The Effects of
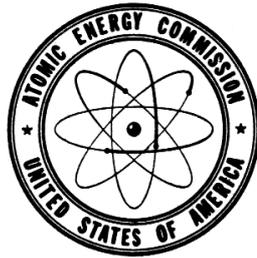
Nuclear Weapons

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Editor

Prepared by the

UNITED STATES DEPARTMENT OF DEFENSE

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Foreword

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

CHARLES E. WILSON
Secretary of Defense

LEWIS L. STRAUSS
Chairman
Atomic Energy Commission

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

VAL PETERSON
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Acknowledgment

vii

Contents

Preface

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

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

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

ning defensive measures for the protection of civilian lives and property.

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

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20 KILOTON AIR BURST - 0.5 SECOND
1 MEGATON AIR BURST - 1.8 SECONDS

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

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

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

	Diameter of fireball (feet)	
	20 kilotons	1 megaton
At time indicated_____	1, 460	6, 300
Maximum_____	1, 550	7, 200

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

NUCLEAR AND THERMAL RADIATION

PRIMARY SHOCK FRONT

REFLECTED SHOCK FRONT

COMMENCEMENT OF MACH REFLECTION
OVERPRESSURE 16 PSI

| 20 KT | MILES | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 |

| 1 MT | MILES | 0 | 1 | 2 | 3 | 4 | 5 | 6 |

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

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

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

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

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

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

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

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

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

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

Nuclear radiations still continue to reach the ground in significant amounts. But after 3 seconds from the detonation of a 20-kiloton bomb, the fireball, although still very hot, has cooled to such an extent that the thermal radiation is no longer important. The total accumulated amounts of thermal radiation, expressed in calories per square centimeter, received at various distances from ground zero after a 20-kiloton air burst, are shown on the scale at the bottom of the figure (for further details, see Chapter VII). Appreciable amounts of thermal radiation still continue to be emitted from the fireball at 11 seconds after a 1-megaton explosion; the thermal radiation emission is spread over a longer time interval than for an explosion of lower energy yield.
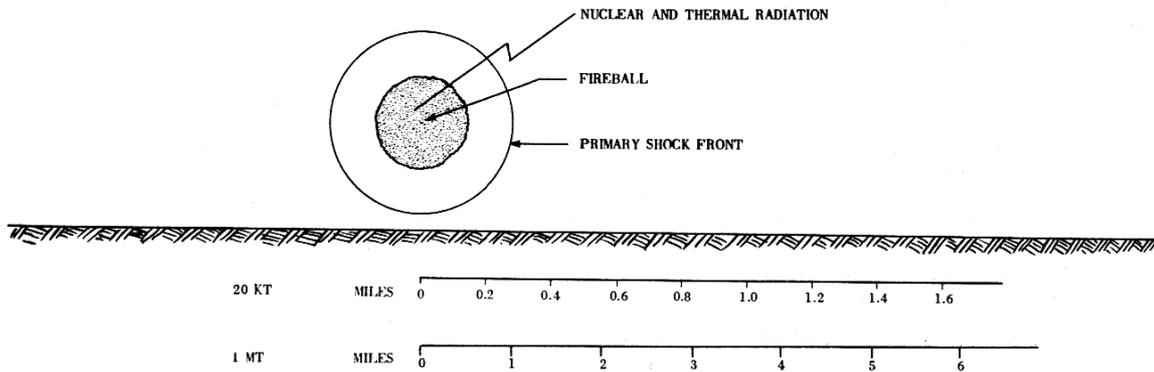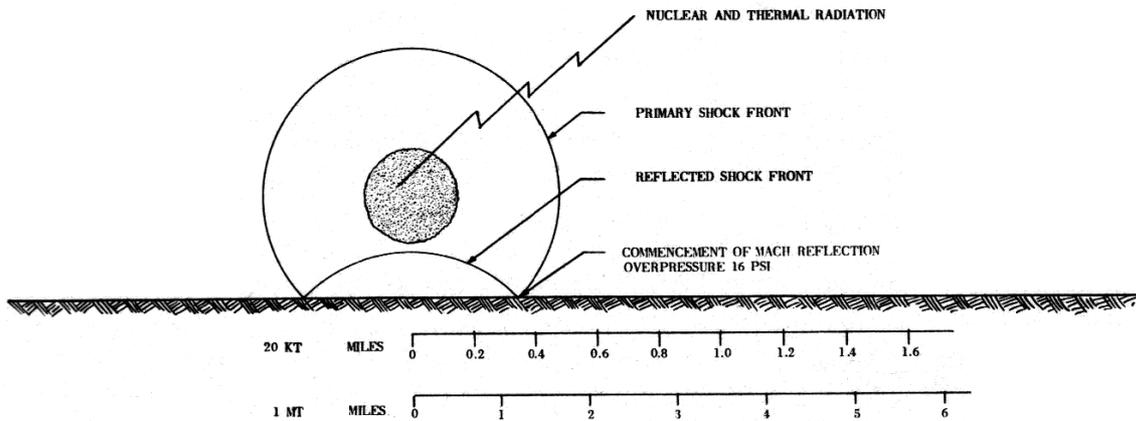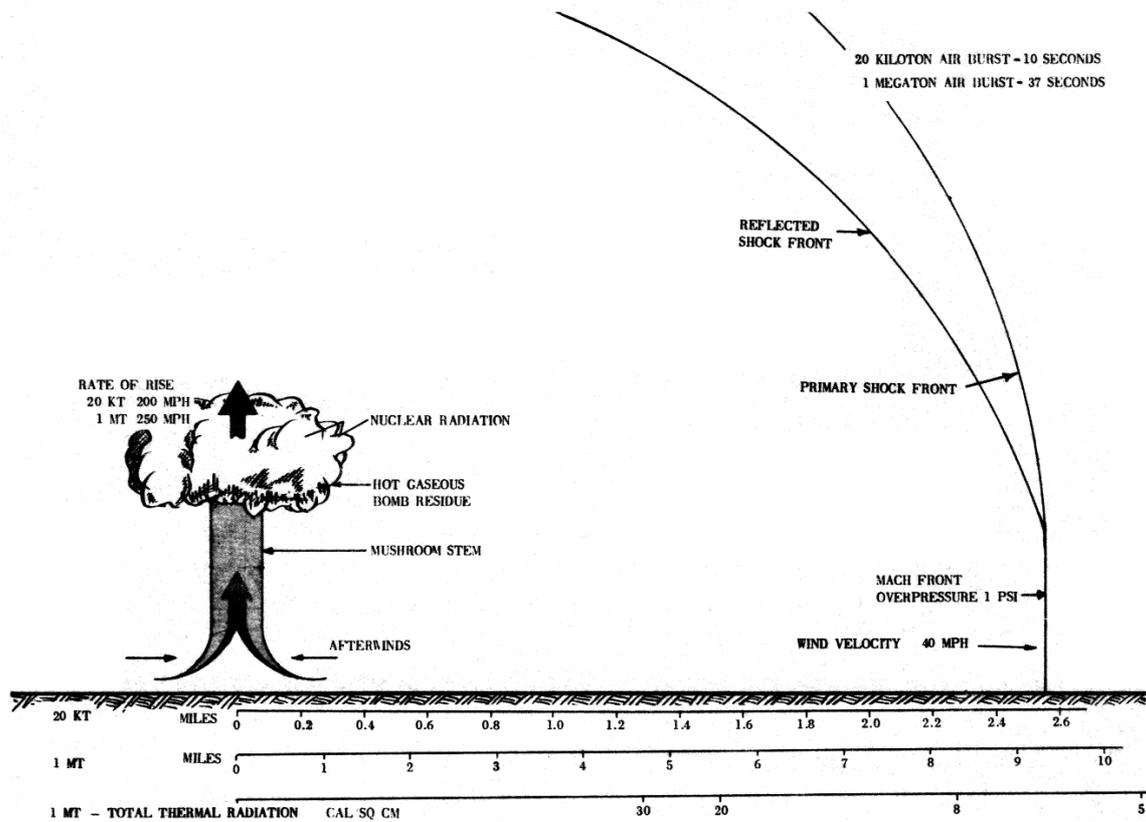
Figure 2.47d. Chronological development of an air burst: 10 seconds after 20-kiloton detonation; 37 seconds after 1-megaton detonation.

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

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

RATE OF RISE
20 KT 100–150 MPH
1 MT 130–170 MPH

RADIOACTIVE CLOUD

20 KILOTON AIR BURST - 30 SECONDS
1 MEGATON AIR BURST - 110 SECONDS

WIND VELOCITY
20 KT 200 MPH
1 MT 275 MPH

AFTERWINDS

| 20 KT | MILES | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 |

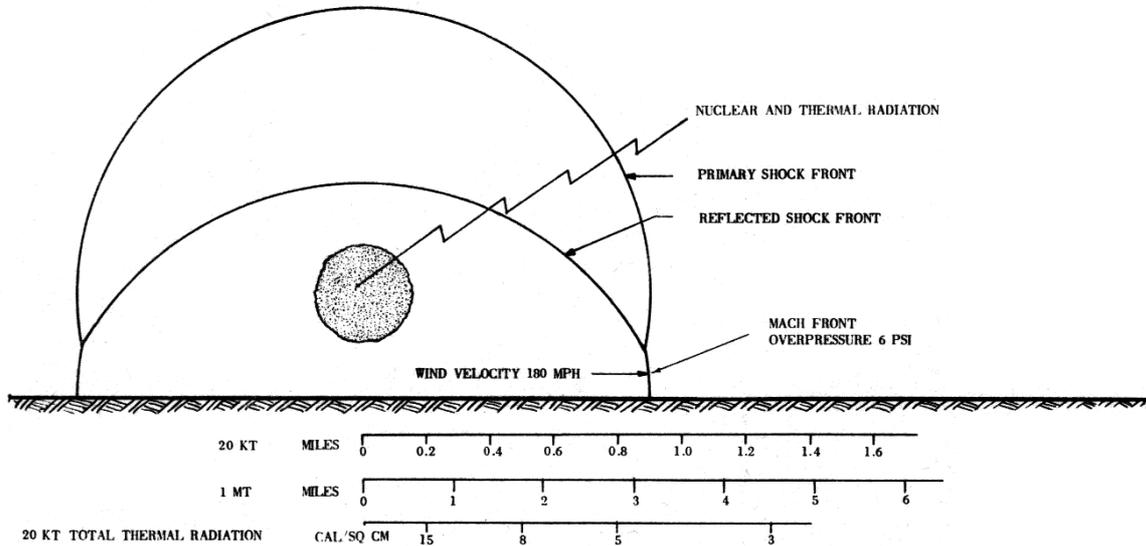| 1 MT | MILES | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
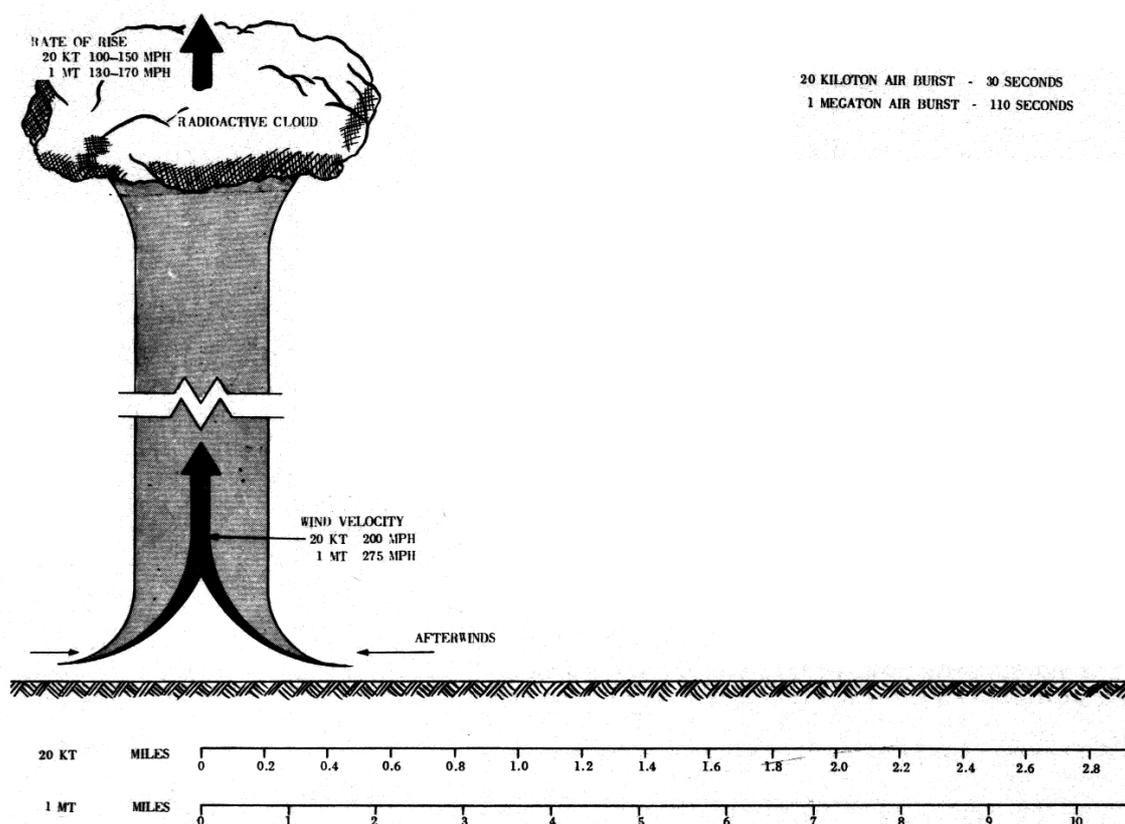
Figure 2.47e. Chronological development of an air burst: 30 seconds after 20-kiloton detonation; 110 seconds after 1-megaton detonation.

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

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

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

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

DESCRIPTION OF AN UNDERWATER BURST

UNDERWATER EXPLOSION PHENOMENA

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

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

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

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

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

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

Figure 2.52. The "spray dome" formed over the point of burst in an underwater explosion.
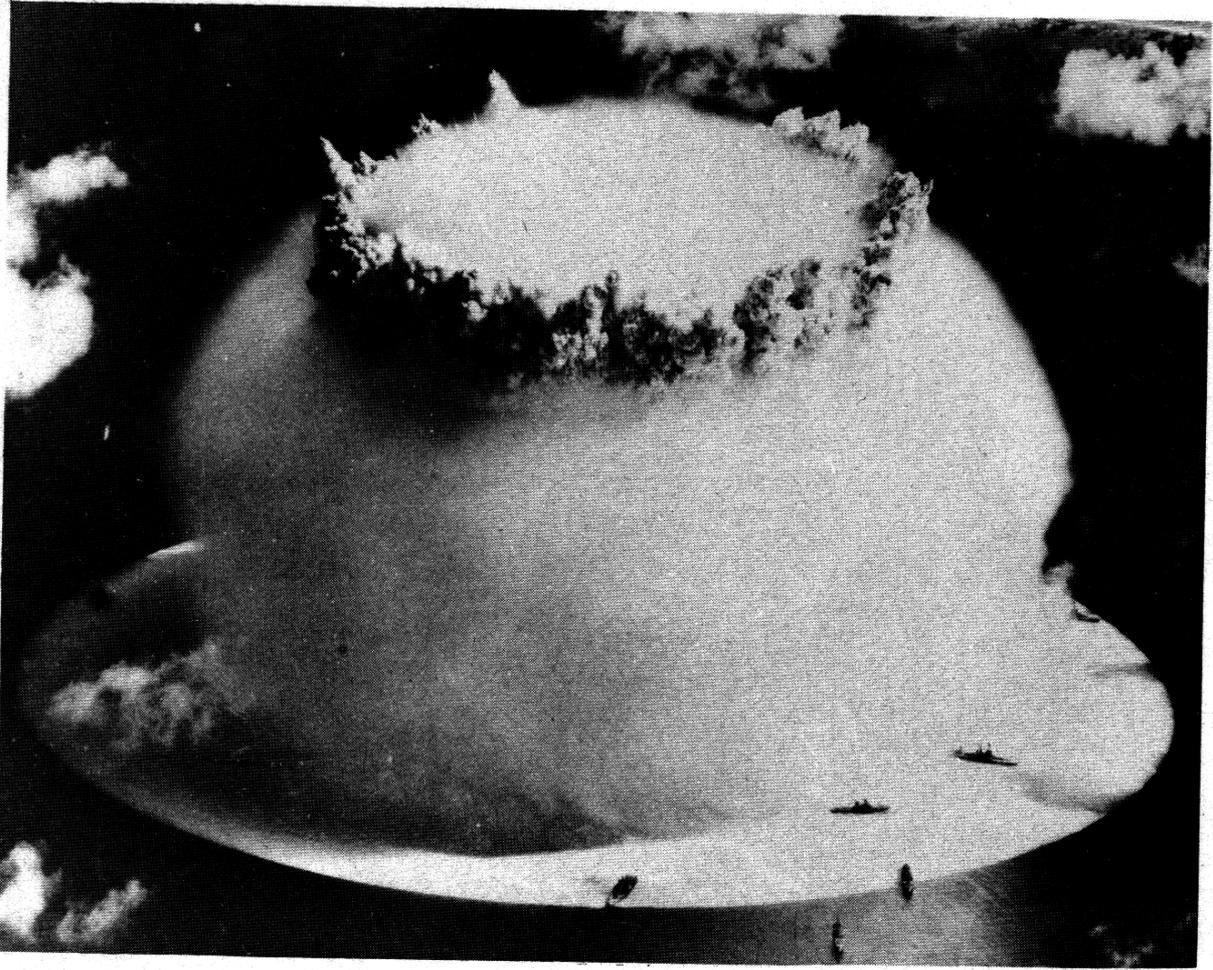
Figure 2.53a.   The condensation cloud formed after a shallow underwater explosion.   (The "slick," due to the shock wave, can be seen on the water surface.)
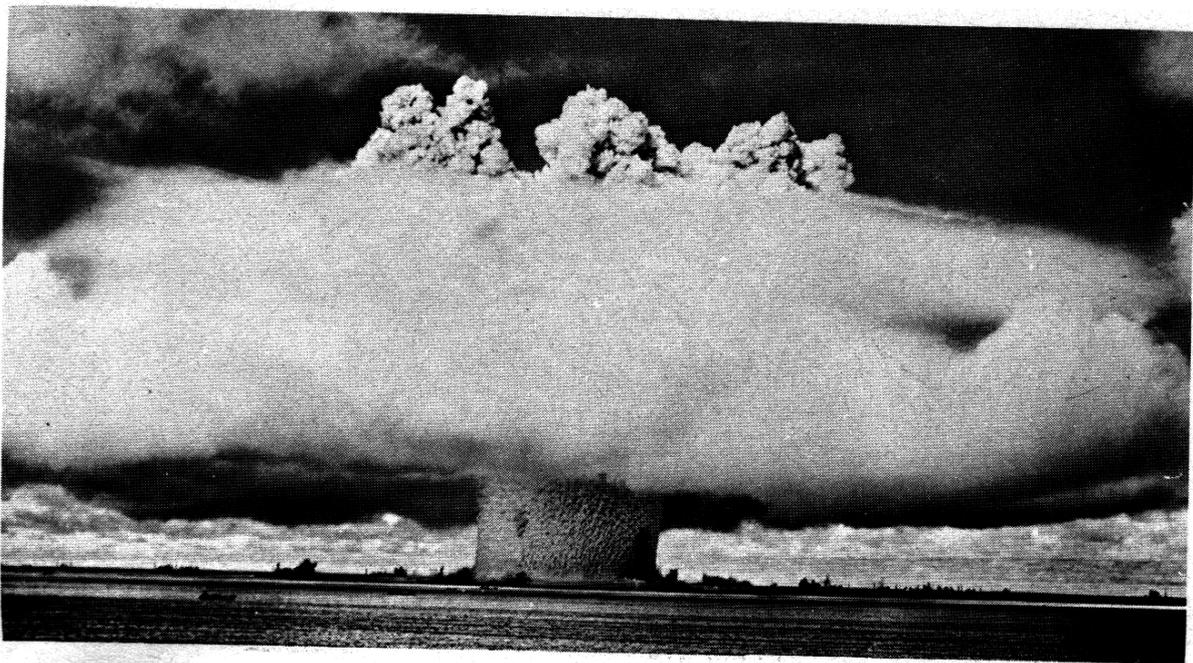
Figure 2.53b.   Formation of the hollow column in an underwater explosion, the top is surrounded by a late stage of the condensation cloud.

mum height attained by the hollow column, through which the gases vented, could not be estimated exactly because the upper part was surrounded by the atomic cloud (Fig. 2.54). The column was probably some 6,000 feet high and the maximum diameter was about 2,000 feet. The walls were probably 300 feet thick, and approximately a million tons of water were raised in the column.
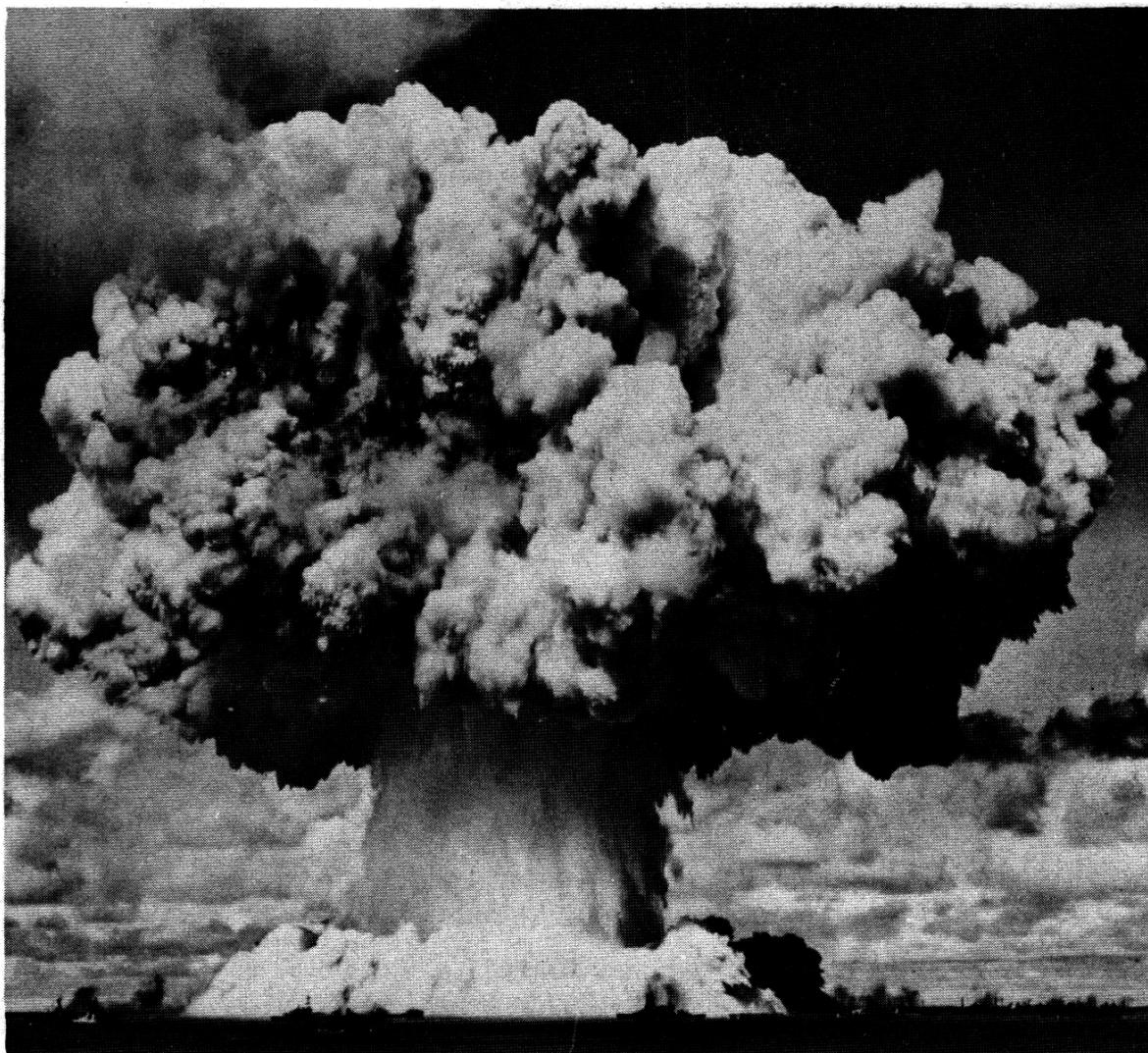
Figure 2.54. The radioactive cloud and first stages of the base surge following an underwater burst. Water is beginning to fall back from the column into the lagoon.

2.55 The cauliflower-shaped cloud, which concealed part of the upper portion of the column, contained some of the fission products and other bomb residues, as well as a large quantity of water in small droplet form. In addition, there is evidence that material sucked up from the bottom of the lagoon was also present, for a calcareous (or chalky) sediment, which must have dropped from the atomic cloud, was found on the decks of ships some distance from the burst. The

cloud was roughly 6,000 feet across and ultimately rose to a height of nearly 10,000 feet before being dispersed. This is considerably less than the height attained by an atomic cloud in an air burst.

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

The Base Surge

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

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

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

2.60 From the weapons effects standpoint, the importance of the base surge lies in the fact that it is likely to be highly radioactive due to fission products present either at its inception, or dropped into it from the atomic cloud. Because of its radioactivity, it may represent a serious hazard for a distance of several miles, especially in the downwind direction (see Chapter IX). Any object over which
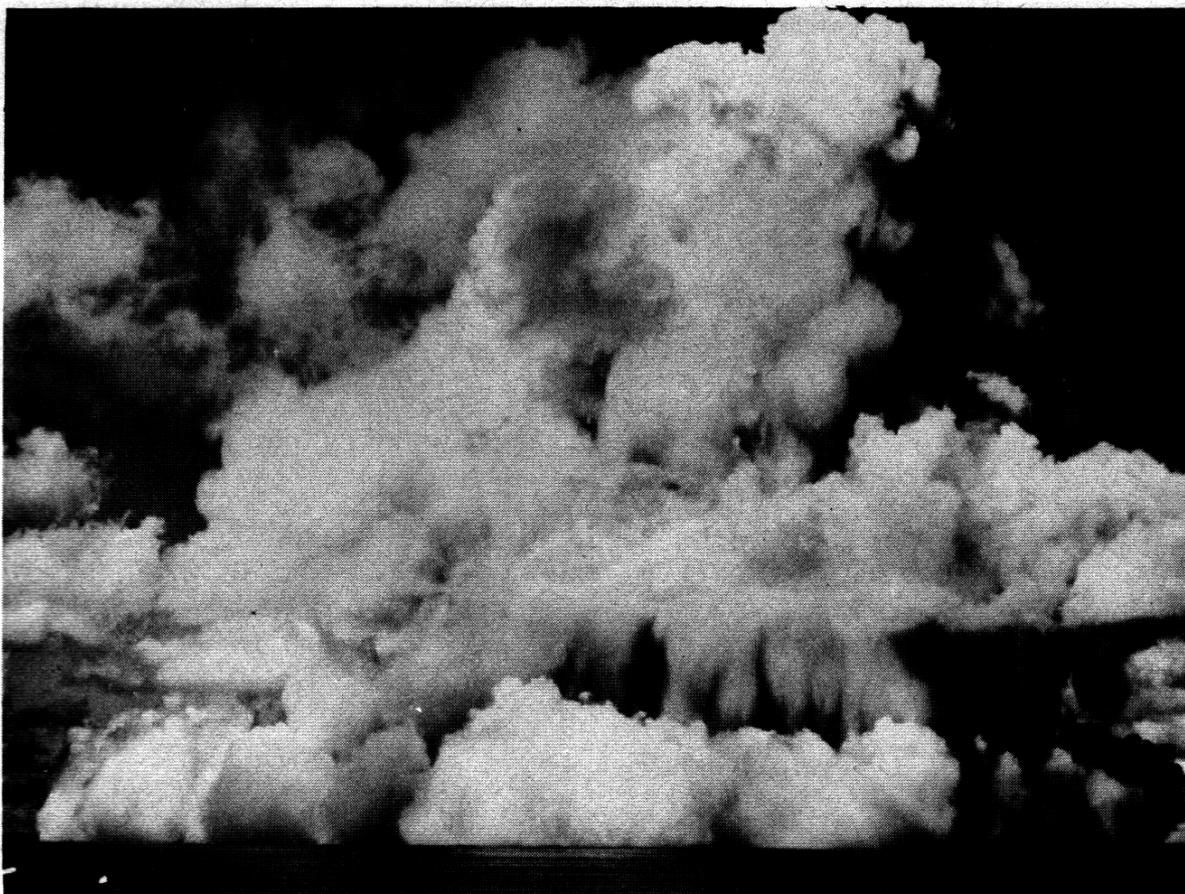
Figure 2.58. The development of the base surge following an underwater explosion.

the base surge passes is likely to become contaminated, due to the deposition of water droplets to which fission products may have become attached. The base surge and the fallout or "rainout" from the atomic cloud constitute the sources of the residual nuclear radiation following an underwater nuclear explosion.

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

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

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

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

THERMAL AND NUCLEAR RADIATIONS

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

2.64   It is probable, too, that most of the neutrons and gamma rays liberated within a short time of the initiation of the explosion will also be absorbed by the water.   But, when the fireball reaches the surface and the gases are expelled, the gamma rays (and beta particles) from

the fission products will represent a form of initial nuclear radiation. In addition, the radiation from the fission (and induced radioactive) products, present in the column, atomic cloud, and base surge, all three of which are formed within a few seconds of the burst, will contribute to the initial effects.

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

CHRONOLOGICAL DEVELOPMENT OF A SHALLOW UNDERWATER BURST

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

DESCRIPTION OF AN UNDERGROUND BURST

UNDERGROUND EXPLOSION PHENOMENA

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

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

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

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

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

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

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

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

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

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

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

100 KILOTON SHALLOW UNDERWATER BURST - 20 SECONDS

CLOUD

NUCLEAR RADIATION

WATER FALLING FROM CLOUD
VELOCITY 50 FEET/SEC

BASE SURGE FORMING
VELOCITY 150 FEET/SEC

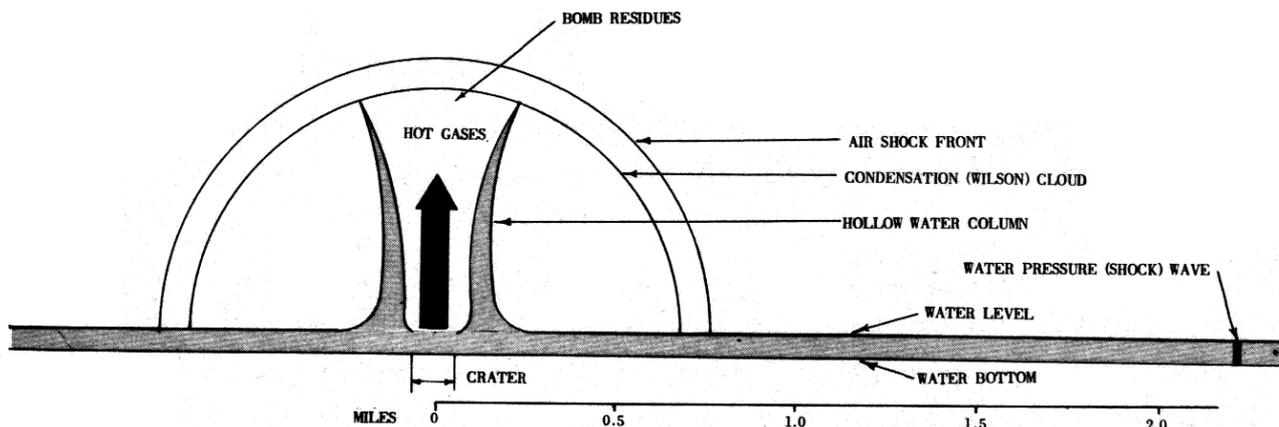WAVE HEIGHT 106 FEET

MILES   0   0.5   1.0   1.5   2.0
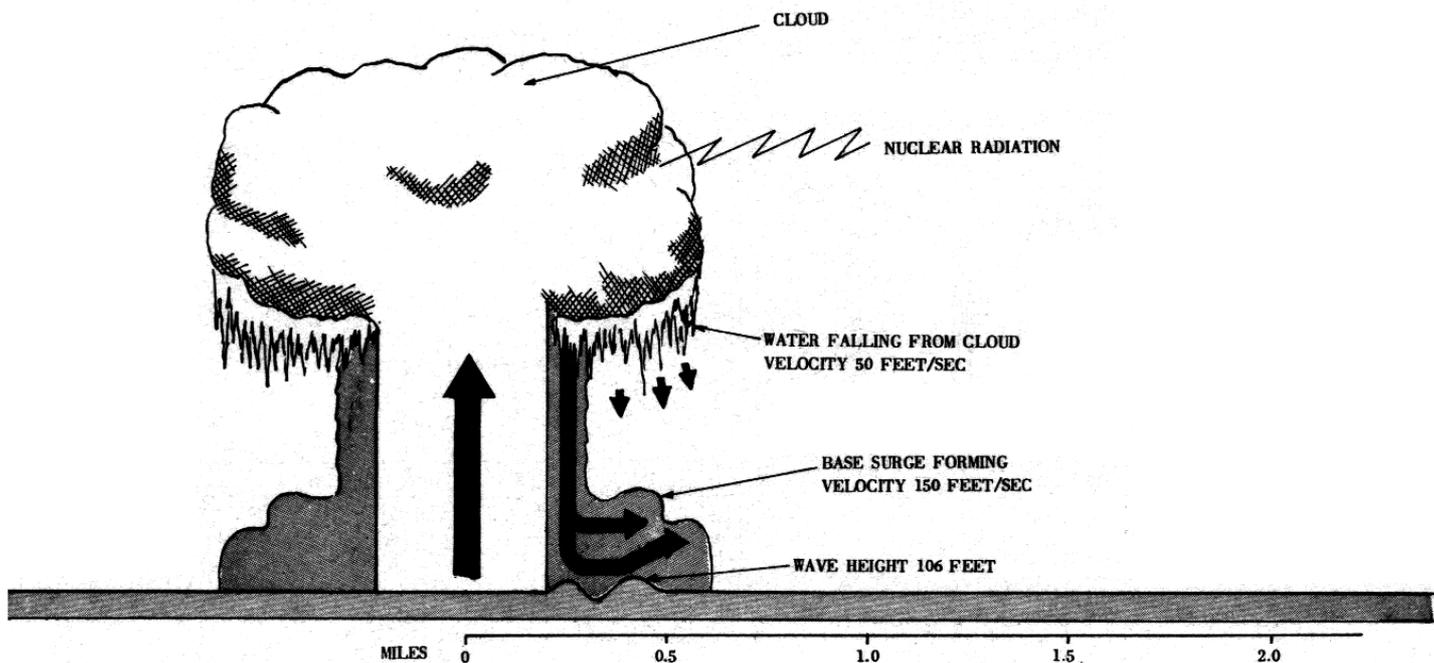
Figure 2.66c.   Chronological development of a 100-kiloton shallow underwater
burst: 20 seconds after detonation.

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

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

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

100 KILOTON SHALLOW UNDERWATER BURST - 1 MINUTE

MIST OR CLOUD

NUCLEAR RADIATION

REGION OF PRIMARY
CLOUD FALLOUT

BASE SURGE
VELOCITY 75 FEET/SEC

WAVE HEIGHT 42 FEET

MILES   0   0.5   1.0   1.5   2.0
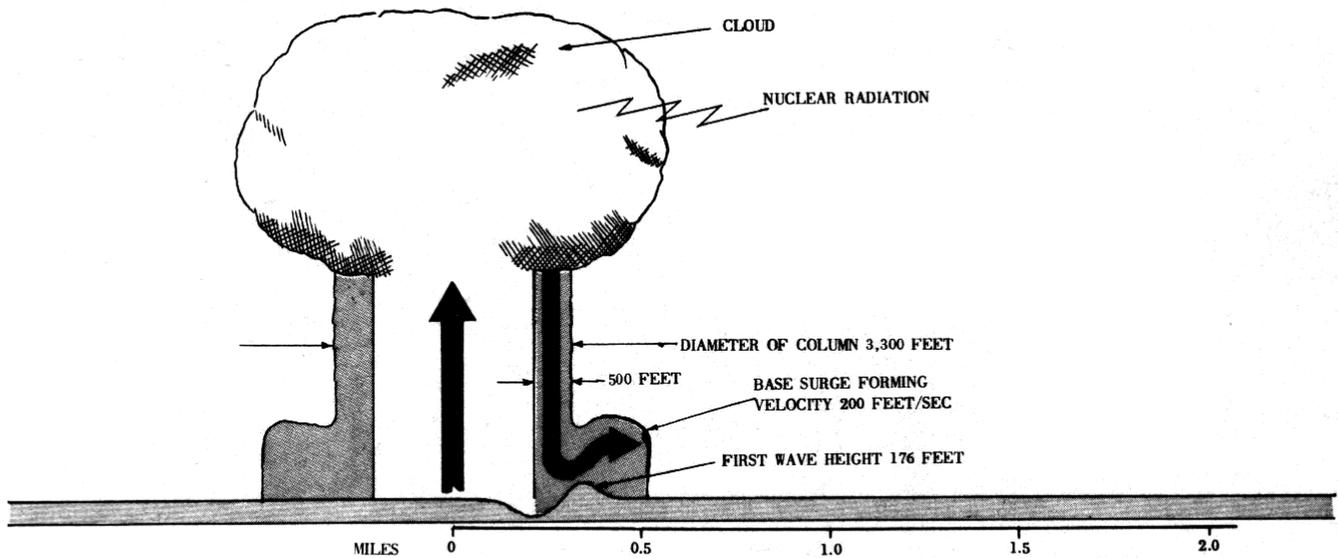
3   2   1   SURFACE WAVES
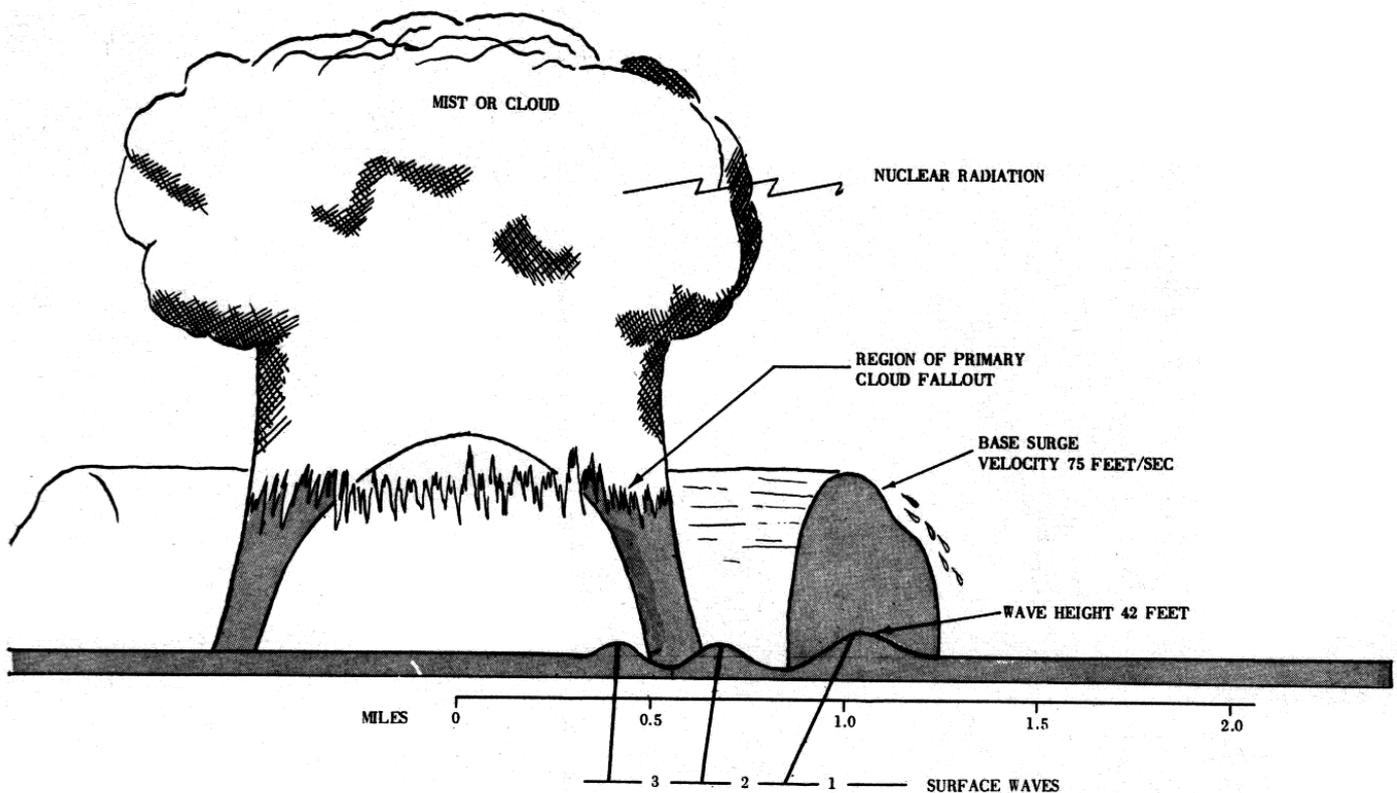
Figure 2.66d.   Chronological development of a 100-kiloton shallow underwater burst: 1 minute after detonation.

