloud Base	Mean Sea Level (Feet) Tropopause	Yield	Remarks
TRINITY:										
Trinity	16/7/45	1230	Alamogordo, N.M.	100	Tower	35,000			19 KT	First test of an A-bomb.
WORLD WAR II	5/8/45	2315	Hiroshima, Japan	~1,850	Air				Nominal	First combat use.
	9/8/45	0158	Nagasaki, Japan	~1,850	Air				Nominal	Second combat use.
CROSSROADS:										
Able	30/6/46	2201	Bikini	520	Air	35,000			Nominal	Air burst over ships.
Baker	24/7/46	2135	Bikini	−90	UW	8,000			Nominal	First underwater test.
SANDSTONE:										
X-ray	14/4/48	1817	Eniwetok	200	Tower	56,000	25,000	56,000	37 KT	2:1 U:Pu core.
Yoke	30/4/48	1809	Eniwetok	200	Tower	55,000	35,000	54,000	49 KT	} levitated U cores.
Zebra	14/5/48	1804	Eniwetok	200	Tower	28,000	20,000	54,000	18 KT	
RANGER:										
Able	27/1/51	1345	Nevada	1,060	Air	17,000		33,000	1 KT	U core.
Baker	28/1/51	1352	Nevada	1,080	Air	35,000		32,000	8 KT	
Easy	1/2/51	1347	Nevada	1,080	Air	12,000		35,000	1 KT	
Baker-2	2/2/51	1349	Nevada	1,100	Air	36,000		38,000	8 KT	
Fox	6/2/51	1347	Nevada	1,435	Air	42,000		40,000	22 KT	Composite core, MK-6.
GREENHOUSE:										
Dog	7/4/51	1834	Eniwetok	300	Tower			55,000	81kt	
Easy	20/4/51	1827	Eniwetok	300	Tower	40,000	30,000	54,000	47 KT	
George	8/5/51	2130	Eniwetok	200	Tower			55,000	225 kt	DEUTERIUM BURN.
Item	24/5/51	1817	Eniwetok	200	Tower			55,000	45.5 kt	FIRST TRITIUM BOOSTED BOMB.
BUSTER-JANGLE:										
Able	22/10/51	1400	Nevada	100	Tower	8,000	6,700		<0.1 KT	Fizzle.
Baker	28/10/51	1520	Nevada	1,118	Air	29,000	23,000	39,000	3.5 KT	Pu core; no tamper.
Charlie	30/10/51	1500	Nevada	1,132	Air	40,000	32,000	38,000	14 KT	U/Pu composite core.
Dog	1/11/51	1530	Nevada	1,417	Air	40,000	27,000	38,000	21 KT	" " "
Easy	5/11/51	1630	Nevada	1,314	Air	45,000	31,000	35,000	31 KT	", MK-7 prototype
Sugar	19/11/51	1700	Nevada	4	Surface	16,000	11,000		1.2 KT	MK-6 with U core
Uncle	29/11/51	2000	Nevada	−17	UG	11,000			1.2 KT	", First underground shot.

