# The Effects of

# ATOMIC

# WEAPONS

# The Effects of

# Atomic Weapons

PREPARED FOR AND IN COOPERATION WITH THE U. S. DEPARTMENT OF
DEFENSE AND THE U. S. ATOMIC ENERGY COMMISSION

*Under the direction of the*

## LOS ALAMOS SCIENTIFIC LABORATORY

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# Foreword

It was recommended some time ago that the Los Alamos Scientific Laboratory be given the responsibility for preparing for publication a handbook on the effects of atomic weapons. The recommendation was made by the Weapons Effects Classification Board, a committee of military and civilian scientists serving as advisers to the Atomic Energy Commission. The Board's recommendation was approved by the Atomic Energy Commission late in 1948, and this volume is the result.

Its purpose is to present, as accurately as is possible in the light of present knowledge, a technical summary of the results to be expected from the detonation of atomic weapons. Of necessity, classified information vital to the national security has been omitted.

The need for such a book, and the difficulties encountered in its preparation, arise from a common origin: the tremendous energy release resulting from an atomic bomb explosion. The need is for a book that can promote intelligent understanding of the effects of this enormous energy release when used as a weapon in war. The difficulties stem from the fact that the energy is released on a scale never before used by man, so that previous experience with conventional high explosives provides an inadequate basis for scientific prediction of results. In addition, atomic explosion phenomena are so complex as to make precise quantitative evaluation of their results almost impossible.

With the concurrence of the Atomic Energy Commission a technical staff was appointed by the Los Alamos Scientific Laboratory to compile the material for the book. Members of this staff were: Dr. Joseph O. Hirschfelder, professor of chemistry at the University of Wisconsin; Lt. Col. David B. Parker, Office of Deputy Assistant Chief of Staff, G–3, for Atomic Energy, U. S. Army General Staff; Arnold Kramish, a physicist on the staff of the Atomic Energy Commission in Washington, D. C.; and Dr. Ralph Carlisle Smith, an assistant director of the Los Alamos Scientific Laboratory.

Because experts in all the many aspects of this problem could not be found solely at Los Alamos, distinguished scientists were called upon by the editors to prepare their views on the subjects in which they were specialists. The various chapters of this book represent

the integration of their ideas with those of equally distinguished critics and consultants.

When the first compilation had been prepared, Dr. Samuel Glasstone, professor of physical chemistry and the author of well-known scientific treatises, including the Atomic Energy Commission Sourcebook on Atomic Energy, was requested by the editors to join them as Executive Editor in the final rewriting of the manuscript. Part of his work was to minimize as far as possible the repetition of subject matter and the inconsistencies resulting from the multiple sources and from the lack of accurate knowledge in this relatively new field.

While the predictions of this book cannot be guaranteed to be precise, nevertheless they probably represent the most nearly quantitative approach to atomic bomb phenomenology which can be published at this time.

NORRIS E. BRADBURY
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*Miscellaneous Material*

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# PRINCIPLES OF AN ATOMIC EXPLOSION

## A.  INTRODUCTION

### CHARACTERISTICS OF AN ATOMIC EXPLOSION

1.1   The atomic bomb is a new weapon of great destructive power. It resembles bombs of the more conventional type in so far as its explosive effect is the result of the very rapid liberation of a large quantity of energy in a relatively small space.   But it differs from other bombs in three important respects: first, the amount of energy released by an atomic bomb is a thousand or more times as great as that produced by the most powerful TNT bombs; second, the explosion of the bomb is accompanied by highly-penetrating, and deleterious, invisible rays, in addition to intense heat and light; and third, the substances which remain after the explosion are radioactive, emitting radiations capable of producing harmful consequences in living organisms.   It is on account of these differences that the effects of the atomic bomb require special consideration.

1.2   A knowledge and understanding of the mechanical and radiation phenomena associated with an atomic explosion are of vital importance.   The information may be utilized, on the one hand, by architects and engineers in the design of structures; while on the other hand, those responsible for civil defense, including treatment of the injured, can make preparations to deal with the emergencies that may arise from an atomic explosion.

1.3   During World War II many large cities in England, Germany, and Japan were subjected to terrific attacks by high-explosive and incendiary bombs.   Yet, when proper steps had been taken for the protection of the civilian population and for the restoration of services after the bombing, there was little, if any, evidence of panic.   It is the purpose of this book to state the facts concerning the atomic bomb, and to make an objective, scientific analysis of these facts. It is hoped that as a result, although it may not be feasible completely to allay fear, it will at least be possible to avoid panic.

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[1] Material contributed by G. Gamow, S. Glasstone, J. O. Hirschfelder.

TABLE 1.18

HALF LIVES OF SOME RADIOISOTOPES

| Isotope | Activity | Half Life | Isotope | Activity | Half Life |
|---------|----------|-----------|---------|----------|-----------|
| Sodium 24 | $\beta^-$ | 14.8 hr. | Cesium 137 | $\beta^-$ | 37 yr. |
| Potassium 40 | $\beta^-$ | $1.5 \times 10^9$ yr. | Polonium 212 | $\alpha$ | $3 \times 10^{-7}$ sec. |
| Selenium 81 | $\beta^-$ | 17 min. | Radium 226 | $\alpha$ | 1,590 yr. |
| Bromine 87 | $\beta^-$ | 55.6 sec. | Thorium 232 | $\alpha$ | $1.39 \times 10^{10}$ yr. |
| Strontium 90 | $\beta^-$ | 25 yr. | Uranium 233 | $\alpha$ | $1.65 \times 10^5$ yr. |
| Krypton 92 | $\beta^-$ | 3 sec. | Uranium 235 | $\alpha$ | $7.07 \times 10^8$ yr. |
| Yttrium 93 | $\beta^-$ | 10 hr. | Uranium 238 | $\alpha$ | $4.51 \times 10^9$ yr. |
| Molybdenum 93 | $\beta^+$ | 6.7 hr. | Uranium 239 | $\beta^-$ | 23 min. |
| Technetium 99 | $\beta^-$ | $9.4 \times 10^5$ yr. | Neptunium 239 | $\beta^-$ | 2.3 days |
| Iodine 131 | $\beta^-$ | 8.0 days | Plutonium 239 | $\alpha$ | $2.41 \times 10^4$ yr. |

1.19   It is because of the very long half lives of uranium 238, uranium 235, and thorium 232 that radioactive species of high atomic weight occur in nature, in spite of their instability.   Of the 42 such known isotopes, 39 are formed in various stages of decay of these three parents, or precursors, of three radioactive decay series.   The familiar element radium, for example, is a member of the series of which uranium 238 is the parent.   In nature the several products decay at various rates, but they are replaced virtually as fast as they decay, so that the amounts remain essentially unchanged.   In the course of millions of years, however, a slight decrease would become apparent, because of the slow decay of the parent element.   The final or end products of the three decay series are stable isotopes of lead, and so the quantity of this element in nature is increasing very slowly at the expense of the uranium and thorium.