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

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

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

100 KILOTON SHALLOW UNDERWATER BURST - 2.5 MINUTES

MIST OR CLOUD

NUCLEAR RADIATION

RAIN OUT PRODUCES
CLEARING AT BASE

BASE SURGE
VELOCITY 30 FEET/SEC

WAVE HEIGHT 18 FEET

MILES   0   0.5   1.0   1.5   2.0

6   5   4   3   2   1   SURFACE WAVES
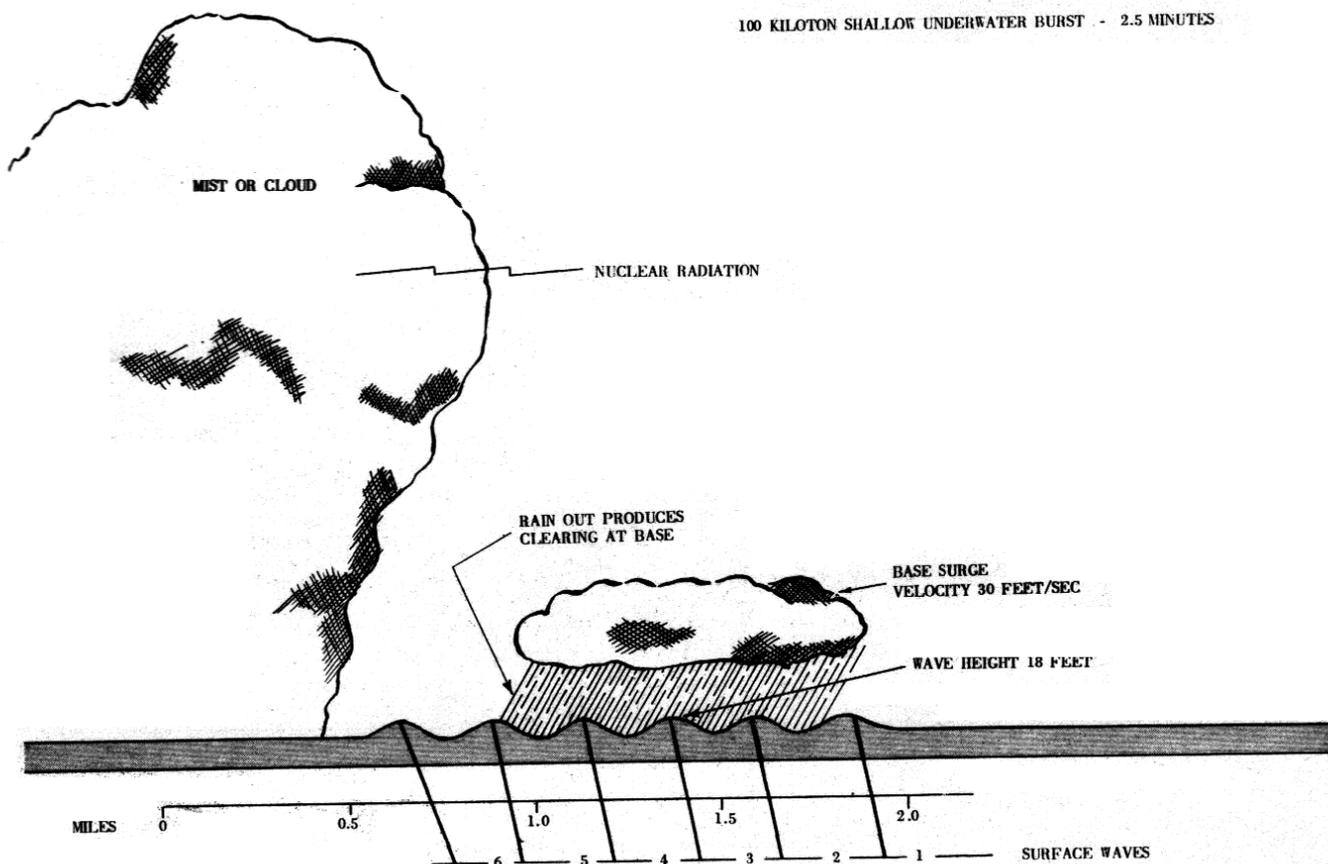
Figure 2.66e.   Chronological development of a 100-kiloton shallow underwater
burst: 2.5 minutes after detonation.

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

The descent of water and spray from the column and from con-
densation in the atomic cloud results in the formation of a continuous
mass of mist or cloud down to the surface of the water. Ultimately,
this merges with the base surge, which has spread and increased in
height, and also with the natural clouds of the sky, to be finally
dispersed by the wind.
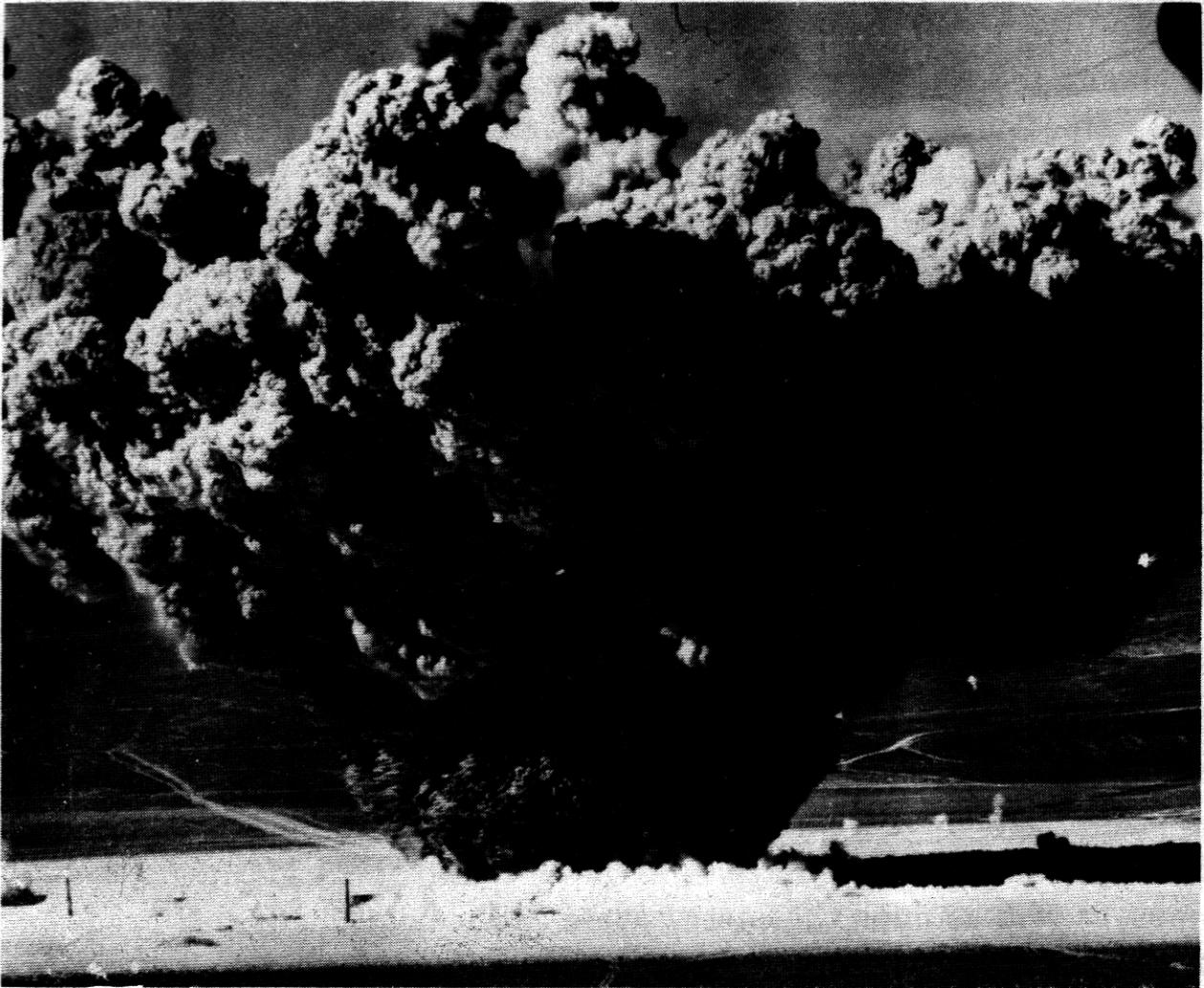
Figure 2.67.   Shallow underground burst.

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

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

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

BASE SURGE AND FALLOUT

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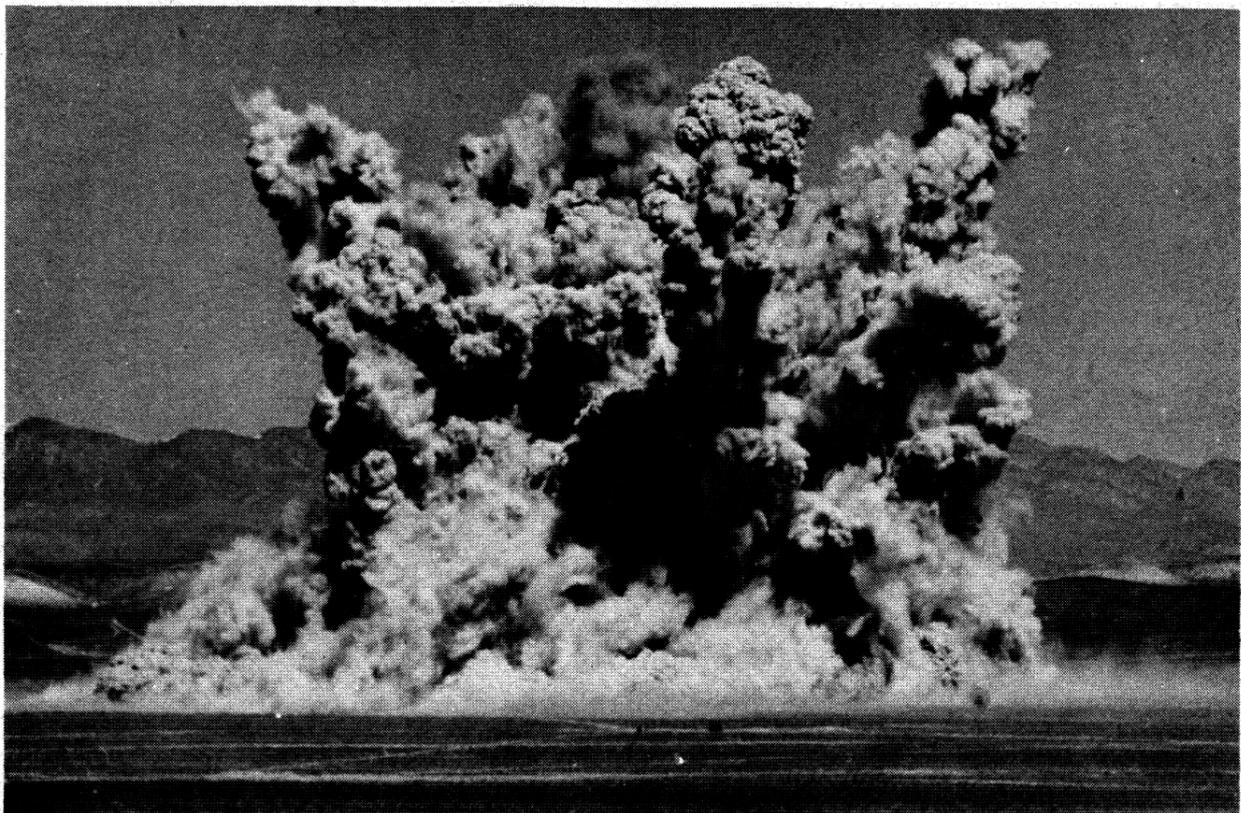
Figure 2.71.   Base surge formation in underground burst.

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

THERMAL AND NUCLEAR RADIATIONS

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

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

CHRONOLOGICAL DEVELOPMENT OF A SHALLOW UNDERGROUND BURST

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

100 KILOTON SHALLOW UNDERGROUND BURST - 2 SECONDS

BOMB RESIDUES AND DEBRIS

HOT GASES

AIR SHOCK FRONT

DIRT COLUMN

THROWOUT

MILES   0   0.5   1.0   1.5   2.0
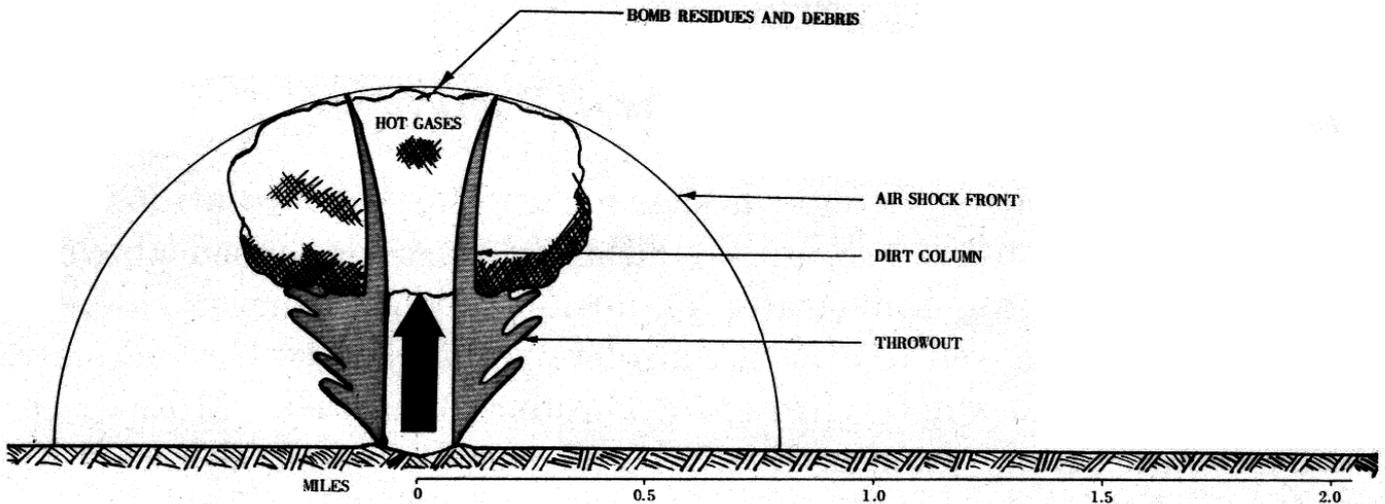
Figure 2.75a.   Chronological development of a 100-kiloton shallow underground burst: 2.0 seconds after detonation.

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

In addition to the shock (or pressure) wave in the ground, somewhat related to an earthquake wave, the explosion is accompanied by a shock (or blast) wave in the air. At 2 seconds after the explosion, the shock front in air is about $3/4$ mile from surface zero.
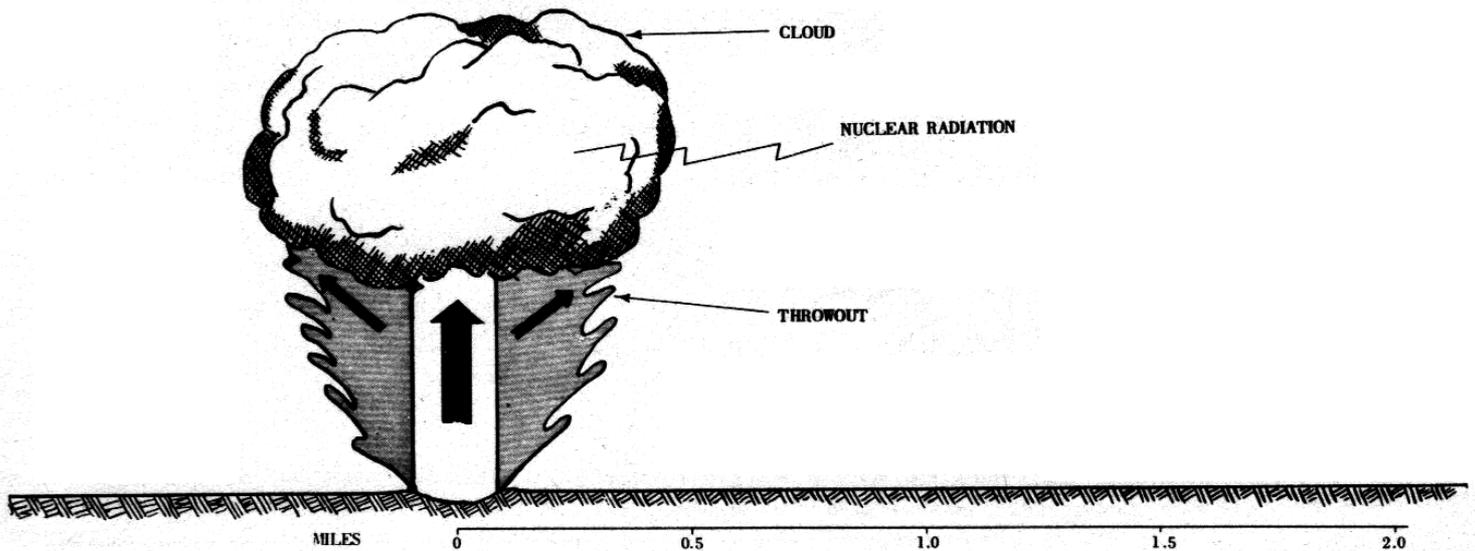
Figure 2.75b. Chronological development of a 100-kiloton shallow underground burst : 9.0 seconds after detonation.

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

100 KILOTON SHALLOW UNDERGROUND BURST - 45 SECONDS
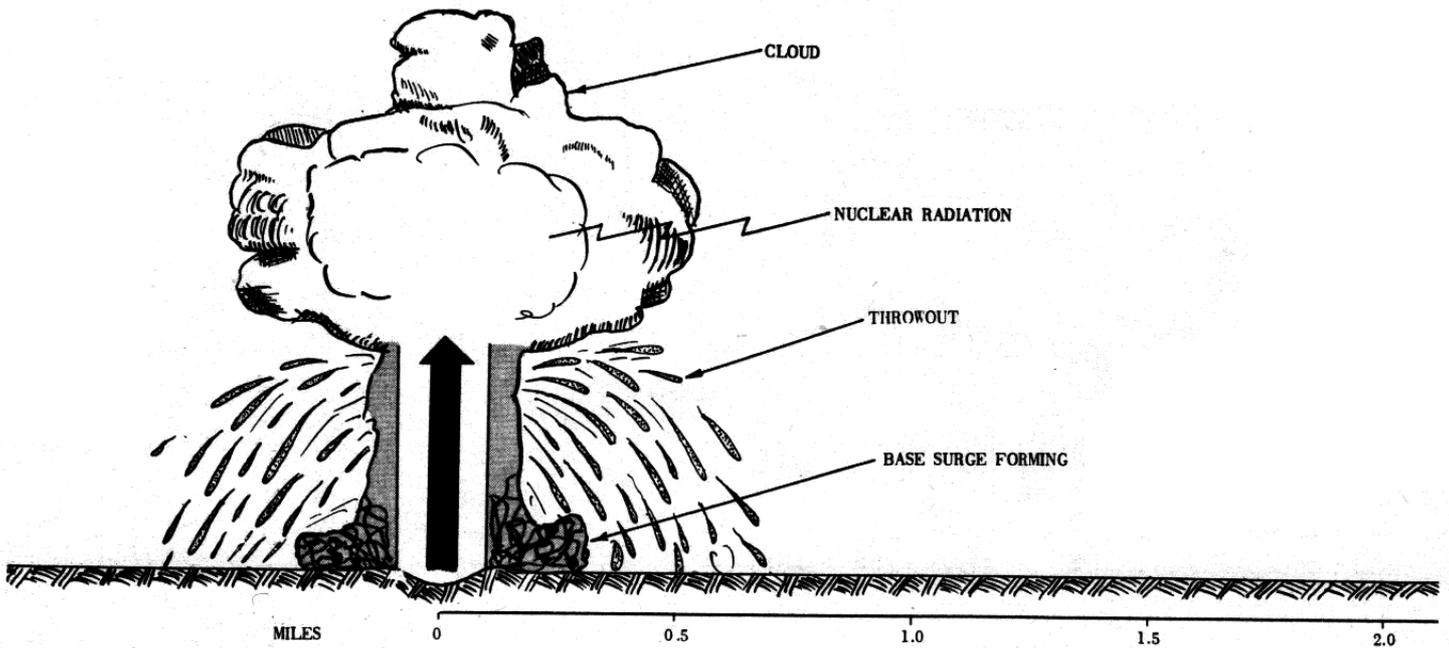
Figure 2.75c.   Chronological development of a 100-kiloton shallow underground
burst: 45 seconds after detonation.

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

100 KILOTON SHALLOW UNDERGROUND BURST - 4.5 MINUTES

CLOUD

NUCLEAR RADIATION

COLUMN

BASE SURGE

MILES   0   0.5   1.0   1.5   2.0
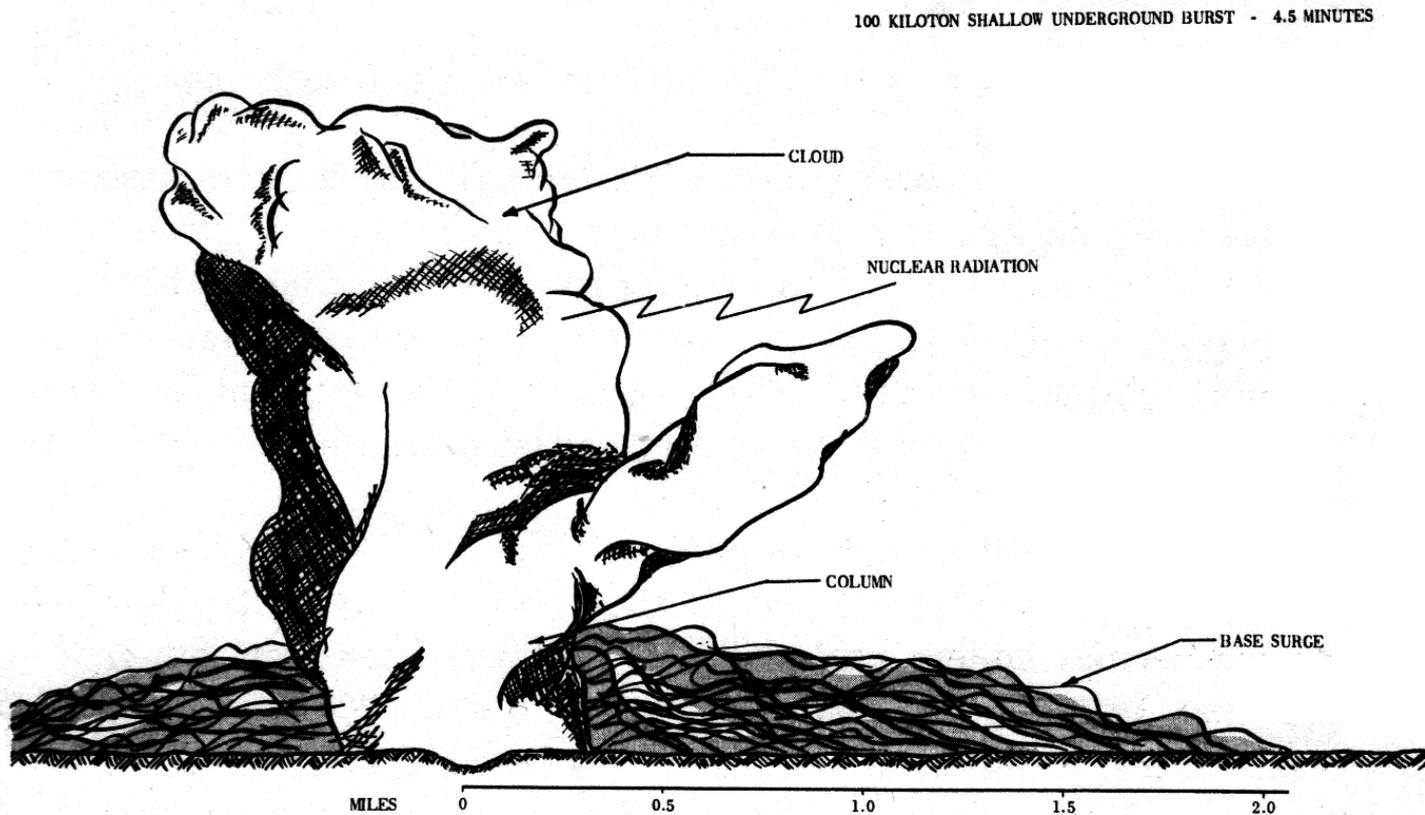
Figure 2.75d.   Chronological development of a 100-kiloton shallow underground burst: 4.5 minutes after detonation.

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

SCIENTIFIC ASPECTS OF NUCLEAR EXPLOSION PHENOMENA[5]

DEVELOPMENT OF THE BALL OF FIRE IN AN AIR BURST

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

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

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

2.79   On the average, each photon moves with the velocity of light for a distance of a mean free path.   It is then absorbed by an atom, molecule, or gaseous ion, usually of nitrogen or oxygen present in the air, which is thereby converted into a high-energy (or excited) state. The material remains in the excited state for a certain time, after which it reverts to its lower energy (or ground) state by the emission of a photon.   This photon then moves on in a random direction, with the speed of light, only to be subsequently captured by an atom or

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

molecule of the air, followed by a re-emission, and so on. Because of the short mean free path of the radiations of wave length less than 1,860 A, and also on account of the fact that the photons move in a random path, due to their successive absorptions and emissions, the over-all rate of transport of such radiation is relatively small.

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

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

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

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

pressure near the surface of the fireball. Within less than 1 milli-
second the steep-fronted shock wave has traveled some distance ahead
of the isothermal region. The rise of the pressure in the fireball to a
peak, which is characteristic of a shock wave, followed by a sharp drop
at the external surface, implies that the latter is identical with the
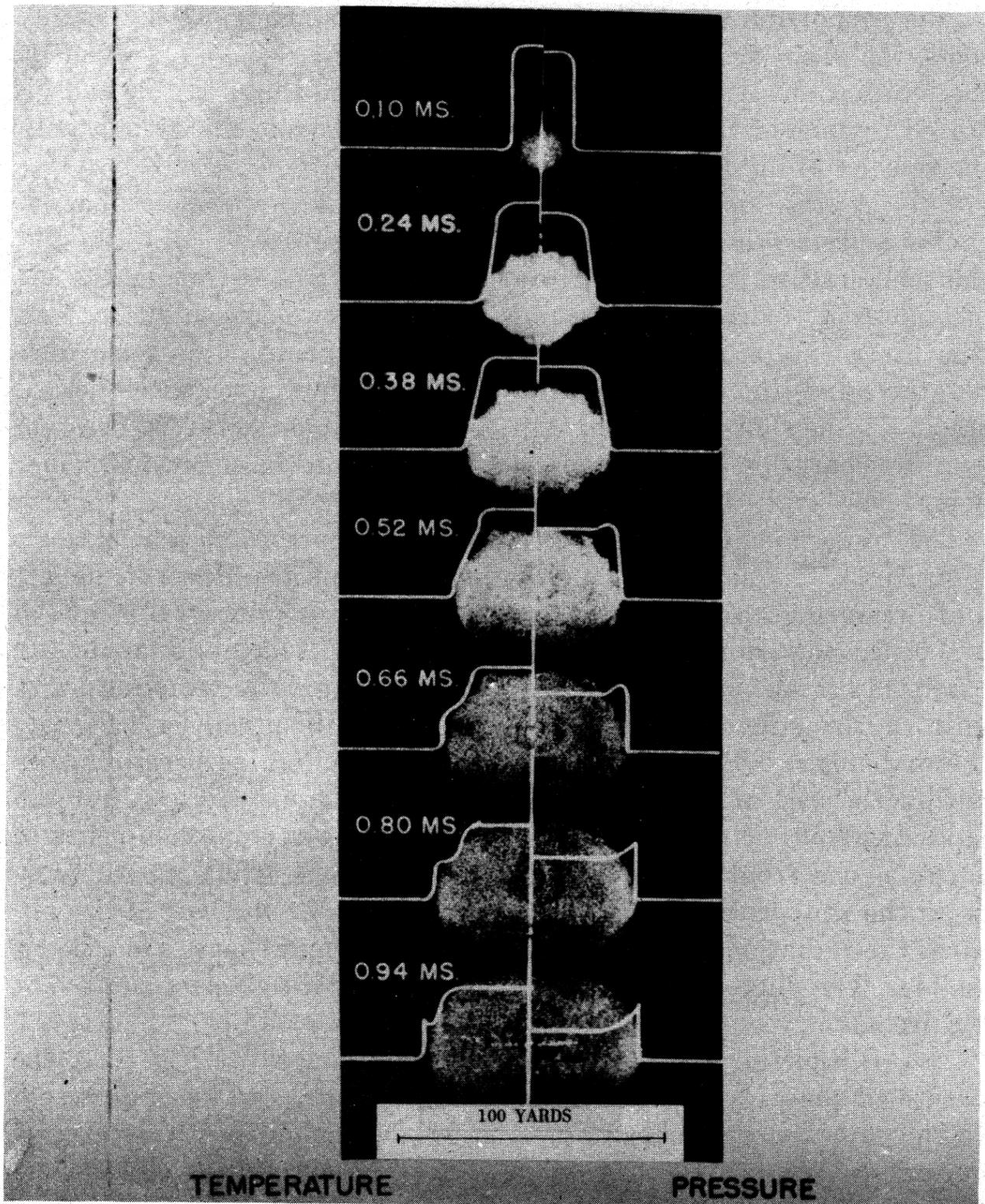
Figure 2.82.   Variation of temperature and pressure in the ball of fire.   (Times
and dimensions apply to a 20-kiloton explosion.)

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

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

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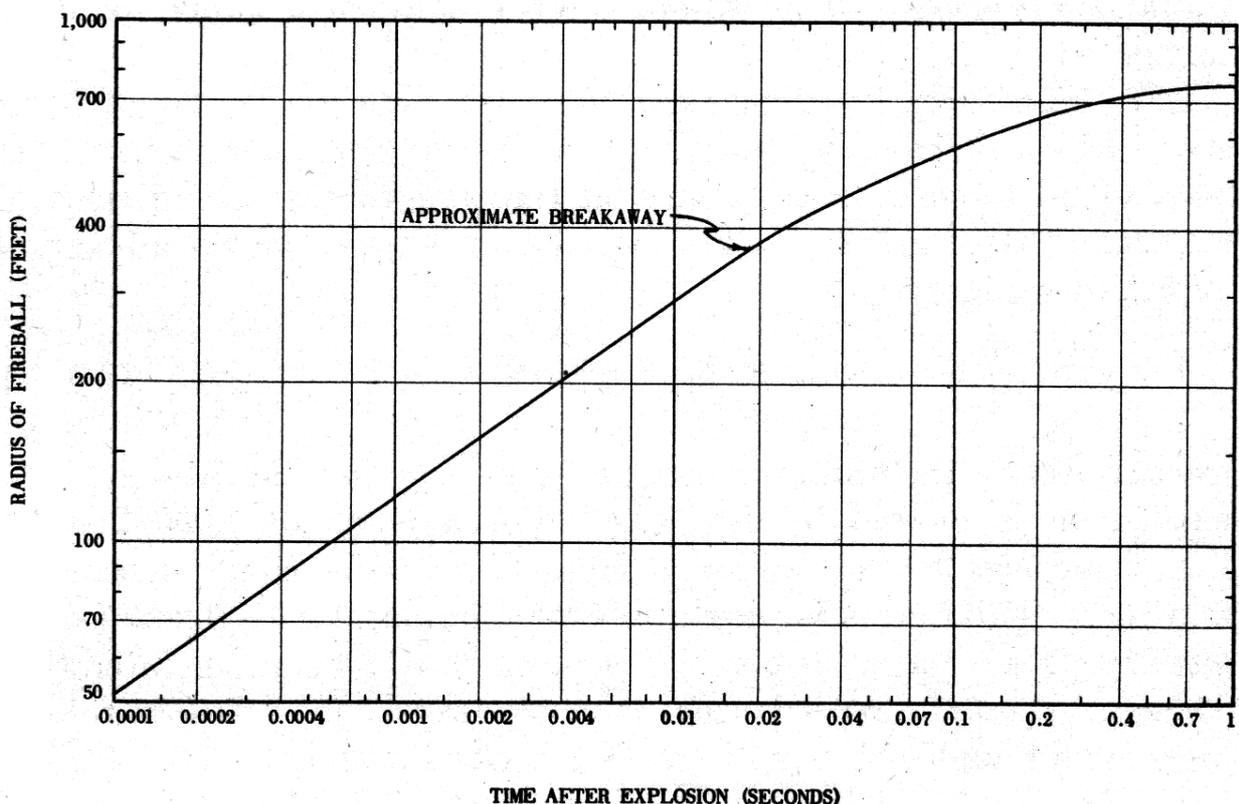
Figure 2.85.   Variation of radius of luminous ball of fire with time in a 20-kiloton explosion.

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

BOMB ENERGY AND SIZE OF BALL OF FIRE

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

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

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

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

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

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

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

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

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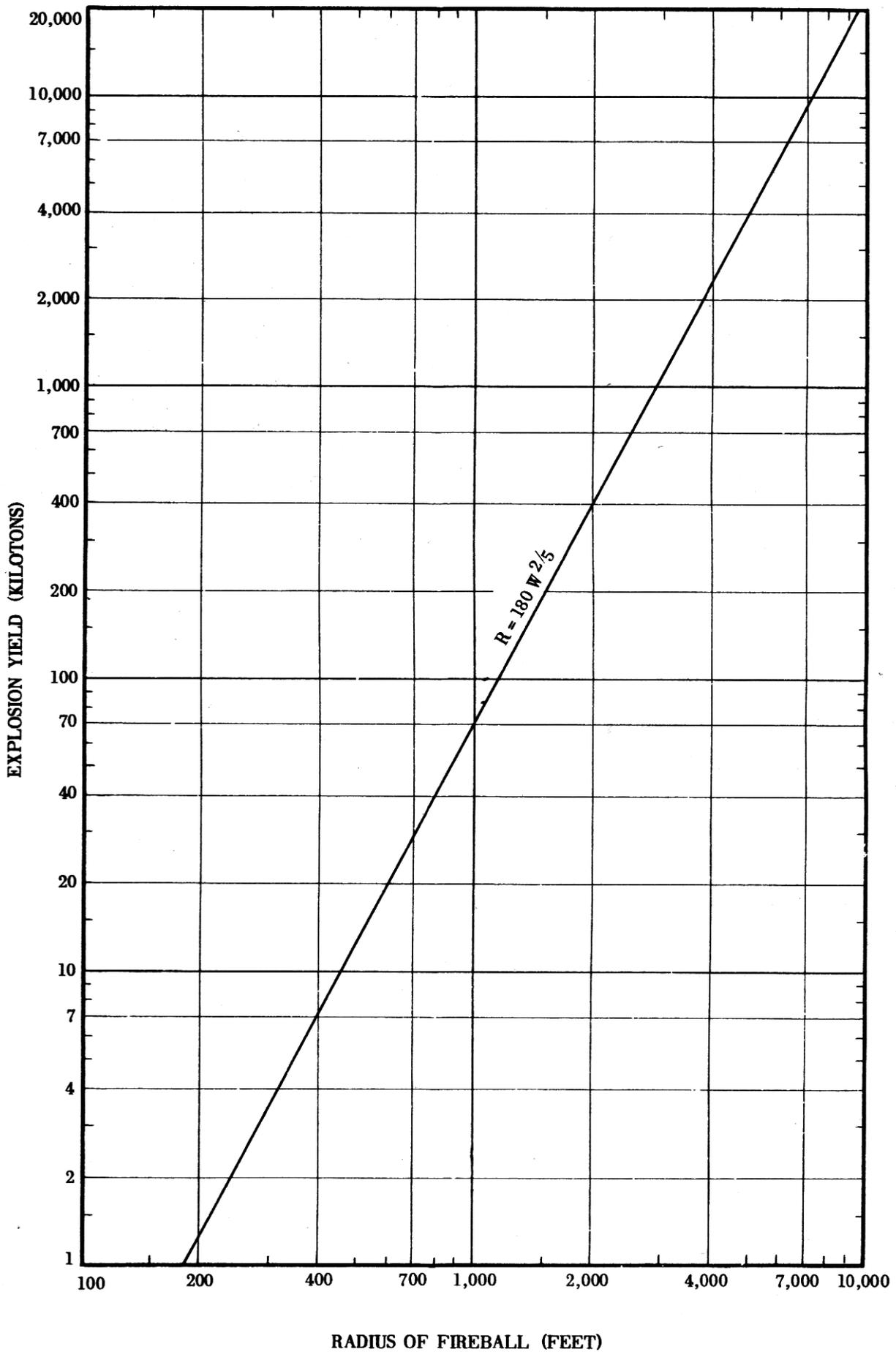
Figure 2.88.   Fireball radius for local fallout.