TUMBLER-SNAPPER:										
Able	1/4/52	1700	Nevada	793	Air	16,000		42,000	1 KT	
Baker	15/4/52	1730	Nevada	1,050	Air	16,000	10,000	38,000	1 KT	
Charlie	22/4/52	1730	Nevada	3,447	Air	42,000	31,000	38,000	31 KT	
Dog	1/5/52	1630	Nevada	1,040	Air	42,000	28,000	38,000	19 KT	
Easy	7/5/52	1215	Nevada	300	Tower	34,000		41,000	12 KT	
Fox	25/5/52	1200	Nevada	300	Tower	41,000		37,000	11 KT	
George	1/6/52	1155	Nevada	300	Tower	37,000		37,000	15 KT	
How	5/6/52	1155	Nevada	300	Tower	41,000		40,000	14 KT	
IVY:										
Mike	31/10/52	1915	Eniwetok		Surface	~100,000		56,000	10.4 MT	Experimental thermo-nuclear device.
King	15/11/52	2330	Eniwetok	1,480	Air	~70,000		55,000	High yield	500 kt pure fission implosion, U-235.
UPSHOT-KNOTHOLE:										
Annie	17/3/53	1320	Nevada	300	Tower	41,000	28,000	36,000	16 KT	
Nancy	24/3/53	1310	Nevada	300	Tower	42,000	26,000	40,000	24 KT	
Ruth	31/3/53	1300	Nevada	300	Tower	14,000	11,000	36,000	0.2 KT	
Dixie	6/4/53	1530	Nevada	6,020	Air	43,000	33,000	36,000	11 KT	
Ray	11/4/53	1245	Nevada	100	Tower	13,000	8,000	38,000	0.2 KT	
Badger	18/4/53	1235	Nevada	300	Tower	35,000	23,000	39,000	23 KT	
Simon	25/4/53	1230	Nevada	300	Tower	45,000	31,000	38,000	43 KT	
Encore	8/5/53	1530	Nevada	2,425	Air	41,000	29,000	39,000	27 KT	
Harry	19/5/53	1205	Nevada	300	Tower	43,000	27,000	42,000	32 KT	
Grable	25/5/53	1530	Nevada	524	Gun	38,000	23,000	38,000	15 KT	Fired from 280 mm gun.
Climax	4/6/53	1115	Nevada	1,334	Air	43,000	35,000	39,000	61 KT	
CASTLE:										
Bravo	28/2/54	1845	Bikini		Surface	114,000	55,000	55,000	15 MT	Experimental thermo-nuclear device.
Romeo	26/3/54	1830	Bikini		Barge			55,000	11 Mt	Natural LiD fuel.
Koon	6/4/54	1820	Bikini		Surface			53,000	~100 KT	110 kt, 90% fission
Union	25/4/54	1810	Bikini		Barge			57,000	6.9 Mt	
Yankee	4/5/54	1810	Bikini		Barge			55,000	13.5 Mt	
Nectar	13/5/54	1820	Eniwetok		Barge			56,000	1.69 Mt	
TEAPOT:										
Wasp	18/2/55	2000	Nevada	762	Air	22,000	15,000		1 KT	
Moth	22/2/55	1345	Nevada	300	Tower	25,000	16,000		2 KT	
Tesla	1/3/55	1330	Nevada	300	Tower	30,000	18,000	38,000	7 KT	
Turk	7/3/55	1320	Nevada	500	Tower	44,000	36,000	40,000	43 KT	
Hornet	12/3/55	1320	Nevada	300	Tower	35,000	27,000	38,000	4 KT	
Bee	22/3/55	1305	Nevada	500	Tower	40,000	29,000	37,000	8 KT	
Ess	23/3/55	2030	Nevada	−67	UG	12,000		39,000	1 KT	