1.20   Since the activity of a particular radioactive product is reduced to one-half in the half-life period, represented by the symbol $T$, it is evident that the amount remaining after $n$ such intervals, i. e., after time $nT$, will be $(\frac{1}{2})^n$.   Thus, after five times the half life, the activity has fallen to $(\frac{1}{2})^5$, which is about 0.03, or 3 percent, of the original amount.   After 10 times the half-life period, the activity is reduced to only 0.1 percent of the initial value.   Hence, after the lapse of sufficient time decay may be regarded as virtually complete.

1.21   Except where the rate of decay is extremely rapid, the half lives of most of the known radioisotopes have been measured, usually by means of instruments of the type described in Chapter IX, and the results have been tabulated.   It is thus often a simple matter to identify a particular radioisotope if its rate of decay has been determined, and its half life calculated.

mentioned above. In other words, the product of the radiative capture of neutrons may well be a radioactive isotope of the element which captured the neutrons.

## NUCLEAR FISSION

1.27   The great majority of nuclear reactions, whether spontaneous or the result of bombardment of atomic nuclei by neutrons or by charged particles, are accompanied either by the emission of gamma rays or by the expulsion of a relatively small particle, such as an alpha particle, a proton, a neutron or an electron (beta particle). The product nucleus is then still close, both in atomic number and mass number, to the original nucleus. With elements of high atomic number, that is, with the heavy elements lying toward the end of the periodic system, an entirely different type of nuclear reaction, known as *fission*, becomes possible. The reacting nucleus then splits up into two, more or less equal, parts, both of which differ considerably in atomic number and mass number from the original nucleus. Nuclear fission can be brought about in various ways, but by far the most important, especially for present purposes, is that in which neutrons are employed. It is, in fact, the fission of certain atomic nuclei by neutrons which is the fundamental reaction in the atomic bomb.

1.28   Uranium, the element of highest atomic number existing in nature, occurs naturally as a mixture of three isotopic forms, with mass numbers 234, 235, and 238, respectively. The uranium 238 isotope is present to the extent of 99.282 percent, while uranium 235 constitutes 0.712 percent; the very small remainder, which may be ignored here, consists of uranium 234 (Table 1.28). It has been found that the more abundant uranium 238 undergoes fission when subjected to fast (high-energy) neutrons, but either fast or slow neutrons will induce fission of the less common uranium 235 isotope.

### TABLE 1.28

#### ISOTOPIC COMPOSITION OF NATURAL URANIUM

| Mass Number | Percent | Half Life |
|---|---|---|
| 238 | 99. 282 | 4. 51×10$^9$ yr. |
| 235 | 0. 712 | 7. 07×10$^8$ |
| 234 | 0. 006 | 2. 35×10$^5$ |

1.29   The fission of uranium 238 by fast neutrons competes, to some extent, with a radiative capture reaction, and for neutrons of

lower speed, the latter process takes place exclusively. The result of the radiative capture is an isotope of uranium, mass number 239, formed by the reaction

$$U^{238} + n^1 \rightarrow U^{239} + \gamma.$$
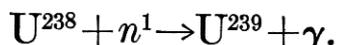
The uranium 239 decays by the emission of a negative beta particle, with a half life of 23 minutes (Table 1.18), thus

$$U^{239} \rightarrow \beta + Np^{239},$$
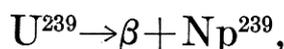
the product being neptunium 239, an isotope of which only the merest traces, if any, exist in nature. This substance also exhibits negative beta activity, its half life being 2.3 days, thus

$$Np^{239} \rightarrow \beta + Pu^{239},$$
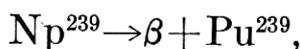
forming plutonium 239. This isotope, like its parent, i. e., neptunium 239, is extremely scarce in nature.

1.30 Plutonium 239 is a substance of special interest. Like uranium 235, it will undergo fission as a result of the action of either slow or fast neutrons. It has a relatively long half life, about 24,000 years, so that it decays very slowly, accompanied by the emission of alpha particles. The decay product of plutonium 239 is the long-lived uranium 235, so that the fission properties would remain essentially unchanged for millions of years. The fission of uranium 235 or of plutonium 239 can be utilized in atomic bombs.

## ENERGY RELEASE IN FISSION

1.31 One of the notable characteristics of the fission reaction is that it is associated with the release of a large amount of energy, about ten times as great as for any previously known nuclear process. The reason for the large energy release is due to circumstances which are essentially the same as those responsible for the energy liberated in the decomposition of TNT or other chemical explosive. In the case of nuclear fission, the binding forces between the nucleons, i. e., the protons and neutrons, in the uranium or other nucleus undergoing fission is less than they are in the nuclei formed as a consequence of fission. As seen in § 1.6, this state of affairs must lead to a liberation of energy, as is actually observed.

1.32 It is of interest to consider briefly why the binding forces are greater in the lighter fission-product nuclei than they are in the

heavier uranium or plutonium nuclei undergoing the fission reaction. It has been established that within the nucleus very strong forces of attraction exist between neutrons and protons and also between neutrons themselves. But the protons, being positively charged, repel one another and so introduce a force of repulsion, which is approximately proportional to the square of the number of protons present. The stability of a given nucleus is determined by the balance between these forces of attraction and repulsion.

1.33   With increasing atomic number, the number of protons in the nucleus, and hence the magnitude of the force of repulsion, increases rapidly, and relative stability can be attained only as a result of increasing the number of neutrons. The increased attractive force then counteracts, to some extent, the force of repulsion. The ratio of neutrons to protons is thus higher among elements of high atomic (or mass) number than among those of lower atomic (or mass) number (see Fig. 1.12). For example, the nucleus of uranium 238 contains 146 neutrons and 92 protons, so that the neutron-to-proton ratio is nearly 1.6. On the other hand, in the nucleus of tin 119, with half the mass number, there are 69 neutrons and 50 protons, so that the ratio is close to 1.4. In spite of the increased number of neutrons, which serve to provide some degree of stability, in the nuclei of high mass number, it is not surprising to find that the mean resultant binding force between the nucleons is smaller than it is for nuclei of lower mass number. Support for this statement is found in the fact, mentioned in § 1.16 that no stable isotopes of the heaviest elements are known, for they are all radioactive, thus indicating their relative instability.