TEMPERATURE OF THE BALL OF FIRE

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

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

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

2.92   The variation with time of the apparent surface temperature of the ball of fire, from 10^{-4} second to 3 seconds after a 20-kiloton nuclear explosion, is shown in Fig. 2.92. Corresponding with the rapid growth of the fireball, within the first hundredth of a second (Fig. 2.85), the apparent surface temperature drops sharply from about 15,000° C. at 10^{-4} second (0.1 millisecond) to about 2,100° C. at 0.013 second (13 milliseconds), the thermal minimum. Subsequently, there is a relatively slow rise to the maximum of 8,000° C. at about 0.15 sec-
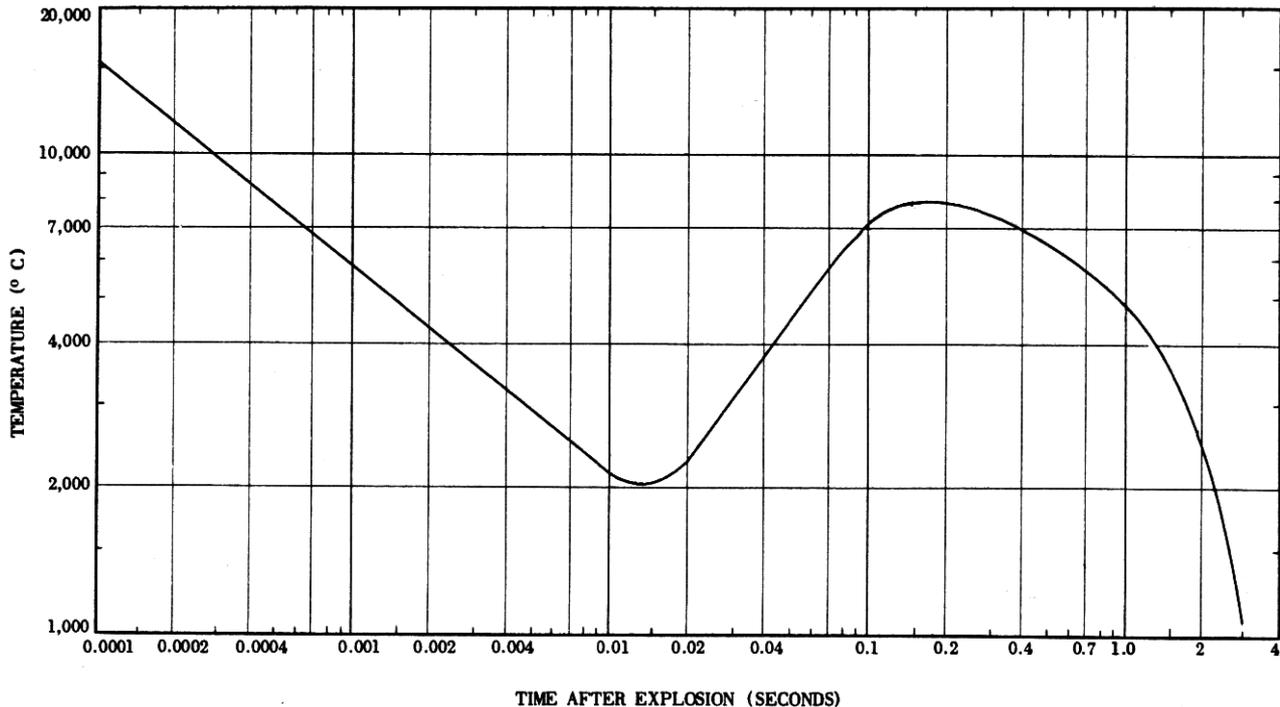
Figure 2.92. Variation of apparent surface temperature with time in a 20-kiloton explosion.

ond, followed by the steady decrease over a period of several seconds, until the ambient atmospheric temperature is reached. By this time the ball of fire is, of course, no longer visible as such and its place has been taken by the atomic cloud.

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

NUCLEAR BOMBS AND THE WEATHER

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

natural store of energy from the path it might otherwise have followed.

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

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

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

2.98 Within two or three hours after the Bikini ABLE (air) burst in 1946, light rain showers developed throughout the northern Marshall Islands. Some attempt was made to relate the formation of the showers to the atomic cloud. But the showers were very widespread and were readily explained on the basis of the existing meteoro-

logical conditions. The records show that the only detectable changes which occurred in the wind or atmospheric structure were the momentary effects of the blast and thermal radiation. In any event, such changes were significant only in the immediate vicinity of the burst. The main cloud pattern over the lagoon was unchanged apart from the atomic cloud directly associated with the explosion.

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

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

2.101 The variability of weather phenomena due to natural causes makes it difficult to prove (or disprove) that any change in the weather following a nuclear explosion was due to the detonation. However, the general opinion of competent meteorologists, both in the United States and in other countries, is that, apart from localized effects in the vicinity of the test area, there has been no known influence of nuclear explosions on the weather.
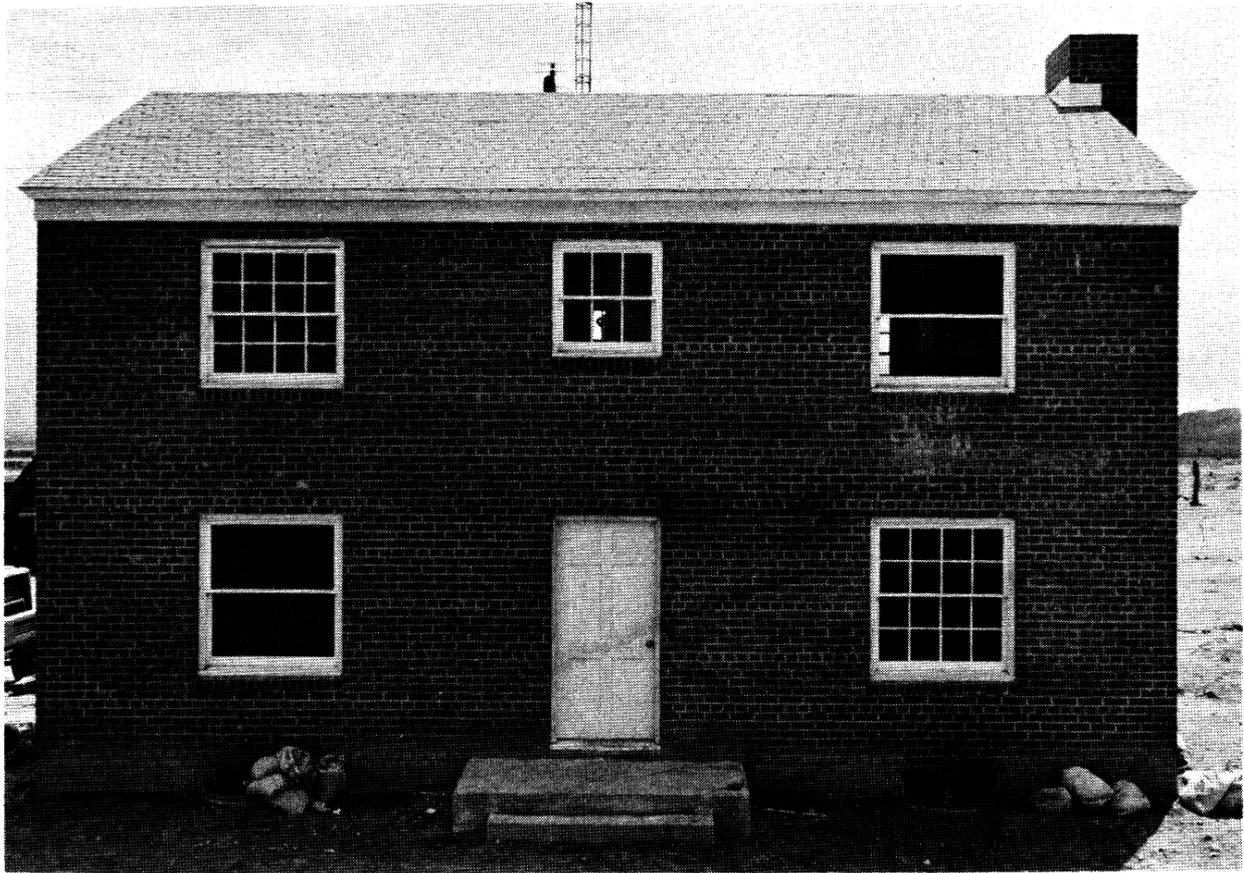
Figure 4.29.   Unreinforced brick house before a nuclear explosion, Nevada Test Site.

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

NOTE: SPACE UNDER STAIRCASE SURVIVED!
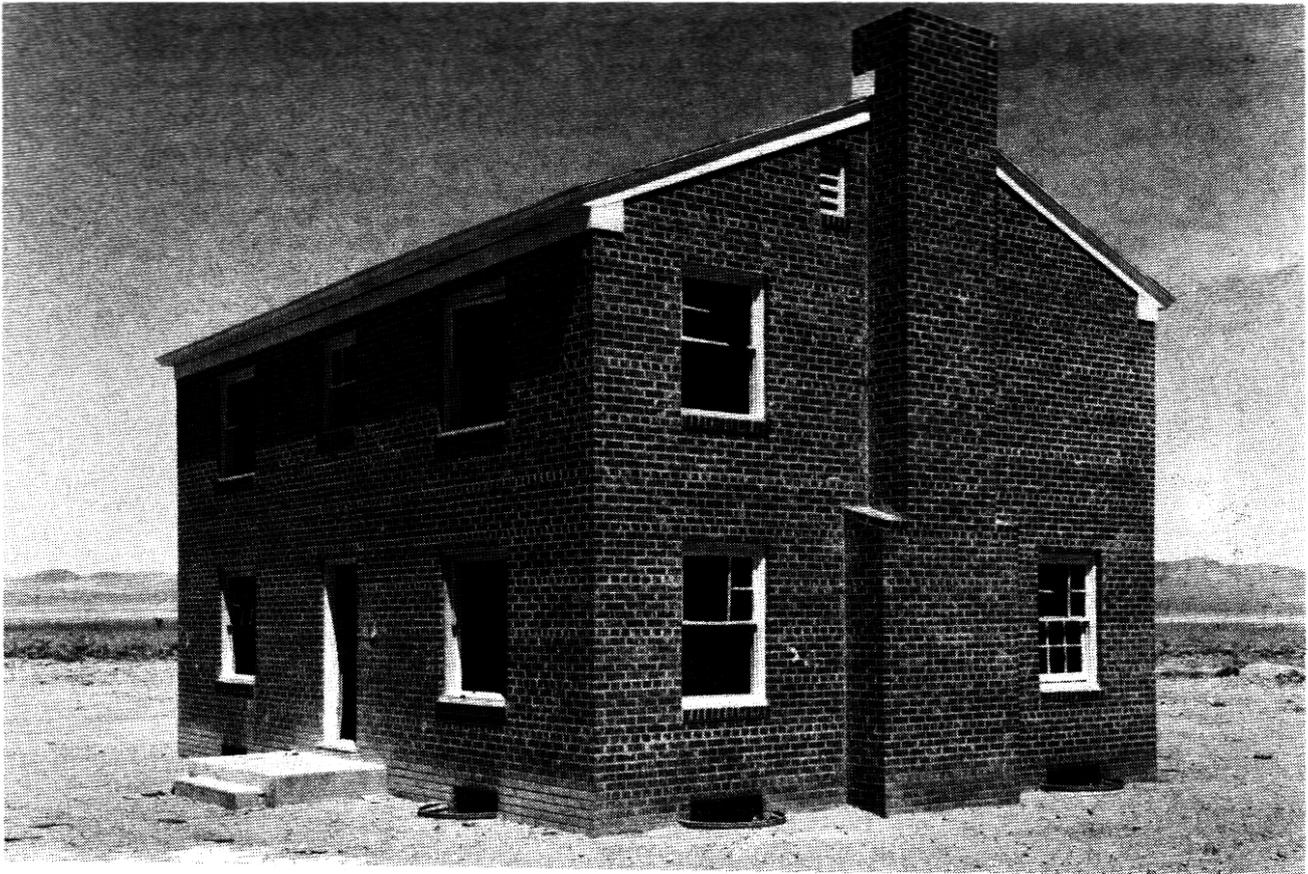
Figure 4.31. Unreinforced brick house after the nuclear explosion (1.7 psi overpressure).

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

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

4.33 The glass in the front and side windows was blown in, but the rear windows suffered much less. The exterior doors were demolished and several interior bedroom and closet doors were blown off their hinges.
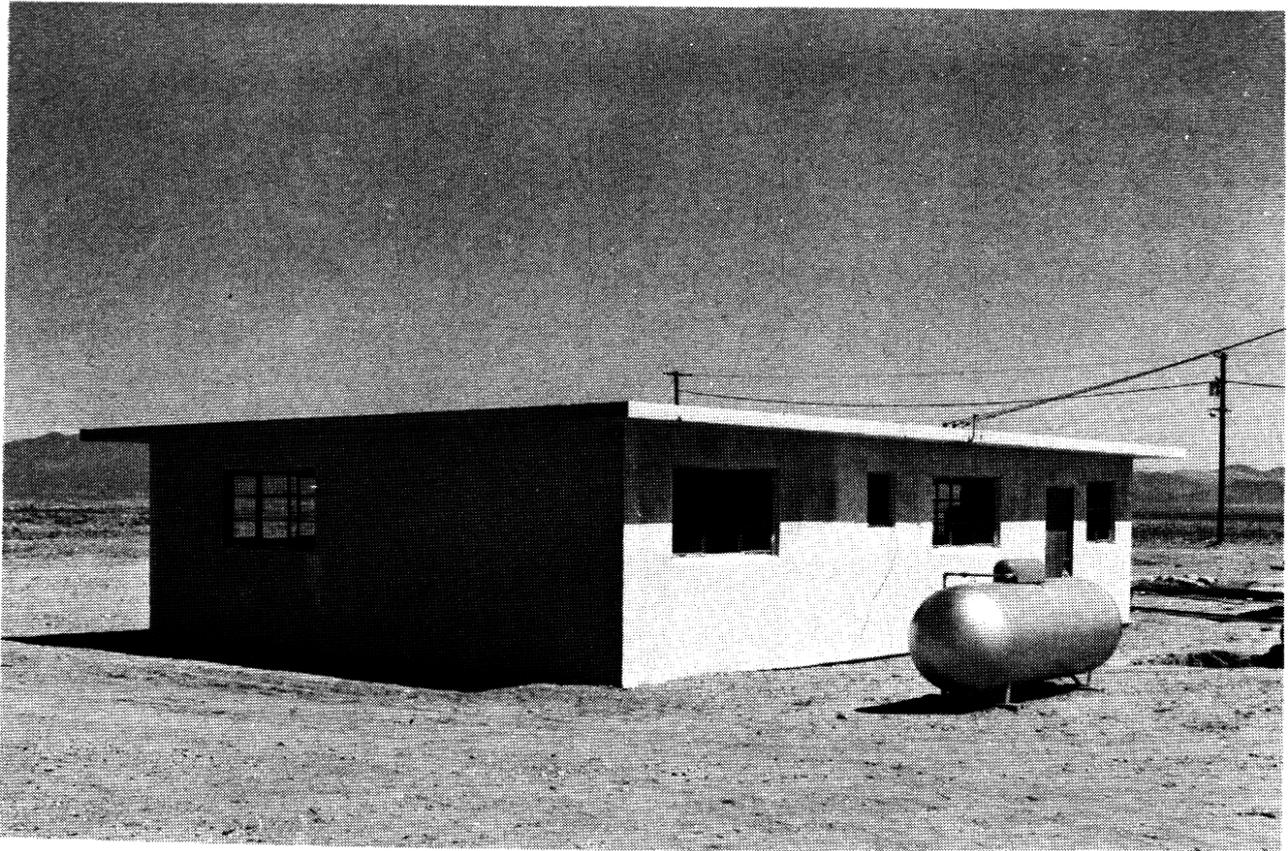
Figure 4.37. Reinforced precast concrete house before a nuclear explosion, Nevada Test Site.
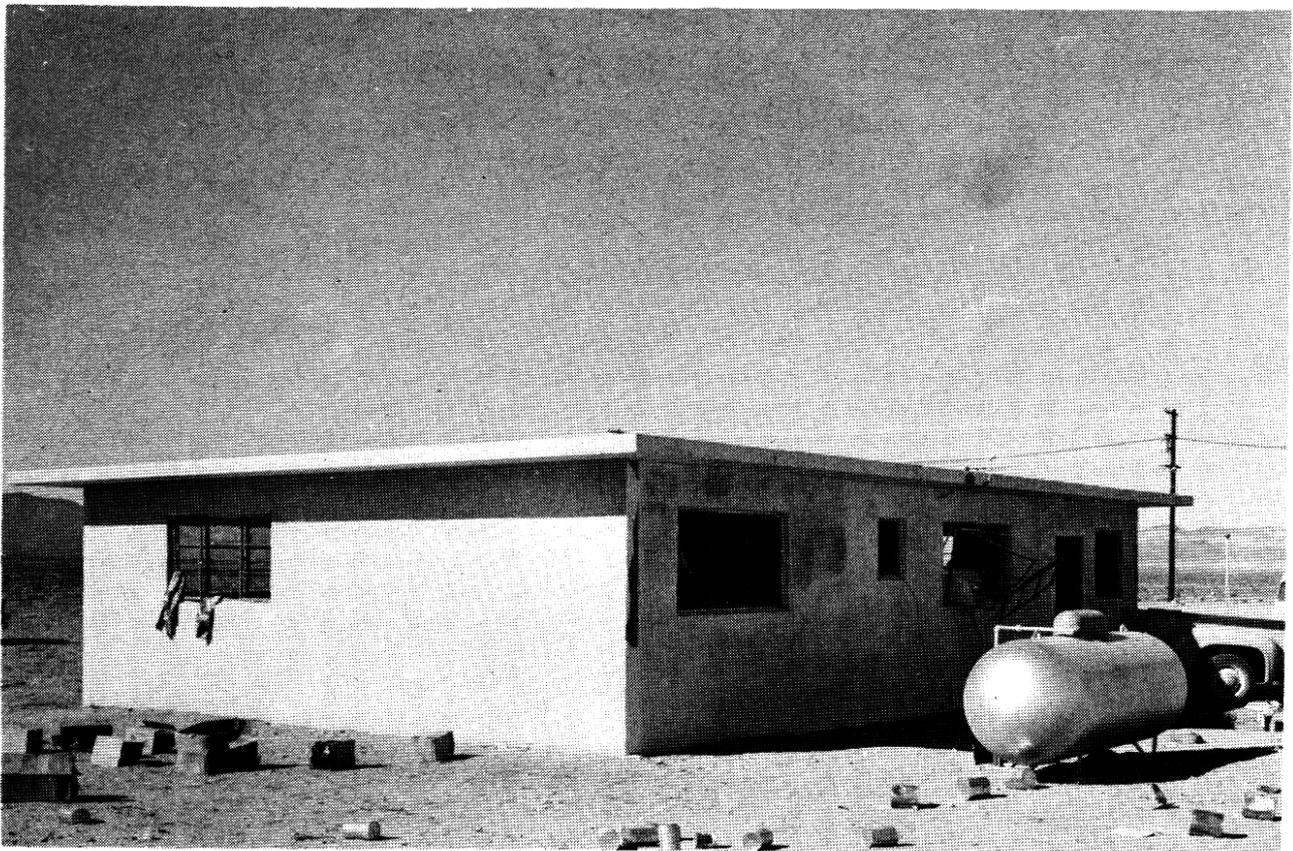
Figure 4.38. Reinforced precast concrete house after the nuclear explosion (5 psi overpressure). The LP-gas tank, sheltered by the house, is essentially undamaged.
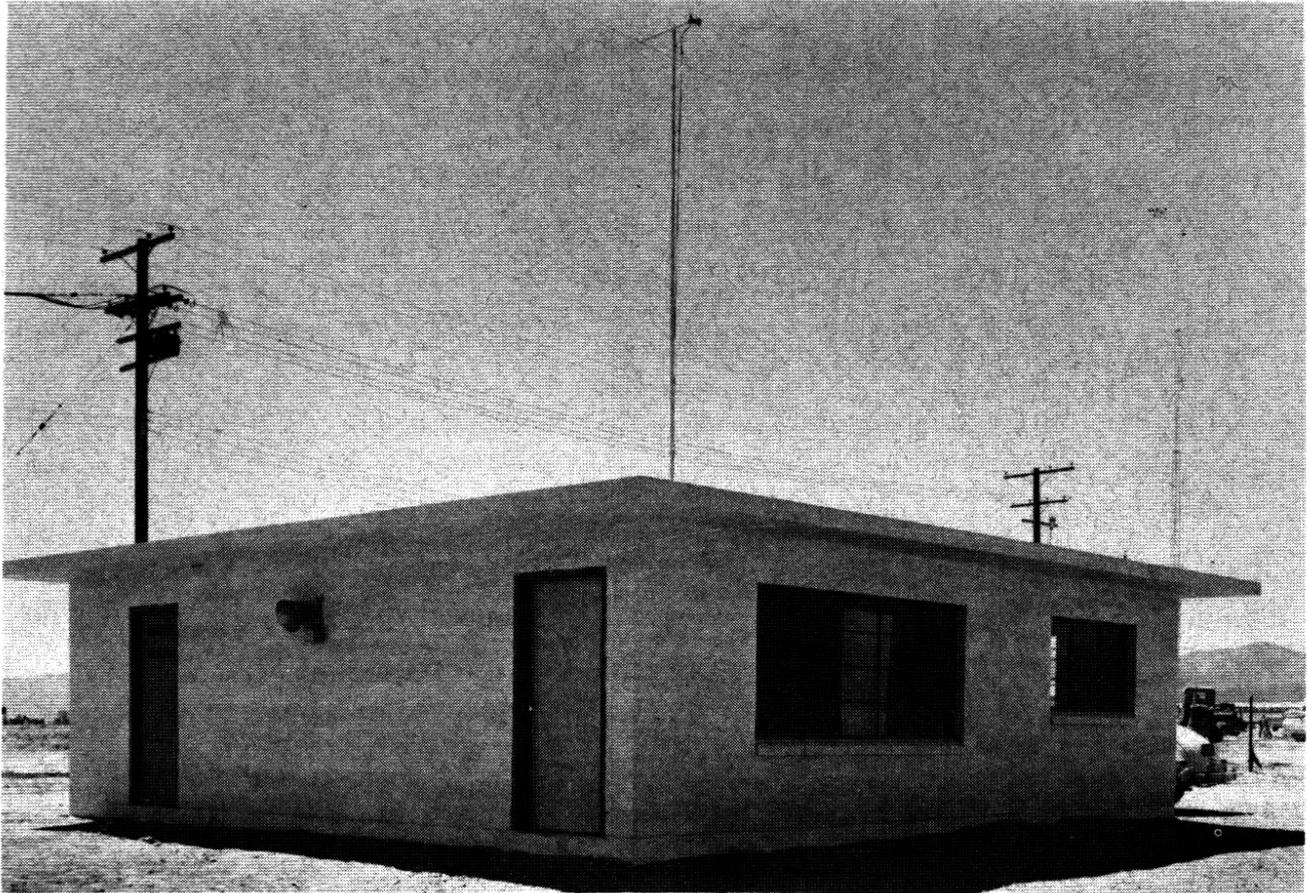
Figure 4.41. Reinforced masonry-block house before a nuclear explosion, Nevada Test Site.
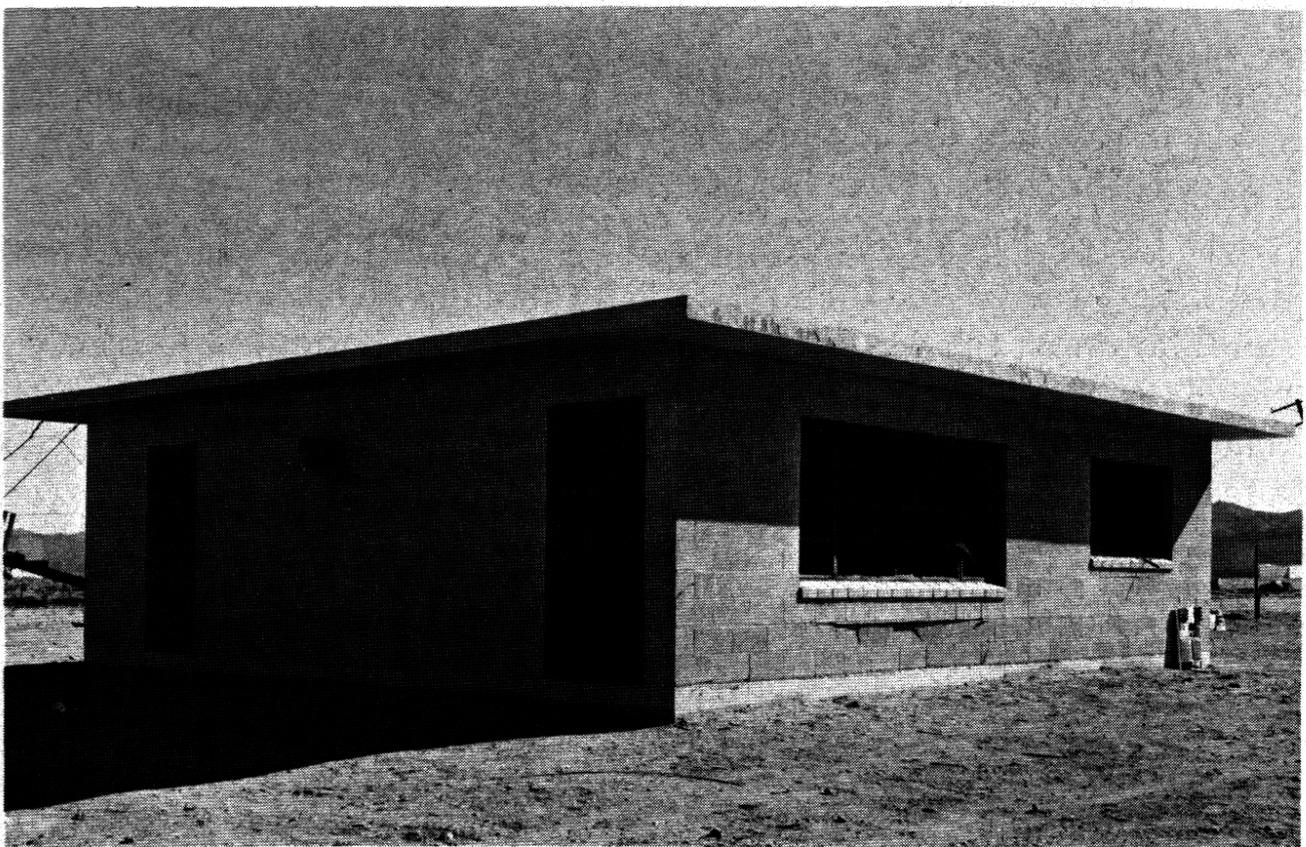
Figure 4.42. Reinforced masonry-block house after the nuclear explosion (5 psi overpressure).
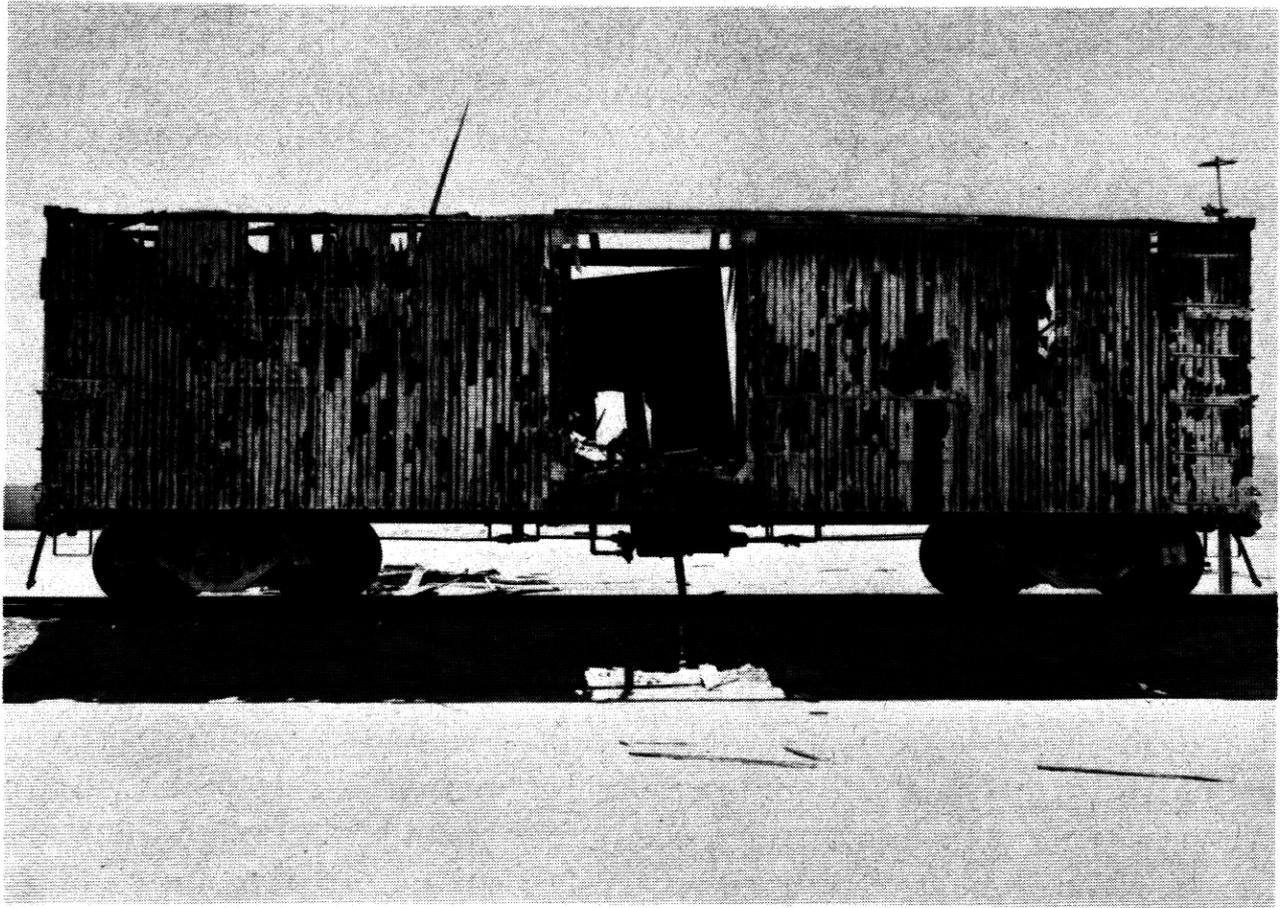
Figure 4.97a. Loaded wooden boxcar after a nuclear explosion (4 psi overpressure).
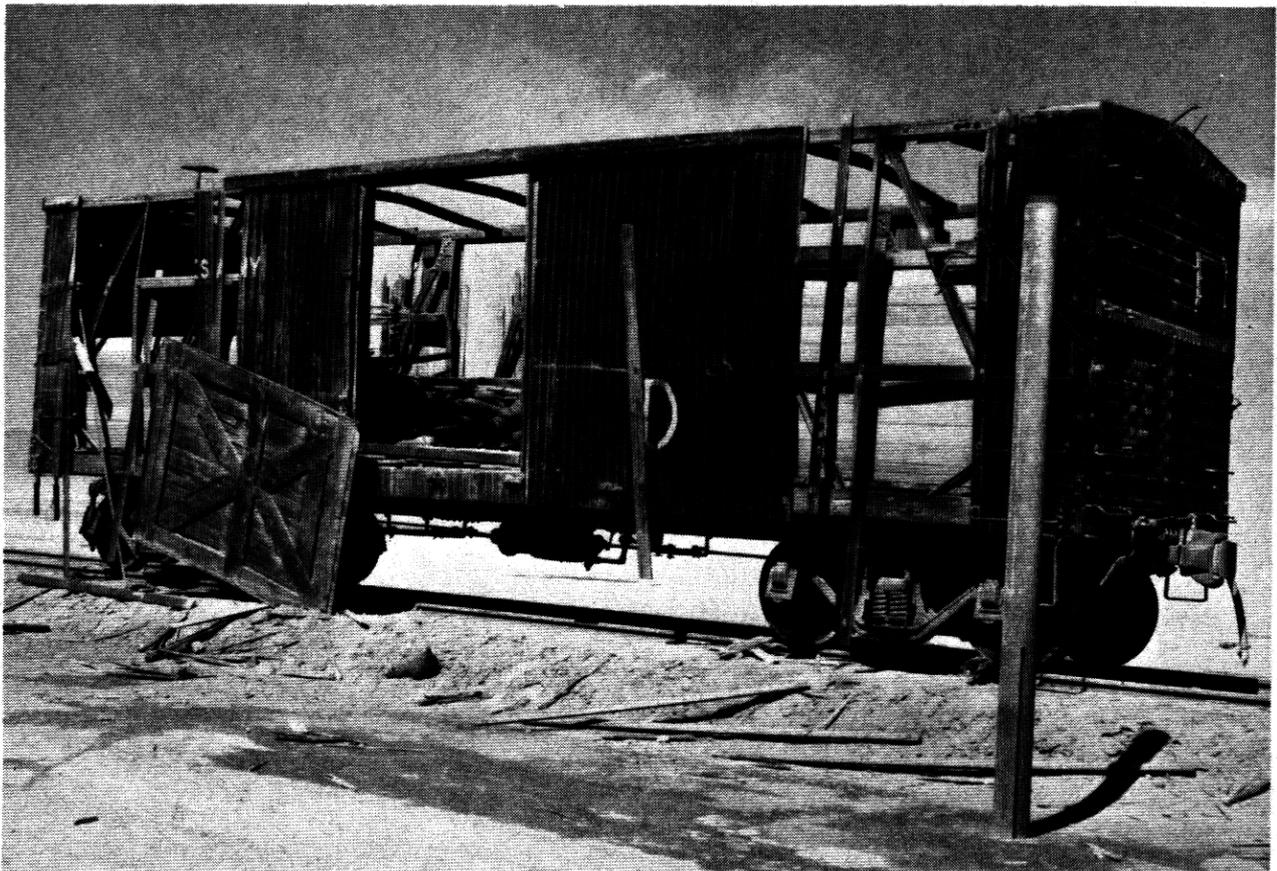
Figure 4.97b. Loaded wooden boxcar after a nuclear explosion (6 psi overpressure).
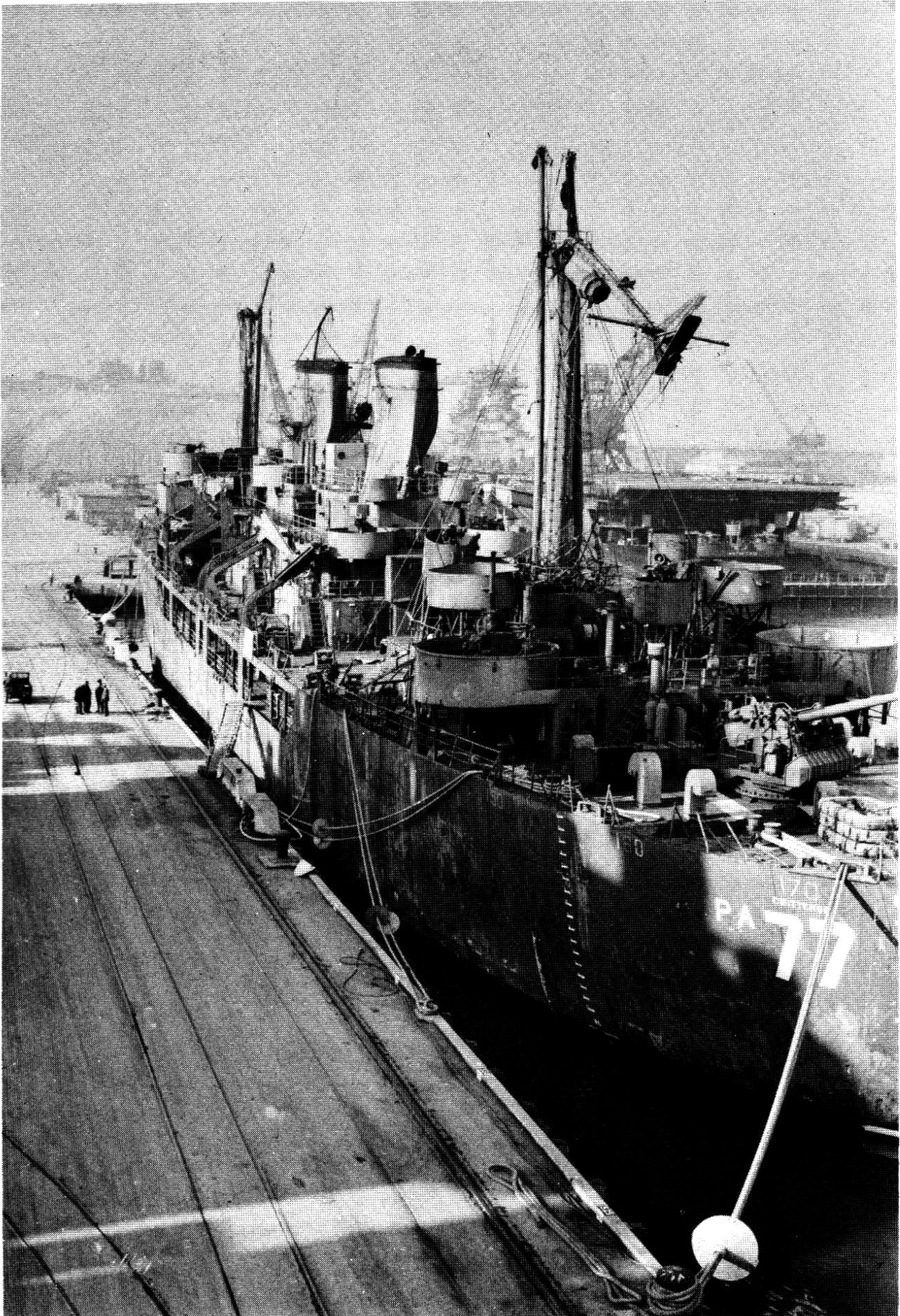
Figure 4.101a. The U. S. S. Crittenden after ABLE test; damage resulting was generally moderate (0.47 mile from surface zero).
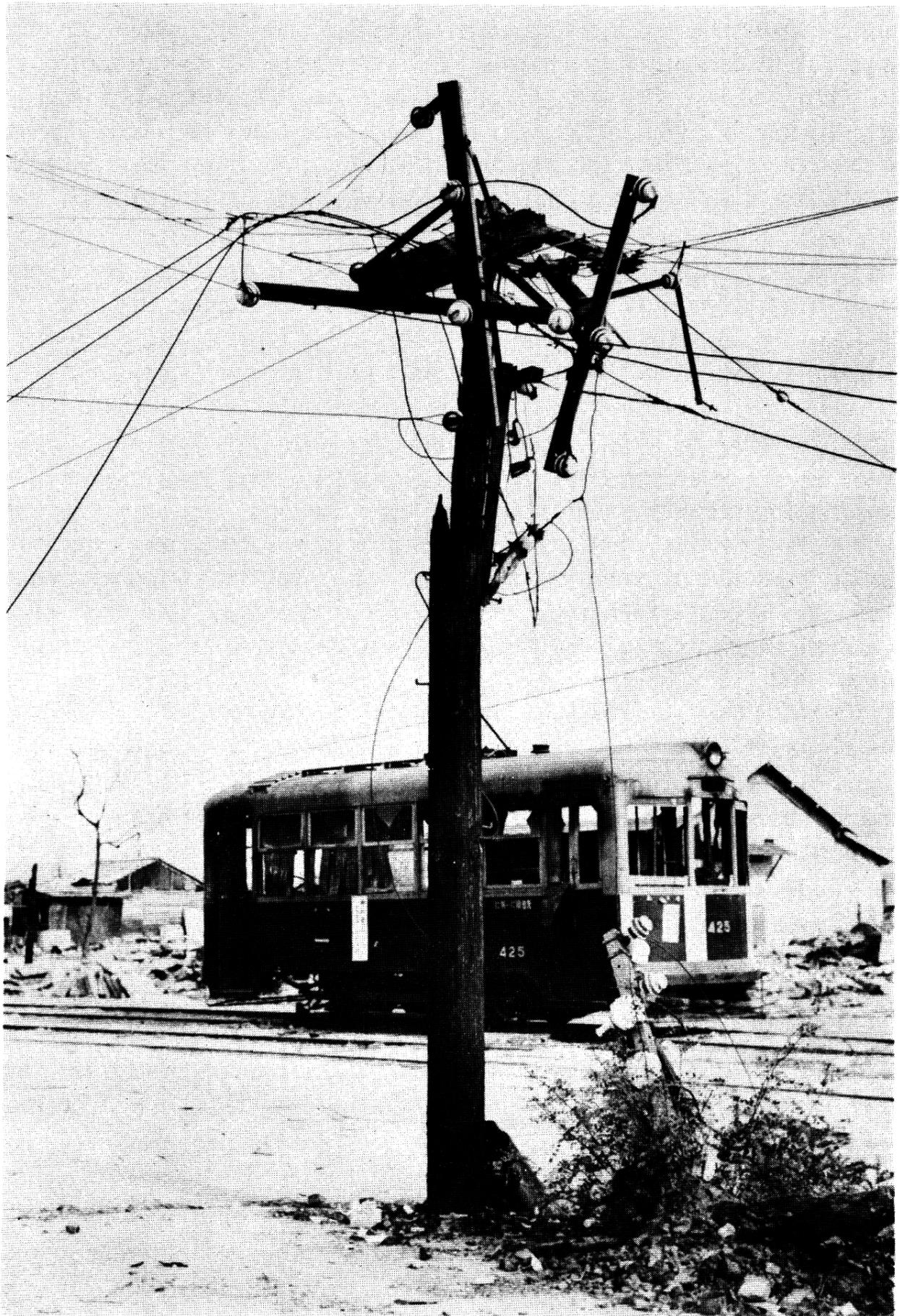
Figure 4.105. Damage to utility pole (0.80 mile from ground zero at Hiroshima).
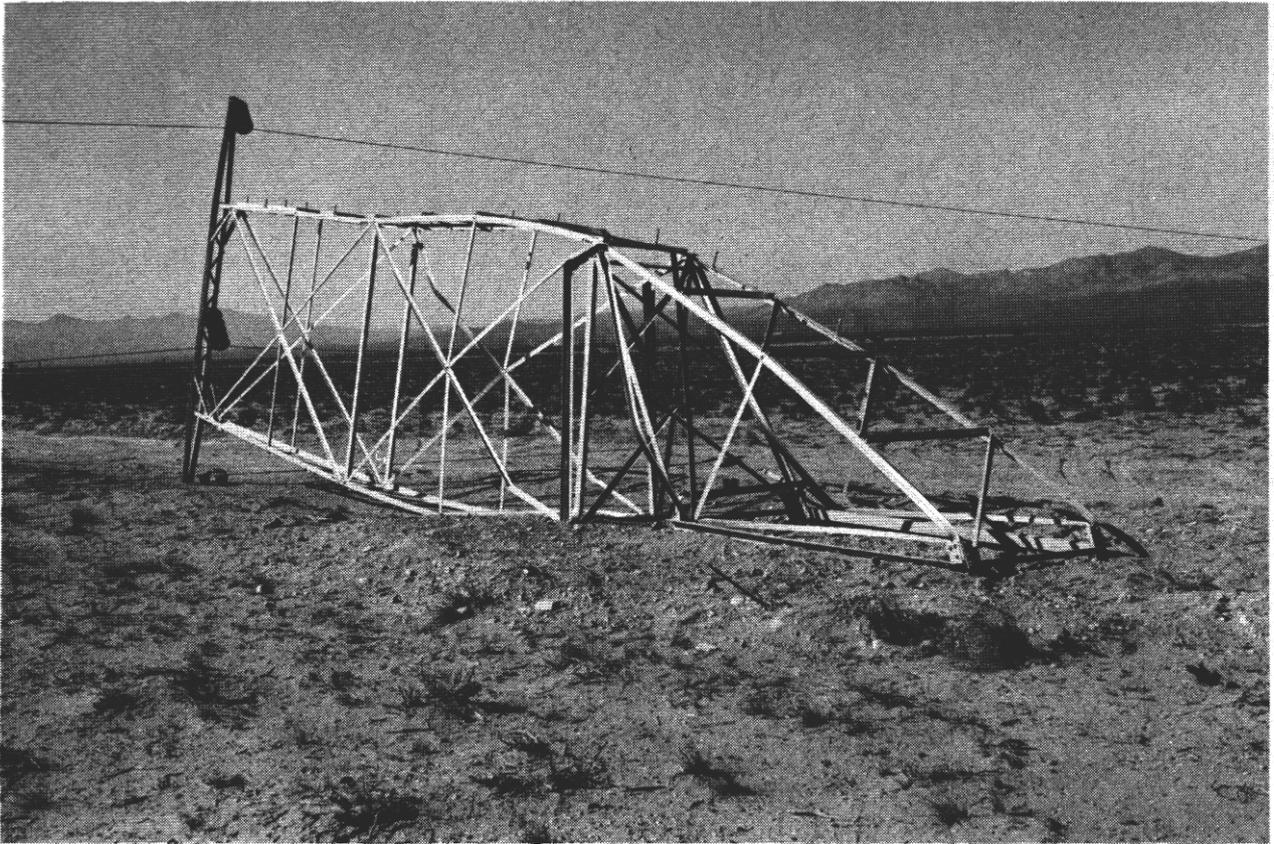
Figure 4.109a. Collapsed suspension tower (5 psi overpressure from 30-kiloton explosion, Nevada Test Site).
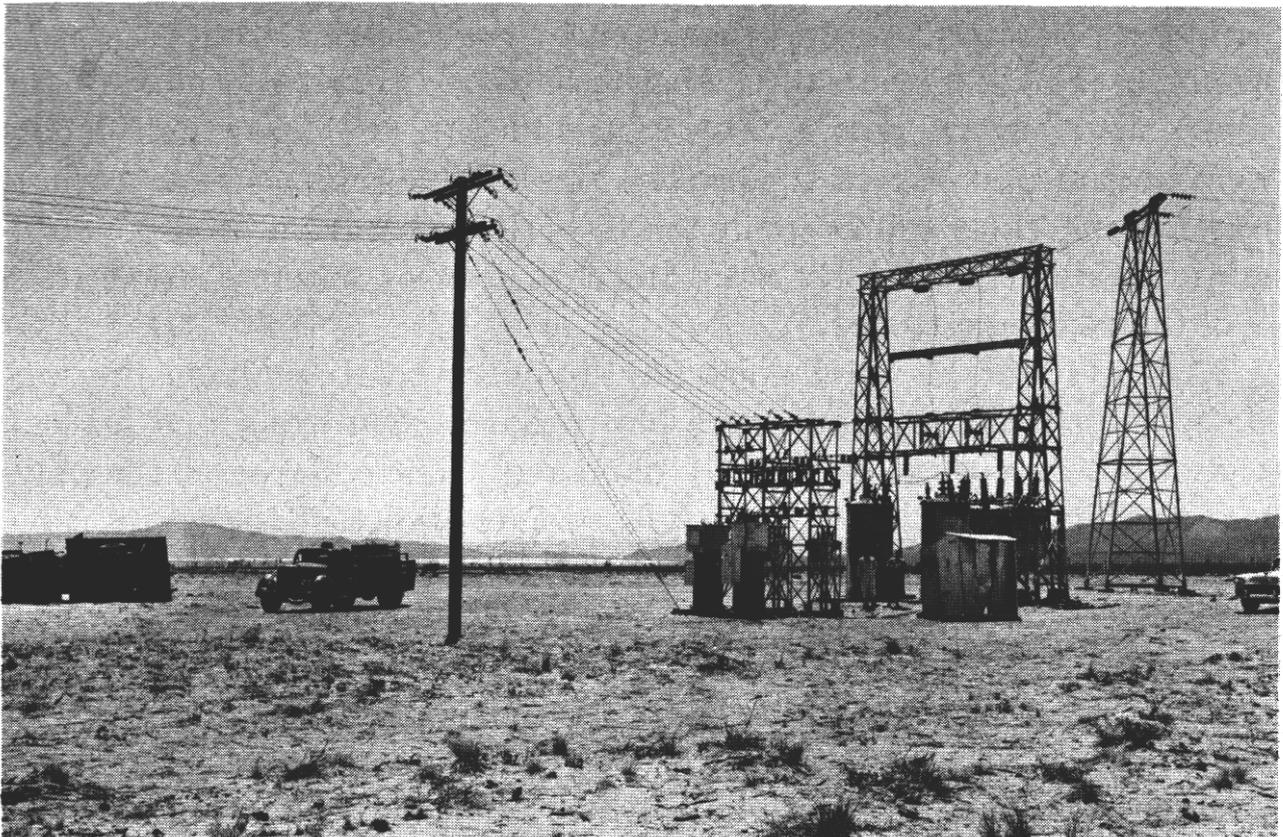
Figure 4.109b. Dead-end tower, suspension tower, and transformers (5 psi overpressure from 30-kiloton explosion, Nevada Test Site).
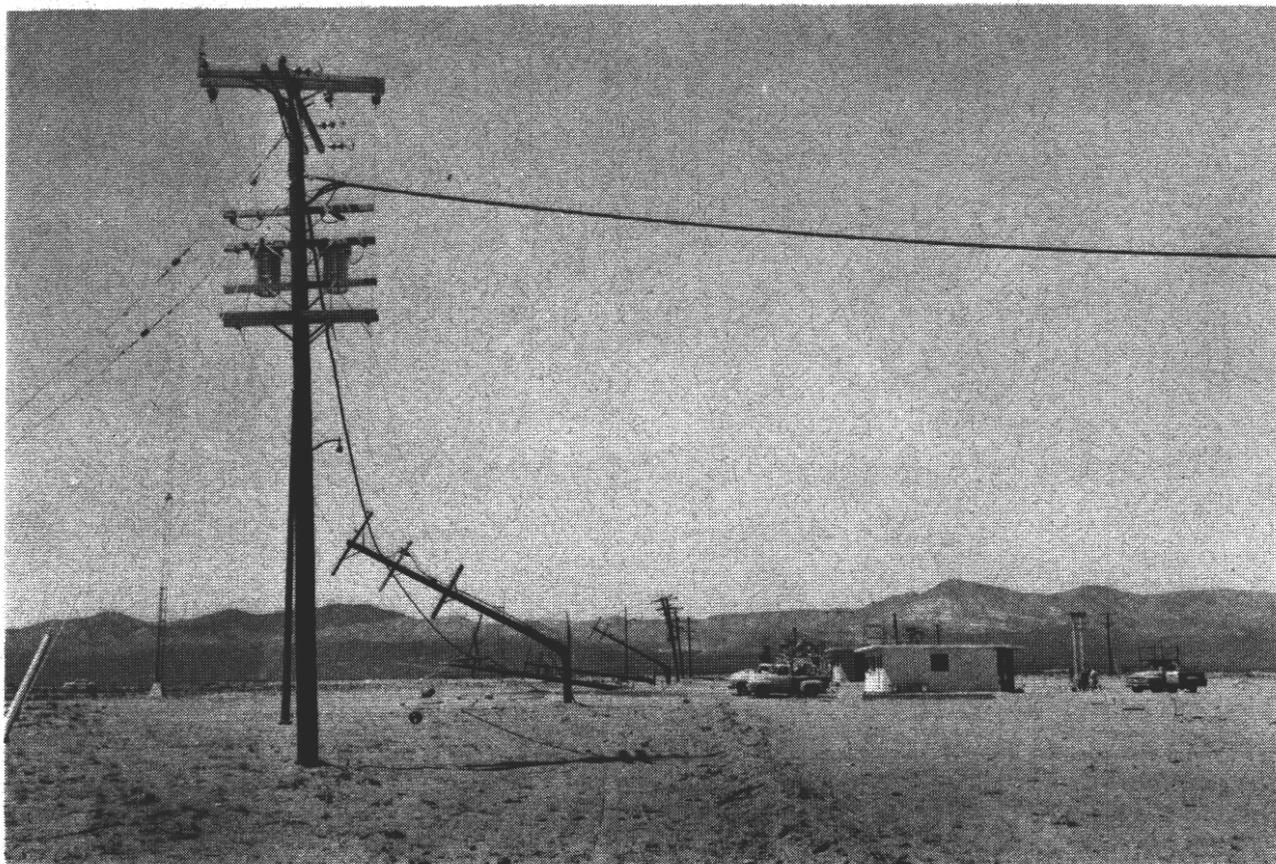
Figure 4.111.   Collapse of utility poles on line (5 psi overpressure from 30-kiloton explosion, Nevada Test Site).