ANNOUNCED UNITED STATES NUCLEAR DETONATIONS—Continued

Name	Date (GCT)	Time (GCT)	Location of Shot	Height of Burst (Feet)	Type of Burst	Mean Sea Level (Feet)			Yield	Remarks
						Cloud Top	Cloud Base	Tropopause		
TEAPOT—Continued										
Apple-1	29/3/55	1255	Nevada	500	Tower	32,000	22,000	39,000	14 KT	
Wasp Prime	29/3/55	1800	Nevada	740	Air	32,000		40,000	3 KT	
HA	6/4/55	1800	Nevada	36,620 (MSL)	Air	55,000		31,000	3 KT	
Post	9/4/55	1230	Nevada	300	Tower	16,000	13,000		2 KT	
Met	15/4/55	1915	Nevada	400	Tower	40,000	31,000	37,000	22 KT	
Apple-2	5/5/55	1210	Nevada	500	Tower	43,000	34,000	41,000	29 KT	
Zucchini	15/5/55	1200	Nevada	500	Tower	35,000	25,000	44,000	28 KT	
WIGWAM:										
Wigwam	14/5/55	2000	29° N. 126° W	−2,000	UW				30 KT	
REDWING:										
Lacrosse	4/5/56	1825	Eniwetok		Surface			53,000	40 Kt	Kiloton range.
Cherokee	20/5/56	1751	Bikini	4,320	Air			53,000	3.8 Mt 50% fission	Several megatons. First air drop by U.S. of a thermonuclear weapon.
Zuni	27/5/56	1756	Bikini		Surface			51,000	3.53 Mt	15% fission.
Erie	30/5/56	1815	Eniwetok	300	Tower			54,000	14.9 Kt	Boosted primary test.
Seminole	6/6/56	0055	Eniwetok		Surface			52,000	13.7 Kt	Inside water tank.
Flathead	11/6/56	1826	Bikini		Barge			50,000	365 Kt	73% fission
Blackfoot	11/6/56	1826	Eniwetok	200	Tower			52,000	8 Kt	
Osage	16/6/56	0114	Eniwetok	680	Air			52,000	1.7 Kt	
Dakota	25/6/56	1806	Bikini		Barge			54,000	1.1 Mt	
Apache	8/7/56	1806	Eniwetok		Barge			52,000	1.85 Mt	
Navajo	10/7/56	1756	Bikini		Barge			50,000	4.5 Mt	5% fission: "CLEAN"!
Tewa	20/7/56	1748	Bikini		Barge			52,000	5.01 Mt	87% fission: DIRTY.
Huron	21/7/56	1816	Eniwetok		Barge			51,000	250 Kt	
Inca	21/6/56	2126	Eniwetok	200	Tower				15.2 Kt	Fallout studies test, boosted tactical bomb.

PLUMBBOB:										
Boltzmann	28/5/57	1155	Nevada	500	Tower	33,000	23,000	41,000	12 KT	
Franklin	2/6/57	1155	Nevada	300	Tower	17,000	14,000		140 T	
Lassen	5/6/57	1145	Nevada	500	Balloon	7,000		43,000	0.5 T	
Wilson	18/6/57	1145	Nevada	500	Balloon	35,000	25,000	40,000	10 KT	
Priscilla	24/6/57	1330	Nevada	700	Balloon	43,000	24,000	49,000	37 KT	
Hood	5/7/57	1140	Nevada	1,500	Balloon	48,000	35,000	53,000	74 KT	
Diablo	15/7/57	1130	Nevada	500	Tower	32,000	20,000	43,000	17 KT	
John	19/7/57	1400	Nevada	20,000	Rocket	44,000		48,000	~2 KT	
Kepler	24/7/57	1150	Nevada	500	Tower	28,000	20,000	34,000	10 KT	
Owens	25/7/57	1330	Nevada	500	Balloon	35,000	20,000	49,000	9.7 KT	
Stokes	7/8/57	1225	Nevada	1,500	Balloon	37,000	27,000	47,000	19 KT	
Shasta	18/8/57	1200	Nevada	500	Tower	32,000	16,000	50,000	17 KT	
Doppler	23/8/57	1230	Nevada	1,500	Balloon	38,000	23,000	43,000	11 KT	
Franklin Prime	30/8/57	1240	Nevada	750	Balloon	32,000	21,000	32,000	4.7 KT	
Smoky	31/8/57	1230	Nevada	700	Tower	38,000		35,000	44 KT	
Galileo	2/9/57	1240	Nevada	500	Tower	37,000	17,000	39,000	11 KT	
Wheeler	6/9/57	1245	Nevada	500	Balloon	17,000	14,000	50,000	197 T	
Laplace	8/9/57	1300	Nevada	750	Balloon	20,000	14,000	44,000	1 KT	
Fizeau	14/9/57	1645	Nevada	500	Tower	40,000	27,000	43,000	11 KT	
Newton	16/9/57	1250	Nevada	1,500	Balloon	32,000	19,000	52,000	12 KT	
Rainier	19/9/57	1700	Nevada	−790	UG				1.7 KT	There was no tunnel venting.
Whitney	23/9/57	1230	Nevada	500	Tower	30,000	18,000	53,000	19 KT	
Charleston	28/9/57	1300	Nevada	1,500	Balloon	32,000	20,000	45,000	12 KT	
Morgan	7/10/57	1300	Nevada	500	Balloon	40,000	26,000	37,000	8 KT	
HARDTACK PHASE I:										
Yucca	28/4/58	0240	12° 37′ N., 163° 01′ E	86,000	Balloon			53,000	1.7 Kt	High altitude test.
Cactus	5/5/58	1815	Eniwetok		Surface			51,000	18 Kt	
Fir	11/5/58	1750	Bikini		Barge			54,000	1.36 Mt	
Butternut	11/5/58	1815	Eniwetok		Barge			53,000	81 Kt	
Koa	12/5/58	1830	Eniwetok		Surface			57,000	1.37 Mt	
Wahoo	16/5/58	0130	Eniwetok	−500	UW			59,000	9 Kt	
Holly	20/5/58	1830	Eniwetok		Barge			52,000	5.9 Kt	
Nutmeg	21/5/58	2120	Bikini		Barge			54,000	25.1 Kt	
Yellowwood	26/5/58	0200	Eniwetok		Barge			55,000	330 Kt	
Magnolia	26/5/58	1800	Eniwetok		Barge			54,000	57 Kt	
Tobacco	30/5/58	0215	Eniwetok		Barge			55,000	11.6 Kt	
Sycamore	31/5/58	0300	Bikini		Barge			55,000	92 Kt	