1.34   Because the binding forces between nucleons in a nucleus are very much greater than those operative between the atoms in a molecule of a chemical compound, the amounts of energy released in nuclear reactions, particularly in fission, are considerably larger than those liberated in chemical processes. A convenient way of calculating the energy change is to utilize the fact that the forces in atomic nuclei manifest themselves in the respective nuclear masses. According to the theory of relativity there is an equivalence of mass and energy, which can be represented in the form of the Einstein equation

$$E = mc^2, \tag{1.34.1}$$

where $E$ is the energy equivalent of the mass $m$, and $c$ is the velocity of light. If $m$ is expressed in grams, and $c$ is taken as $3 \times 10^{10}$ centimeters per second, then the energy $E$ will be in ergs; thus

$$E \text{ (ergs)} = 9 \times 10^{20} m \text{ (grams).} \tag{1.34.2}$$

In order to obtain the energy in calories, this result is divided by $4.2 \times 10^7$. The energy change in any nuclear reaction can then be obtained from this equation by inserting for $m$ the difference in mass between the interacting nuclei and other particles, on the one hand, and the products of the nuclear reaction, on the other hand.

1.35  The total mass of a uranium 235 nucleus and a neutron, is known to be greater than the sum of the masses of the immediate products formed as a result of fission. This difference in mass is the equivalent of the energy released in the process. When 1 kilogram, i. e, 1,000 grams, of uranium 235 undergoes fission the decrease of mass is just less than 1 gram and, by equation (1.34.2), this is equivalent to somewhat below $9 \times 10^{20}$ ergs, or $2.1 \times 10^{13}$ calories.

1.36  In order to provide a definite basis for discussion, the present book will consider, primarily, the effects of a *nominal atomic bomb*, similar to those used at Hiroshima and Nagasaki. The energy release of such a bomb is approximately equivalent to that of 20 kilotons, i. e., 20,000 tons, of TNT, and since the energy equivalent of a ton of TNT is taken to be $10^9$ calories, the energy release of the nominal atomic bomb is $2 \times 10^{13}$ calories. Comparing this result with that given above for the energy produced in the fission of uranium 235, it is seen that in the complete fission of 1 kilogram, i. e., 2.2 pounds, of uranium 235 the energy released is essentially equivalent to that of 20 kilotons of TNT. Consequently, the fission of uranium 235 would liberate nearly 20 million times as much energy as the explosion of an equivalent weight of TNT. The same general ratio applies also to plutonium 239.

1.37  The amount of energy produced in the fission of 1 kilogram of uranium 235 or plutonium is expressed in various units in Table 1.37. It is of interest to add that it is also equivalent to about

TABLE 1.37

ENERGY EQUIVALENT OF FISSION OF 1 KILOGRAM OF URANIUM 235

20,000 tons of TNT
$2 \times 10^{13}$ calories
$8.4 \times 10^{20}$ ergs
$6.2 \times 10^{13}$ foot-pounds
$2.3 \times 10^7$ kilowatt hours

7,000 tons of coal and to the daily output of Hoover Dam. Although the energy released in fission is very impressive, it is relatively small compared with the energies involved in the forces of nature. For example, it is about the same as the energy of the sun's rays falling

on 2 square miles of ground during an average day, or to that released in a moderate rainstorm producing a quarter of an inch of precipitation over Washington, D. C. A strong earthquake involves almost as much energy as would be supplied by a million atomic bombs of the type under consideration.

1.38    When uranium 235 or plutonium undergoes fission, not all of the energy is released promptly; about 89 percent is liberated within the first second, while the remaining 11 percent appears later, as will be explained below (§ 1.55). Since the latter is not available to contribute either to the blast or to other immediate primary effects of an atomic bomb, it is not included in the energy values given above. The fission of a single atom of uranium or plutonium releases $6.7 \times 10^{-12}$ calories, and hence, in order to produce $2 \times 10^{13}$ calories, it is necessary for about $3 \times 10^{24}$ atoms to suffer fission to release the energy equivalent to 20 kilotons of TNT. This number of atoms is, of course, approximately the total number present in 1 kilogram of uranium 235 or plutonium.

## FISSION CHAIN REACTION

1.39    In spite of the enormous energy liberation in nuclear fission, this alone would not have made the atomic bomb possible. The important point, in addition, is that the fission process, initiated by neutrons, is accompanied by the almost instantaneous emission of more than one neutron for each nucleus undergoing fission. When it is recalled, as indicated above, that the proportion of neutrons to protons in the fissionable nucleus is normally much greater than in the lighter nuclei which result, it is not surprising that some neutrons are set free in the actual fission process. The neutrons liberated in this manner are able to induce fission of other nuclei, each such process resulting in the emission of more neutrons which produce further fission, and so on. Thus, in principle, a single neutron could start off a chain of fissions, the number of nuclei involved increasing at a tremendous rate.

1.40    Suppose, for simplicity, that for each uranium or plutonium nucleus suffering fission two neutrons are liberated; if each of these causes fission, with the release of two neutrons in each case, there will be four neutrons available. These could induce fission of four more nuclei, accompanied by the emission of eight neutrons, the chain continuing, in theory, until no more fissionable material remains. A single neutron might thus cause the fission of a large quantity of ura-

nium 235, just as the detonation of a few molecules of TNT might bring about the explosion of a considerable charge.

1.41 If, as just suggested, the number of neutrons, and hence of nuclei undergoing fission, is doubled in each generation, then starting with a single neutron the numbers would increase steadily, thus, 1, 2, 4, 8, 16, 32, 64, . . . . In about 80 generations enough neutrons would have been produced to cause the fission of every nucleus in 1 kilogram of uranium, resulting in the liberation of $2 \times 10^{13}$ calories of energy. The time required for the actual fission process is very small, and most of the resulting neutrons are emitted promptly. Consequently, the interval between successive generations is determined by the average time required for a free neutron to be captured by a fissionable nucleus. Supposing this to be about $10^{-8}$ second, then the eightieth generation would be attained in less than a millionth of a second. The release of the enormous amount of energy in such a short interval of time would provide the conditions for a tremendous explosion. It is seen, therefore, that because the fission process is accompanied by the instantaneous liberation of neutrons, as well as of large quantities of energy, it is possible, in principle, to produce a self-sustaining, chain reaction capable of being utilized in an extremely powerful bomb. This is the atomic bomb, so called because it makes use of the energy of the fissionable atoms or, more correctly, of the nuclei of such atoms.