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

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

4.112   Several distributor transformers had fallen from the poles, and secondary wires and service drops were down. Nevertheless, the transformers, pot heads, arresters, cut-outs, primary conductors of both aluminum and copper, and the aerial cables were unharmed. Although the pole line would have required some rebuilding, the general damage was such that it could have been repaired within a day or so with materials normally carried in stock by electric utility companies.
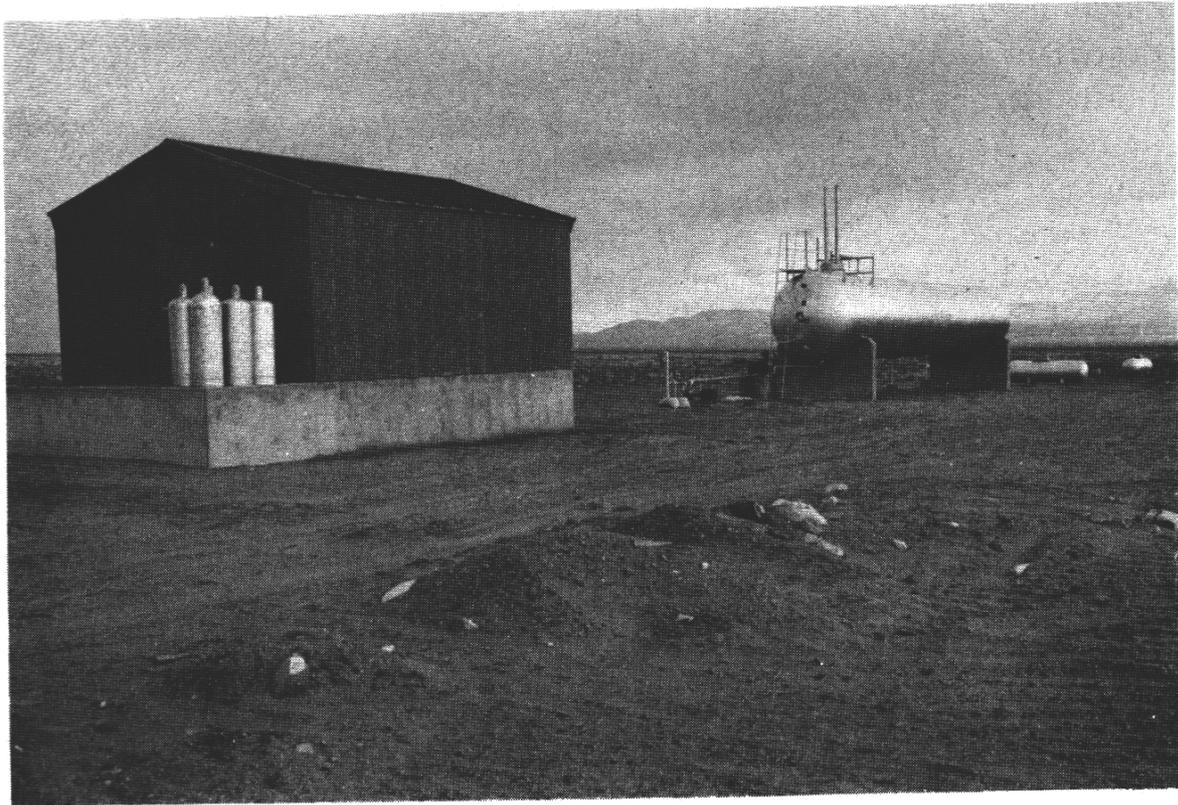
Figure 4.128. *Upper photo:* LP-Gas bulk storage and filling plant before a nuclear explosion. *Lower photo:* The plant after the explosion (5 psi overpressure).

above: 18,000 gallon
Storage tank: Superficial damage only?

TABLE 6.23

DAMAGE CRITERIA FOR TRANSMITTING TOWERS

Damage class	Nature of damage
A and B	Towers demolished or flat on the ground (Fig. 4.109a).
C	Towers partially buckled, but held by guy lines; ineffective for transmission.
D	Guy lines somewhat slack, but tower able to transmit (Fig. 4.109b).

DAMAGE TO FORESTS

6.24   In considering damage to forests, the discussion will refer more specifically to naturally occurring broadleaf and coniferous stands averaging about 175 trees per acre.   Because trees are primarily sensitive to drag forces, the zone in which the damage decreases from class A to class D is relatively narrow.   In particular, the transition from A to B is difficult to delineate, and so these two types of damage are taken together.   The different classifications are described in Table 6.24.   Since the effect of air blast on forests is similar to that of strong

Figure 6.24a.   Forest stand after a nuclear explosion, B damage (3.8 psi overpressure).
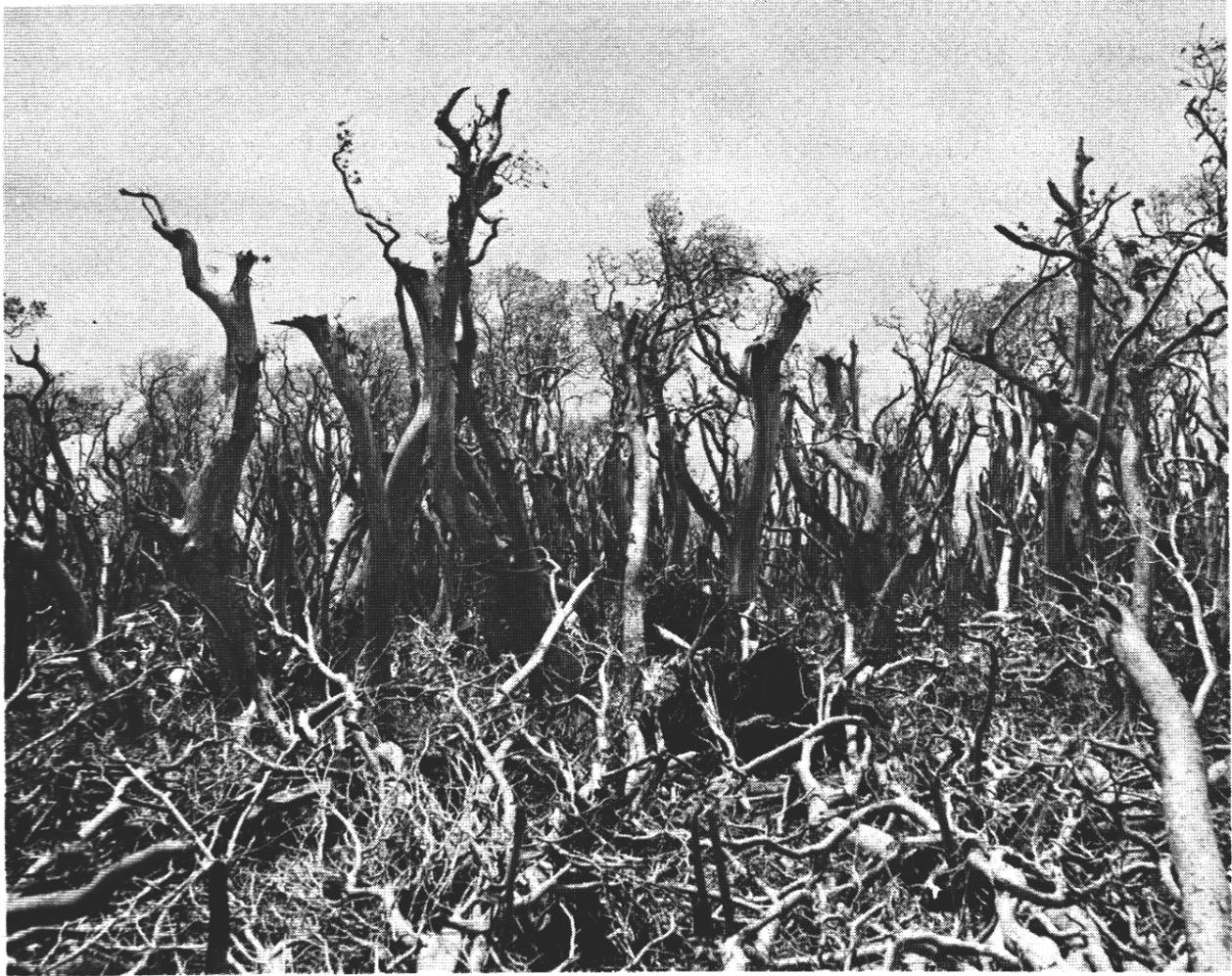
Figure 6.24b. Forest stand after a nuclear explosion, C damage (2.4 psi overpressure).

TABLE 6.24

DAMAGE CRITERIA FOR FORESTS

Damage class	Nature of damage	Equivalent hurricane wind velocity (miles per hour)
A & B	Up to 90 percent of trees blown down; remainder denuded of branches and leaves (Fig. 6.24a). (Area impassable to vehicles and very difficult on foot.)	130–140
C	About 30 percent of trees blown down; remainder have some branches and leaves blown off (Fig. 6.24b). (Area passable to vehicles only after extensive clearing.)	90–100
D	Very few trees blown down; some leaves and branches blown off. (Area passable to vehicles.)	60–80
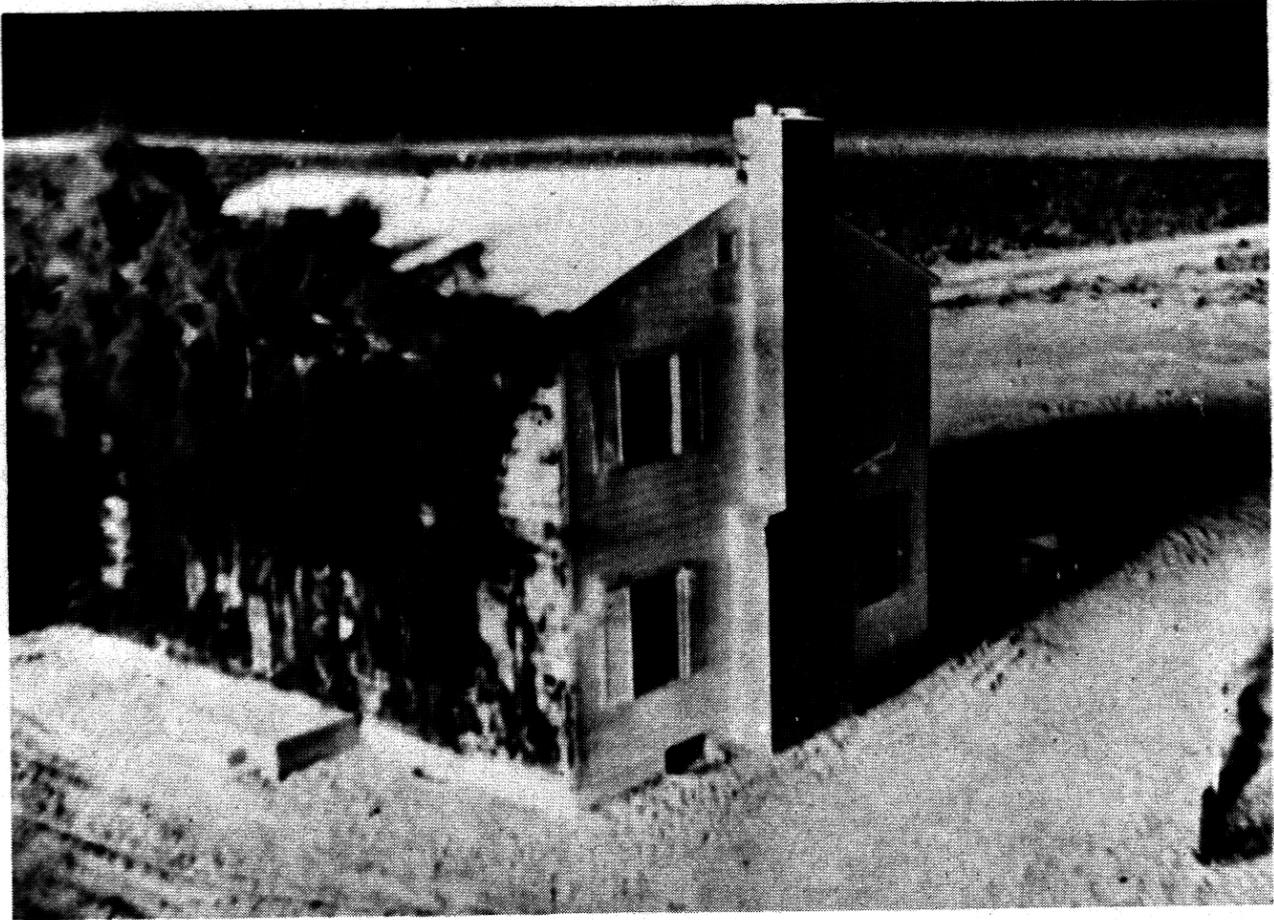
Figure 7.34a. Thermal effects on wood frame house almost immediately after explosion (about 25 cal/sq cm).
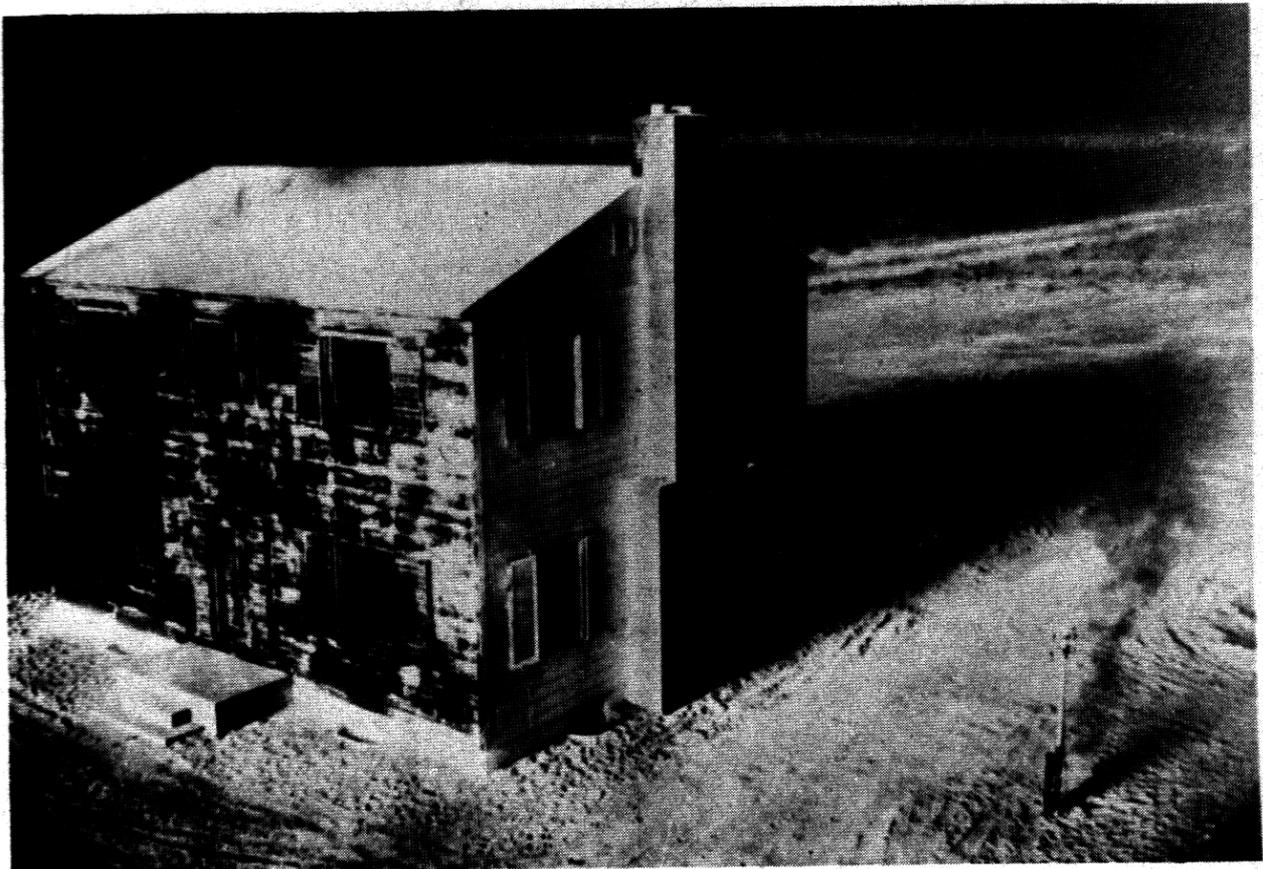
Figure 7.34b. Thermal effects on wood frame house 2 seconds later.

SKIN BURNS DUE TO THERMAL RADIATION

CLASSIFICATION OF BURNS

7.37   Thermal radiation can cause burn injuries either directly, i. e., by absorption of the radiant energy by the skin, or indirectly, as a result of fires started by the radiation.   The direct burns are often called "flash burns," since they are produced by the flash of thermal radiation from the ball of fire.   The indirect (or secondary) burns are referred to as "flame burns"; they are identical with skin burns that would accompany (or are caused by) any large fire no matter what its origin.

7.38   A highly significant aspect of a nuclear explosion is the very large number of flash burns (see § 7.69), as a consequence of the considerable emission of thermal radiation energy.   Due to the very rapid heating of the skin, flash burns differ to some extent, in their physical and physiological aspects, from the more familiar flame burns.   However, from the view point of their over-all effects on the body and their treatment, both types of burns appear to be similar.   They also resemble burns produced in other ways, e. g., by contact with hot metal.

7.39   Burns, irrespective of their cause, are generally classified according to their severity, in terms of the degree (or depth) of the injury.   In first-degree burns, of which moderate sunburn is an example, there is only redness of the skin.   Healing should occur without special treatment and there will be no scar formation.   Second-degree burns are deeper and more severe, and are characterized by the formation of blisters.   Severe sunburn with blistering is an example of a second-degree burn.   In third-degree burns, the full thickness of the skin is destroyed.   Unless skin grafting techniques are employed, there will be scar formation at the site of the injury.

7.40   The distribution of burns into three groups obviously has certain limitations since it is not possible to draw a sharp line of demarcation between first- and second-degree, or between second- and third-degree burns.   Within each class the burn may be mild, moderate, or severe, so that upon preliminary examination it may be difficult to distinguish between a severe burn of the second degree and a mild third-degree burn.   Subsequent pathology of the injury, however, will usually make a distinction possible.   In the following discussion, reference to a particular degree of burn should be taken to imply a moderate burn of that type.

7.41   The depth of the burn is not the only factor in determining

7.70   A distinctive feature of the thermal radiation burns was their sharp limitation to exposed areas of the skin facing the center of the explosion.   For this reason they were sometimes called "profile burns" (Fig. 7.70).   The phenomenon was due to the fact that most of the radiation received had traveled in a straight line from the ball of fire, and so only regions that were directly exposed were affected.   A striking illustration of this behavior was that of a man writing before a window.   His hands were seriously burned, but his face and neck, which were not covered, suffered only slight burns because the angle of entry of the radiation through the window was such as to place them in partial shadow.

7.71   Although flash burns were largely confined to exposed parts of the body, there were a few cases where such burns occurred through one, and very occasionally more, layers of clothing.   Instances of this kind, however, were observed only near to ground zero where fairly large amounts of radiant energy were received.   When burns did occur through clothing, these generally involved regions where the clothes were tightly drawn over the skin, at the elbows and shoulders, for example.   Such burns may have been due to contact with the hot fabric,
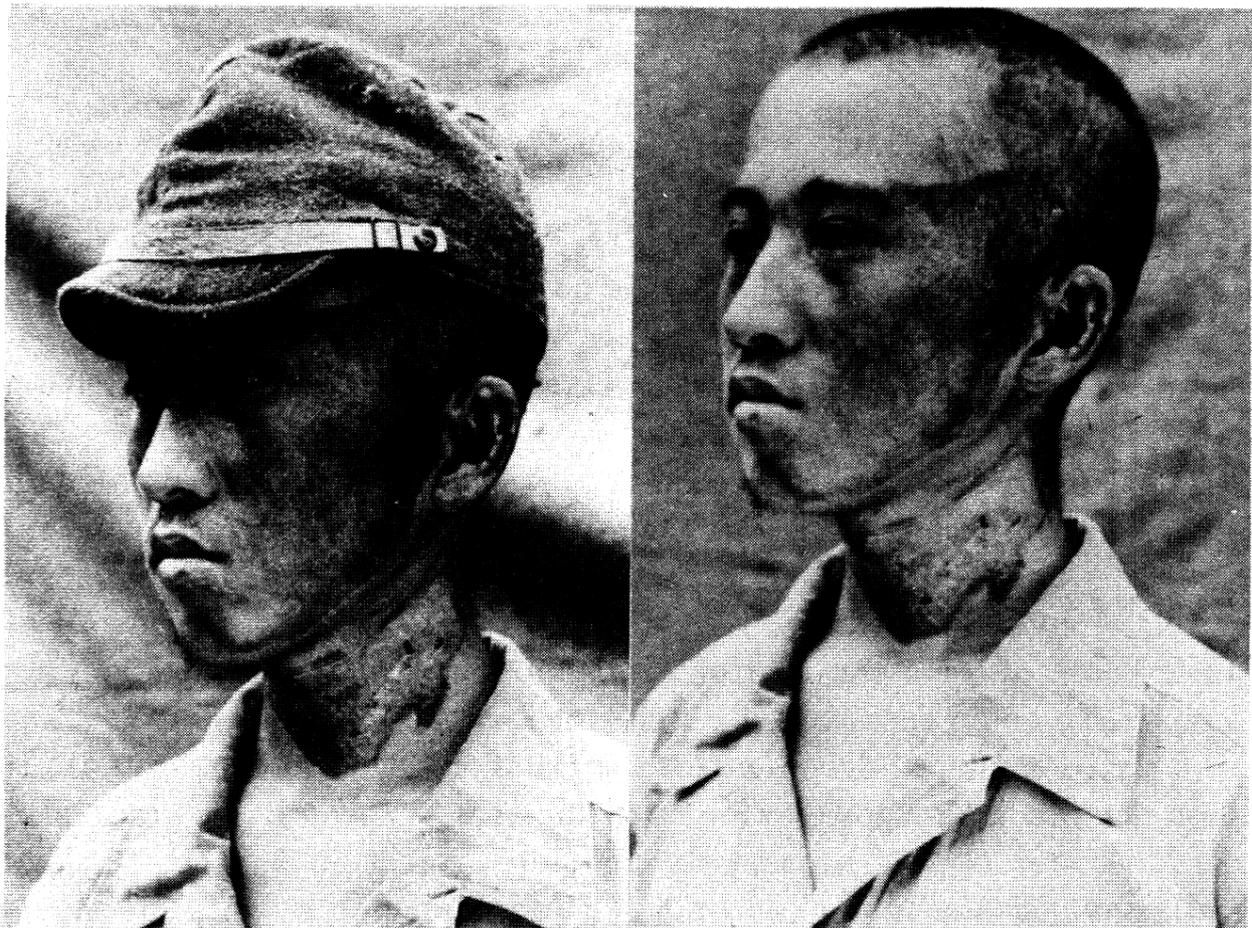
Figure 7.70   Partial protection against thermal radiation produced "profile" burns (1.23 miles from ground zero).   The cap was sufficient to protect the top of the head against flash burn.

Figure 7.71. The skin under the areas of contact with clothing is burned. The protective effect of thicker layers can be seen on the shoulders and across the back.

as described in § 7.57, rather than to the direct effect of radiation. Areas over which the clothing fitted loosely, so that an air space separated it from the skin, were generally unharmed by the radiation (Fig. 7.71).

7.72   There were many instances in which burns occurred through black clothing, but not through white material worn by the same individuals (Fig. 7.72). This was attributed to the reflection of thermal radiation by white or other light-colored fabrics, whereas materials of dark color absorbed radiation, became hot, and so caused contact burns. In some cases black outer clothing actually burst into flame and ignited the undergarments, so that flame burns resulted. It should be recalled, however, as mentioned in § 7.57, that white clothing does not always necessarily provide protection against thermal radiation. Some materials of this kind transmit enough radiation to permit flash burning of the skin to occur.

Figure 7.72. The patient's skin is burned in a pattern corresponding to the dark portions of a kimono worn at the time of the explosion.

OTHER EFFECTS OF THERMAL RADIATION

7.73   Apart from the actual ignition of combustible materials resulting in fires being started, which will be referred to later, a number of other phenomena observed in Japan testified to the intense heat due
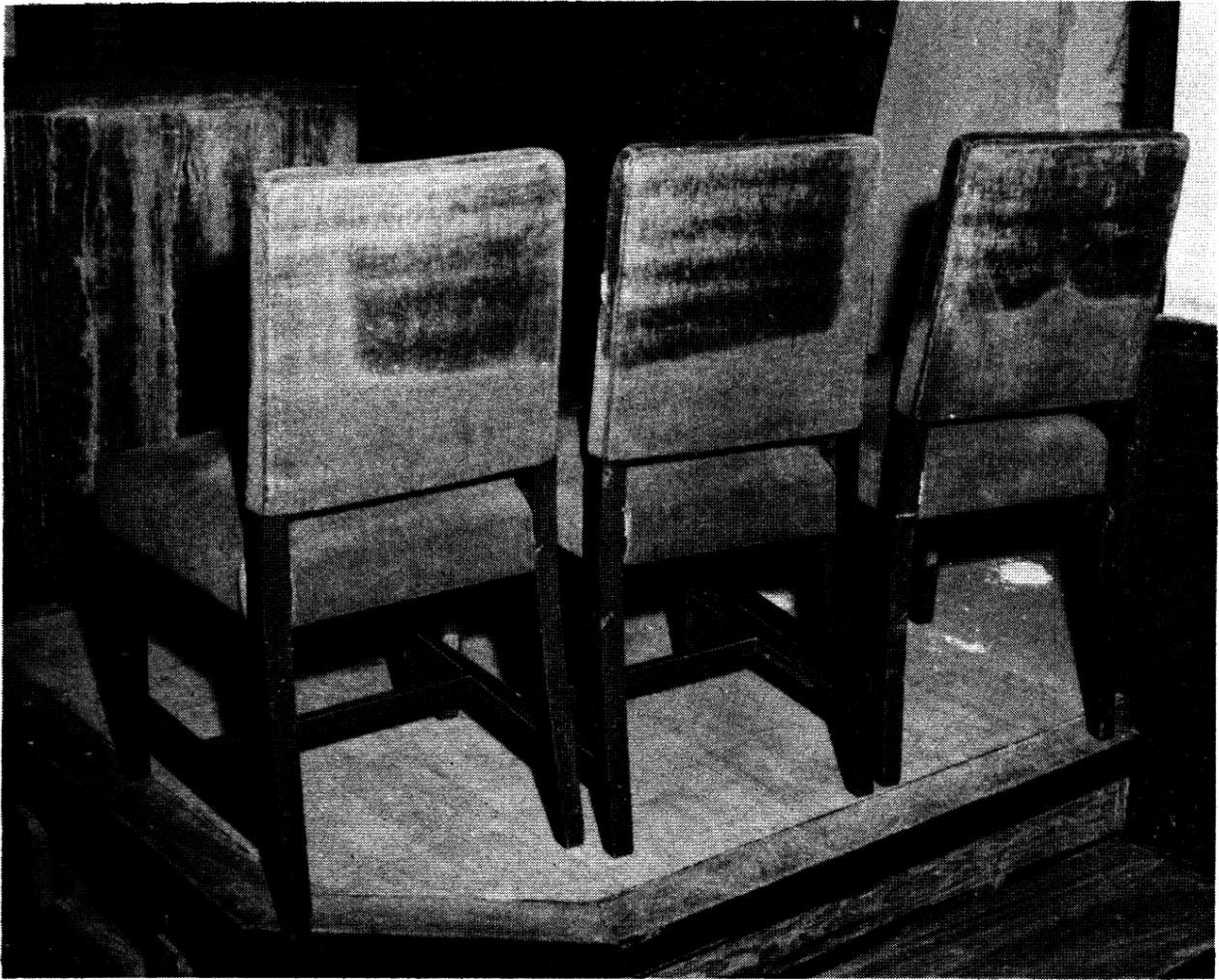
Figure 7.73a.   Flash burns on upholstery of chairs exposed to bomb flash at
window (1 mile from ground zero at Hiroshima).

to the absorption of thermal radiation. Fabrics (Fig. 7.73a), utility
poles (Fig. 7.73b), trees, and wooden posts, up to a radius of 11,000
feet (2.1 miles) from ground zero at Nagasaki, and 9,000 feet (1.7
miles) at Hiroshima (3 to 4 calories per square centimeter), if not
destroyed in the general conflagration, were charred and blackened,
but only on the side facing the point of burst. Where there was pro-
tection by buildings, walls, hills, and other objects there was no evi-
dence of thermal radiation effects.