ANNOUNCED UNITED STATES NUCLEAR DETONATIONS—Continued

Name	Date (GCT)	Time (GCT)	Location of Shot	Height of Burst (Feet)	Type of Burst	Mean Sea Level (Feet) Cloud Top	Cloud Base	Tropopause	Yield	Remarks
HARDTACK PHASE I—Continued										
Rose	2/6/58	1845	Eniwetok		Barge			57,000	15 Kt	
Umbrella	8/6/58	2315	Eniwetok	−150	UW			54,000	8 Kt	Lagoon bottom burst,
Maple	10/6/58	1730	Bikini		Barge			53,000	213 Kt	
Aspen	14/6/58	1730	Bikini		Barge			52,000	319 Kt	
Walnut	14/6/58	1830	Eniwetok		Barge			54,000	1.45 Mt	
Linden	18/6/58	0300	Eniwetok		Barge			54,000	11 Kt	
Redwood	27/6/58	1730	Bikini		Barge			52,000	412 Kt	
Elder	27/6/58	1830	Eniwetok		Barge			52,000	880 Kt	
Oak	28/6/58	1930	Eniwetok		Barge			52,000	8.9 Mt	
Hickory	29/6/58	0000	Bikini		Barge			50,000	14 Kt	
Sequoia	1/7/58	1830	Eniwetok		Barge			51,000	5.2 Kt	
Cedar	2/7/58	1730	Bikini		Barge			52,000	220 Kt	
Dogwood	5/7/58	1830	Eniwetok		Barge			51,000	397 Kt	
Poplar	12/7/58	0330	Bikini		Barge			52,000	9.3 Mt	
Juniper	22/7/58	0420	Bikini		Barge			55,000	65 Kt	
Oliver	22/7/58	2030	Eniwetok		Barge			51,000	202 Kt	
Pine	26/7/58	2030	Eniwetok		Barge			48,000	2 Mt	
Teak	1/8/58	1050	Johnston Island	252,000	Rocket			52,000	3.8 Mt	Megaton range. 50%
Orange	12/8/58	1030	Johnston Island	141,000	Rocket				3.8 Mt	Megaton range. fission.
HARDTACK PHASE II:										
Eddy	19/9/58	1400	Nevada	500	Balloon	11,000	7,500	48,000	83 T	
Mora	29/9/58	1405	Nevada	1,500	Balloon	18,500	10,000	40,000	2 KT	
Tamalpais	8/10/58	2200	Nevada	−330	UG	Low diffuse cloud			72 T	Slight venting.
Quay	10/10/58	1430	Nevada	100	Tower	10,000	7,500		79 T	
Lea	13/10/58	1320	Nevada	1,500	Balloon	17,000	12,000		1.4 KT	
Hamilton	15/10/58	1600	Nevada	50	Tower	6,000	4,500		1.2 T	
Logan	16/10/58	0600	Nevada	−830	UG				5 KT	No venting.
Dona Ana	16/10/58	1420	Nevada	450	Balloon	11,000	6,500	49,000	37 T	