1.42 It may be pointed out that the foregoing calculations have been based on the postulate that every neutron liberated in the fission of each uranium nucleus goes on to produce fission in other nuclei. In actual practice this is not the case. A proportion of the neutrons are always absorbed as a result of competing capture processes, while others escape from the system altogether. If the rate at which the neutrons are lost in these ways exceeds the rate at which they are formed by the fission of nuclei, the fission reaction would soon come to a stop. The escape of neutrons occurs at the exterior of the fissionable material, and this depends on the surface area, whereas the fission process, which results in the formation of more neutrons, takes place in the interior, so that it is proportional to the volume. Hence, the relative rate of loss of neutrons by escape can be minimized by increasing the size of the system, for in this manner the ratio of area to volume is decreased.

### Critical Size of Atomic Bomb

1.43 If the quantity of material is too small, that is to say, if the ratio of the surface area to volume is too large, the loss of neutrons

will be so great that the propagation of the fission chain reaction, and hence the production of an explosion, will not be possible.   But as the size of the system undergoing fission is increased, and the relative loss of neutrons by escape is decreased, as is shown diagrammatically in Fig. 1.43, a point is reached at which the reaction becomes self-
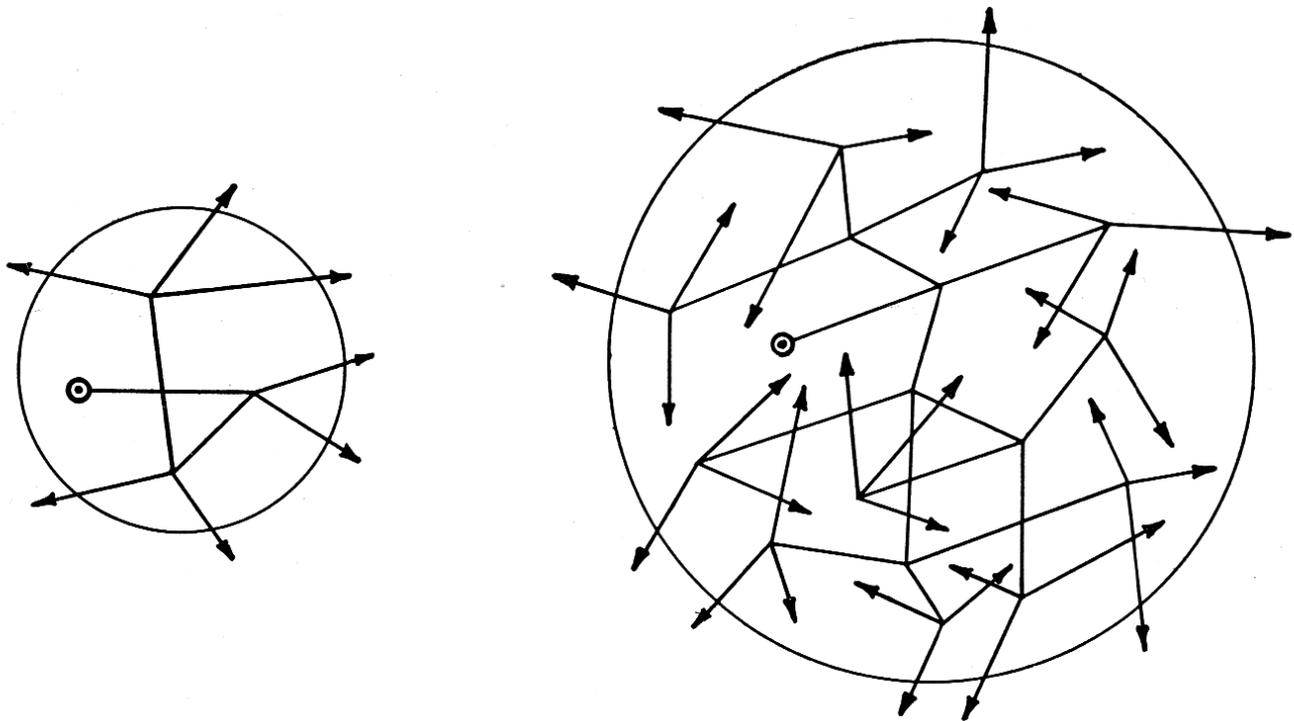


Figure 1.43.   Diagrammatic representation of effect of size of fissionable material on relative loss of neutrons by escape.

sustaining, once it has been initiated.   This is referred to as the *critical size* of the chain-reacting system.   An atomic bomb, to be effective, must thus contain a sufficient amount of fissionable material to exceed the critical size.[5]   The critical size depends, among other things, on the isotopic composition of the fissionable material and on the presence of substances which capture neutrons.   By surrounding the system with a suitable neutron reflector, the loss of neutrons by escape can be reduced, and hence the critical size diminished to some extent.

1.44   Because of the presence of stray neutrons in the atmosphere, a quantity of fissionable material exceeding the critical dimensions would be liable to explode.   Therefore, it is necessary that before detonation the bomb should consist of two or more separate parts, each of which is less than the critical size.   To cause an explosion, these parts must be brought together very rapidly.   Extreme rapidity

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[5] The atomic bomb differs from conventional bombs in the respect that the former must contain more than a critical quantity of fissionable (explosive) material, while the latter can contain any desired quantity of explosive from a pound or so up to several tons.   Consequently, conventional bombs may have large or small energy releases, but a "small" effective atomic bomb cannot be made.