7.74   An interesting case of shadowing of this kind was recorded
at Nagasaki. The tops and upper parts of a row of wooden posts were
heavily charred, but the charred area was sharply limited by the
shadow of a wall. The wall was, however, completely demolished by
the blast wave which arrived after the thermal radiation. As stated
earlier, this radiation travels with the speed of light, whereas the
blast wave advances much more slowly (§ 3.14).

7.75   From observations of the shadows left by intervening ob-
jects where they shielded otherwise exposed surfaces (Figs. 7.75a and
b), the direction of the center of the explosion was located with con-
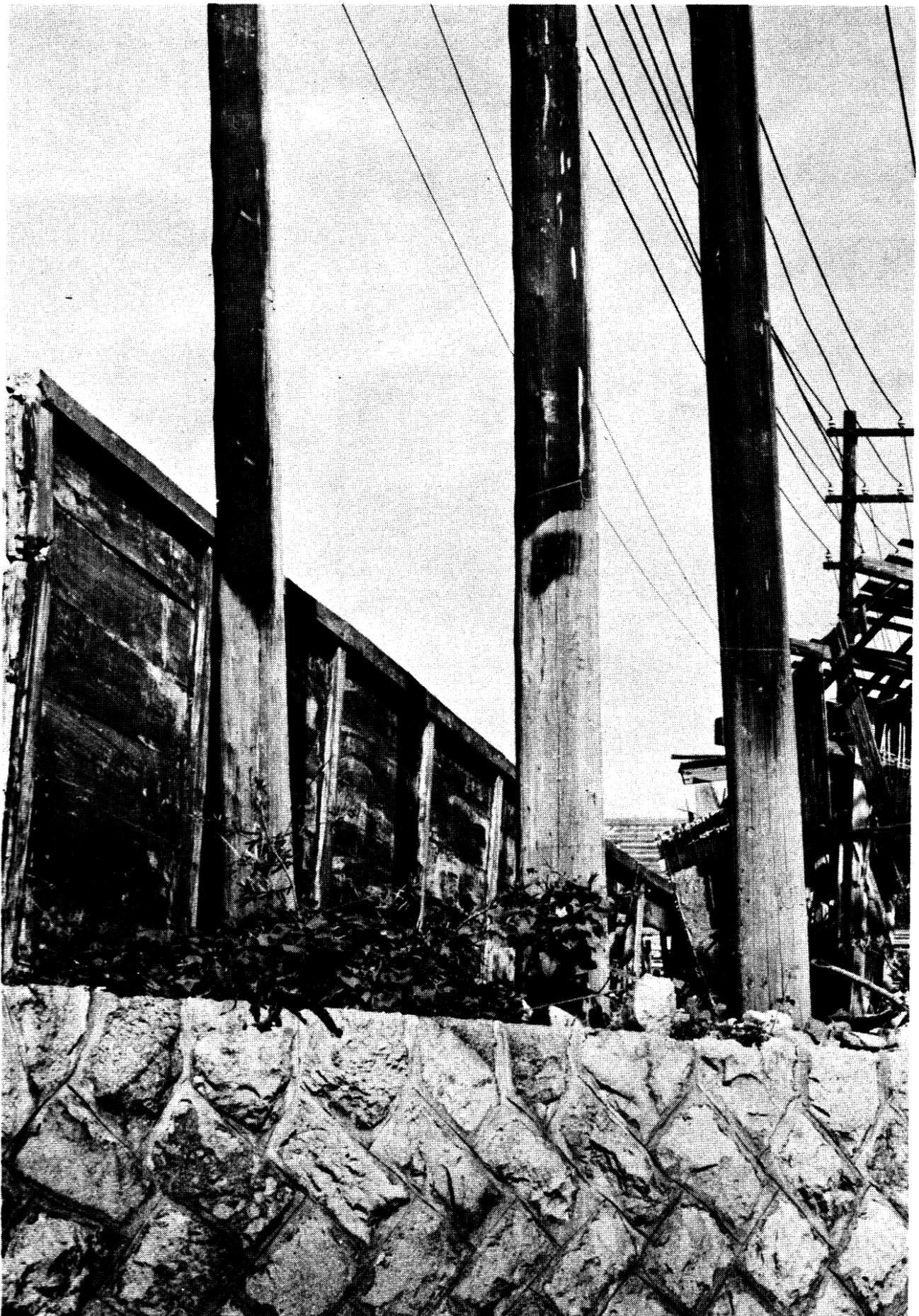
Figure 7.73b. Flash burns on wooden poles (1.17 miles from ground zero at Nagasaki). The uncharred portions were protected from thermal radiation by a fence.

Figure 7.75a. Flash marks produced by thermal radiation on asphalt of bridge in Hiroshima. Where the railings served as a protection from the radiation, there were no marks; the length and direction of the "shadows" indicate the point of the bomb explosion.

siderable accuracy. Further, by examining the shadow effects at various places around the explosion, a good indication was obtained of the height of burst. Occasionally, a distinct penumbra was found, and from this it was possible to calculate the diameter of the ball of fire at the time the thermal radiation intensity was at a maximum.

7.76 One of the striking effects of the radiation was the roughening of the surface of polished granite where there was direct exposure. This roughening was attributed to the unequal expansion of the constituent crystals of the stone, and it is estimated that a temperature of at least 600° C. (1,100° F.) was necessary to produce the observed re-

Figure 7.77.   Blistered surface of roof tile; left portion of the tile was shielded by an overlapping one (0.37 mile from the explosion at Hiroshima).

1,800° C. (3,270° F.) was attained for a period of less than 4 seconds.

7.78   The difference in behavior of light and dark fabrics exposed to thermal radiation in Japan is also of considerable interest. Light-colored fabrics either reflect or transmit most of the thermal radiation and absorb very little. Consequently, they will not reach such a high temperature, and so will suffer less damage than dark fabrics which absorb a large proportion of the radiation. In one case, a shirt consisting of alternate narrow light and dark gray stripes had the dark stripes burned out, whereas the light-colored stripes were undamaged (Fig. 7.78). Similarly, a piece of paper, which had been exposed about 7,800 feet (1.5 miles) from ground zero (5 calories per square centimeter), had the characters, written in black ink, burned out, but the rest of the paper was not greatly affected.

INCENDIARY EFFECTS

Origin of Fires

7.79   There are two general ways in which fires can originate in a nuclear explosion. First, by the ignition of paper, trash, window curtains, awnings, excelsior, dry grass, and leaves, as a direct result of the absorption of thermal radiation. And second, as an indirect
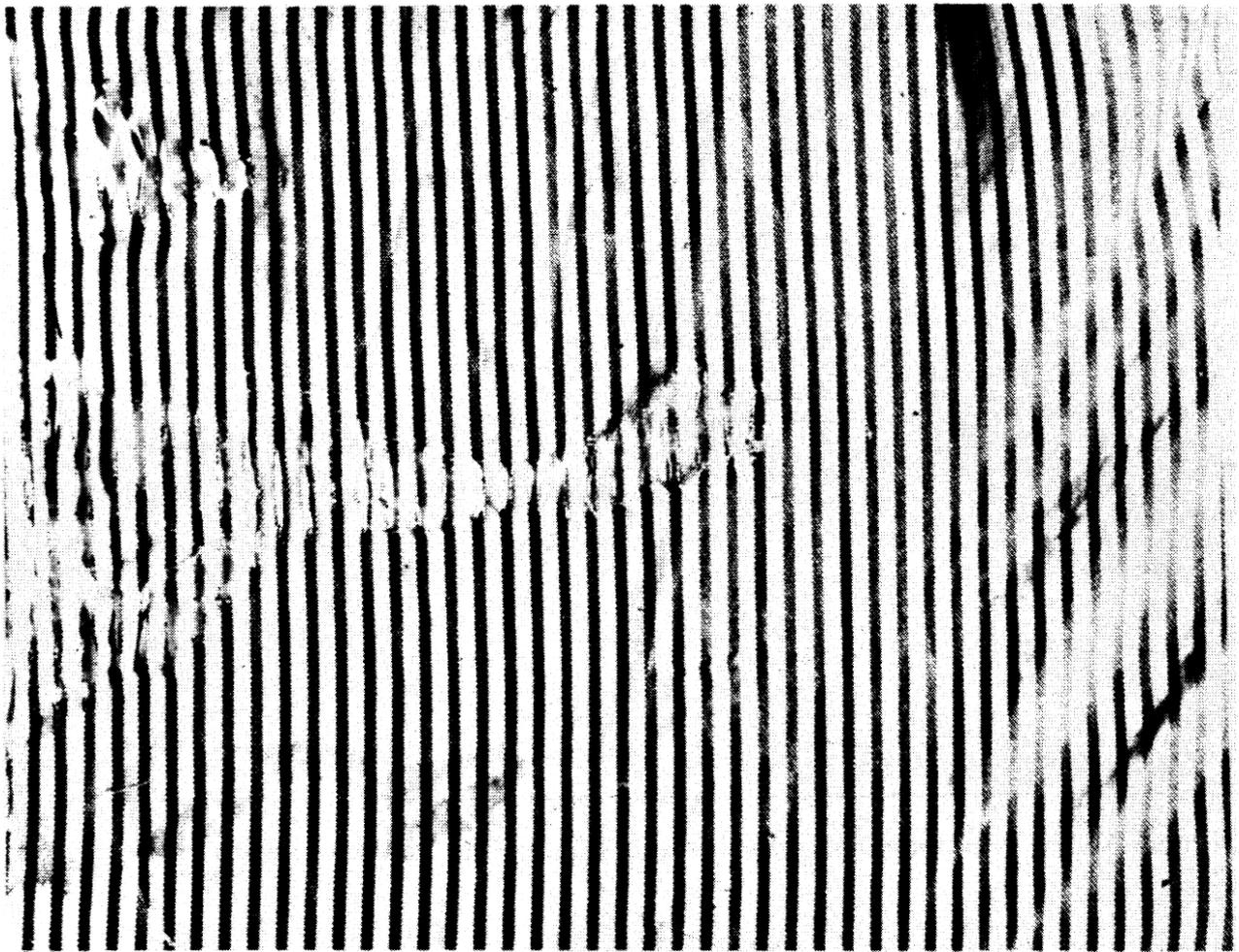
Figure 7.78. The light-colored portions of the material are intact, but some of
the dark-colored stripes have been destroyed by the heat from the thermal
radiation.

effect of the destruction caused by the blast wave, fires can be started
by upset stoves and furnaces, electrical short-circuits, and broken gas
lines. No matter how the fire originates, its subsequent spread will
be determined by the amount and distribution of combustible materials
in the vicinity. It is seen, therefore, that the problem of the develop-
ment of fires accompanying a nuclear explosion falls into two distinct
categories: (1) the number of points at which fires originate, and
(2) the character of the surrounding area.

7.80 The initiation of secondary (or indirect) fires is difficult to
analyze, but there are some aspects of direct ignition by thermal radia-
tion 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 com-
bustible materials, such as those mentioned in the preceding paragraph,
might be found. In general, these materials might be expected to
ignite when exposed to from 3 to 5 calories per square centimeter of
radiant energy. The data in Fig. 7.80 are based on surveys made in a

USE CLASS	NUMBER OF TRANSIENT EXTERIOR IGNITION POINTS PER ACRE
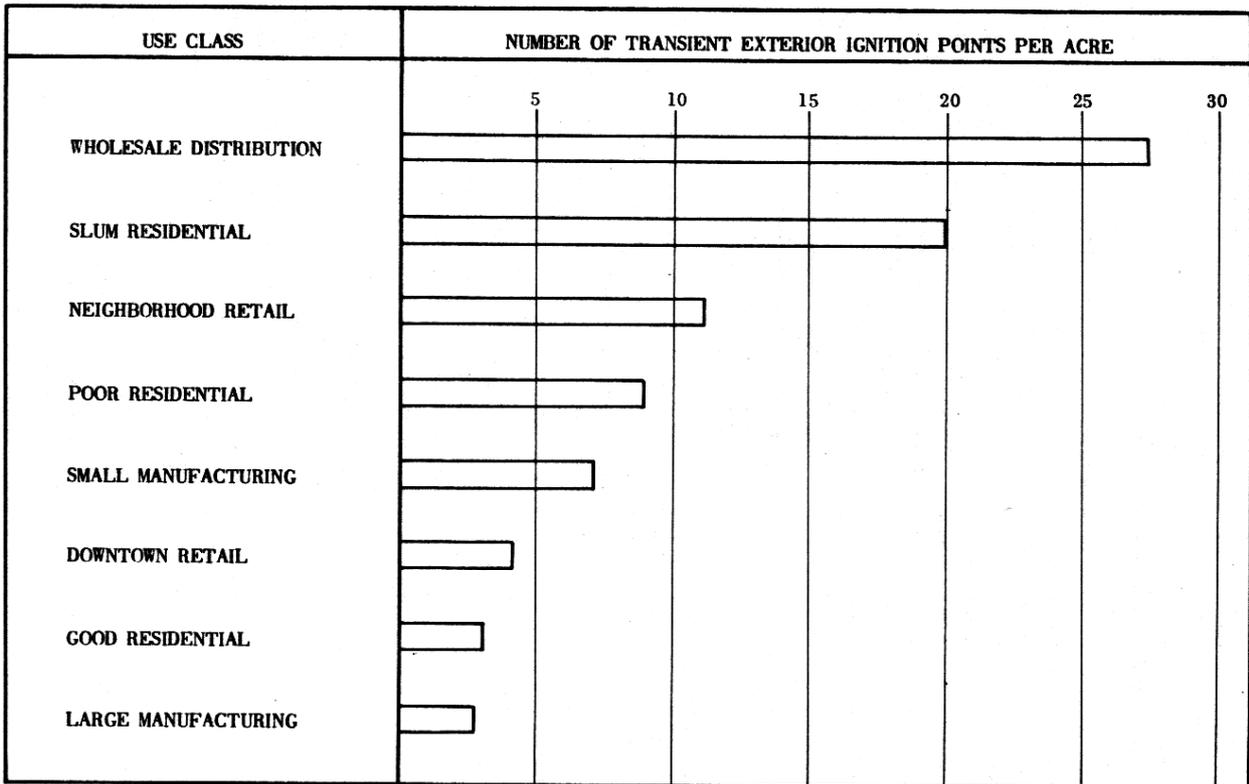
Figure 7.80. Frequency of exterior ignition points for various areas in a city.

number of large cities in the United States. It is seen that the density of ignition points is greatest in wholesale distribution and slum residential areas, and is least in good residential and large manufacturing areas.[5] Paper was the commonest ignitable material found everywhere except in downtown retail areas where awnings represented the major source of fire.

7.81 The density of ignition points provides some indication of the chance of fires being started under ideal weather conditions. But the results in Fig. 7.80 are by themselves not sufficient to permit an estimate to be made of the number of significant fires that will actually result. In the first place, at locations closer to ground zero, where the thermal energy exceeds about 12 calories per square centimeter, almost all the ignitable materials will actually flame (Table 7.65). On the other hand, at greater distances, only those most easily ignitable will catch fire. Further, the formation of a significant fire, capable of spreading, will require appreciable quantities of combustible material close by, and this may not always be available.

7.82 The fact that accumulations of ignitable trash close to a wooden structure represent a real fire hazard was demonstrated at the nuclear tests carried out in Nevada in 1953. In these tests, three miniature wooden houses, each having a yard enclosed with a wooden

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

fence, were exposed to 12 calories per square centimeter of thermal radiation. One house, at the left of Fig. 7.82, had weathered siding showing considerable decay, but the yard was free from trash. The next house also had a clean yard and, further, the exterior siding was well maintained and painted. In the third house, at the right of the photograph, the siding, which was poorly maintained, was weathered, and the yard was littered with trash.

7.83. The state of the three houses after the explosion is seen in Fig. 7.83. The third house, at the right, soon burst into flame and was burned to the ground. The first house, on the left, did ignite but it did not burst into flame for 15 minutes. The well maintained house in the center with the clean yard suffered scorching only. It is of interest to recall that the wood of a newly erected white-painted house exposed to about 25 calories per square centimeter was badly charred but did not ignite (Fig. 7.34b).

7.84 The value of fire-resistive furnishing in decreasing the number of ignition points was also demonstrated in the 1953 tests. Two identical, sturdily constructed houses, each having a window 4 feet by 6 feet facing the point of burst, were erected where the thermal radiation exposure was 17 calories per square centimeter. One of the houses contained rayon drapery, cotton rugs, and clothing, and, as was expected, it burst into flame immediately after the explosion and burned completely. In the other house, the draperies were of vinyl plastic, and rugs and clothing were made of wool. Although more ignition occurred, the recovery party, entering an hour after the explosion, was able to extinguish fires.

7.85 There is another point in connection with the initiation of fires by thermal radiation that needs consideration. This is the possibility that the flame resulting from the ignition of a combustible material may be subsequently extinguished by the blast wind. It was thought that there was evidence for such an effect from an observation made in Japan (§ 7.92), but this may have been an exceptional case. The matter has been studied, both in connection with the effects in Japan and at various nuclear tests, and the general conclusion is that the blast wind has no significant effect in extinguishing fires (see § 7.93).

Spread of Fires

7.86 The spread of fires in a city, depends upon a variety of conditions, e. g., weather, terrain, and closeness and combustibility of the buildings. A detailed review of large-scale fires has shown, however, that if other circumstances are more-or-less the same, the most

Figure 7.82.   Wooden test houses before exposure to a nuclear explosion, Nevada Test Site.
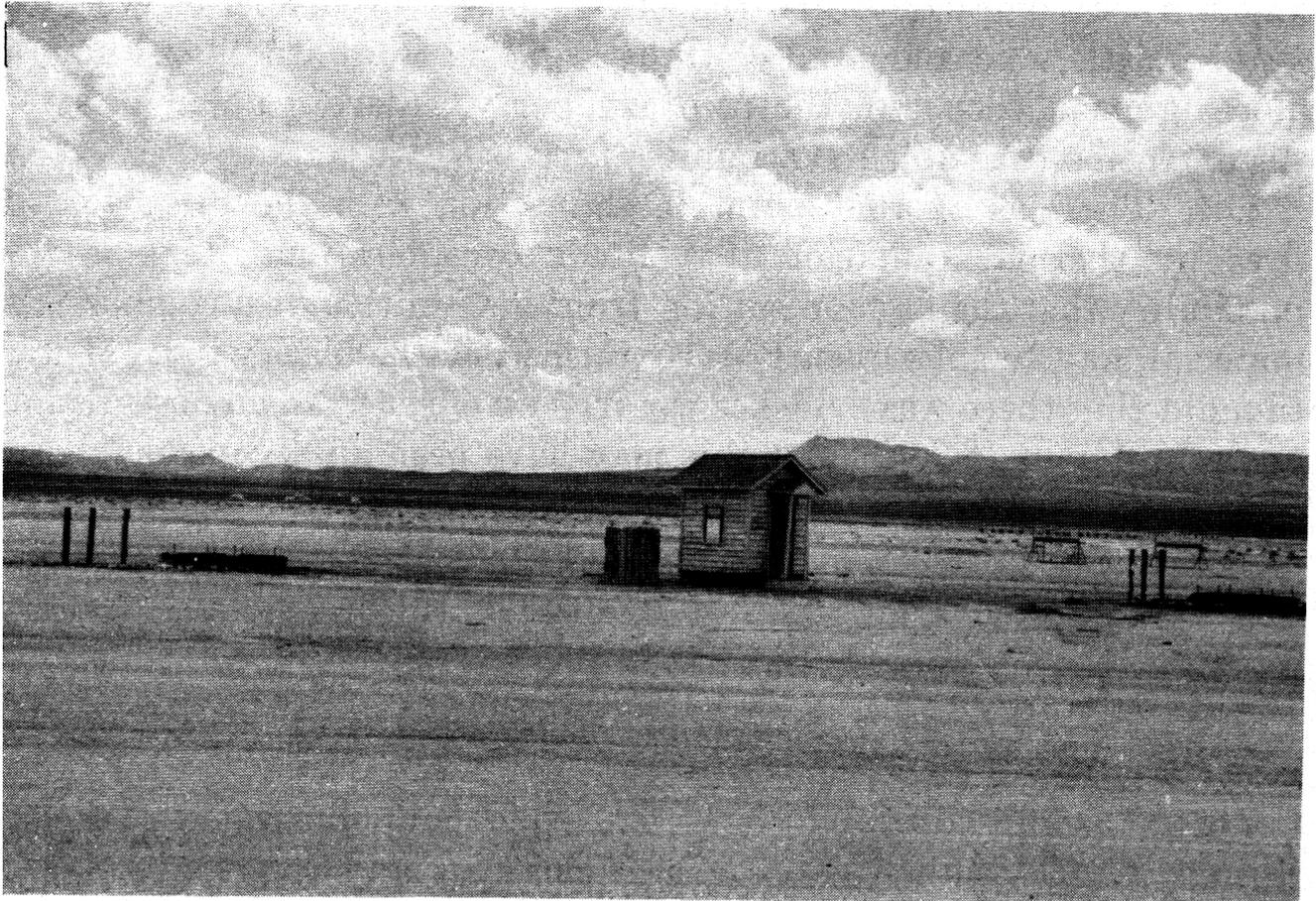
Figure 7.83.   Wooden test houses after exposure to the nuclear explosion.

important criterion of the probability of fire spread is the distance between buildings. It is evident, from general considerations, that the lower the building density or "built-upness" of an area, the less will be the probability that fire will spread from one structure to another. Further, the larger the spaces between buildings the greater the chances that the fire can be extinguished.

7.87 The curve in Fig. 7.87 gives a rough idea of how the probability of fire spread, expressed as a percentage, depends upon the average distance between buildings in a city. The results will be dependent, to some extent, upon the types of structures involved, e. g., whether they are fire-resistive or not, as well as upon the damage caused by the blast wave (§ 7.79). It should be noted that Fig. 7.87 applies to fire spread accompanying a nuclear explosion, when a large number of small fires are started directly by thermal radiation and indirectly in other ways.

7.88 Another aspect of fire spread is the development of mass fires in a forest following primary ignition of dried leaves, grass, and rotten wood by the thermal radiation. Some of the factors which will influence the growth of such fires are the moisture content of the trees,
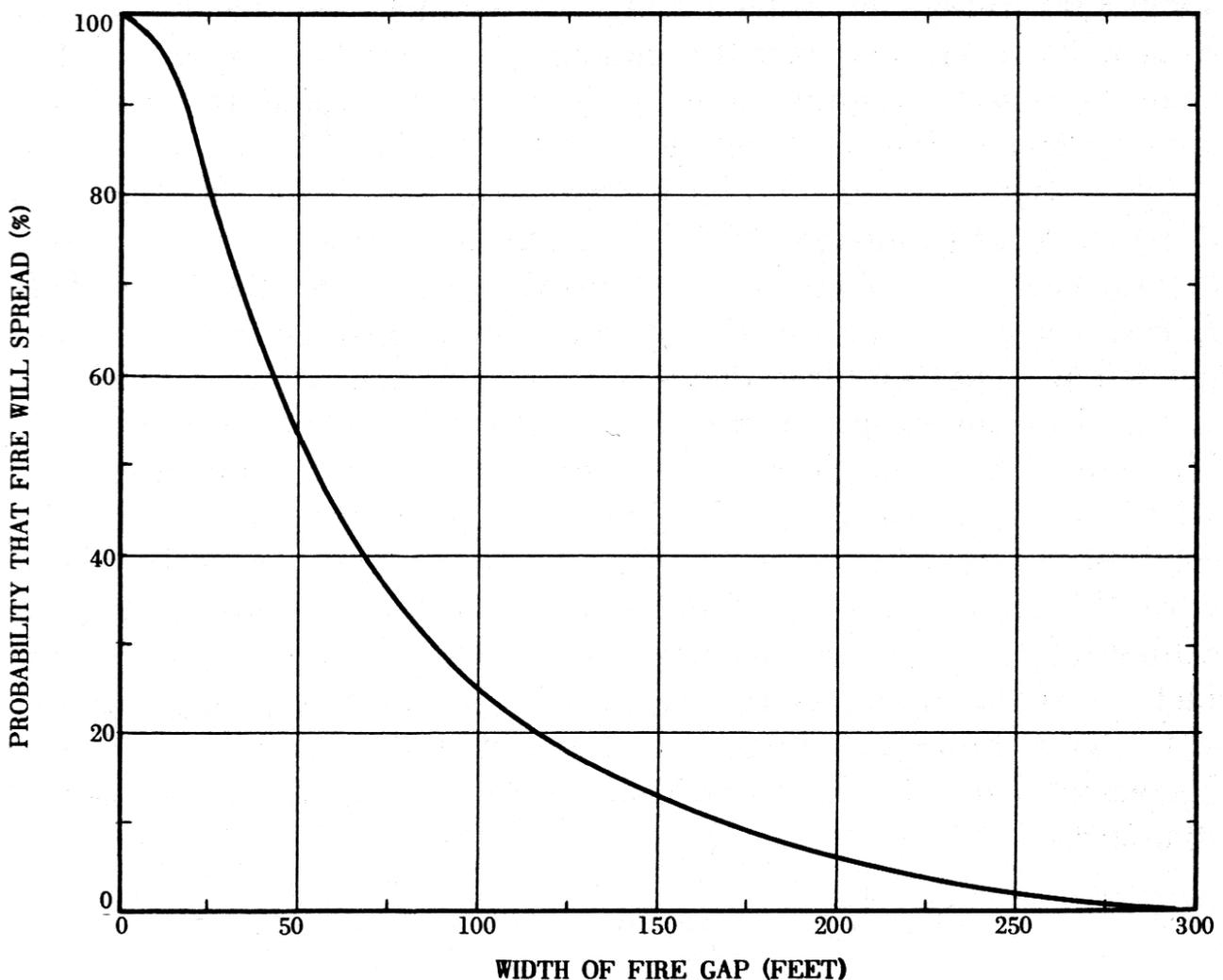
Figure 7.87. Width of gap and probability of fire spread.

topography, and meteorological conditions. Low atmospheric humidity, strong winds, and steep terrain favor the development of forest fires. In general, a deciduous forest, particularly when in leaf, may be expected to burn less rapidly and with less intensity than a forest of coniferous trees. Green leaves and the trunks of trees would act as shields against thermal radiation, so that the number of points at which ignition occurs in a forest may well be less than would appear at first sight.

INCENDIARY EFFECTS IN JAPAN

THE NUCLEAR BOMB AS AN INCENDIARY WEAPON

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

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

ORIGIN AND SPREAD OF FIRES IN JAPAN

7.91   Definite evidence was obtained from Japanese observers that the thermal radiation caused thin, dark cotton cloth, such as the

black-out curtains that were in common use during the war, thin paper, and dry, rotted wood to catch fire at distances up to 3,500 feet (0.66 mile) from ground zero (about 35 calories per square centimeter). It was reported that a cedar bark roof farther out was seen to burst into flame, apparently spontaneously, but this was not definitely confirmed. Abnormal enhanced amounts of radiation, due to reflection, scattering, and focusing effects, might have caused fires to originate at isolated points (Fig. 7.91).

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

7.93 From the evidence of charred wood found at both Hiroshima and Nagasaki, it was originally concluded that such wood had actually been ignited by thermal radiation and that the flames were subsequently extinguished by the blast. But it now seems more probable that, apart from some exceptional instances, such as that just described, there was no actual ignition of the wood. The absorption of the thermal radiation caused charring in sound wood but the temperatures were generally not high enough for ignition to occur (§ 7.34). Rotted and checked wood and excelsior, however, have been known to burn completely, and the flame is not greatly affected by the blast wave.

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

7.95 Once the fires had started, there were several factors, directly related to the destruction caused by the nuclear explosion, that influenced their spreading. By breaking windows and blowing in or
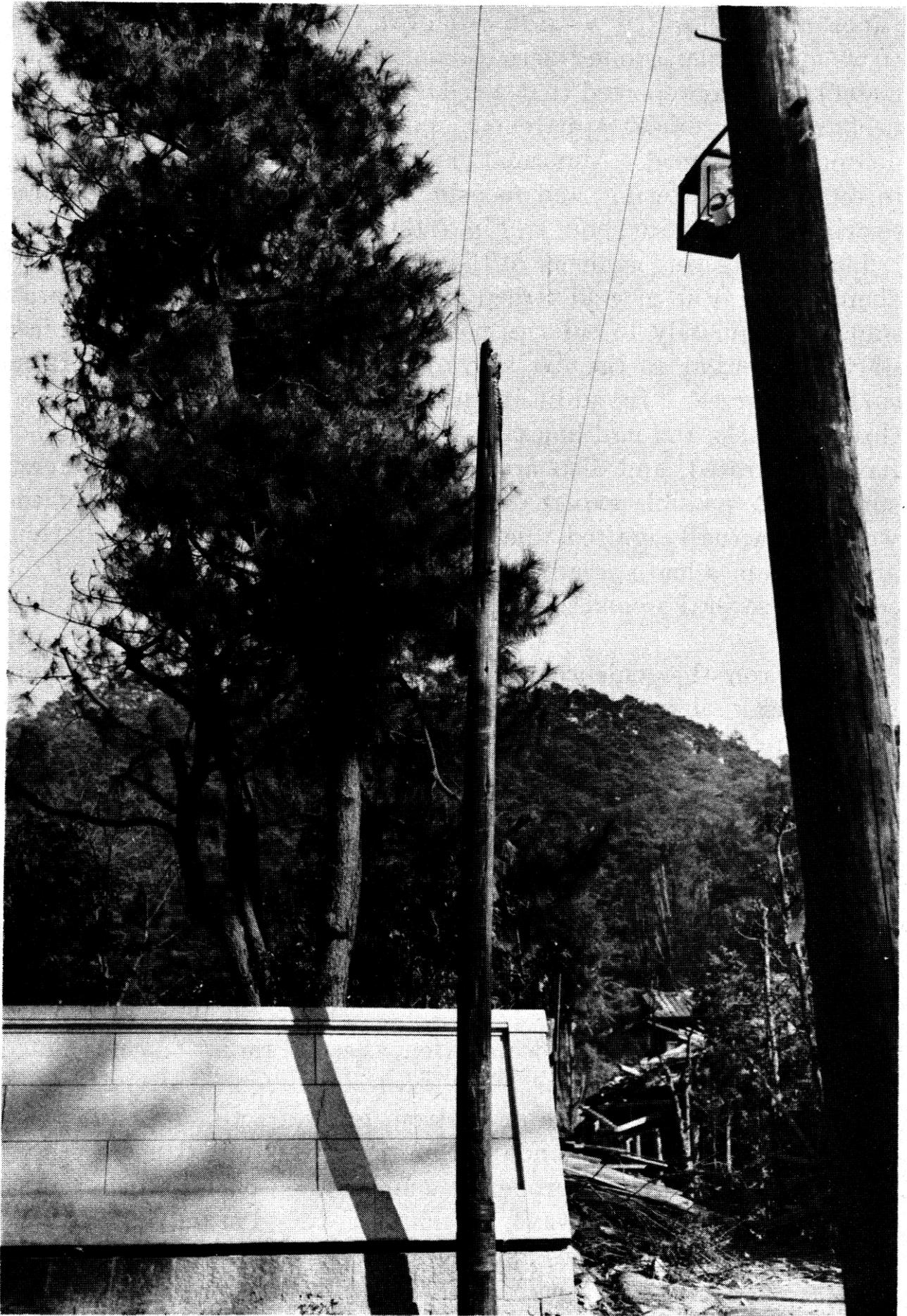
Figure 7.91.   The top of a wood pole was reported as being ignited by the thermal radiation (1.25 miles from ground zero at Hiroshima).   Note the unburned surroundings; the nearest burned building was 360 feet away.

damaging fire shutters (Fig. 7.95), by stripping wall and roof sheathing, and collapsing walls and roofs, the blast made many buildings more vulnerable to fire. Noncombustible (fire-resistive) structures were often left in a condition favorable to the internal spread of fires by damage at stairways, elevators, and in firewall openings, as well as by the rupture and collapse of floors and partitions (Fig. 4.85d).

Figure 7.95. Fire shutters in building blown in or damaged by the blast; shutter at center probably blown outward by blast passing through building (0.57 mile from ground zero at Hiroshima).

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

7.97 Although there were firebreaks, both natural, e. g., rivers and open spaces, and artificial, e. g., roads and cleared areas, in the Jap-

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

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

7.99   Another contributory factor to the destruction by fire was the failure of the water supply in both Hiroshima and Nagasaki. The pumping stations were not largely affected, but serious damage was sustained by distribution pipes and mains, with a resulting leakage and drop in available water pressure. Most of the lines above ground were broken by collapsing buildings and by heat from the fires which melted the pipes. Some buried water mains were fractured and others were broken due to the collapse or distortion of bridges upon which they were supported (§4.113).

Fire Storm in Hiroshima

7.100   About 20 minutes after the detonation of the nuclear bomb at Hiroshima, there developed the phenomenon known as "fire storm." This consisted of a wind which blew toward the burning area of the city from all directions, reaching a maximum velocity of 30 to 40 miles per hour about 2 to 3 hours after the explosion, decreasing to light or moderate and variable in direction about 6 hours after. The

wind was accompanied by intermittent rain, light over the center of the city and heavier about 3,500 to 5,000 feet (0.67 to 0.95 mile) to the north and west. Because of the strong inward draft at ground level, the fire storm was a decisive factor in limiting the spread of the fire beyond the initial ignited area. It accounts for the fact that the radius of the burned-out area was so uniform in Hiroshima and was not much greater than the range in which fires started soon after the explosion. However, virtually everything combustible within this region was destroyed.

7.101 It should be noted that the fire storm is by no means a special characteristic of the nuclear bomb. Similar fire storms have been reported as accompanying large forest fires in the United States, and especially after incendiary bomb attacks in both Germany and Japan during World War II. The high winds are produced largely by the updraft of the heated air over an extensive burning area. They are thus the equivalent, on a very large scale, of the draft of a chimney under which a fire is burning. The rain associated with a fire storm is apparently due to the condensation of moisture on particles from the fire when they reach a cooler area.

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

TECHNICAL ASPECTS OF THERMAL RADIATION[6]

SPECTRAL DISTRIBUTION OF ENERGY FROM BALL OF FIRE

7.103 If it can be assumed that the ball of fire in a nuclear explosion, like the sun, behaves rather like a black body, i. e., as a perfect radiator, the distribution of the thermal radiation energy over the

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[6] The remaining sections of this chapter may be omitted without loss of continuity.
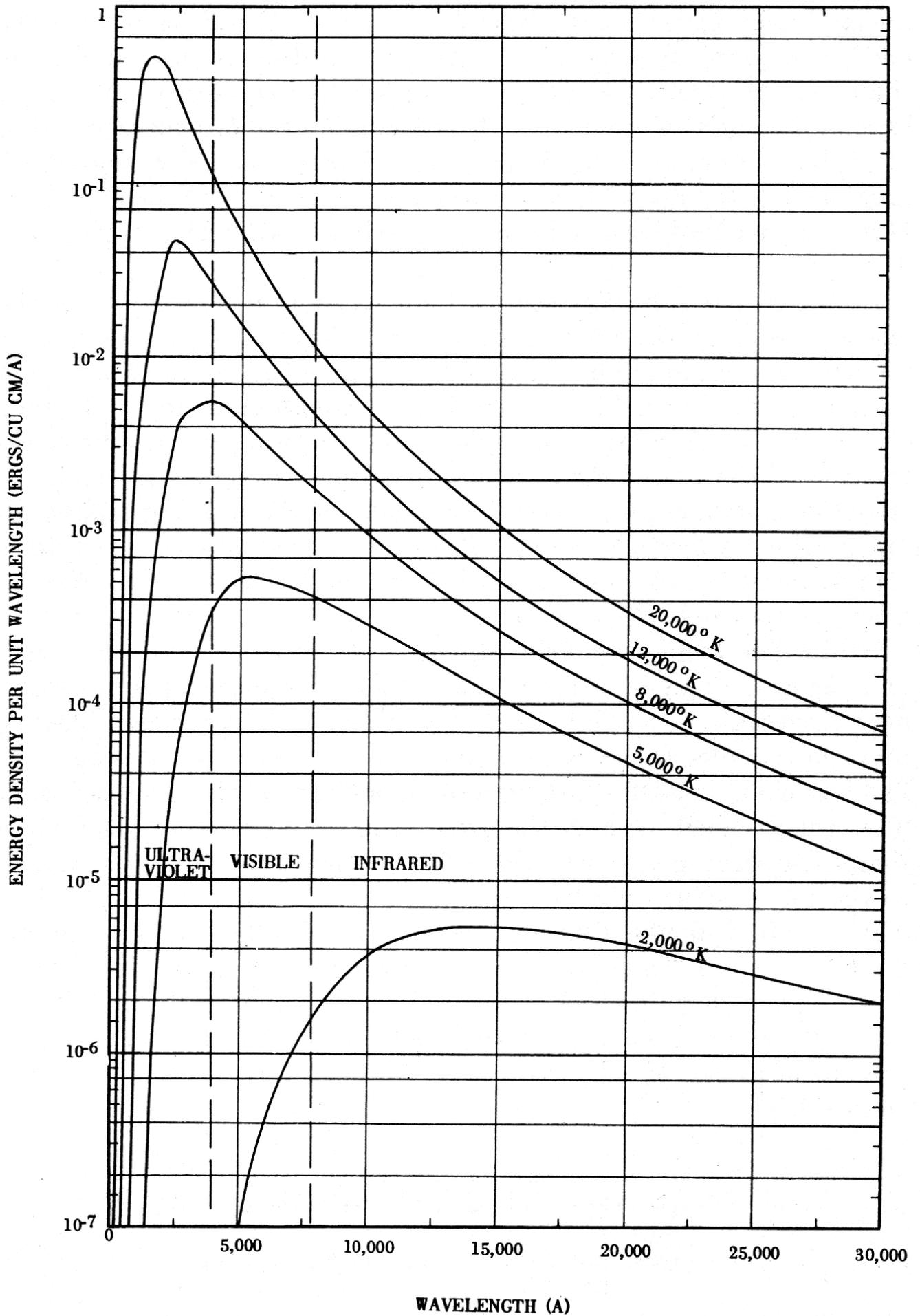
Figure 7.104.   Energy density per unit wave length of radiations of various wave lengths.

spectrum can be related to the surface temperature by Planck's radiation equation. If $E_\lambda d\lambda$ denotes the energy density, i. e., energy per unit volume, in the wave length interval λ to $\lambda + d\lambda$, then,

$$E_\lambda = \frac{8\pi hc}{\lambda^5} \cdot \frac{1}{e^{hc/\lambda kT} - 1},\qquad (7.103.1)$$

where c is the velocity of light, h is Planck's quantum of action, k is Boltzmann's constant, i. e., the gas constant per molecule, and T is the absolute temperature.

7.104   From the Planck equation it is possible to calculate the energy density of the thermal radiation from a nuclear explosion over a range of wave lengths for any specified temperature. The results obtained for several temperatures are shown by the curves in Fig. 7.104. It will be apparent that at temperatures exceeding about 8,000° K., such as is the case during most of the first radiation pulse from the ball of fire, i. e., prior to the first temperature minimum, much of the thermal energy emitted lies in the short wave length (ultraviolet) region of the spectrum.