Rio Arriba	18/10/58	1425	Nevada	72.5	Tower	13,500	11,000		90 T	
Socorro	22/10/58	1330	Nevada	1,450	Balloon	26,000	20,000		6 KT	
Wrangell	22/10/58	1650	Nevada	1,500	Balloon	10,000	7,000		115 T	
Rushmore	22/10/58	2340	Nevada	500	Balloon	11,500		42,000	188 T	
Sanford	26/10/58	1020	Nevada	1,500	Balloon	26,000	12,500		4.9 KT	
De Baca	26/10/58	1600	Nevada	1,500	Balloon	17,500	10,000		2.2 KT	
Evans	29/10/58	0000	Nevada	−848	UG				55 T	Venting.
Humboldt	29/10/58	1445	Nevada	25	Tower	7,500	6,000		7.8 T	
Santa Fe	30/10/58	0300	Nevada	1,500	Balloon	18,000	13,000	39,000	1.3 KT	
Blanca	30/10/58	1500	Nevada	−835	UG	7,700			19 KT	Slight venting.
ARGUS:										
Argus I	27/8/58		South Atlantic (38° S. 12° W.)	124 miles ~~~300 miles~~	Rocket				1 − 2 KT	1.7 kt
Argus II	30/8/58		South Atlantic (50° S. 8° W.)	159 miles ~~~300 miles~~	Rocket				1 − 2 KT	1.7 kt
Argus III	6/9/58		South Atlantic (50° S. 10° W.)	335 miles ~~~300 miles~~	Rocket				1 − 2 KT	1.7 kt created trapped β-radiation belts.

ANNOUNCED U.S. NUCLEAR DETONATIONS, 1961–63

NEVADA SERIES

Name	Date (GCT)	Time (GCT)	Depth[1] (feet)	Type	Medium	Depression[2] (Diam. & Depth, feet)	Yield[3] (KT)	Remarks
Antler	15/ 9/61	1700	1,319	Underground	Tuff	None	2.4	Tunnel.
Shrew	16/ 9/61	1945	322	Underground	Alluvium	None	Low	0.017 kt
Chena	10/10/61	1800	838	Underground	Tuff	None	Low	Tunnel.
Mink	29/10/61	1830	630	Underground	Alluvium	None	Low	
Fisher	3/12/61	2304	1,193	Underground	Alluvium	600; 14	13.5	
Mad	13/12/61	1800	594	Underground	Alluvium	None	0.43	
Ringtail	17/12/61	1635	1,191	Underground	Alluvium	778; 2.17	Low	
Feather	22/12/61	1630	812	Underground	Tuff	None	Low	Tunnel. 0.15 kt
Stoat	9/ 1/62	1630	992	Underground	Alluvium	602; 7.1	4.5	
Agouti	18/ 1/62	1800	856	Underground	Alluvium	604; 40	5.9	
Dormouse	30/ 1/62	1800	1,191	Underground	Alluvium	547; 14.4	Low	
Stillwater	8/ 2/62	1800	625	Underground	Alluvium	406; 39	2.7	
Armadillo	9/ 2/62	1800	786	Underground	Alluvium	590; 29	6.6	
Hardhat	15/ 2/62	1800	943	Underground	Granite	None	5.9	
Chinchilla	19/ 2/62	1630	492	Underground	Alluvium	302; 27	1.8	
Codsaw	19/ 2/62	1750	696	Underground	Tuff	230; 11	Low	
Cimarron	23/ 2/62	1800	1,000	Underground	Alluvium	484; 34	11.2	
Platypus	24/ 2/62	1630	190	Underground	Alluvium	None	Low	
Danny Boy	5/ 3/62	1815	110	See remarks	Basalt		0.42	Cratering test; crater diam. 265 ft, depth 84 ft .
Ermine	6/ 3/62	1630	240	Underground	Alluvium	None	Low	
Brazos	8/ 3/62	1800	841	Uhderground	Alluvium	466; 31	7.6	
Hognose	15/ 3/62	1630	789	Underground	Alluvium	478; 65	Low	
Hoosic	28/ 3/62	1800	614	Underground	Tuff	294; 20	3	
Chinchilla II	31/ 3/62	1800	448	Underground	Alluvium	235; 11	Low	
Dormouse II	5/ 4/62	1800	856	Underground	Alluvium	538; 96	10	
Passaic	6/ 4/62	1800	764	Underground	Tuff	512; 63	Low	
Hudson	12/ 4/62	1800	480	Underground	Tuff	None	Low	
Platte	14/ 4/62	1800	560	Underground	Tuff	None	1.7	Tunnel.
Dead	21/ 4/62	1840	634	Underground	Tuff	256; 11	Low	