after an explosion, expansion of the hot gases initiates a pressure wave in the surrounding medium as represented very roughly by the curve in Fig. 1.57a; this shows the general nature of the variation of pressure with the distance from the explosion at a given instant. As the wave is propagated away from the center of the explosion, the following (or inner) part moves through a region which has been already compressed and heated by the leading (or outer) parts of the wave. The disturbance moves with the velocity of sound characteristic of the medium, and since this velocity increases with temperature and pressure the former part of the wave moves more rapidly and catches up on the latter, as shown in Fig. 1.57b. The wave front thus gets steeper and steeper, and within a very short period it becomes mathematically abrupt, as indicated in Fig. 1.57c. This represents the
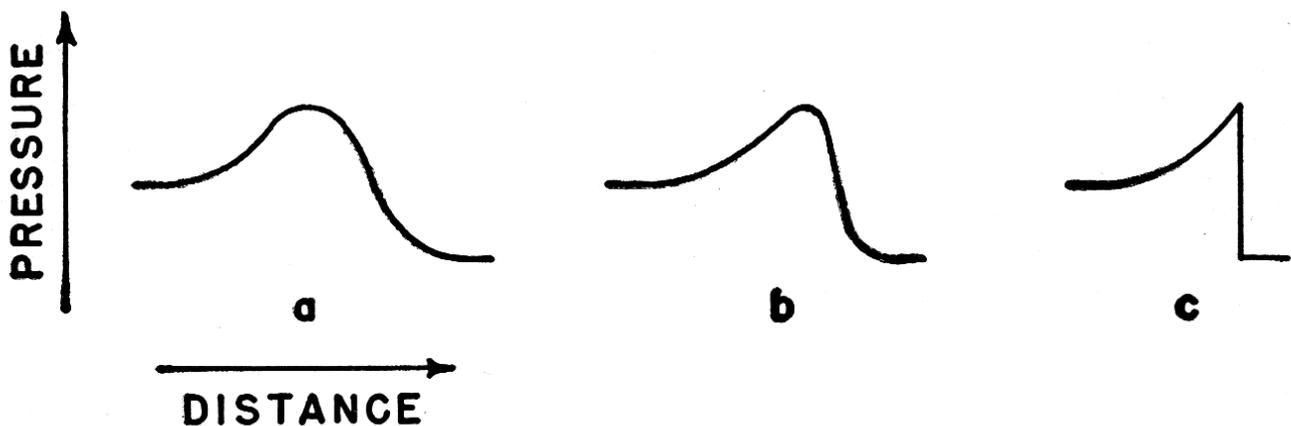


Figure 1.57.   Simplified representation of development of shock wave.

destructive shock wave which continues to move forward through the medium for some time, essentially unchanged in form, but with gradually decreasing intensity. It can be seen that at the advancing front of the wave, called the *shock front*, there is a very sudden drop of pressure, to that of the surrounding atmosphere. The shock front thus behaves like a moving wall of highly compressed air or water.

1.58   When the shock wave strikes a resistant surface, such as the earth, it is reflected back; this reflected wave is also capable of causing material damage. Under certain conditions the incident and reflected shock waves fuse for a limited distance, so that the air blast in this range is much greater than that due to the incident shock (see Chapter III).

### EMISSION OF RADIATION IN ATOMIC EXPLOSION

1.59   Apart from the mechanical or blast damage, which is characteristic of all bombs, the atomic bomb produces additional

nearly saturated, with water vapor, condensation, accompanied by cloud formation, will occur in these circumstances (Fig. 2.19).
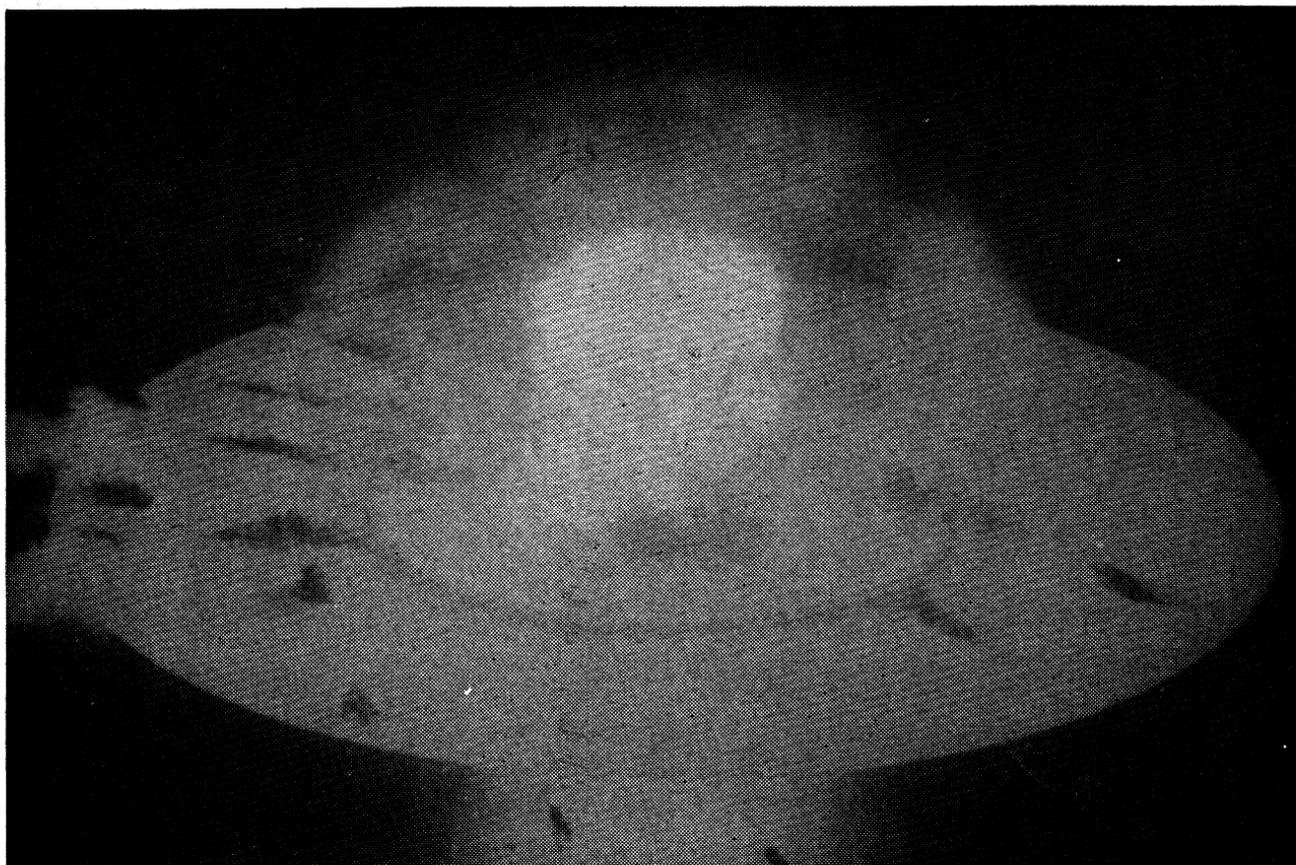


Figure 2.19. The ball of fire visible within the "cloud-chamber" effect after the Bikini "Able" explosion.