7.105   As the temperature of the black-body radiator decreases, the wave length at which the energy density is a maximum is seen to move to the right, i. e., to regions of higher wave length. An expression for the wave length for maximum energy density, λ_m, can be obtained by differentiating equation (7.103.1) with respect to wave length and equating the result to zero. It is then found that

$$\lambda_m = \frac{A}{T},\qquad (7.105.1)$$

where A is a constant, equal to 0.2897 angstrom-degree K. Hence, the wave length for maximum energy density is inversely related to the absolute temperature.

7.106   From the known value of A, it can be calculated that the maximum energy density of thermal radiation just falls into the visible region of the spectrum at a temperature of about 7,600° K. This happens to be very close to the maximum surface temperature of the ball of fire after the minimum, i. e., during the second radiation pulse (Fig. 2.92). Since the temperature does not exceed 7,600° K. and the average is considerably less, it is evident that most of the radiant energy emitted in the second pulse consists of visible and infrared rays, with very little in the ultraviolet region of the spectrum.

THERMAL ENERGY FROM BALL OF FIRE

7.107.   For the present purpose, the total rate of emission of thermal radiation energy from the ball of fire is more significant than the

distribution of radiation density. According to the Stefan-Boltzmann law for black-body radiation, the flux (or intensity) of radiant energy, ϕ, i. e., the amount of energy passing through 1 square centimeter of surface of a black body per second, is related to the absolute temperature, T, by the equation,

$$\phi = \sigma T^4, \tag{7.107.1}$$

where σ is a constant. The value of ϕ can also be obtained by integration of the Planck equation (7.103.1), at constant temperature, over the whole range of wave lengths, from zero to infinity. It is then found that

$$\sigma = 2\pi^5 k^4 / 15 h^3 c^2$$
$$= 1.38 \times 10^{-12} \text{cal}/(\text{cm}^2)(\text{sec})(\text{deg}^4).$$

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

7.108   According to equation (7.107.1), the intensity of the radiation emitted from the ball of fire at any temperature is proportional to the fourth power of that temperature on the absolute scale. Since the surface temperatures are very high during the first radiation pulse, the rate of energy emission (per unit area), mainly in the ultraviolet region, will also be high. However, because of the short duration of the initial pulse, the total *quantity* of energy emitted is relatively small. In any case, most of what is emitted is absorbed and scattered by the atmosphere before it travels any appreciable distance from the fireball.

7.109   In accordance with the definition of radiation flux, ϕ, given in § 7.107, it follows that the total rate of emission of radiant energy from the ball of fire can be obtained upon multiplying the expression in equation (7.107.1) by the area. If R is the radius of the fireball, its area is $4\pi R^2$, so that the rate of thermal energy emission is $\sigma T^4 \times 4\pi R^2$. This is the same as the thermal power, since power is defined as the rate of production (or expenditure) of energy. Representing this quantity by the symbol P, it follows that

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

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

$$P = 1.59 \times 10^{-8} T^4 R^2 \text{ calories per second.} \tag{7.109.1}$$

7.110   The results of numerous tests have shown that the ball of fire

does not, in fact, behave as a perfect radiator. This is due to a number of factors. The surface temperature during the first radiation pulse is modified by the disturbed air immediately around the fireball and, at later times, the temperature is not that of the surface but the result of radiation some distance inside the fireball. The radius of the ball of fire during the second thermal pulse is very difficult to determine because the surface of the luminous ball of fire becomes very diffuse. Since the radii and surface temperatures will depend on the energy yield of the explosion, a different curve will be obtained for every value of the yield. However, it is possible to generalize the results, by means of scaling laws, so that a curve applicable to the second pulse for all energy yields can be obtained from a single set of calculations.

7.111   Actually the power, P, is measured directly as a function of time, t, for each explosion. However, instead of plotting P versus t, a curve is drawn of the scaled power, i. e., P/P_{max}, versus the scaled time, i. e., t/t_{max}, where P_{max} is the maximum value of the thermal power, corresponding to the temperature maximum in the second pulse, and t_{max} is the time at which this maximum is attained. The resulting (left scale) curve, shown in Fig. 7.111 is then of general applicability, irrespective of the yield of the explosion.

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

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

and

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

The application of these equations is illustrated in the example facing Fig. 7.111.

7.113   The amount of thermal energy, E, emitted by the ball of fire up to any specified time can be obtained from the area under the curve of P versus t up to that time. The result, expressed in percent as E/E_{tot} versus t/t_{max}, is shown by the second curve (right scale) in Fig. 7.111. The quantity E_{tot} is the total thermal energy emitted by the ball of fire; this is related to the total energy yield of the explosion, W kilotons, by the expression,

$$E_{tot} \text{ (kilotons)} = \tfrac{1}{3} W, \tag{7.113.1}$$

derived from measurements made at a number of test explosions. This equation gives the thermal energy in terms of kilotons of TNT

The curves show the variation with the scaled time, t/t_{max}, of the scaled fireball power, P/P_{max} (left ordinate) and of the percent of the total thermal energy emitted, E/E_{tot} (right ordinate).

Scaling. In order to apply the data in Fig. 7.111 to an explosion of any energy, W kilotons, the following expressions are used:

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

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

$$E_{tot} = \tfrac{1}{3}\ W\ \text{kilotons,}$$

where

$t_{max} =$ time after explosion for temperature maximum in second thermal pulse,

$P_{max} =$ maximum rate (at t_{max}) of emission of thermal energy from fireball,
and

$E_{tot} =$ total thermal energy emitted by fireball.

Example

Given: A 500 KT burst.

Find: (a) The rate of emission of thermal energy, (b) the amount of thermal energy emitted, at 2 seconds after the explosion.

Solution: Since W is 500 KT, the value of $W^{1/2}$ is 22.4, so that $t_{max} = 0.032 \times 22.4 = 0.72$ second, and the scaled time at 2 seconds after the explosion is

$$t/t_{max} = 2.0/0.72 = 2.8.$$

(a) From Fig. 7.111, the value of P/P_{max} at this scaled time is 0.26, and since $P_{max} = 4 \times 22.4 = 90$ kilotons per second, it follows that,

$$P = 0.26 \times 90 = 23\ \text{kilotons per second}$$
$$= 23 \times 10^{12}\ \text{calories per second.}\quad \textit{Answer}$$

(b) At the scaled time of 2.8, the value of E/E_{tot} from Fig. 7.111 is 58 percent, i. e., 0.58.

$$E_{tot} = \tfrac{1}{3} \times 500 = 167\ \text{kilotons}$$

Hence,

$$E = 0.58 \times 167 = 97\ \text{kilotons}$$
$$= 97 \times 10^{12}\ \text{calories.}\quad \textit{Answer}$$
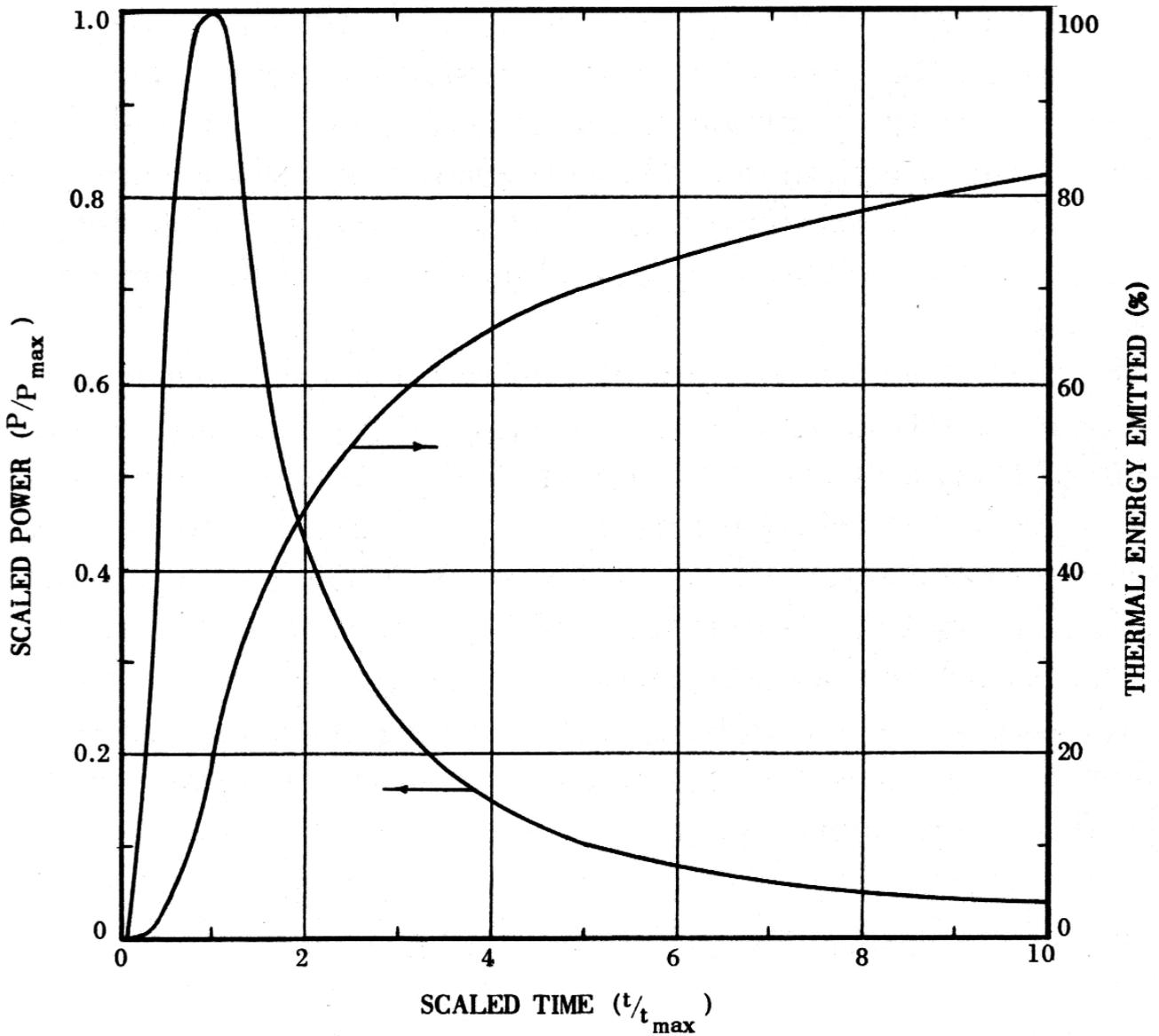
Figure 7.111. Scaled fireball power and fraction of thermal energy versus scaled time in second thermal pulse.

equivalent, but if it is required in calories the result is multiplied by 10^{12}.

7.114 The curves in Fig. 7.111 present some features of special interest. As is to be expected, the thermal power (or rate of emission of radiant energy) of the fireball rises to a maximum, just as does the temperature in the second radiation pulse. However, since the thermal power is roughly proportional to T^4, it increases and decreases much more rapidly than does the temperature. This accounts for the sharp rise to the maximum in the P/P_{max} curve, followed by a somewhat less sharp drop which tapers off as the ball of fire approaches its final stages.

7.115 From the standpoint of protection against skin burns, by taking evasive action, the important quantity is t_{max}, since the rate of emission of thermal radiation from the ball of fire is then a maximum. It is seen from the relationship in § 7.112 that this time increases in proportion to the square root of the energy yield of the explosion. Thus, t_{max} is about 0.1 second for a 10-kiloton explosion, but it is over 3 seconds for a burst with 10 megatons energy yield. At such respective distances where severe burns might be experienced, evasive action would thus be expected to achieve greater relative success for explosions of high energy yield.

THERMAL ENERGY-DISTANCE RELATIONSHIP

7.116 The next matter to consider is the variation with distance from the explosion of the total thermal energy (in calories) received per square centimeter of a target material. As seen earlier in this chapter, such information, combined with the data in Tables 7.45, 7.61, and 7.65, permits estimates to be made of the probable ranges for various thermal radiation effects.

7.117 If there is no atmospheric attenuation, the thermal energy, E_{tot}, at a distance D from the explosion, may be regarded as being spread uniformly over the surface of a sphere of area $4\pi D^2$. If attenuation were due only to absorption, this quantity would be multiplied by the factor e^{-kD}, where k is an absorption coefficient averaged over the whole spectrum of wave lengths. Hence, in these circumstances, using the symbol Q to represent the thermal energy received per unit area at a distance D from the explosion, it follows that

$$Q = \frac{E_{tot}}{4\pi D^2} e^{-kD}.$$
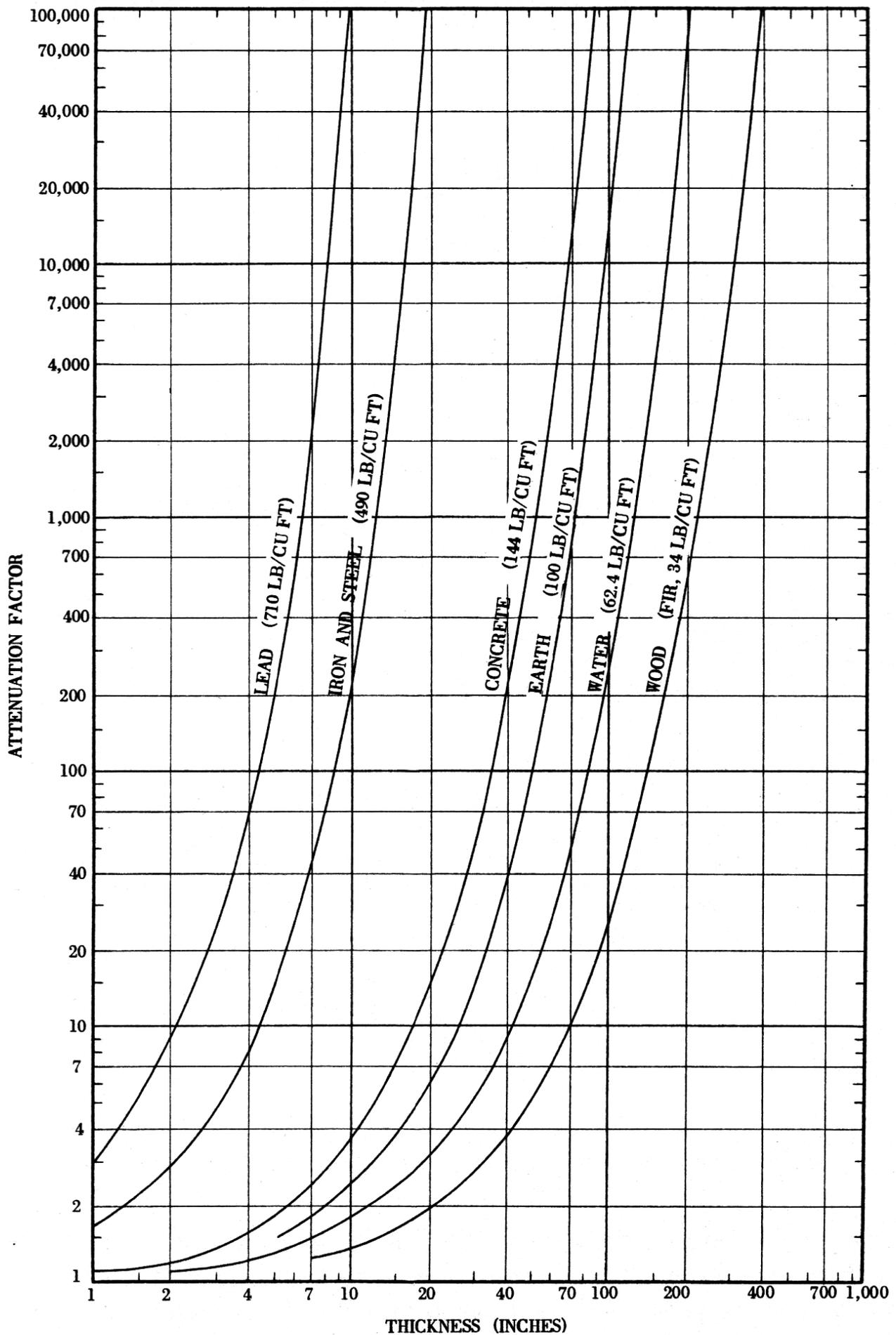
Figure 8.47. Attenuation of initial gamma radiation.
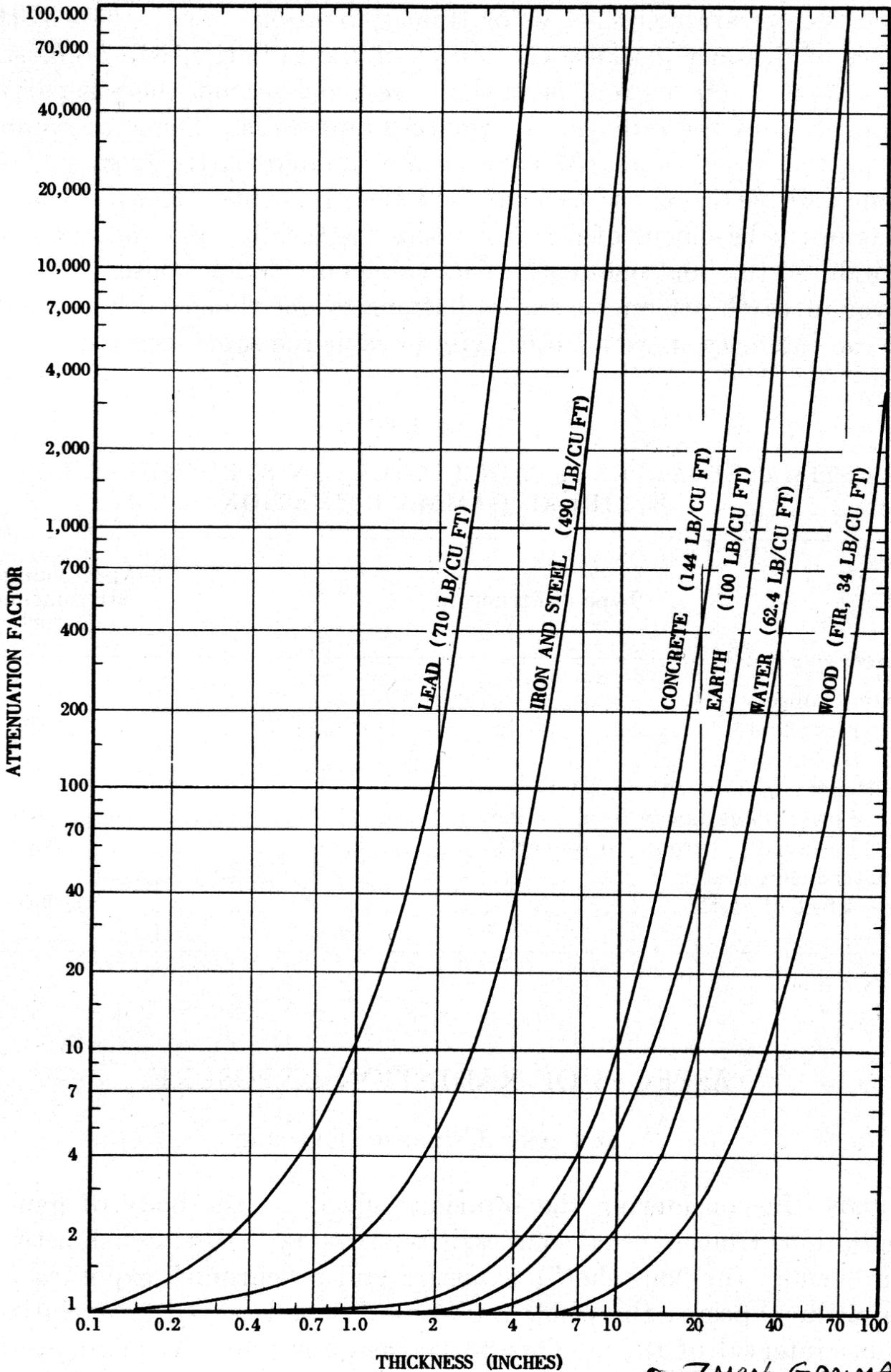
Figure 9.36. Attenuation of fission product radiation. (FALLOUT)

O·7 MeV GAMMAS

RADIOACTIVE CONTAMINATION IN NUCLEAR EXPLOSIONS

CONTAMINATION IN AN AIR BURST

9.48 There are two main ways in which the earth's surface can become contaminated with radioactive material as a result of a nuclear explosion. One is by the induced activity following the capture of neutrons by various elements present in the soil (or sea), and the other is by the fallout, that is, by the subsidence of radioactive particles from the column and cloud formed in the explosion (§ 2.21). Both the relative and actual importance of these two sources of contamination depend very greatly upon the location of the point of burst with regard to the surface of the earth, and also upon the energy yield of the explosion. Other factors which may affect the contamination are the nature of the terrain and meteorological conditions.

9.49 In an air burst the radioactive bomb residues, consisting largely of the fission products, condense into very small solid particles. In this finely divided state a portion of the radioactive particles enter the stratosphere and will remain suspended for many years, even circling the earth several times, before descending to the surface. During this period they undergo decay and loss of activity. Hence, when the particles do reach the earth's surface, they will be widely dispersed and their radioactivity will be very greatly reduced. In fact the external radiation produced by the fallout from a weapon with a fission yield in the megaton range would be extremely small in comparison with the natural background radiation (see, however, Chapter X).

9.50 Under certain meteorological conditions, e. g., abnormal winds or a rainfall situation, there might be appreciable fallout, probably of a localized character. For example, in a moist atmosphere the fine particles of bomb residue could attach themselves to water droplets which might subsequently fall as radioactive rain. Such was apparently the case in the moderately low air burst over Bikini Lagoon (Test ABLE) in 1946, as stated in § 2.98. The extent of the activity was, however, small, since most of the fission products were probably above the rain clouds at the time.

9.51 A special case of interest is that of a warm front rainfall situation, such as frequently occurs in temperate latitudes. The rain-bearing clouds may have a thickness of 20,000 feet and can extend over many hundreds of square miles. The rain is usually gentle, but continues to fall steadily for some time. If the situation existed at the time of the explosion, the radioactive particles formed in the air burst might ascend into the rain-bearing clouds. In a short time, the atomic cloud, if it did not rise above the rain-bearing cloud, would become so mixed with the latter as to become an integral part of the rain-

producing system. The radioactive material might then be expected to deposit with the rain over a large area, in a surface pattern dependent upon the winds at the cloud level.

9.52 An air burst of a small yield weapon would not be accompanied by serious local fallout except possibly in unusual circumstances, as is borne out by the fact that there were no casualties in the nuclear bombings of Japan that could be attributed to residual radiation. At Nagasaki, about 0.02 percent of the fission products was deposited on the surface within a radius of 2,000 feet (0.4 mile) of ground zero. However, at no time did this represent a significant radiation hazard. Observations made at tests indicate that the local fallout from air bursts is also small for large yield weapons.

9.53 An important source of contamination due to residual nuclear radiation from an air burst can be the activity induced by neutrons captured by elements, notably sodium and manganese, on the earth's surface (§ 9.21, *et seq.*) The amount of the contamination, which will be appreciable only in a limited area about ground zero, will depend upon the height of burst, the energy yield, and the time elapsed since the explosion. At Hiroshima and Nagasaki, for example, the induced radioactivity on the surface was believed to be negligible. In the ABLE test at Bikini, however, where the height of burst was less than in the Japanese explosions, an appreciable amount of radioactive sodium-24 was formed in the water. The gamma rays from this isotope gave a dose rate of about 1 roentgen per hour just above the surface of the lagoon at 2 hours after the burst.

9.54 A low air burst of a nuclear weapon of high energy could result in extensive contamination due to induced activity in the vicinity of ground zero. In this region, destruction by blast and fire, except for strong underground structures, would be virtually complete.

CONTAMINATION IN A SURFACE BURST

9.55 In an air burst, the neutron-induced activity may be significant, but the local fallout, soon after the explosion, will generally be unimportant. The fission products will, however, contribute to the activity of the gradual fallout extending over large areas. With a surface (or subsurface) burst, on the other hand, the local fallout will assume major significance. Although there will undoubtedly be a considerable amount of induced radioactivity near ground zero, the activity of the fission product fallout will be so much greater in a surface burst that the induced activity can be neglected in comparison.

Consequently, the subsequent discussion of the residual radiation following a surface burst will deal mainly with the (local) fallout of fission products.

9.56 The fraction of the total radioactivity of the bomb residues that appears in the fallout depends upon the extent to which the ball of fire touches the surface. Thus, the proportion of the available activity increases as the height of burst decreases and more of the fireball comes into contact with the earth. In the case of a contact burst, i. e., one in which the bomb is actually on the surface when it explodes, some 50 percent of the total residual radioactivity will be deposited on the ground within a few hundred miles of the explosion. The remainder of the activity will stay suspended for a long time and will eventually reach the earth many hundreds or thousands of miles away, as in the case of an air burst (§ 9.49).

9.57 In a surface burst, large amounts of earth, dust, and debris are taken up into the fireball in its early stages. Here they are fused or are vaporized and become intimately mixed with the fission products and other bomb residues, as described in § 2.21. As a result, there is formed upon cooling a tremendous number of small particles contaminated to some distance below their surfaces with radioactive matter. In addition, there are considerable quantities of pieces and particles, covering a range of sizes from large lumps to fine dust, to the surfaces of which fission products are more or less firmly attached.

9.58 The larger (heavier) pieces, which will include a great deal of contaminated material scoured and thrown out of the crater (§ 5.4), will not be carrried up into the mushroom cloud, but will descend from the column. Provided the wind is not excessive, this large particulate material, as it falls, will form a roughly circular pattern around ground zero. Actually, the center of this circular pattern, called the "ground zero circle," will usually be displaced somewhat from ground zero by the wind.

9.59 Most of the contaminated material referred to above, forming the ground zero circle, descends within a short time, not more than an hour or so. The smaller particles present in the atomic column are, however, carried upward to a height of several miles (§ 2.16) and may spread out some distance in the mushroom cloud before they begin to descend. The time taken to reach the earth and the horizontal distance traveled will depend upon the height reached before they begin to fall, the size of the particles, and upon the wind pattern in the upper atmosphere. The smallest (and lightest) particles, like those formed in an air burst, will enter the stratosphere and remain suspended for long periods and may travel many thousands of miles

before descending (§ 9.49). Most of the larger particulate matter, however, will probably reach the earth as local fallout within a few hundred miles from ground zero.

9.60 As a general rule, it is to be expected that, except for the very smallest particles which descend over a wide area, the fallout of particles of moderate and small size will form, in the course of time, a kind of elongated (or cigar-shaped) pattern of contamination. The shape and dimensions will be determined by the wind velocities and directions at all altitudes between the ground and the atomic cloud. For simplicity of representation, the actual complex wind pattern may be replaced by an approximately equivalent "effective wind." The direction and velocity of this wind are intended to represent weighted averages over the whole wind system to which the particles of the fallout are subjected as they descend to earth as local fallout from the atomic cloud (see § 9.140).

9.61 In Fig. 9.61 an attempt is made to generalize the pattern of contamination due to the residual nuclear radioactivity from a nuclear
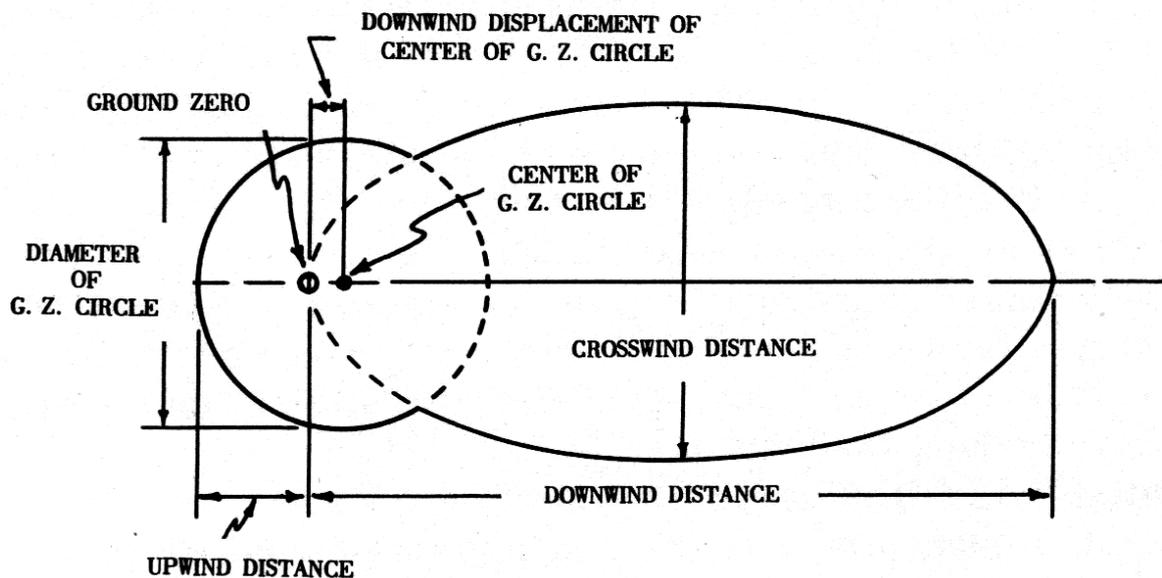
Figure 9.61. Generalized fallout pattern.

explosion near the earth's surface. The figure shows the **ground zero** (GZ) circle, corresponding to a particular dose rate (or total dose) of nuclear radiation at a specified time. Its center is somewhat displaced from actual ground zero by the wind in the vicinity of the explosion. The direction of this wind is assumed to be the same as that of the effective wind for the fallout, but this will not necessarily always be the case. The complete ground zero contamination pattern will consist of a series of circles, each representing a dose-rate (or dose) contour, for a specified dose-rate (or dose) of residual radiation.

9.68   In the program of nuclear test explosions in Nevada, the contamination in the vicinity of the burst has been given detailed study. The majority of these tests produced contamination patterns of the general form shown in Fig. 9.61. Hence, idealized contours of the same type are useful to indicate average, representative values for planning purposes. The contour dimensions for various 1-hour (reference) dose rates from the fallout from a 20-kiloton surface explosion, assuming a 15-mile per hour effective wind, are recorded in Table 9.68. These reference values were calculated from the dose-rate measurements made after fallout was complete, as indicated in § 9.9.

TABLE 9.68

APPROXIMATE RESIDUAL RADIATION 1-HOUR (REFERENCE) DOSE-RATE CONTOURS ON GROUND FOR 20-KILOTON SURFACE BURST

Dose rate (r/hr)	Radius of GZ circle (miles)	Displacement of center of GZ circle (miles)	Downwind distance (miles)	Crosswind distance (miles)
3,000	0. 10	0. 08	1. 0	0. 3
1,000	0. 22	0. 14	2. 3	0. 7
300	0. 41	0. 22	5. 3	1. 2
100	0. 66	0. 28	11. 5	1. 8
30	0. 95	0. 36	22	2. 8
10	1. 4	0. 42	50	5. 1

9.69   It is apparent that the dose rate close to ground zero, especially in the crater region, is very high, so that the area would be uninhabitable because of the radiation hazard. However, this area would be uninhabitable, in any event, because of the complete destruction due to blast and shock, and cratering of the ground.

9.70   In addition to the contamination in the vicinity of ground zero, which is equivalent to the ground zero circle representation in Fig. 9.61, regions of somewhat higher radioactivity than the surroundings, called "hot spots," have been detected on the surface several miles from the explosion center, both at Alamogordo and at the Nevada Test Site. This fallout of fission products is probably due to a special combination of meteorological, atmospheric, and ground conditions leading to increased deposition in a particular region.

HIGH FISSION-YIELD EXPLOSIONS

9.71 The contour dimensions for a number of hypothetical (reference) 1-hour dose rates, relating to a 1-megaton fission yield surface burst, are given in Table 9.71, based on an effective wind velocity of 15 miles per hour. The data are obtained, as before, by using the fission product decay curve (Fig. 9.8), or an equivalent mathematical expression, to determine what the dose rate would have been at 1 hour after the explosion, if the fallout at each location had been complete at that time. The upwind extent of any particular dose rate contour given in the table is obtained by subtracting the ground zero (GZ) circle displacement from the ground zero circle radius. For example, the 10 roentgens per hour reference contour extends $11.0 - 1.65 = 9.35$ miles upwind.

TABLE 9.71

APPROXIMATE RESIDUAL RADIATION 1-HOUR (REFERENCE) DOSE-RATE CONTOURS ON GROUND FOR 1-MEGATON SURFACE BURST

Dose rate (r/hr)	Radius of GZ circle (miles)	Displacement of center of GZ circle (miles)	Downwind distance (miles)	Crosswind distance (miles)
3,000	0. 43	0. 60	22	3. 1
1,000	1. 4	0. 80	40	6. 8
300	2. 8	1. 02	70	11. 8
100	4. 7	1. 24	114	16. 7
30	7. 5	1. 46	183	22. 8
10	11. 0	1. 65	317	34. 1

9.72 A more complete (idealized) representation of the contour pattern of the 1-hour (reference) dose rates, for the conditions stated above, is given in Fig. 9.72. Because of the lack of symmetry in the terrain and the effects of winds, the elliptical fallout contours for the residual radiation will not look exactly like those in Fig. 9.72. However, for representation purposes the contours are idealized in accordance with the form shown in Fig. 9.61.

9.73 It is of the utmost importance that the significance of the contours in Fig. 9.72 should not be misunderstood. The fact that the 1-hour (reference) dose rates extend to great distances from ground zero must not be taken to imply that such dose rates exist at 1 hour

shall Islands was the result of a combination of circumstances involving the energy yield of the explosion, the height of burst, the nature of the surface below the point of burst, the wind system over a large area and to a great height, and other meteorological conditions. A change in any one of these factors could have affected considerably the details of the fallout pattern.

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

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

RADIOLOGICAL WARFARE

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

9.96   Even if a radioisotope with suitable properties and which could be readily manufactured were selected as a radiological war-

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

9.97 The situation has undergone a change with the development of bombs having high fission energy yields. The explosion of such bombs at low altitudes can cause radioactive contamination over large areas that are beyond the range of physical damage. Consequently, they are, in effect, weapons of radiological warfare. Instead of preparing and stockpiling the contaminating agent in advance, with its attendant difficulties, the radioactive substances are produced by fission at the time of the explosion. Radiological warfare has thus become an automatic extension of the offensive use of nuclear weapons of high yield.

CONTAMINATION OF AREAS

9.98 It was suggested in § 9.95 that radioactive contamination could deny the use of considerable areas for an appreciable period of time. There are two aspects of this situation which merit consideration. First, the direct effect of the radiation exposure on human beings who might have to live or work in a contaminated region, and second, the indirect effect due to the consumption of food grown (and animals raised) in such an area. The methods for calculating exposure doses from fission products, assuming no protection, have been given in this chapter (see also Figs. 12.107 and 12.108). The time that may be spent at a given location can thus be determined, provided some limit has been set concerning the total exposure dose. The value of such an emergency dose cannot be prescribed in advance, since it will depend entirely on the conditions existing in the particular circumstances.

9.99 In contaminated agricultural areas, the hazard to workers could be reduced by turning over the earth, so as to bury the fallout particles. But there still remains the matter of the absorption of fission products from the soil by plants and their ultimate entry into the human system in food. It is known that some elements are taken

up more easily than others, but the actual behavior depends on the nature of the soil and other factors. This highly complex problem is being studied to determine the extent of the hazard which would result from the absorption of fission products by plants in various circumstances and how it might be minimized.

CONTAMINATION IN SUBSURFACE BURSTS

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

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

9.102 Since a shallow burst, in which the fireball emerges from the ground, is essentially similar to a low surface burst, in which a large part of the fireball touches the earth, this type of nuclear explosion need not be discussed further. The case of interest, however, is that of a subsurface burst at such a depth that the ball of fire does not emerge, yet a considerable amount of dirt (or water) is thrown up as a column into the air (§ 2.67).

9.103 It may be noted that some contribution to the residual nuclear radiations following a subsurface detonation is made by the radioisotopes, e. g., sodium-24 (§ 9.21), formed by neutron capture. However, as with a surface burst, this is so small in comparison with the radiations from the fission products that it may be ignored.

9.104 In the case of an underground explosion at a moderate depth there will be considerable crater formation. Much of the radioactive material will remain in the crater area, partly because it does not escape and partly because the larger pieces of contaminated rock, soil, and debris thrown up into the air will descend in the vicinity of the explosion. The finer particles produced directly or in the form of a base surge (§ 2.71) will remain suspended in the air and will descend as a fallout at some distance from ground zero.

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

9.106 The fallout following a shallow underwater burst, of the type used in the Bikini BAKER test in July 1946 (§ 2.49), will be very much like that of an underground explosion, as just described. In this particular test, the cloud did not ascend as high as in an air burst of the same energy yield. As a result, the fallout, which was in effect a radioactive rain, commenced to descend very soon after the explosion. In fact, the first fallout (or rain-out) reached the surface of the lagoon within about a minute of the detonation. A large proportion of the fission product (and other) activity was thus precipitated in a short time within a radius of a few thousand yards of the approximately 20-kiloton burst.

9.107 In the Bikini BAKER test the base surge, consisting of a contaminated cloud or mist of small water droplets, formed 10 to 12 seconds after the explosion and moved rapidly outward (§ 2.57). This undoubtedly contributed to the radioactivity deposited on the ships in the lagoon, but the base surge is now thought to be less significant as a source of contamination than the water (rain-out) which descended from the cloud system.

9.108 An important difference between an underwater burst and one occurring under the ground, is that the radioactivity remaining in the water is gradually dispersed, whereas that in ground is not. As a result of diffusion of the various bomb residues, mixing with large volumes of water outside the contaminated area, and natural decay, the radiation intensity of the water in which a nuclear explosion has occurred will decrease fairly rapidly. Some indication of the rate of decrease and of the spread of the active material is pro-

WORLD-WIDE FALLOUT AND LONG-TERM RESIDUAL RADIATION

LOCAL AND WORLD-WIDE FALLOUT

INTRODUCTION

10.1   The fallout of nuclear bomb debris considered in the preceding chapter may be described as being "local" in character. It consists chiefly of the larger particles which descend to earth, under the influence of gravity, in a matter of hours. The distances traveled are comparatively short and are not more than a few hundred miles from ground zero, in a downwind direction, even for the largest explosions. The early danger from the local fallout is due primarily to nuclear radiations from radioactive materials outside the body. During the first few days or weeks after the detonation, the radiation levels may be high enough to represent a danger to exposed persons. The radiation intensity decreases rapidly with time and, except for areas of very high initial contamination, it ceases to be a serious hazard within a few weeks. However, as seen earlier, the radioactivity diminishes more slowly as time passes, so that, even after several years, some will still persist.

10.2   There is another form of fallout that is much more widespread than the local type. It is that portion of the bomb residues which consists of very fine material that remains suspended in the air for times ranging from days to years. These fine particles can be carried over large areas by the wind and may, ultimately, be deposited in parts of the earth remote from the point of burst. The fallout of this fine debris is referred to as "world-wide fallout". It should not be inferred from this term, however, that none of the fine material is deposited in areas near the explosions, nor that such material is deposited uniformly over the earth. The nature of the distribution will be considered below; for the present, the main point is that the fallout under consideration is very much more widespread than the local type.

446

10.3   An overexposure to radiation from the local fallout could lead to harmful consequences that are experienced within a few days (or weeks) of the explosion; these are called "short-term" effects. In addition, there will be certain "long term" (or delayed) effects which may never become apparent or may become apparent years after the explosion. Nuclear radiation from early (or local) fallout as well as that received at much lower dose rates over succeeding months or years, from both local and world-wide fallout, could contribute to the probability of these delayed effects. Such radiation may originate in material both inside and outside the body.