Black	27/ 4/62	1800	714	Underground	Tuff	408; 55	Low	
Paca	7/ 5/62	1933	848	Underground	Alluvium	484; 60	Low	
Aardvark	12/ 5/62	1900	1,424	Underground	Tuff	924; 72	38	
Eel	19/ 5/62	1500	714	Underground	Tuff	234; 11	Low	4.5 kt
White	25/ 5/62	1500	635	Underground	Tuff	490; 50	Low	
Raccoon	1/ 6/62	1700	539	Underground	Alluvium	314; 24	Low	
Packrat	6/ 6/62	1700	860	Underground	Alluvium	598; 44	Low	
Des Moines	13/ 6/62	2200	610	Underground	Tuff	None	Low	Tunnel. 2.9 kt
Daman I	21/ 6/62	1700	854	Underground	Alluvium	556; 96	Low	
Haymaker	27/ 6/62	1800	1,340	Underground	Alluvium	974; 107	56	
Marshmallow	28/ 6/62	1700	900	Underground	Tuff	None	Low	Tunnel.
Sacramento	30/ 6/62	2130	500	Underground	Alluvium	356; 41	Low	
Little Feller II W-54 bomb	7/ 7/62	1900		Surface		None	Low 0.022 kt	Slightly above ground.
Johnny Boy W-30 bomb	11/ 7/62	1645	2	Surface	Alluvium		0.5	Slightly below ground.
Merrimac	13/ 7/62	1600	1,356	Underground	Alluvium	662; 50	Low	
Small Boy	14/ 7/62	1830		Surface		None	Low 1.65 kt	Slightly above ground.
Little Feller I W-54 bomb	17/ 7/62	1700		Surface		None	Low ~~0.018 kt~~ 0.018 kt	Slightly above ground. Troop participation.
Wichita	27/ 7/62	2100	493	Underground	Alluvium	390; 36	Low	
York	24/ 8/62	1500	744	Underground	Tuff	500; 80	Low	
Bobac	24/ 8/62	1700	675	Underground	Alluvium	425; 45	Low	
Hyrax	14/ 9/62	1710	720	Underground	Alluvium	474; 100	Low	
Peba	20/ 9/62	1700	793	Underground	Alluvium	400; 80	Low	
Allegheny	29/ 9/62	1700	692	Underground	Tuff	100; 10	Low	
Mississippi	5/10/62	1700	1,620	Underground	Tuff	425; 125	Intermediate	115 kt
Roanoke	12/10/62	1500	510	Underground	Tuff	80; 5	Low	
Bandicoot	19/10/62	1800	800	Underground	Alluvium	300; 100	Low	12.5 kt
Santee	27/10/62	1500	1,050	Underground	Alluvium	400; 20	Low	
Madison	12/12/62	1725	1,160	Underground	Tuff	None	Low	Tunnel.
Numbat	12/12/62	1745	775	Underground	Alluvium	500; 60	Low	
Casselman	8/ 2/63	1600	1,000	Underground	Alluvium	450; 75	Intermediate or less.	
Acushi	8/ 2/63	1830	856	Underground	Alluvium	300; 50	Intermediate or less.	
Carmel	21/ 2/63	1947	536	Underground	Alluvium	None	Low	
Gerbil	29/ 3/63	1549	925	Underground	Alluvium	555; 48	Low	
Ferret Prime	5/ 4/63	1752	792	Underground	Alluvium	400; 100	Low	
Stones	22/ 5/63	1540	1,289	Underground	Alluvium	850; 90	Intermediate	3.1 kt
Yuba	5/ 6/63	1700	796	Underground	Tuff	None	Low	
Hutia	6/ 6/63	1400	442	Underground	Alluvium	300; 20	Low	