2.20 The water-drop cloud actually forms at some distance from the ball of fire, because the shock wave has to travel a considerable distance before the pressure at the shock front has fallen sufficiently for the conditions necessary for condensation to be realized. For example, air which is fully saturated with water vapor will form a cloud at a distance in the neighborhood of 2,500 feet from a bomb burst. Because of the necessity for relatively high humidity of the air, the cloud-chamber effect can be best observed in an atomic explosion occurring over or under water, for example, in the experimental bursts at Bikini. Restoration of the air pressure causes the water droplets to vaporize and the cloud is dispelled, the whole effect being over in about a second or so.

## Atomic Cloud Effects

2.21 There remain now to be considered what may be described as the residual effects of the atomic explosion, some of which, like the characteristic mushroom-shaped cloud, are merely spectacular, but others are a possible source of danger. While the ball of fire is still

luminous, the temperature, at least in the interior, is high enough to vaporize all the substances present, namely, fission products and unchanged uranium or plutonium, as well as the materials used for the casing of the bomb.

2.22    Because of its high temperature, and consequent low density, the ball of fire rises, as stated above, and as it rises it is cooled. At temperatures down to about 1,500° C. the cooling is mainly due to loss of energy as thermal radiation; subsequently, the temperature is lowered as a result of adiabatic expansion of the gases and by mixing with the surrounding air through turbulent convection. When the ball of fire is no longer luminous, it may be regarded as a large bubble of hot gases rising in the atmosphere, its temperature falling as it ascends.

2.23    As they cool, the constituents of the bubble condense, thus forming water droplets and a metallic oxide smoke made up of solid particles of varying sizes. If the bomb is detonated at a low altitude, e. g., less than 500 feet, so that the ball of fire touches the ground, a considerable amount of dirt, steel or other material located in this area will be vaporized and taken into the ball of fire.[10]  Small solid particles of these materials will also separate out as the gas bubble cools.

2.24    Depending on the height of burst of the atomic bomb and on the nature of the terrain, high winds will occur in the immediate vicinity of the explosion. These, together with the air blast due to the shock wave, will cause various amounts of dirt and other particles from the earth's surface to be sucked up. In the event of a crater being formed, as it was in the Alamogordo ("Trinity") test, considerable quantities of dirt will be present (Fig. 2.11). But it appears unlikely that there will be any appreciable crater formation for the explosion of a nominal atomic bomb at heights exceeding 250 feet.

2.25    At first the rising ball of fire carries the particles upward, but after a time they begin to fall under the influence of gravity at various rates dependent on their size. Consequently, an ascending and expanding column of smoke is observed to form; it consists of water droplets, radioactive oxides of the fission products, and more or less debris, largely determined by the height of the explosion. The rate of ascent depends on various meteorological conditions, as will be seen below, but the results in Table 2.25 may be taken as fairly typical.

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[10] The energy required to heat up and vaporize sand, which may be taken to be representative of soil material, is 2,700 calories per gram. Consequently, if 5 percent of the bomb's energy is used in vaporizing soil, about 360 tons of this material would be added to the gaseous constituents of the ball of fire.

TABLE 2.25

RATE OF RISE OF ATOMIC CLOUD

| Height, feet | Time, minutes | Rate of rise, miles per hour |
|---|---|---|
| 10, 000 | 0. 8 | ~200 |
| 15, 000 | 1. 5 | ~50 |
| 20, 000 | 2. 6 | ~33 |
| 25, 000 | 4. 6 | ~20 |
| 30, 000 | 8. 5 | ~12 |

2.26  The height to which an atomic cloud will rise depends on the thermal (heat) energy emitted by the bomb, the temperature of the surrounding air, and the density of the air.   The greater the energy liberated as heat, the larger will be the buoyancy thrust on the rising cloud, and hence the greater will be the distance it ascends.   It is believed that the maximum height attainable by an atomic cloud will be limited by the height of the base of the stratosphere.  This is apparently in agreement with the observation on the "Trinity" test bomb at Alamogordo, New Mexico, for the cloud in this case rose to 40,000 feet.

2.27  If the radioactive cloud should pass through a temperature inversion layer [11] in the atmosphere, it will tend to "mushroom" out to a small extent.   Because the air in the inversion layer is fairly stagnant, some of the particles in the cloud will tend to spread out horizontally instead of continuing to move vertically.   Nevertheless, as a result of the enormous thermal energy of the hot gas bubble, most of the cloud will usually pass through an inversion layer.

2.28  Upon attaining a region where the density of the gas bubble is the same as that of the surrounding air, or upon reaching the base of the stratosphere, at about 40,000 to 60,000 feet, where the temperature of the atmosphere is almost constant and there is practically no motion due to convection, the radioactive column will spread out for a distance of several miles and form the characteristic mushroom shaped cloud (Fig. 2.28).   The latter, having reached the final stage of its development, remains visible for an hour or more, until it is dispersed by the winds into the surrounding atmosphere.

THE FALL-OUT

2.29  When the radioactive, metallic oxide particles in the cloud collide with the particles of dirt, which are in general considerably