10.4   One of the long-term effects may be that of genetic changes brought about by exposure to nuclear radiation of the cells which transmit inherited characteristics from one generation to the next. This aspect of the action of residual (and other) radiations will be examined in more detail in Chapter XI. The long term effects to be considered here are those which could result from exposure of body tissues to radiation from materials which may have accumulated within the body over long periods of time. It is in this connection that the world-wide fallout is of interest.

Tropospheric Fallout

10.5   It has already been seen in earlier chapters of this book that local fallout is important only when the nuclear burst occurs at or near (above or below) the earth's surface, so that a large amount of debris is carried up into the atomic cloud. On the other hand, contributions to world-wide fallout can come from nuclear explosions of all types, except those so far beneath the surface that the ball of fire does not break through and there is no atomic cloud. However, with regard to the mechanism of the world-wide fallout, a distinction must be drawn between the behavior of explosions of low energy yield and those of high energy yield. It will be assumed that the burst occurs in the lower part of the troposphere. (The troposphere is that part of the atmosphere which extends to a height of some 30,000 to 50,000 feet, depending on the existing climatic conditions.) Then, from nuclear detonations in the kiloton range, the atomic cloud will not generally rise above the top of the troposphere (§§ 2.14, 2.15). Consequently, nearly all the fine particles present in the bomb debris from such explosions will remain in the troposphere until they are eventually deposited.

10.6   The mechanism of deposition of the fine fallout particles from the troposphere is complex, since various processes, in addition

to simple gravitational settling, are involved. The most important of these processes appears to be the scavenging effect of rain or other form of moisture precipitation. The rate of removal of material from the troposphere at any time is apparently proportional to the amount present at that time. Hence, the time for one half of the material to be deposited, called the "residence half-time," is a characteristic quantity. For the tropospheric fallout this half-time is of the order of a few weeks, so that bomb debris does not remain for very long in the troposphere.

10.7 While the fine debris is suspended in the troposphere, the major part of the material is moved by the wind at high altitudes. In general, the wind pattern is such that the debris is carried rapidly in an easterly direction, making a complete circuit of the globe in some 4 to 7 weeks. Diffusion of the cloud to the north and south is relatively slow, with the result that most of the fine tropospheric fallout is deposited, in a short period of weeks, in a fairly narrow band encircling the world at the latitude of the nuclear detonation.

STRATOSPHERIC FALLOUT

10.8 For explosions of high energy yield, in the megaton range, nearly all of the bomb debris will pass up through the troposphere and enter the stratosphere. The larger particles will be deposited locally for a surface or subsurface burst. The very fine particles, from bursts of all types, can then be assumed to remain in the stratospheric debris, which spreads worldwide. Due to their fineness, and the absence of clouds and rainfall at such high altitudes, the particles will settle earthward very slowly. Estimates based on the limited information at present available indicate that about 10 percent of the debris stored in the stratosphere descends to earth annually; the corresponding residence half-time is thus about 7 years. During its long residence in the stratosphere, the bomb residues diffuse slowly but widely, so that they can enter the troposphere above any point of the globe. Once in the troposphere, the fine material probably behaves like that which remained initially in that part of the atmosphere from a low energy explosion, and so is brought to earth fairly rapidly by rain or snow.

10.9 An important feature of this stratospheric world-wide fallout is the fact that the radioactive particles are, in effect, stored in the stratosphere, with a small fraction continuously dribbling down to the earth's surface. While in stratospheric storage, the debris does not represent a direct radioactive hazard. In fact, during this time

most of the short-lived activity decays away, and some of the longer-lived activities are appreciably reduced. Thus, stratospheric world-wide fallout is a slow, continuous deposition of radioactive material over the entire surface of the earth, the rate of deposition depending on the total amount of bomb debris still present in the stratosphere.

LONG-TERM RESIDUAL RADIATION HAZARD

INTRODUCTION

10.10 Of the fission products which present a potential long-term hazard, from either the testing of nuclear weapons in peacetime or their use in warfare, the most important are probably the radioactive isotopes cesium-137 and strontium-90. Since both of these isotopes are fairly abundant among the fission products and have relatively long half-lives, they will constitute a large percentage of any world-wide fallout. Of course, the activity level due to these isotopes at late times in the local fallout pattern from a surface or subsurface burst will be considerably larger than in the world-wide fallout from a given nuclear burst.

CESIUM-137

10.11 Cesium has a radioactive half-life of 30 years and is of particular interest in fallout that is more than a year old because it is the principal constituent whose radioactive decay is accompanied by the emission of gamma rays.[1] The chemical properties of cesium resemble those of potassium. The compounds of these elements are generally more soluble than the corresponding compounds of strontium and calcium (see § 10.17); and the details of the transfer of these two pairs of elements from the soil to the human body are quite different.

10.12 Cesium is a relatively rare element in nature and the body normally contains only small traces. Consequently, the biochemistry of cesium has not been studied as extensively as that of some of the more common elements. It has been determined, however, that cesium-137 distributes itself within living cells in the same way as potassium, so that it is found mostly in muscle. Based on one experiment with several human subjects, the current estimate of the time required for normal biological processes to reduce the amount of ce-

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[1] The gamma rays are actually emitted, within a very short time, by a high-energy state of the decay product, barium-137.

sium in the body by one-half, i. e., the biological half-life (see § 11.110), is 140 days. Because of the penetrating properties of the gamma rays from the decay of cesium-137, the radiation is distributed more or less uniformly to all parts of the body. Although the radioactive decay of cesium-137 is accompanied by gamma-ray emission, the relatively short time of stay, together with most of the cesium being in a less sensitive location in the body, indicates that, for the same amount of stratospheric fallout, the residual cesium-137 will be less of a general pathological hazard than the residual strontium-90.

STRONTIUM-90

10.13　Attention will now be given to what is probably the more serious long-term hazard. Because of its relatively long radioactive half-life of 28 years and its appreciable yield in the fission process, strontium-90 accounts for a considerable fraction of the total activity of fission products which are several years old. Thus, even such material as has been stored in the stratosphere for several years will be found to contain a large percentage of this radioactive species.

10.14　Strontium is chemically similar to calcium, an element essential to both plant and animal life; a grown human being, for example, contains over 2 pounds of calcium, mainly in bone. As a consequence of the chemical similarity, strontium entering the body follows a path similar to calcium and therefore is found almost entirely in the skeleton, from which it is eliminated very slowly. Thus, the half-life of strontium in human bone is estimated to be about 10 years.

10.15　The probability of serious pathological change in the body of a particular individual, due to the effects of internal radioactive material, depends upon the intensity and energy of the radioactivity and upon the length of time the source remains in the body (see § 11.102, *et seq.*). Although strontium-90 emits only beta particles (no gamma rays), a sufficient amount of this isotope can produce damage because once it gets into the skeleton it will stay there for a long time. As a result of animal experimentation, it is believed that the pathological effects which may result from damaging quantities of strontium-90 are anemia, bone necrosis, cancer, and possibly leukemia. It is the combination of physical and chemical properties of strontium-90, namely, its long radioactive half-life and its similarity to calcium, with the nature of the pathological changes which can result from concentrations of radioactive material in the skeleton, that make strontium-90 the most important isotope, so far as is known, as a possible cause of harmful long-term effects of fallout.

10.16 Genetic effects due to strontium-90 are relatively insignificant. In the first place, owing to their very short range in the body, the beta particles from this isotope in the skeleton do not penetrate to the reproductive organs. Further, the intensity of the secondary radiation (bremsstrahlung) produced by the beta particles is low. Finally, the amount of strontium-90 in soft tissue, from which the beta particles might reach the reproductive organs, is small and may be neglected in this regard.

TRANSFER OF STRONTIUM-90 FROM SOIL TO THE HUMAN BODY

10.17 Since most of the strontium-90 is ultimately brought to earth by rain or snow, it will make its way into the soil and eventually into the human body through plants. At first thought, it might appear that the ratio of strontium to calcium in man would become similar to that in the soil from which he obtains his food. Fortunately, however, several processes in the chain of biological transfer of these elements from soil to the human body operate collectively to decrease the quantity of strontium-90 that is stored in man. These transfer processes include the following stages: (1) soil to plant, (2) plant to animal, and (3) animal to man. A certain proportion of calcium (and strontium) is obtained directly from plants, e. g., fruits and vegetables, but this is not very large, as will be seen shortly. Experiments show that in each of the three stages mentioned there is a natural discrimination in favor of calcium and against strontium, so that the ratio of strontium-90 to calcium in the human body is less than that in the top few inches of the soil.

10.18 Several factors make it difficult to generalize concerning the ratio of strontium-90 to calcium in the plant compared to that in the soil in which it grows. First, plants obtain most of their minerals through their root systems, but such systems vary from plant to plant, some having deep roots and others shallow roots. Most of the strontium-90 in undisturbed soil has been found close to the surface, so that the uptake of this isotope may be expected to vary with the growth habit of the plant. Second, although strontium and calcium, because of their chemical similarity, may be thought of as competing for entry into the root system of plants, not all of the calcium in soil is always available for assimilation. There are natural calcium compounds in soil which are insoluble and are not available as plant food until they have been converted to other compounds by agencies such as humic acid. Most of the strontium-90 in the present world-wide fallout, however, is in a water-soluble form. Third, although plants can sub-

stitute strontium for calcium, to some extent, it is apparent that they prefer calcium. Fourth, in addition to the strontium-90 which plants obtain from the soil, growing plants will also gather a certain amount of strontium-90 from fallout deposited directly on the surface of the plant. The experimental data at present available, however, indicate that the strontium-90/calcium ratio in plants is generally somewhat less than in the soil from which they were grown.

10.19   As the next link in the chain, animals consume plants as food, thereby introducing strontium-90 into their bodies. Once again, the evidence indicates that natural discrimination factors result in a strontium-90/calcium ratio in the edible animal products that is less than in the animal's feed. Very little strontium is retained in the soft tissue, so that the amount of strontium-90 in the edible parts of the animal is negligible. It is of particular interest, too, that the strontium-90/calcium ratio in cow's milk is also much lower than that in the cow's feed, since this is an important barrier to the consumption of strontium-90 by man. This barrier does not operate, of course, when plant food is consumed directly by human beings. However, it appears that about three-fourths of the calcium, and hence a large fraction of the strontium-90, in the average diet in the United States is obtained from milk and milk products. The situation may be different in areas where a greater or lesser dependence is placed upon milk and milk products in the diet.

10.20   Not all of the strontium-90 that enters the body in food is deposited in the human skeleton. An appreciable fraction of the strontium-90 is eliminated, just as is most of the daily intake of calcium. However, there is always some fresh deposition of calcium taking place in the skeletal structure of healthy individuals, so that strontium-90 is incorporated at the same time. The rate of deposition of both calcium and strontium-90 is, of course, greater in growing children than in adults.

10.21   In addition to the fact that the human metabolism discriminates against strontium, it will be noted that, in each link in the food chain, the amount of strontium-90 retained is somewhat less than in the previous link. Thus, a series of safeguards reduce deposition of strontium in human bone. A comparison, made in 1955, of the strontium-90/calcium ratio in the bones of children compared with the ratio in the soil gave a discrimination factor of about one-twelfth, that is to say, the strontium-90/calcium ratio in children's bones was found to be one-twelfth of the ratio in soil. Later measurements indicate that the proportion of strontium-90 getting into the bones may be considerably smaller than this.

STRONTIUM-90 ACTIVITY LEVELS

10.22   As there has been no experience with appreciable quantities of strontium-90 in the human body, the relationship between the probability of serious biological effect and the body burden of this isotope is not known with certainty, since it must be estimated indirectly. Such tentative estimates have been based on a comparison of the effects of strontium-90 with radium on experimental animals, and on the known effects of radium on human beings. From these comparisons it has been estimated that a body content of 10 microcuries (1 microcurie is a one-millionth part of a curie, as defined in § 9.118) of strontium-90 in a large proportion of the population would produce a noticeable increase in the occurrence of bone cancer. On this basis, the National Committee on Radiation Protection and the International Commission on Radiological Protection have suggested that, for individuals exposed to strontium-90 due to their occupation, the maximum permissible (or safe) amount of strontium-90 in the body should be 1 microcurie. Since the average amount of calcium in the skeleton of an adult human is about 1 kilogram, this corresponds to a concentration in the skeleton of 1 microcurie of strontium-90 per kilogram of calcium, i. e., one-tenth of the concentration which might be expected, on the average, to produce an observable effect above normal. For the population as a whole, the limit generally considered to be acceptable is 0.1 microcurie of strontium-90 per kilogram of calcium. This limit is in accord with the recommendations made in 1956 by the U. S. National Academy of Sciences.

10.23   As a result of nuclear test explosions in various countries during the past several years, there has been a small but steady gain in the strontium-90 content of the soil, plants, and the bones of animals. This increase is world-wide and is not restricted to areas in the vicinity of the test sites, although it is naturally somewhat higher in these regions because of the more localized fallout.[2] As the fine particles descend from the stratosphere, over a period of years, the gradual increase in the amount of strontium-90 may be expected to continue for some time, although there will be a certain amount of compensation due to natural decay.

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[2] As stated in § 10.10, in the case of a surface or near-surface burst, an appreciable proportion of the strontium-90 formed will be found in the local fallout. It is then to be expected that areas near the explosion will be more highly contaminated in this isotope than are more distant regions, to an extent dependent upon such factors as the height (or depth) of burst, the total and fission yields of the explosion, and the prevailing atmospheric conditions. There is evidence that in the local fallout the strontium-90 constitutes a smaller percentage of the total fission products than it does farther away. This may be accounted for by the fact that the strontium-90 is not a direct fission product and so it is not formed at the instant of the explosion. It is produced gradually over a period of some minutes, as a result of two stages of radioactive decay starting with the gas krypton-90 which is formed in the fission process (see § 11.121).

10.24 The quantities of strontium-90 that have accumulated so far in human beings are well below limits regarded as acceptable for the general population, and much less than those which might be expected to cause an observable increase in the frequency of bone tumors. Because the skeletons of very young children have developed under current fallout conditions, their content of strontium-90 provides the best indication of the maximum levels which might be expected to exist. As of January 1957, this was somewhat below one-thousandth (0.001) microcurie of strontium-90 per kilogram of calcium. Although there will be some increase toward a higher level, it is fairly certain, that if nuclear tests are carried out in the future at about the same rate as in the past, the long-term biological effects of strontium-90 will not be detectable. In the event that nuclear weapons with high fission yields were used extensively in warfare, calculations, based on somewhat uncertain premises, suggest that bomb debris from many thousands of megatons of fission would have to be added to the stratosphere before the worldwide fallout from these weapons would lead to a concentration of 1 microcurie of strontium-90 per kilogram of calcium in human beings.[3]

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[3] A very thorough and comprehensive investigation of the strontium-90 hazard and of methods for combating it is being sponsored by the U. S. Atomic Energy Commission (Project Sunshine) ; for summary reports and references, see W. F. Libby, *Science, 123,* 657 (1956) ; *Proceedings of the National Academy of Sciences, 42,* 365, 945, (1956) ; J. L. Kulp, W. R. Eckelmann, and A. R. Schulert, *Science, 125,* 219 (1957).

realized. In the course of time, however, recommendations for preventing overexposures were adopted and radiation injuries became less frequent. Nevertheless, occasional overexposures have occurred among personnel operating radiographic equipment, powerful X-ray machines in industrial laboratories, cyclotrons, and nuclear reactors, or working with radioactive or fissionable materials.

11.45 The harmful effects of radiation appear to be due to the ionization (and excitation) produced in the cells composing living tissue. As a result of ionization, some of the constituents, which are essential to their normal functioning, are damaged or destroyed. In addition, the products formed may act as cell poisons. Among the observed consequences of the action of nuclear (or ionizing) radiations on cells is breaking of the chromosomes, swelling of the nucleus and of the entire cell, destruction of cells, increase in viscosity of the cell fluid, and increased permeability of the cell membrane. In addition, the process of cell division (or "mitosis") is delayed by exposure to radiation. Frequently, the cells are unable to undergo mitosis, so that the normal cell replacement occurring in the living organism is inhibited.

11.46 Before the bombings of Hiroshima and Nagasaki, radiation injury was a rare occurrence and relatively little was known of the phenomena associated with radiation sickness. In Japan, however, a large number of individuals were exposed to doses of radiation ranging from insignificant quantities to amounts which proved fatal. The effects were often complicated by other injuries and shock, so that the symptoms of radiation sickness could not always be isolated. Further, the great number of patients and the lack of facilities after the explosions made it impossible to make detailed observations and keep accurate records. Nevertheless, certain important conclusions have been drawn from Japanese experience with regard to the effects of nuclear radiation on the human organism.

11.47 Since 1945, further information on this subject has been gathered from other sources. These include animal experiments and a few laboratory accidents, involving about a dozen or so human beings. The most detailed knowledge, however, was obtained from a careful study of over 250 persons in the Marshall Islands, who were accidentally exposed to nuclear radiation from fallout following the test explosion on March 1, 1954 (§ 9.86). The exposed individuals included both Marshallese and a small group of American servicemen. The whole-body radiation doses ranged from relatively small values (14 roentgens), which produced no symptoms, to amounts (175

roentgens) somewhat less than would be expected to result in fatality to a few percent of those exposed.

11.48 It has been established that all radiations capable of producing ionization (or excitation) directly, e. g., alpha and beta particles, or indirectly, e.g., X-rays, gamma rays, and neutrons, can cause radiation injury of the same general type. However, although the effects are qualitatively similar, the various radiations differ in the depth to which they penetrate the body and in the degree of injury corresponding to a specified amount of energy absorption. As stated in § 8.31, this difference is (partly) expressed by means of the relative biological effectiveness (or RBE).

11.49 For beta particles, the RBE is close to unity; this means that for the same amount of energy absorbed in living tissue, beta particles produce about the same extent of injury within the body as do X-rays or gamma rays.[2] The RBE for alpha particles from radioactive sources has been variously reported to be from 10 to 20, but this is believed to be too large in most cases of interest. For nuclear bomb neutrons, the RBE for acute radiation injury has been taken as 1.7 (§ 8.69), but it is appreciably larger where the formation of opacities of the lens of the eye (cataracts) are concerned. In other words, neutrons are much more effective than other nuclear radiations in causing cataracts.

GENERAL RADIATION EFFECTS

11.50 The effects of nuclear radiations on living organisms depend not only on the total dose, that is, on the amount absorbed, but also on the rate of absorption, i. e., on whether it is acute or chronic, and on the region and extent of the body exposed (§ 9.38). A few radiation phenomena, such as genetic effects (see § 11.124, *et seq.*), apparently depend only upon the total dose received and are independent of the rate of delivery. In other words, the injury caused by radiation to the germ cells is cumulative. In the majority of instances, however, the biological effect of a given total dose of radiation decreases as the rate of exposure decreases. Thus, to cite an extreme case, 700 roentgens in a single dose would be fatal, if the whole body were exposed, but it would not cause death or have any noticeable external effects if supplied more or less evenly over a period of 30 years.

11.51 A skin exposure dose of 700 roentgens of X-rays will cause a certain degree of erythema (reddening) if administered locally to

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[2] Beta particles from sources on or near the body can also cause skin burns (see § 11.94).

a small area over a period of 1 hour. However, to produce the same apparent effect with two shorter treatments separated by an interval of 24 hours, each dose must be about 535 roentgens, so that a total of 1,070 roentgens is required. If the exposure is spread over a period of 1 month, the total dose may approach 2,000 roentgens in order to cause the same degree of erythema. The explanation of these results is that in the skin new cells are continually being produced at a rapid rate in order to take care of normal wear and tear. Hence, the majority of cells damaged (or killed) by radiation are replaced by new cells and there is a certain amount of natural recovery between successive doses.

11.52 Although in most cases the rate of formation of new cells is not as great as it is in the skin, the ability to recover, to some extent, from the effects of radiation appears to be possessed by many body tissues. The rate of replacement of mature cells of blood-forming tissues and of the lining of the gastro-intestinal tract, as well as of sperm cells, is also very great.

11.53 It was seen in Chapter IX that the human body is able to withstand continual exposure to small doses of radiation from natural sources without any obviously harmful consequences. The probable reason, as implied above, is that most of the cells damaged by the radiation are replaced by new ones. But if the rate of delivery of the radiation is high or the total dose received in a relatively short time is large, recovery cannot keep pace with the damage, and injury results.

11.54 Whether the injury due to nuclear radiation is reparable or not, appears to depend to a large extent on the natural capability of the affected organ (or organ system) to repair itself as a result of damage of any kind. Thus, radiation injury to brain and kidney is largely irreparable, but damage to bone marrow, the gastro-intestinal tract, and skin, on the other hand, is to a great extent reparable.

11.55 It has already been indicated that the injury caused by a certain dose of radiation will depend upon the extent and part of the body that is exposed. For example, an acute exposure dose of 700 roentgens applied to a small region may result in considerable biological damage to the irradiated area, but the over-all health of the individual may be apparently unaffected. If the whole body receives the dose of 700 roentgens, however, death will probably result. One reason for this difference is that when the exposure is restricted, the unexposed regions can contribute to the recovery of the injured area. But if the whole body is exposed, many organs are affected and recovery is much more difficult.

11.56   Different portions of the body show different sensitivities to radiation, although there are undoubtedly variations of degree among individuals, as will be seen below.   In general, the mòst radiosensitive parts include the lymphoid tissue, bone marrow, spleen, organs of reproduction, and gastro-intestinal tract.   Of intermediate sensitivity are the skin, lungs, kidney, and liver, whereas muscle and full-grown bones are the least sensitive.

EFFECTS OF ACUTE RADIATION DOSES

11.57   In the present section there will be described some of the more obvious effects of an acute dose of radiation received over the whole body.   Such a situation could result from exposure of persons to the initial nuclear radiation from a nuclear explosion.   The results given in Table 11.57, which apply to man, are based upon experiments with animals, as well as upon the conclusions drawn from observations made in Japan and of the individuals exposed on the Marshall Islands. The percentage of fatalities corresponding to any particular dose may be decreased to some extent by treatment without delay.   The data in Table 11.57 are also plotted in Fig. 11.57; the two curves show the
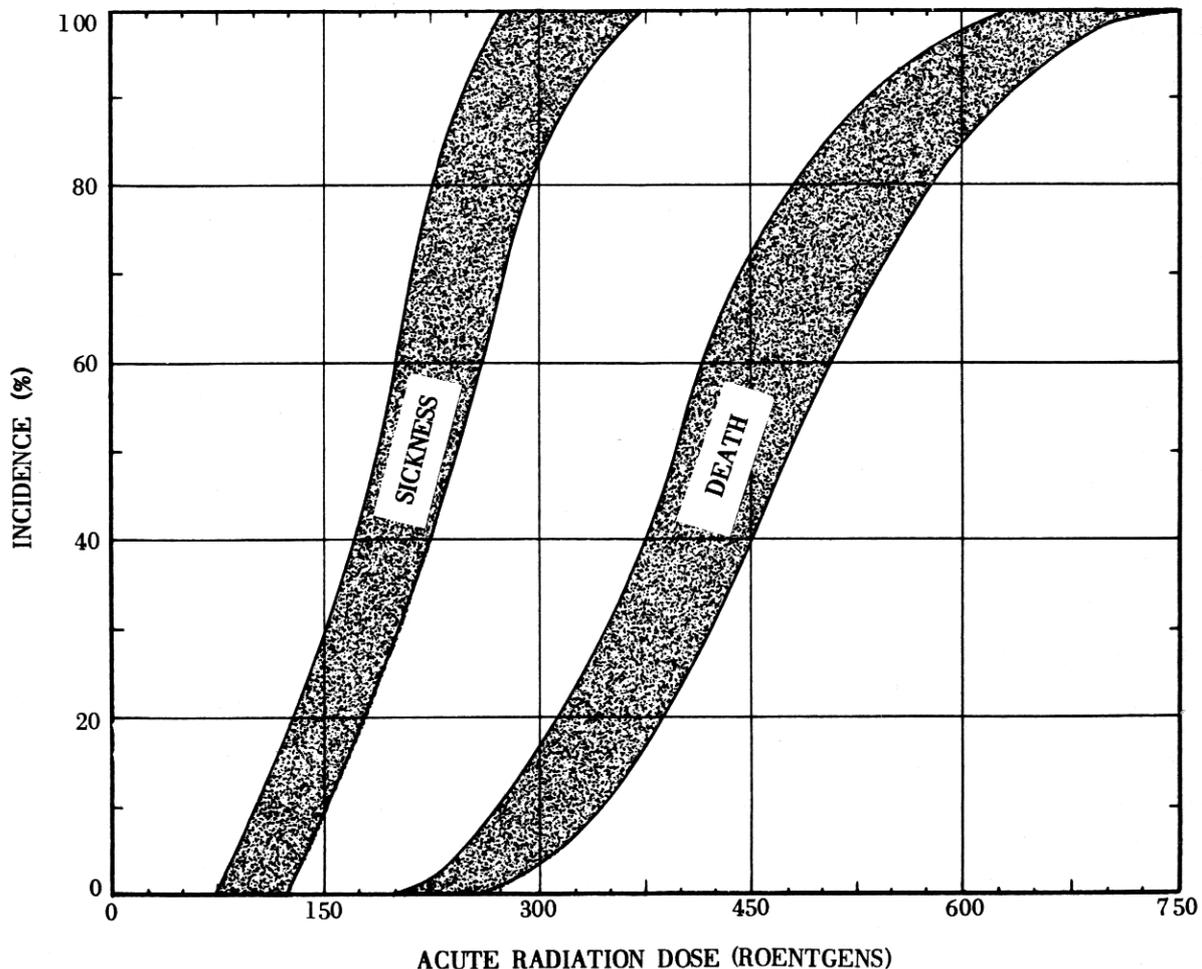

Figure 11.57.   Incidence of sickness and death due to acute exposure to various doses of nuclear radiation.

CHAPTER XII

PROTECTIVE MEASURES

INTRODUCTION

TYPES OF PROTECTION

12.1 In the preceding chapters of this book the destructive effects of nuclear weapons have been described and discussed. These effects include damage to structures and injury to personnel caused by air blast, ground and water shock, thermal radiations, and initial and residual nuclear radiations. In the present chapter an attempt will be made to state some of the many considerations involved in planning countermeasures against these various effects. The problem of protection is a complex one, since it involves not only the effects themselves, but also economic, social, and psychological considerations, in addition to the methods and efficacy of the systems for providing warning of an impending attack.

12.2 The descriptions of various effects in this book have been given in terms that are reasonably exact. But in planning protection, so many uncertainties are encountered that precise analysis of a particular situation is impossible. Among the more obvious variables are the aiming point for a given target, yield of weapon, height and nature of burst, bombing errors, topography of the target, and weather conditions.

12.3 In general, there are two categories of protection against weapons effects; they may be summed up as "distance" and "shielding." In other words, it is necessary either to get beyond the reach of the effects, or to provide protection against them within their radii of damage. The first principle, that of distance, determines the Civil Defense concept of evacuation of populations from potential target areas.[1] In any discussion of evacuation, this book is of value only as an aid to determining what might constitute a safe distance for evac-

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[1] The evacuation problem is treated in the following publications of the Federal Civil Defense Administration: "Procedure for Evacuation Traffic Movement Studies," TM–27–1; "Evacuation of Civil Populations in Civil Defense Emergencies," TB–27–1; "Evacuation Check List," TB–27–2.

uees, bearing in mind that the effect of fallout enormously complicates the evacuation problem by producing a hazard far beyond the zone of direct damage. Consequently, this chapter will be devoted only to some of the considerations involved in the principle of shielding, which may also be defined as shelter or protective construction.

12.4 The problem of protection by the provision of suitable shielding is itself a very complex one. It is not quite as difficult, however, as the existence of so many factors, as mentioned in § 12.1, might imply. In many cases, proper precautions against blast, shock, and fire damage would also decrease the hazards to personnel from various radiations, both thermal and nuclear.

12.5 As far as burning caused by thermal radiation is concerned, the essential points are protection from direct exposure for human beings, and the avoidance of easily combustible trash and dark-colored materials, especially near windows. The only known defense against gamma rays and neutrons present in the nuclear radiations is the interposition of a sufficient mass of material between the individual and the nuclear bomb, including the rising ball of fire and the subsequent fallout, if any. The use of concrete as a construction material, which is desirable for reducing air-blast and ground-shock damage, will diminish to a great extent the nuclear radiation hazard. The addition of an earth cover will be helpful in this connection.

12.6 From the standpoint of physical damage, the problems of construction to resist the action of blast from nuclear weapons are somewhat different from those associated with bombs of the conventional type. A TNT bomb will generally blow a building into pieces, but a nuclear weapon causes failure by collapsing or pushing over the structure as a whole. The relatively long duration of the blast wave from the large energy release of a nuclear explosion, as compared with that from an ordinary explosion, results in a significant difference in the nature of the effects (see Chapter III).

12.7 Another important difference between the consequences of nuclear and conventional explosions is the great increase in the area damaged in the former case. Even bombs of 20-kiloton energy yield, such as were exploded over Japan, can cause devastation over an area of several square miles (Fig. 12.7). With weapons in the megaton range, the damaged region may cover a hundred or more square miles.

GENERAL CONSIDERATION OF PROTECTIVE MEASURES

12.8 The most effective, but not necessarily most practical, method of minimizing the danger from nuclear weapons would be by dispersal
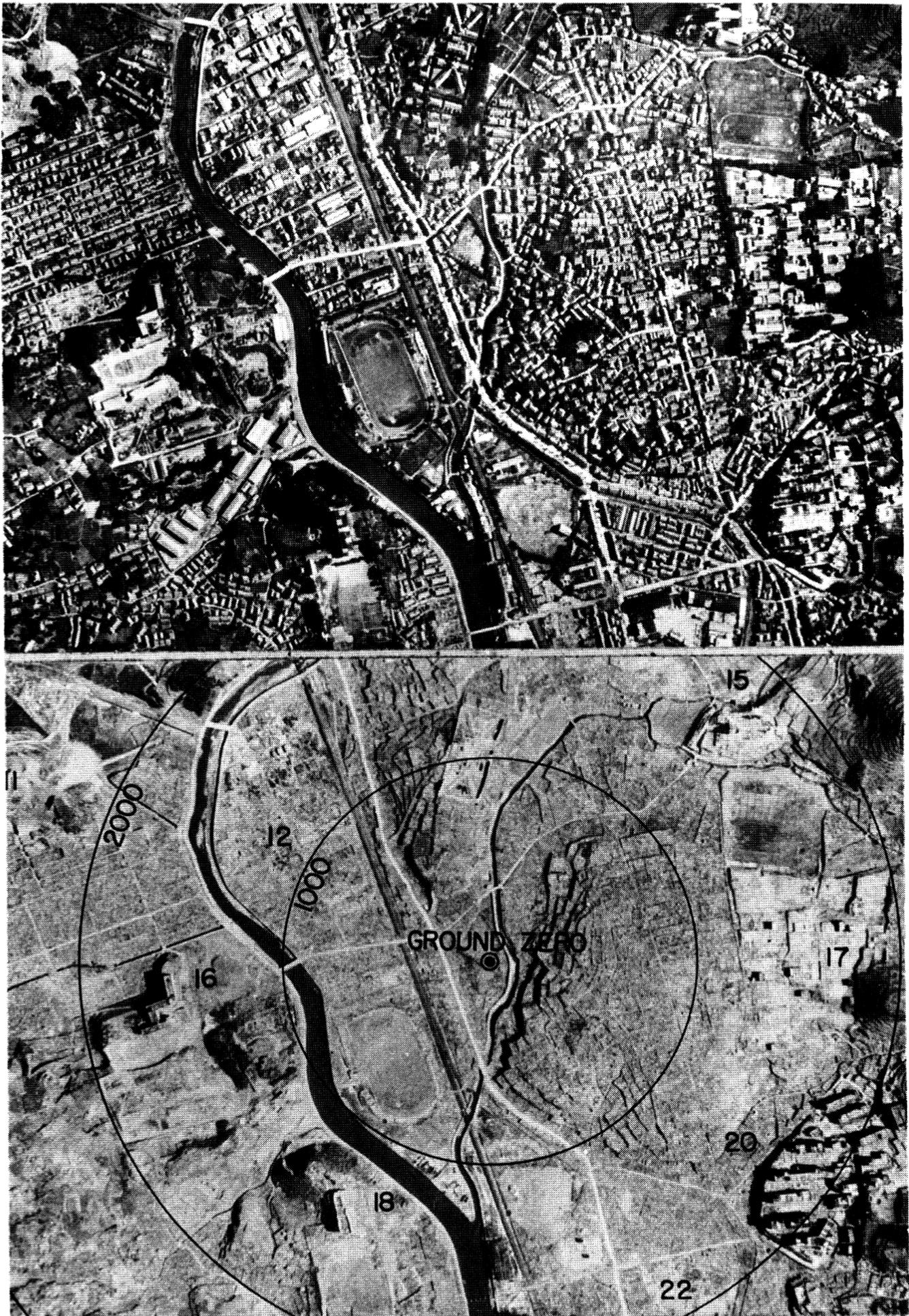
Figure 12.7. Area around ground zero at Nagasaki before and after the atomic explosion (1,000-foot radius circles are shown).
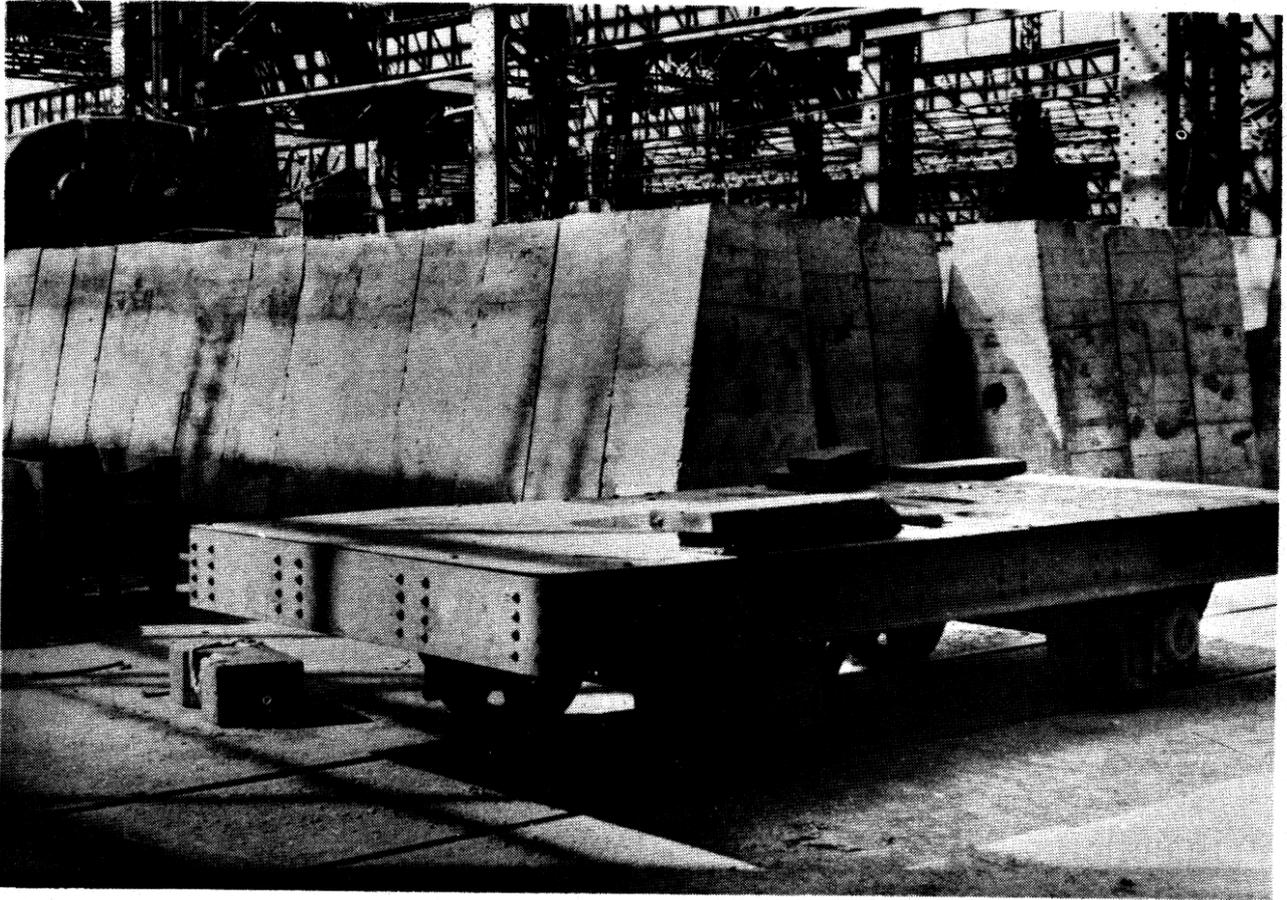
Figure 12.37a.   Precast, reinforced-concrete blast walls (0.85 mile from ground
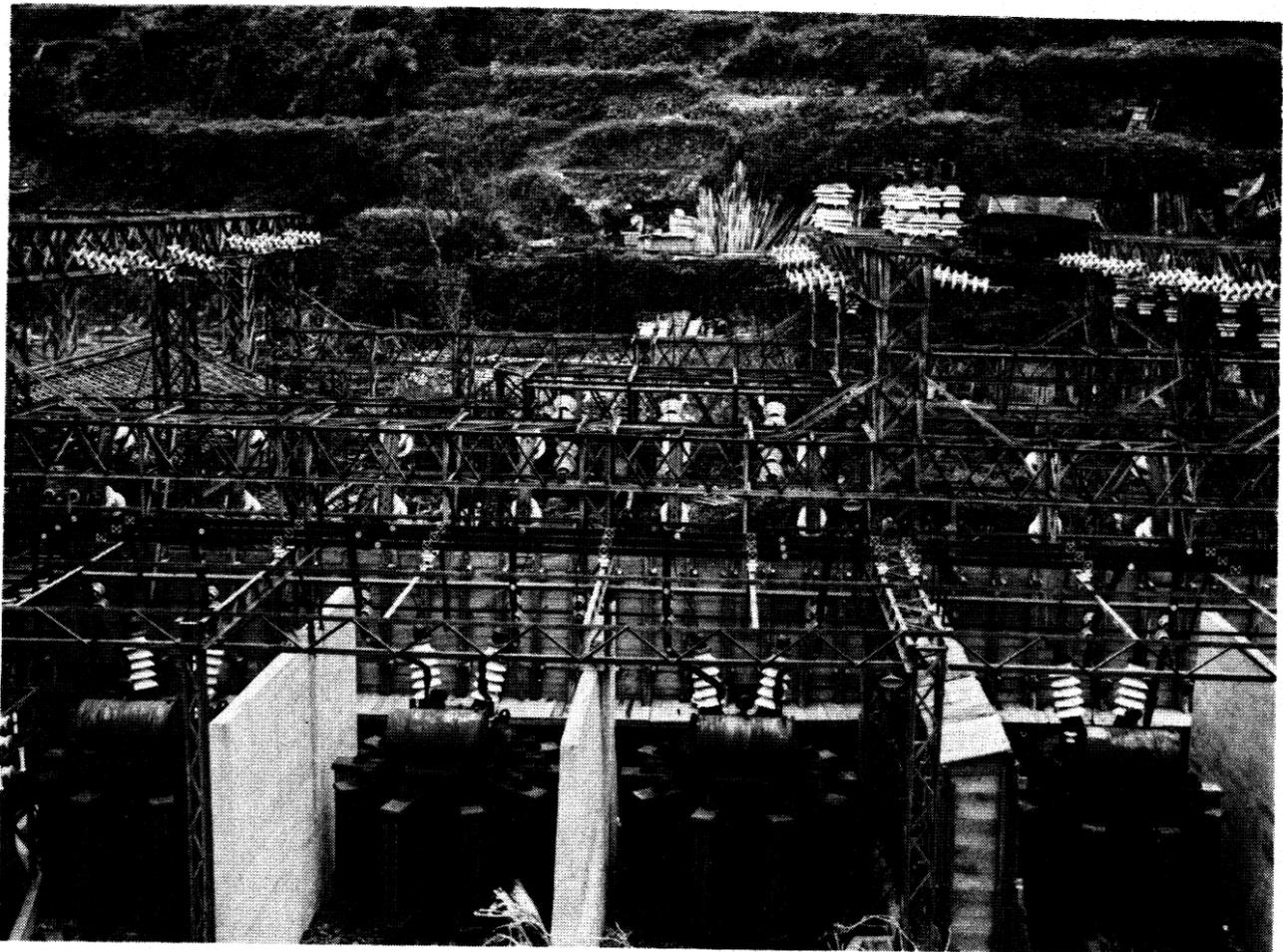zero at Nagasaki).