ANNOUNCED U.S. NUCLEAR DETONATIONS, 1961–63—Continued

NEVADA SERIES—Continued

Name	Date (GCT)	Time (GCT)	Depth [1] (feet)	Type	Medium	Depression [2] (Diam. & Depth, feet)	Yield [3] (KT)	Remarks
Mataco	14/ 6/63	1410	642	Underground	Alluvium	300; 50	Low	
Kennebec	25/ 6/63	2300	740	Underground	Alluvium	200; 30	Low	
Pekan	12/ 8/63	2345	997	Underground	Alluvium	550; 60	Low	
Satsop	15/ 8/63	1300	738	Underground	Alluvium	300; 40	Low	
[4]	20/ 8/63							
Kohocton	23/ 8/63	1320	852	Underground	Alluvium	None	Low	
Antanum	13/ 9/63	1353	740	Underground	Alluvium	None	Low	
Bilby	13/ 9/63	1700	2,413	Underground	Tuff	1800; 80	~200	
Grunion	11/10/63	1400	856	Underground	Alluvium	550; 90	Low	
Clearwater	16/10/63	1700	1,798	Underground	Tuff	None	Intermediate	
Anchovy	14/11/63	1600	853	Underground	Alluvium	600; 65	Low	
Mustang	15/11/63	1500	544	Underground	Alluvium	125; 15	Low	
Greys	22/11/63	1730	988	Underground	Alluvium	470; 42	Low	
Sardine	4/12/63	1638	855	Underground	Alluvium	550; 50	Low	
Eagle	12/12/63	1602	541	Underground	Alluvium	440; 60	Low	5·3 kt

[1] Depth is distance to nearest point at the earth's surface.

[2] Depression is subsidence of earth into underground cavity, as distinguished from crater formed by throw-out of earth.

[3] Low yield means less than 20 kilotons; intermediate means 20 to 999 kilotons inclusive; low megaton means one to several megatons.

[4] For purposes of totaling announced detonations, add 23 undeground U.S. weapons-related tests at the Nevada Test Site as having been conducted between September 15, 1961, and August 20, 1963. No other data on the 23 tests are available for public use.

VELA UNIFORM SEISMIC DETONATION

Name	Date	Depth	Medium	Yield	Location	Remarks
Shoal	10/26/63	1,205	Granite	About 12 KT	Near Fallon, Nev.	Nuclear test detection-research experiment.