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[11] At an inversion layer the temperature, which has been falling with increasing altitude, begins to increase.
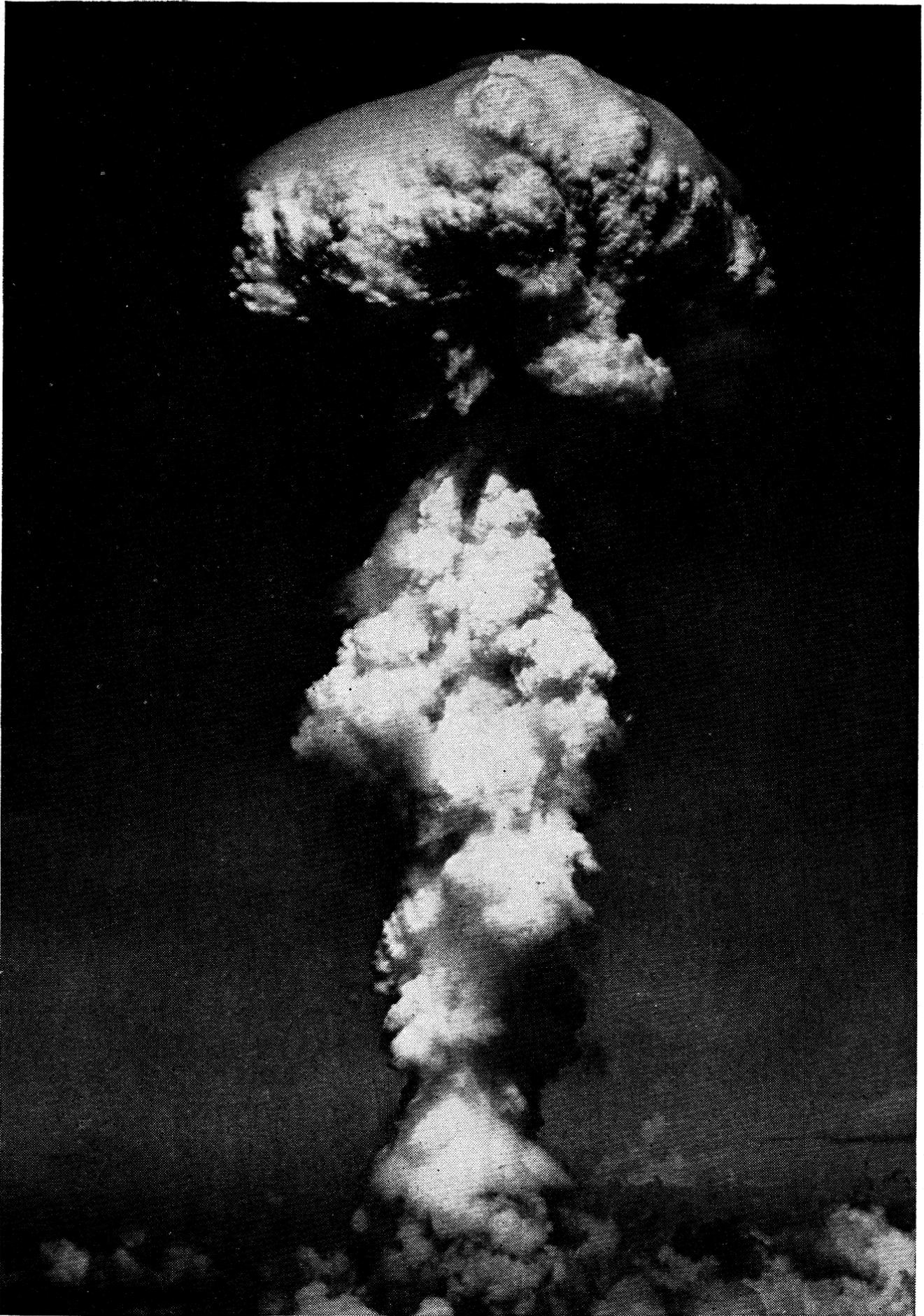
Figure 2.28.    Mushroom cloud attaining a height of 5 miles after the "Able" test explosion.    The ice cap or scarf cloud at the top consists of myriads of small ice crystals; the gases above the mushroom expand and are consequently cooled, thus causing water vapor in the atmosphere to be converted into ice.

larger, they adhere. Consequently, the dirt particles in the cloud become contaminated with radioactivity. When the violence of the disturbance due to the bomb has subsided, the contaminated dirt particles gradually fall back to earth, giving rise to the phenomenon known as the *fall-out*. The extent and nature of this fall-out will be determined by the combination of circumstances associated with the height of the explosion, with the nature of the surface beneath, and with the meterorological conditions. It is possible that if the height of the bomb burst exceeds a certain value, there will be no detectable fall-out since no extraneous particles will be sucked into the cloud.

2.30 The importance of the fall-out in the present discussion lies in its radioactivity. It may be stated at the outset that only in exceptional circumstances would the intensity of the activity be great enough to constitute a hazard upon reaching the ground. The evidence from the Hiroshima and Nagasaki atomic bomb explosions, where the height of burst was about 2,000 feet, is that casualties ascribable to the radioactive fall-out were completely absent. However, if the bomb burst occurred relatively close to the ground, a situation which would be uneconomical from the standpoint of the destructive effect (§ 3.68), and considerable amounts of dirt and other debris were sucked into the radioactive cloud, the fall-out would have to be considered as a danger. The fall-out, consisting mostly of water drops, would also be important if the detonation took place at a low level above the surface of water; and the presence of salt in the water would enhance the hazard (§ 8.25).

### Atomic Bombs and the Weather

2.31 There was at one time considerable speculation concerning the possible effects on the weather of an atomic burst, especially one over water. Forecasts of violent weather reactions were based primarily on two considerations. First, it was thought that large amounts of moisture in the air, such as is common in tropical areas, together with the water expected to be evaporated from the surface of the water, would be conducive to thunderstorm formation consequent upon the release of a large amount of energy by the explosion. Second, there was a possibility that the high concentration of ionized particles [12] resulting from the atomic explosion would serve as nuclei for condensation and thus promote the production of clouds and rainfall.

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[12] The fission products are themselves ionized, i. e., electrically charged, and they, as well as the gamma rays, cause ionization of the air through which they pass.

2.32  Actually no such effects have been observed, and this is not surprising in view of the mechanism of the formation of a thunderstorm. Such storms require the transport aloft of moist masses of air by convection, or by mechanical lifting by fronts for a period of time, over relatively large areas, together with the existence of an appropriate vertical moisture structure. Convection caused by the warm land areas or the lifting of air masses by ascent over a high terrain or a front continues even after the storm has developed. An atomic explosion involves an almost instantaneous release of energy, and convection ceases as the hot gas bubble cools down on ascent and reaches its maximum altitude. An atomic bomb is therefore unable to produce convection of the sustained type necessary for thunderstorm formation. Even if the atmosphere is on the verge of instability, the sudden impulse of an atomic explosion cannot precipitate a thunderstorm because the energy release is so rapid that the atmosphere is unable to rearrange itself, within the limited time, so as to take advantage of the additional energy.

2.33  It is, of course, a well known fact that gaseous ions can act as nuclei for the condensation of water vapor, but quite a high degree of supersaturation is necessary before such condensation can occur. Actually the atmosphere always contains sufficient nuclei for condensation, and this is particularly so over the ocean where hygroscopic salt particles are present. Hence, the ions produced in the atomic explosion would not make any significant contribution to the condensation process.

2.34  The suggestion has been made that certain destructive, natural phenomena, such as hurricanes, tornadoes, or cold waves, could be dispelled by a sudden release of the large amounts of energy provided by an atomic bomb. But it is very doubtful if this could be done, because the amounts of energy that appear to be necessary are of a higher order of magnitude than those at present attainable.

2.35  Intermittent rain fell after the explosion of the atomic bomb over Hiroshima. This was due, indirectly, to the widespread fires which sustained convection for a considerable time after the explosion (§ 6.80). A similar phenomenon has been noted, under suitable air mass conditions, over large forest fires and over burning European cities during World War II.