Figure 12.37b.   Reinforced-concrete blast walls protecting transformers (1 mile
from ground zero at Nagasaki).

Figure 12.37c.   Earth-filled, wooden blast walls protecting machinery (0.85 mile from ground zero at Nagasaki).

Protection by Trenches and Earth Revetments

12.38   Although they are not strictly structures, in the sense used above, attention should be called to the significant protection that can be afforded by trenches and earth revetments, especially to drag-sensitive targets.   A shallow pit provides little shielding, but pits or trenches that are deeper than the target have been found to be very effective in reducing the magnitude of the drag forces impinging on any part of the target.   In these circumstances, the lateral loading is greatly reduced and the damage caused is restricted mainly to that due to the crushing action of the blast wave.

12.39   The only types of shielding against drag forces which have been found to be satisfactory so far are those provided by fairly extensive earth mounds (or revetments) and deep trenches, since these are themselves relatively invulnerable to blast.   Such protective trenches are not recommended for use in cities, however, because of the damage that would result from debris falling into them.   Although sandbag mounds have proved satisfactory for protection against conventional high explosives and projectiles, they are inadequate against nuclear blast because they may become damaging missiles.

Figure 12.40a.   Earth-moving equipment subjected to nuclear blast in open terrain (30 psi overpressure).
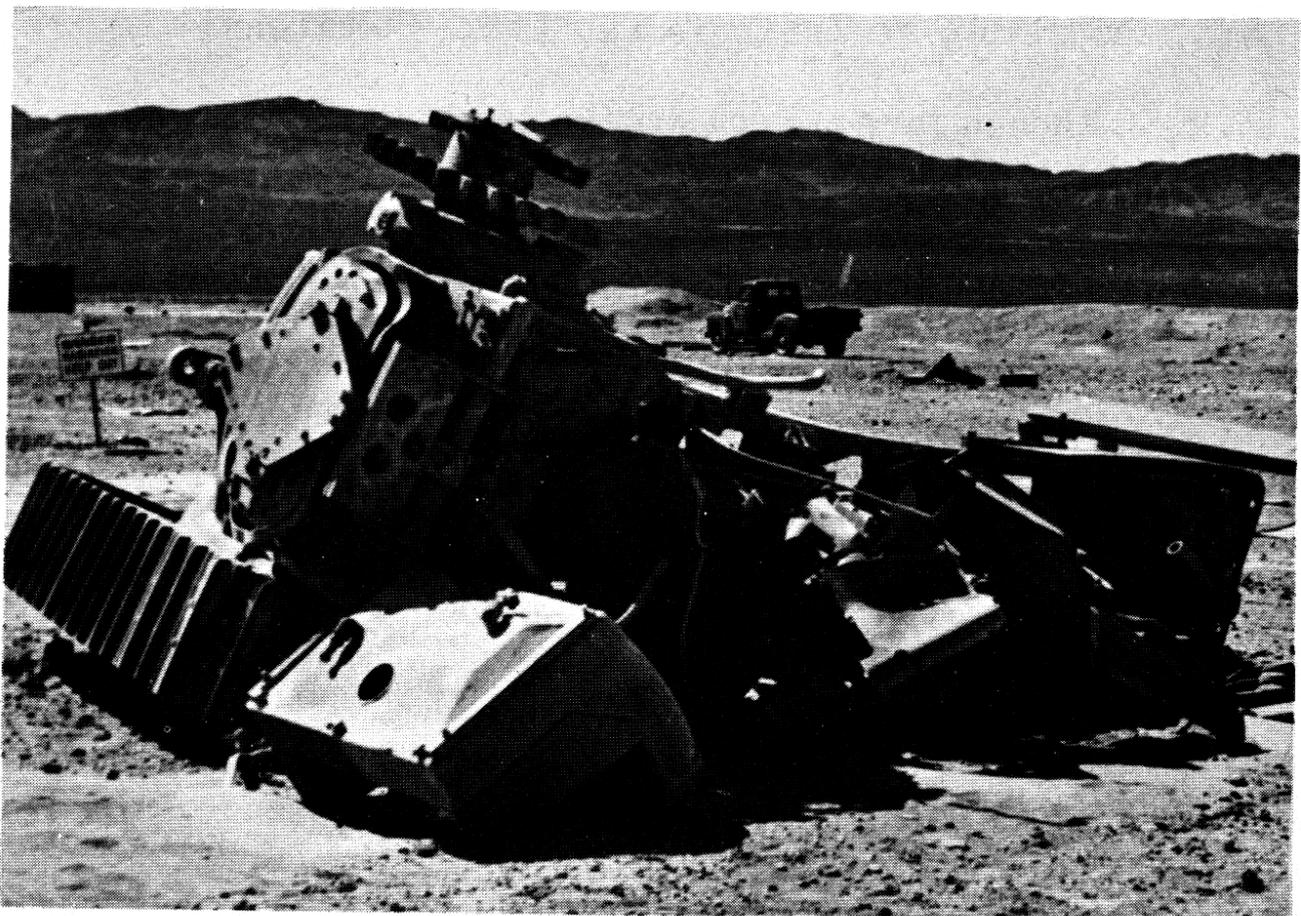

Figure 12.40b.   Earth-moving equipment subjected to nuclear blast in open terrain (30 psi overpressure).

Figure 12.40c. Earth-moving equipment protected in deep trench at right angles to blast wave motion (30 psi overpressure).

12.40   The destruction caused by a nuclear explosion to two pieces of earth-moving equipment, which are largely drag-sensitive, is shown in Figs. 12.40a and b. Two similar pieces of equipment located in a deep trench, at the same distance from the explosion, are seen in Fig. 12.40c to have been essentially unharmed. It is important to mention that the main direction of the trench was at right angles to the motion of the blast wave. If the wave had been traveling in the same direction as the trench, the equipment would probably have been severely damaged. Consequently, in order to provide protection from drag forces, the orientation of the trench or earth revetment, with respect to the expected direction of the explosion, is of great importance.

FIRE PROTECTION

12.41   It was noted in Chapter VII that fires following a nuclear explosion may be started by thermal radiation and by secondary effects, such as overturning stoves and furnaces, rupture of gas pipes, and electrical short circuits. Fire-resistive construction and avoidance of fabrics and other light materials of inflammable character are essential in reducing fire damage. As shown by the tests described in § 7.82, a well-maintained house, with a yard free from inflammable rubbish, was less easily ignited by thermal radiation than a house that has not had adequate care.

12.42   The methods of fire-resistive design and of city planning are well known and the subject need not be treated here. A special requirement is the reduction of the chances of ignition due to thermal radiation by the avoidance of trash piles and other finely divided fuel as well as combustible, especially dark colored, materials that might be exposed at windows or other openings. It has been recommended, in this connection, that all such openings be shielded against thermal radiation from all directions. The simple device of whitewashing windows will greatly reduce the transmission of thermal radiation and so decrease the probability of fires starting in the interior of the building. Other practical possibilities are the use of metal venetian blinds, reflective coatings on the window glass, and nonflammable interior pull curtains.

12.43   To judge from the experience in Japan, where the distortion by heat of exposed structural frames was considerable, it would appear desirable that steel columns and other steel members be protected from fire, especially where the contents of the building are flammable or where the building is located adjacent to flammable structures. Further, narrow firebreaks in Japan were found to be of little value. It is vital, therefore, that such firebreaks as may be provided in city planning or by demolition must be adequate for a major conflagration. A minimum width of 100 feet has been suggested.

12.44   One of the most important lessons learned from the nuclear bomb attacks on Japan is the necessity for the provision of an adequate water supply for the control of fires. In Nagasaki, the water pressure was 30 pounds per square inch at the time of the explosion, but chiefly because of numerous breaks in house service lines it soon dropped to 10 pounds per square inch. On the day following the explosion the water pressure was almost zero. This drop in the pressure contributed greatly to the extensive damage caused by fire. The experience in Hiroshima was quite similar.

SHELTERS FOR PERSONNEL

INTRODUCTION

12.45   Ideally, a shelter for personnel might be required to provide protection against air blast, ground shock, thermal radiation, initial nuclear radiation (neutrons and gamma rays), and residual nuclear radiation from fallout (external and internal sources). Such an ideal shelter is, however, virtually impossible to attain, in view of the uncertainties mentioned in § 12.2. Thus, shelter design, like that of

12.60 In the event of a surprise attack, when there is no opportunity to take shelter, immediate action could mean the difference between life and death. The first indication of an unexpected nuclear explosion would be a sudden increase of the general illumination. It would then be imperative to avoid the instinctive tendency to look at the source of light, but rather to do everything possible to cover all exposed parts of the body. A person inside a building should immediately fall prone and crawl behind or beneath a table or desk. This will provide a partial shield against splintered glass and other flying missiles. No attempt should be made to get up until the blast wave has passed, as indicated possibly by the breaking of glass, cracking of plaster, and other signs of destruction. The sound of the explosion also signifies the arrival of the blast wave.

12.61 A person caught in the open by the sudden brightness due to a nuclear explosion, should drop to the ground while curling up to shade the bare arms, hands, neck, and face with the clothed body. Although this action may have little effect against gamma rays and neutrons, it might possibly help in reducing flash burns due to thermal radiation. The degree of protection provided will vary with the energy yield of the explosion. As stated in § 7.53, it is only with high-yield weapons that evasive action against thermal radiation is likely to be feasible. Nevertheless, there is nothing to be lost, and perhaps much to be gained, by taking such action. The curled-up position should be held until the blast wave has passed.

12.62 If shelter of some kind, no matter how minor, e. g., in a doorway, behind a tree, or in a ditch, or trench can be reached within a second, it might be possible to avoid a significant part of the initial nuclear radiation, as well as the thermal radiation. But shielding from nuclear radiation requires a considerable thickness of material and this may not be available in the open. By dropping to the ground, some advantage may be secured from the shielding provided by the terrain and surrounding objects. However, since the nuclear radiation continues to reach the earth from the atomic cloud as it rises, the protection will be only partial. Further, as a result of scattering, the radiations will come from all directions.

PROTECTION FROM FALLOUT

PASSIVE AND ACTIVE MEASURES

12.63 Protection against the residual nuclear radiation from fallout presents a number of difficult and involved problems. This is so

12.82   Decontamination may be either gross, i. e., rough, or detailed. Gross decontamination is the rapid, partial removal or covering of contamination on a large scale. Its purpose is to reduce the radiation dose rate as quickly as possible to a point where personnel can use a piece of equipment or remain within an area for a limited period of time, at least. Subsequently, detailed decontamination, which is a lengthy and thorough process, may be carried out. As a general rule, decontamination cannot (and need not) be complete. However, the procedure should be carried to the point where the situation no longer constitutes a significant hazard under the particular conditions of use or occupation.

12.83   The decision to undertake decontamination will depend upon the circumstances, and must involve a calculated risk. Since there is always a certain degree of danger to the operating personnel, the procedure should be deferred as long as is reasonably possible, so as to take advantage of natural radioactive decay. In some cases urgent action may be necessary, and decontamination may have to be started while the radiation level is still high. Such a situation might be met by replacement of the workers with fresh, previously unexposed, crews at short intervals.

12.84   There are a few useful general principles relating to contamination and decontamination which should be borné in mind. Because of its particulate nature, the fallout will obviously tend to collect on horizontal surfaces. Such surfaces will thus be more highly contaminated than vertical surfaces. Hence, in preliminary decontamination, at least, the latter can be ignored. Most of the fallout particles can be readily removed either by washing with a stream of water or by sweeping, preferably with a vacuum cleaner to avoid inhalation of dust.

12.85   Gross decontamination can generally be performed in one or other of these ways. For smooth, e. g., painted and metallic, surfaces, wet (washing) methods may be used, but for porous materials, e. g., fabrics, brick, concrete, and stone, dry methods are to be preferred. Broadly speaking, water washing can be employed outdoors and on the exterior of vehicles, whereas vacuum sweeping is more suitable for the interiors of buildings and vehicles. Experimental tests of decontamination procedures have shown that the major portions of contaminating material can be removed by these simple methods. Only a small part of the contamination is strongly held and requires more drastic treatment, e. g., with chemicals or abrasives.[5]

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[5] Contamination due to neutron-induced activity is difficult to remove, but such contamination is of importance only near the explosion center (see § 9.18).

12.86 In a city, decontamination could be carried out by hosing the roofs of buildings and the streets with strong streams of water. The radioactive material would thus be transferred to the storm sewers, where it would represent only a minor hazard. As an alternative to hosing, the dose rate inside a building could also be reduced by covering the ground surrounding the building with uncontaminated earth or by removing the top layer of the ground to a distance with a bulldozer.

12.87 It is important to note, in connection with removal of contaminated earth, for the purpose just described or to provide a means of transit, that the gamma rays from fission products can travel considerable distances through air. For example, at 3 feet above the ground, roughly 50 percent of the dose rate received in the center of a large, flat, uniformly contaminated area comes from distances greater than 25 feet away, and about 25 percent from distances more than 50 feet away. Thus, complete removal of the contaminated surface from a circle 50 feet in radius would reduce the dose rate in the center to about one-fourth of its original value. However, if the contaminated earth were not completely removed, but just pushed to the outside of the circle, the dose rate would be considerably larger than cne-fourth the initial value.

12.88 It is apparent, therefore, that if transit facilities are to be provided across open country which is contaminated over a large area, bulldozing the top few inches of contaminated soil to the sides will be satisfactory only if a wide strip is cleared. Thus, if the strip is 250 feet in width, the radiation dose rate in the middle will be reduced to one-tenth of the value before clearing. A similar result may be achieved by scraping off the top layer of soil and burying it under fresh soil. Something like a foot of earth would be required to decrease the dose rate by a factor of ten.

12.89 Badly contaminated clothing, as well as rugs, curtains, and upholstered furniture, would have to be discarded and buried or stored in an isolated location. When the radioactivity has decayed to a sufficient extent, or if the initial contamination is not too serious, laundering may be effective in reducing the activity of clothing and fabrics, to permit their recovery. Thorough vacuum cleaning of furniture might be adequate in some cases, but an instrument check would be necessary before further use.

PROTECTION OF OPERATING CREWS

12.90 All personnel entering a contaminated area, to perform survey monitoring, decontamination, or other emergency operations, should adapt their clothing to prevent the entry of dust. The main purpose of this precaution is to minimize the possibility of "beta burns" as a result of direct contact of the fallout with the skin (see § 11.94). It should be remembered, of course, that clothing offers virtually no protection against gamma radiation, and so this hazard will still exist to an undiminished extent.

12.91 For dry operations, heavy pants and shoes are recommended, as well as cotton or canvas work gloves and a tight-fitting cap. In dusty areas it is advisable that the bottoms of the pants and the ends of the sleeves (over the gloves) be tied to prevent the entry of contaminated material. A scarf around the neck would also help in this connection. After a nuclear attack, the dust may arise from rubble, disturbance of the ground, etc., and may not necessarily be radioactive. Precautions to reduce inhalation of the dust in large amounts would be desirable, in any event. Consequently, in operations in which considerable quantities of dust may be encountered, goggles and a filter mask are advisable.

12.92 For wet decontamination operations, water-repellent clothing, rubber boots, and rubber gloves will be required (Fig. 12.92). They can be cleaned with a stream of water and used several times, provided there are no breaks or tears.

12.93 In addition to taking steps to prevent radioactive material from reaching the skin, workers will need protection from excessive exposure to radiation. For this purpose, each operator should carry a self-indicating meter, sometimes called an "organizational dosimeter," to record his total radiation exposure. Various types of dosimeters have been devised, and simple and reliable instruments, that can be produced cheaply and in large numbers, are available.[6]

12.94 Survey meters for the determination of radiation intensities (dose rates) will be required in order to detect regions of high activity and for estimating permissible times of stay in a contaminated area. As a general rule, instruments which measure the dose rate of gamma radiation will be satisfactory. In addition, special instruments sensitive to beta radiations are advantageous for such purposes as detecting beta-particle emitters on the body.

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[6] For a description of dosimeters and other radiation instruments developed by the Federal Civil Defense Administration, see "Radiological Instruments for Civil Defense," TB–11–20.

Figure 12.92   Water-repellent clothing for use in wet decontamination operations.

12.95   In connection with this aspect of personnel protection, there arises the question of the amount of nuclear radiation exposure that is permissible for those taking part in emergency operations. It is difficult, if not impossible, to supply an exact answer, for a great deal will depend upon the circumstances and the risks that must inevitably be taken.

12.96   In those phases of emergencies in which immediate action is required, it would rarely be possible to predict in advance the radiation dose that might be received as a result of such action. The consequences to the exposed individuals, would, therefore, be equally unpredictable. However, where the hazard could be estimated from available dose rate data, it might be possible to establish an approxi-

mate guide concerning permissible radiation exposures under emergency conditions.[7]

FOOD AND WATER

12.97 Foods that are properly covered or wrapped or are stored in closed containers should suffer little or no contamination. This will be true for canned and bottled foods as well as for any articles in impervious, dust-proof wrappings. If the contamination is only on the outside, all that would be necessary for recovery purposes would be the careful removal, e. g., by washing, of any fallout particles that might have settled on the exterior of the container.[8] Even vegetables could be satisfactorily decontaminated by washing. If this were followed by removal of the outer layers, by peeling, the food should be perfectly safe for human consumption. Unprotected food products of an absorbent variety that have become contaminated should be disposed of by burial.

12.98 As for food crops grown in contaminated soil, there is not yet sufficient information available. Some radioactive isotopes may be taken up by the plant, but their nature and quantity will vary from one species to another and also, probably, with the soil characteristics (§ 9.99). All that can be stated at the present time is that plants grown in contaminated soil should be regarded with suspicion until their safety can be confirmed by means of radiological instruments.

12.99 Most sources of public water supplies are located at a considerable distance from urban centers that might be targets of a nuclear attack. Nevertheless, appreciable contamination might result if the watershed were in the range of heavy fallout from a surface burst. Other possibilities are fallout particles dropping into a river or reservoir or the explosion of a nuclear bomb near a reservoir. In most cases it is to be expected that, as a result of the operation of several factors, e. g., dilution by flow, natural decay, and removal ("adsorption") by soil, the water will be fit for consumption, on an emergency basis, at least, except perhaps for a limited time immediately following the nuclear explosion. In any event, where the water from a reservoir is subjected to regular treatment, including coagu-

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[7] See, for example, "Emergency Exposures to Nuclear Radiation," Federal Civil Defense Administration Technical Bulletin (TB–18–1).

[8] Food could become contaminated even inside containers due to neutron-induced activity, but this is not likely to be important in locations where the packaged foodstuffs have survived the nuclear explosion intact (§ 9.25).

lation, sedimentation, and filtration, it is probable that much of the radioactive material would be removed.

12.100   Because soil has the ability to take up and retain certain elements by the process of "adsorption," underground sources of water will generally be free from contamination.   For the same reason, moderately deep wells, even under contaminated ground, can be used as safe sources of drinking water, provided, as is almost invariably the case, there is no direct drainage from the surface into the well.

12.101   In some cities, water is taken directly from a river and merely chlorinated before being supplied for domestic purposes.   The water may be unfit for consumption for several days, but, as a result of dilution and natural decay, the degree of contamination will decrease with time.   It would be necessary, in cases of this kind, to subject the water to examination for radioactivity and to withhold the supply until it is reasonably safe.   Assuming the contamination is due to fission products, the acceptable total beta (or gamma) activities under emergency conditions, for 10 and 30 day periods, respectively, are given in Table 12.101.   Thus, if it is anticipated that the water will have to be used regularly for a period of 30 days, the maximum permissible activity is 3×10^{-2} microcuries per cubic centimeter (see § 9.125, *et seq.*).   On the other hand, if it appears that the period will be shorter, water of proportionately higher activity may be consumed in an emergency.

TABLE 12.101

ACCEPTABLE EMERGENCY BETA (OR GAMMA) ACTIVITIES IN DRINKING WATER

| | Activity | |
Consumption period (days)	Microcuries per cubic centimeter	Disintegrations per second per cubic centimeter
10	9×10^{-2}	3×10^3
30	3×10^{-2}	1×10^3

12.102   The emergency limits for alpha particle emitters, such as uranium and plutonium, in water are appreciably less than those given in Table 12.101.   However, it is expected that only in rare circumstances would these elements represent a contamination hazard in drinking water.

12.103   If the regular water supply is not usually subjected to any treatment other than chlorination, and an alternative source is not available, consideration should be given to the provision of ion-exchange columns (or beds) for emergency use in case of contamination.

Home water softeners might serve the same purpose on a small scale. Incidentally, the water contained in a domestic hot-water heater could serve as an emergency supply, provided it can be removed without admitting contaminated water.

12.104 In hospitals and on ships, sufficient water for emergency purposes could be obtained by distillation. It was found after the nuclear tests at Bikini in 1946, for example, that contaminated sea water when distilled was perfectly safe for drinking purposes; the radioactive material remained behind in the residual scale and brine. It should be emphasized, however, that mere boiling of water contaminated with fallout is of absolutely no value as regards removal of the radioactivity.

RADIATION DOSES AND TIMES IN CONTAMINATED AREAS

12.105 For the planning of defensive action, either active or passive, or of survey operations in an area contaminated with fission products, it is necessary either to make some estimate of the permissible time of stay for a prescribed dose or to determine the dose that would be received in a certain time period. The basic equations and the related graphs (Figs. 9.8 and 9.12) were given in Chapter IX, but the same results may be expressed in an alternative form that is more convenient for many purposes.[9]

12.106 If the radiation dose rate from fission products is known at a certain time in a given location, Fig. 12.106 may be used to determine the dose rate at any other time at the same location, assuming there has been no change in the fallout other than natural radioactive decay. The same nomogram can be utilized, alternatively, to determine the time after the explosion at which the dose rate will have attained a specified value. If there has been any change in the situation, either by further contamination or by decontamination, in the period between the two times concerned, the results obtained from Fig. 12.106 will not be valid.

12.107 To determine the total radiation dose received during a specified time of stay in a contaminated area, if the dose rate in that area at any given time is known, use is made of Fig. 12.107, in conjunction with Fig. 12.106. The chart may also be employed to evaluate the time when a particular operation may be commenced in order not to exceed a certain total radiation dose.

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[9] Devices of the slide-rule type, referred to in the footnote to § 9.11, are very useful for making rapid calculations of the kind described here.

12.198 Another type of calculation of radiation dose in a contaminated area is based on a knowledge of the dose rate at the time of entry into that area. The procedure described in the examples facing Fig. 12.107, which also require the use of Fig. 12.106, may then be applied to determine either the total dose received in a specified time of stay or the time required to accumulate a given dose of radiation. The calculation may, however, be simplified by means of Fig. 12.108, which avoids the necessity for evaluating the 1-hour reference dose rate, provided the dose rate at the time of entry into the contaminated area is known.

12.109 If the whole of the fallout reached a given area within a short time, Fig. 12.108 could be used to determine how the total radiation dose received by inhabitants of that area would increase with time, assuming no protection. For example, suppose the fallout arrived at 6 hours after the explosion and the dose rate at that time was R roentgens per hour; the total dose received would be $8R$ roentgens in 1 day, $11R$ roentgens in 2 days, and $13R$ roentgens in 5 days.

12.110. It is evident that the first day or so after the explosion is the most hazardous as far as the exposure to residual nuclear radiation from fallout is concerned. Although the particular values given above apply to the case specified, i. e., complete fallout arrival 6 hours after the explosion, the general conclusions to be drawn are true in all cases. The radiation doses that would be received during the first day or two are considerably greater than on subsequent days. Consequently, it is in the early stages following the explosion that protection from fallout is most important.

The nomogram shows the relationship between the dose rate at any time after the explosion and the 1-hour reference value (R_1). If the dose rate at any time is known, that at any other time can be derived from the figure. Alternatively, the time after the explosion at which a specific dose rate is attained can be determined.

Example

Given: The radiation dose rate due to fallout at a certain location is 8 roentgens per hour at 6 hours after a nuclear explosion.

Find: (*a*) The dose rate at 24 hours after the burst.

(*b*) The time after the explosion at which the dose rate is 1 roentgen per hour.

Solution: By means of a ruler (or straight edge) join the point representing 8 roentgens per hour on the left scale to the time 6 hours on the right scale. The straight line intersects the middle scale at 70 roentgens per hour; this is the 1-hour reference value of the dose rate (R_1).

(*a*) Using the straight edge, connect this reference point (70 r/hr) with that representing 24 hours after the explosion on the right scale, and extend the line to read the corresponding dose rate on the left scale, i. e., 1.5 roentgens per hour. *Answer*

(*b*) Extend the straight line joining the dose rate of 1 roentgen per hour on the left scale to the reference value of 70 roentgens per hour on the middle scale out to the right scale. This is intersected at 34 hours after the explosion. *Answer*
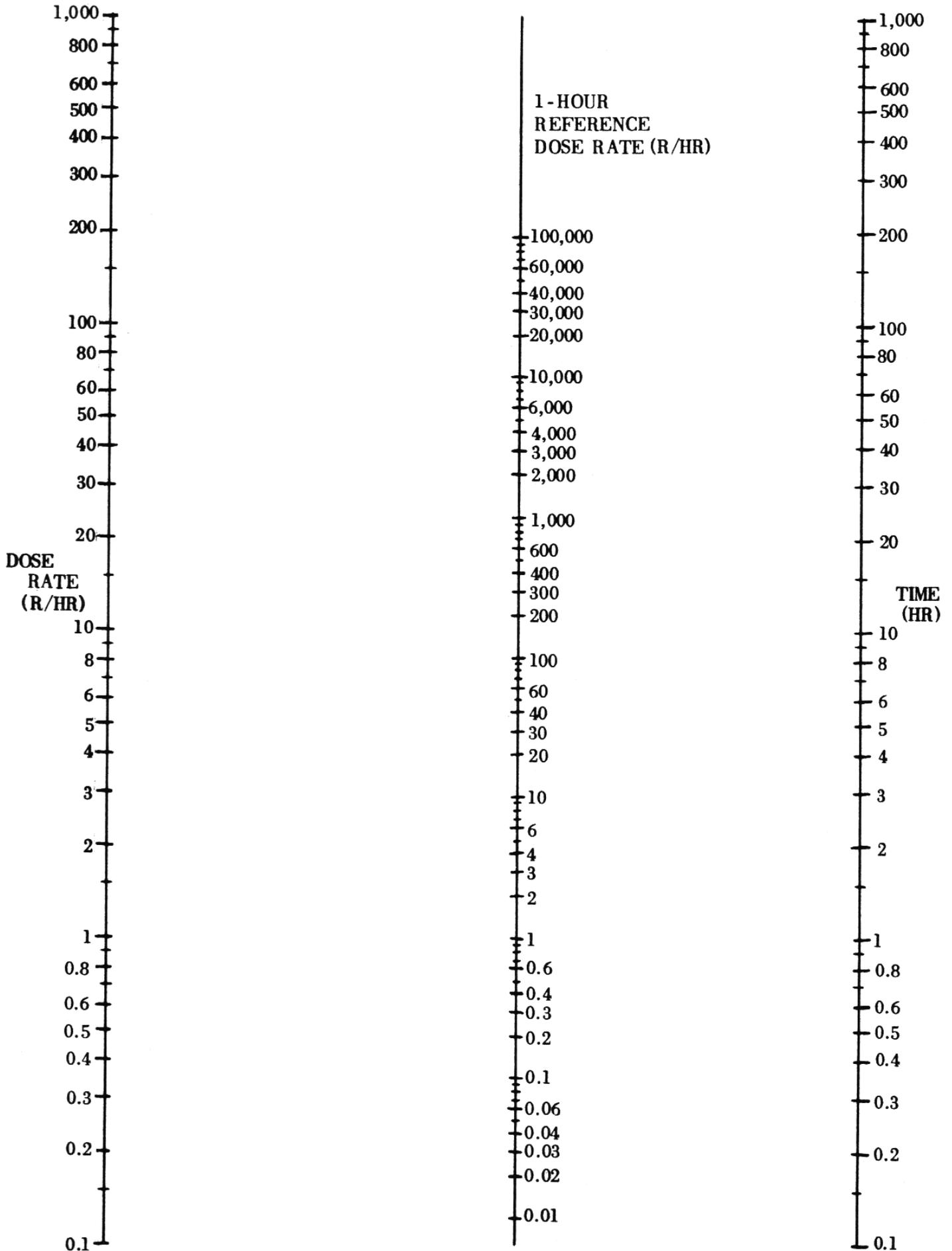
Figure 12.106. Calculation of dose rates from fission products in the fallout.

From the chart, the total radiation dose received from fission product fallout during any specified stay in a contaminated area can be determined if the dose rate at some definite time after the explosion is known. Alternatively, the time can be calculated for commencing an operation requiring a specified stay and a prescribed total radiation dose.

Example

Given: The dose rate at 4 hours after a nuclear explosion is 6 roentgens per hour.

Find: (a) The total dose received during a period of 2 hours commencing at 6 hours after the explosion.

(b) The time after the explosion when an operation requiring a stay of 5 hours can be started if the total dose is to be 4 roentgens.

Solution: The first step is to determine the 1-hour reference dose rate (R_1). From Fig. 12.106, a straight line connecting 6 roentgens per hour on the left scale with 4 hours on the right scale intersects the middle scale at 32 roentgens per hour; this is the value of R_1.

(a) Enter Fig. 12.107 at 6 hours after the explosion (vertical scale) and move across to the curve representing a time of stay of 2 hours. The corresponding reading on the horizontal scale, which gives the multiplying factor to convert R_1 to the required total dose, is seen to be 0.19. Hence, the total dose received is

$$0.19 \times 32 = 6.1 \text{ roentgens.} \quad Answer$$

(b) Since the total dose is given as 4 roentgens and R_1 is 32 roentgens per hour, the multiplying factor is $4/32 = 0.125$. Entering Fig. 12.107 at this point on the horizontal scale and moving upward until the (interpolated) curve for 5 hours stay is reached, the corresponding reading on the vertical scale, giving the time after the explosion, is seen to be 19 hours. *Answer*
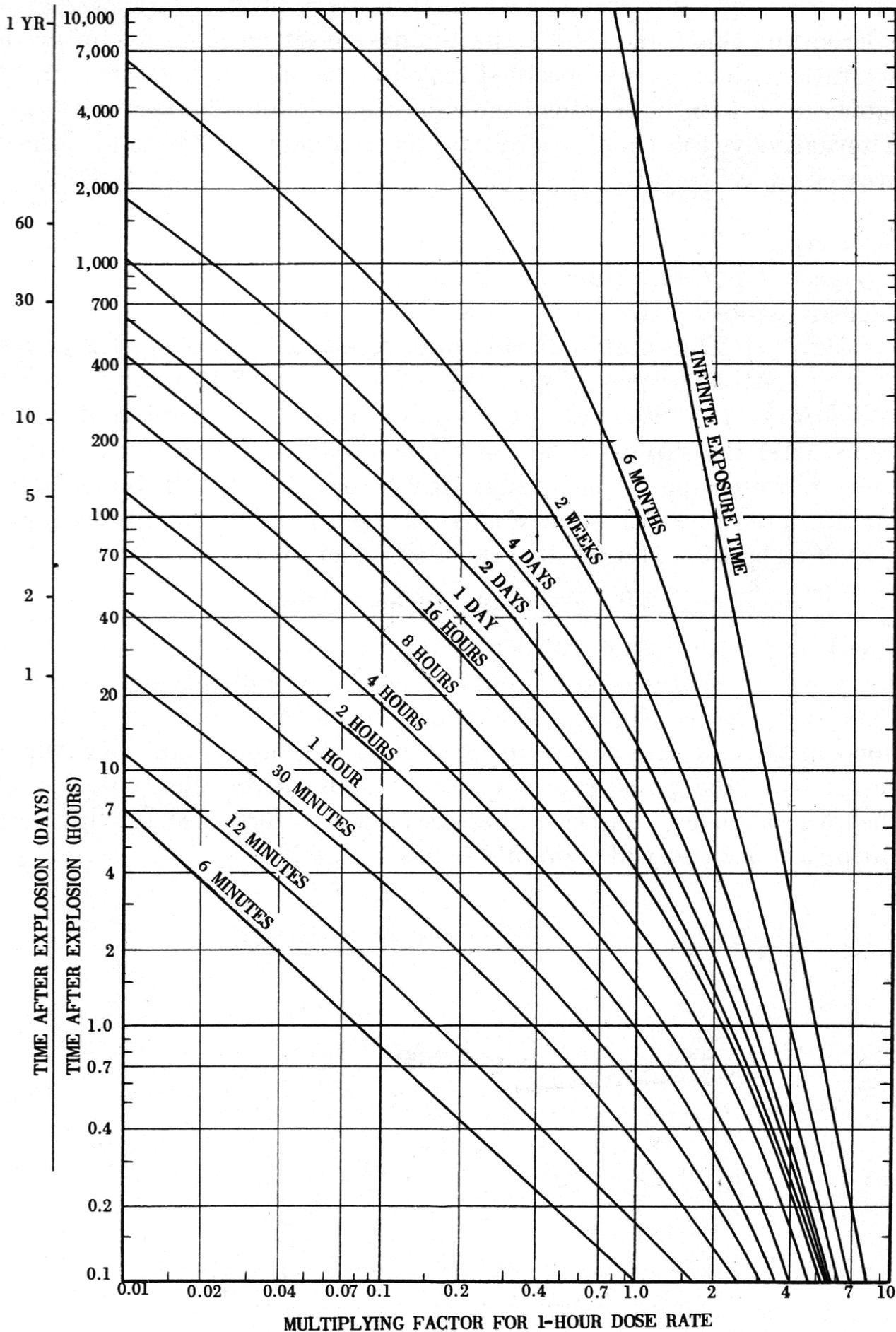
Figure 12.107. Total (accumulated) radiation dose due to fallout in a contaminated area based on 1-hour reference dose rate.

From the chart, the total radiation dose received from fission product fallout during any specified stay in a contaminated area can be determined if the dose rate at the time of entry into the area is known. Alternatively, the time of stay may be evaluated if the total dose is prescribed.

Example

Given: Upon entering a contaminated area at 12 hours after a nuclear explosion the dose rate is 5 roentgens per hour.

Find: (a) The total radiation dose received for a stay of 2 hours.

(b) The time of stay for a total dose of 10 roentgens.

Solution: (a) Start at the point on Fig. 12.108 representing 12 hours after the explosion on the vertical scale and move across to the curve representing a time of stay of 2 hours. The multiplying factor for the dose rate at the time of entry, as read from the horizontal scale, is seen to be 1.9. Hence, the total dose received is

$$1.9 \times 5 = 9.5 \text{ roentgens.} \quad Answer$$

(b) The total dose is 10 roentgens and the dose rate at the time of entry is 5 roentgens per hour; hence, the multiplying factor is $10/5 = 2.0$. Enter Fig. 12.108 at the point corresponding to 2.0 on the horizontal scale and move upward to meet a horizontal line which starts from the point representing 12 hours after the explosion on the vertical scale. The two lines are seen to intersect at a point indicating a time of stay of about 2⅓ hours. *Answer*
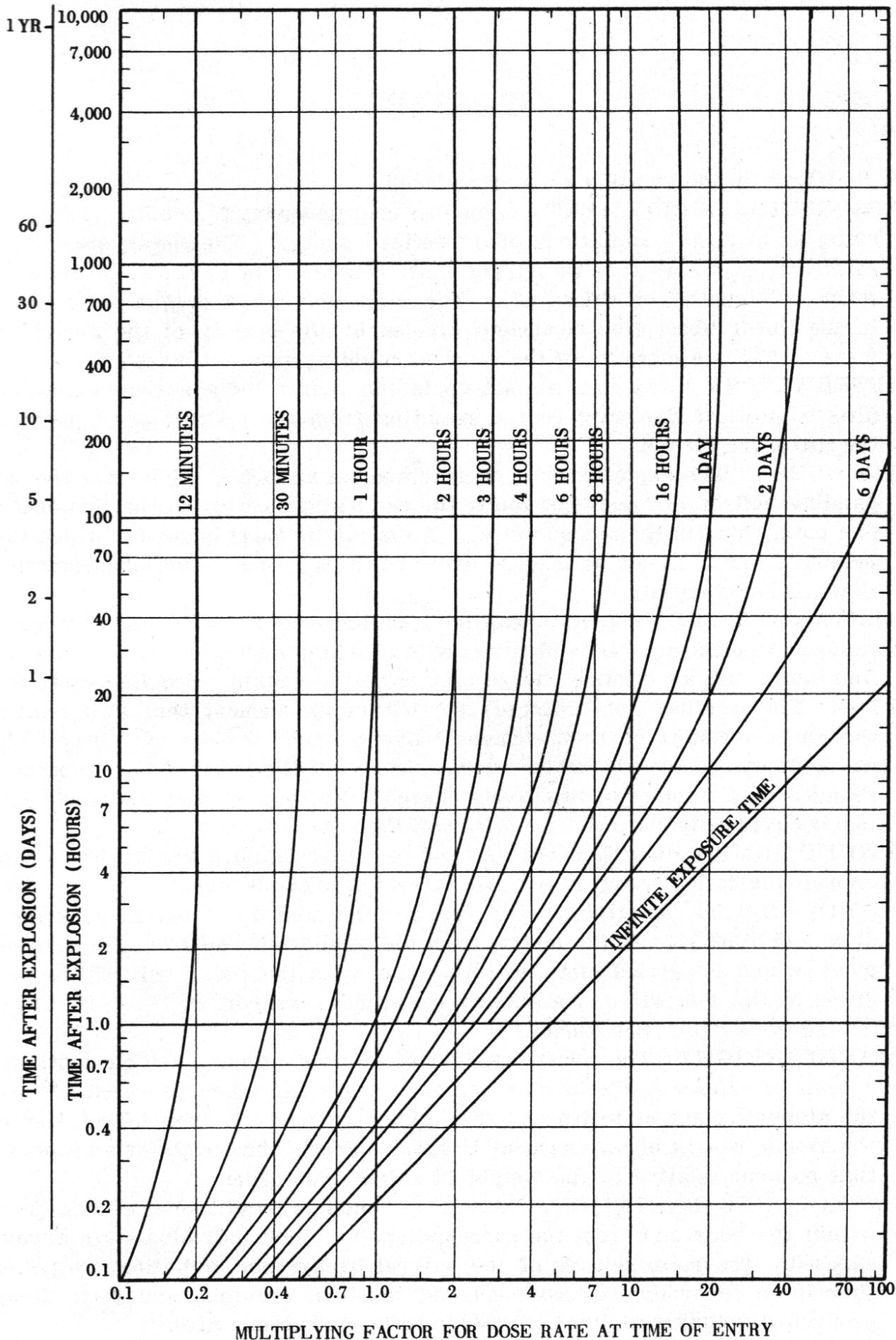
Figure 12.108. Total (accumulated) radiation dose due to fallout in a contaminated area based on dose rate at time of entry.