PACIFIC SERIES

Name	Date (GCT)	Time (GCT)	Location	Height	Type of burst	Yield [1]	Remarks
Adobe	25/ 4/62	1546	Christmas Island area		Air	Intermediate	190 Kt
Aztec	27/ 4/62	1602	Christmas Island area		Air	Intermediate	410 Kt
Arkansas	2/ 5/62	1802	Christmas Island area		Air	Low megaton	1090 Kt
Questa	4/ 5/62	1905	Christmas Island area		Air	Intermediate	670 Kt
Frigate Bird	6/ 5/62	2330	Christmas Island area		Air	600 Kt	Warhead in missile launched from Polaris submarine.
Yukon	8/ 5/62	1801	Christmas Island area		Air	Intermediate	100 Kt
Mesilla	9/ 5/62	1701	Christmas Island area		Air	Intermediate	100 Kt
Muskegon	11/ 5/62	1537	Christmas Island area		Air	Intermediate	50 Kt
Swordfish	11/ 5/62	2002	Eastern Pacific		UW	Low	Antisubmarine rocket (ASROC) system proof test. 18 Kt, 650 ft depth.
Encino	12/ 5/62	1703	Christmas Island area		Air	Intermediate	500 Kt
Swanee	14/ 5/62	1522	Christmas Island area		Air	Intermediate	97 Kt
Chetco	19/ 5/62	1537	Christmas Island area		Air	Intermediate	73 Kt
Tanana	25/ 5/62	1609	Christmas Island area		Air	Low	Fizzle
Nambe	27/ 5/62	1703	Christmas Island area		Air	Intermediate	43 Kt
Alma	8/ 6/62	1703	Christmas Island area		Air	Intermediate	782 Kt
Truckee	9/ 6/62	1537	Christmas Island area		Air	Intermediate	210 Kt
Yeso	10/ 6/62	1601	Christmas Island area		Air	Low megaton	3 Mt
Harlem	12/ 6/62	1537	Christmas Island area		Air	Intermediate	1.2 Mt
Rinconada	15/ 6/62	1601	Christmas Island area		Air	Intermediate	800 Kt
Dulce	17/ 6/62	1601	Christmas Island area		Air	Intermediate	52 Kt
Petit	19/ 6/62	1501	Christmas Island area		Air	Low	Fizzle/failure
Otowi	22/ 6/62	1601	Christmas Island area		Air	Intermediate	—

PACIFIC SERIES—Continued

Name	Date (GCT)	Time (GCT)	Location	Height	Type of burst	Yield	Remarks
Bighorn	27/ 6/62	1519	Christmas Island area		Air	Megaton range	7.65 Mt
Bluestone	30/ 6/62	1521	Christmas Island area		Air	Low megaton	1.27 Mt
Starfish Prime	9/ 7/62	0900	Johnston Island area	400 km	High altitude	1.4 megatons	EMP effects in Hawaii.
Sunset	10/ 7/62	1633	Christmas Island area		Air	Intermediate	1 Mt
Pamlico	11/ 7/62	1537	Christmas Island area		Air	Low megaton	3.88 Mt
Androscoggin	2/10/62	1618	Johnston Island area		Air	Intermediate	75 Kt
Bumping	6/10/62	1603	Johnston Island area		Air	Low	11.3 Mt
Chama	18/10/62	1601	Johnston Island area		Air	Low megaton	1.59 Mt
Checkmate	20/10/62	0830	Johnston Island area	Tens of km	High altitude	Low	7 Kt
Bluegill Triple Prime	26/10/62	1000	Johnston Island area	Tens of km	High altitude	Submegaton	410 Kt
Calamity	27/10/62	1546	Johnston Island area		Air	Intermediate	800 Kt
Housatonic	30/10/62	1602	Johnston Island area		Air	Megaton range	8.3 Mt
Kingfish	1/11/62	1210	Johnston Island area	Tens of km	High altitude	Submegaton	410 Kt
Tightrope	4/11/62	0730	Johnston Island area	Tens of km	High altitude	Low	1 Kt

PLOWSHARE NUCLEAR DETONATIONS[1]

Name	Date (GCT)	Time (GCT)	Depth (ft)	Medium	Yield	Location	Remarks
Gnome	10/12/61	1900	1,184	Salt	3.1 KT	Near Carlsbad, N. Mex.	Multiple-purpose experiment; formed hemispheric cavity, 160–170 ft diameter, 60–80 ft high.
Sedan	6/7/62	1700	635	Alluvium	100 KT 104 Kt total 25 Kt fission	Nevada Test Site	Excavation experiment; formed crater about 1,280 ft diameter, 320 ft max depth; displaced about 6.5 million cu yd or 10.4 million tons of earth.
Anacostia	27/11/62	1800	750	Tuff	Low	Nevada Test Site	Plowshare Device Development Test. 5.2 Kt
Kaweah	21/ 2/63	1947	750	Alluvium	Low	Nevada Test Site	Plowshare Device Development Test. 3 Kt
Tornillo	11/10/63	2100	500	Alluvium	Low	Nevada Test Site	Plowshare Device Development Test. 0.38 Kt

[1] For the development of peaceful uses of nuclear explosives.