2.36  Within 2 or 3 hours after the Bikini "Able" air burst, very small, light rain showers developed throughout the northern Marshall Islands. The rain falling in the path of the radioactive cloud was active, as might have been expected, but the amount of radioactivity was very small. Some attempt was made to relate the formation of

the showers with the atomic cloud.  But the showers were very widespread and were readily explained on the basis of the existing meteorological conditions.  The radioactivity of the rain was the result of radioactive particles falling into the rain clouds, which were less than 6,000 feet high, or to the presence of such particles in the air which became attached to the drops of rain.  The records of the Bikini "Able" test show that the only detectable changes which took place in the wind or atmosphere structure were the momentary effects of the blast and heat waves, and the violent changes occurring in a limited area in the vicinity of the burst.  The main cloud pattern over the lagoon was unchanged, apart from the clouds directly associated with the explosion.  A careful examination of all the available evidence would thus lead to the conclusion that an atomic bomb burst has a negligible effect on the weather.

## C.  ATOMIC EXPLOSION PHENOMENA: UNDERWATER BURST

### SHALLOW UNDERWATER EXPLOSION

2.37   When an atomic bomb is detonated under water the phenomena observed differ, as might be anticipated, from those described above for an air burst.  Although there are certain characteristic effects, the details would undoubtedly vary with the depth and area of the water and the distance below the surface at which detonation occurs.  So far, only one underwater atomic burst, namely, the Bikini "Baker" test, has been reported.  The burst was made well below the surface of the lagoon, which was about 200 feet deep.  From the results of this test many of the effects of a deep underwater burst can be inferred.

2.38   In the underwater detonation, a ball of fire is undoubtedly formed, as in the case of an air burst.  Observers of the "Baker" test at Bikini saw the water, in the vicinity of the explosion, lighted up by the luminosity of the ball of fire.  The distortion due to the waves on the surface of the lagoon prevented any clear view of the ball, the general effect being described as having the appearance of light seen through a ground-glass screen.  The luminosity remained for a few milliseconds, but it disappeared as soon as the bubble of hot gases constituting the ball of fire reached the water surface, for then the gases were expelled and cooled.

2.39   In the course of its rapid expansion the gas bubble, which now contains steam and its dissociation products, namely, atomic

hydrogen and oxygen, in addition to the fission residue, 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 ring, apparently darker than the surrounding water. This ring, sometimes called the *slick* (Fig. 2.39), is visible in contrast to the undisturbed water because the ripples or small waves are partially
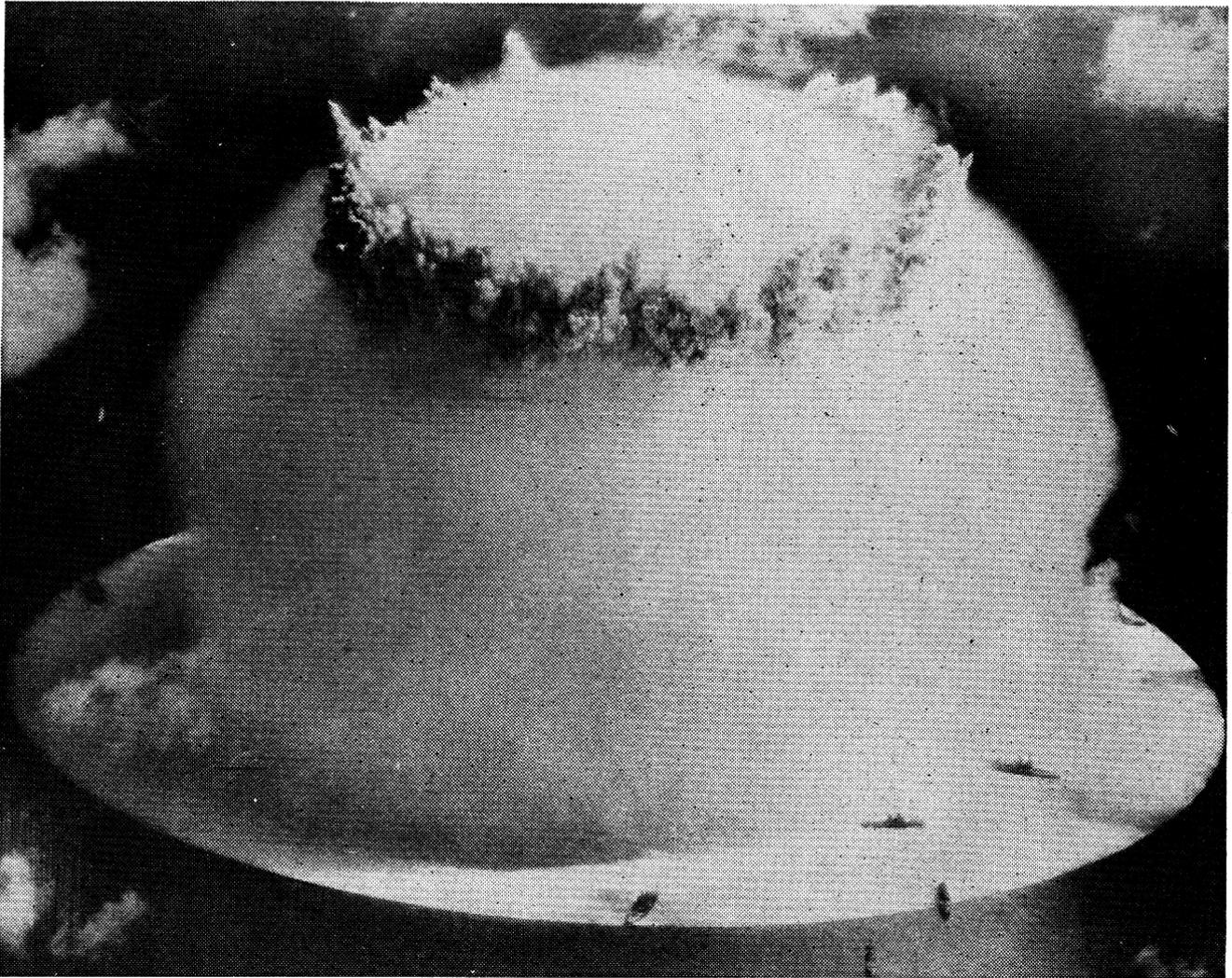


Figure 2.39. The "cloud-chamber" effect observed after the underwater ("Baker") explosion at Bikini. The slick, due to the shock wave, can be seen.

calmed by the reflection of the shock wave as a rarefaction (suction) wave at the surface of the water.

2.40    That part of the shock which passes into the air through the water surface causes a compression of the moist air; when this is followed by a rarefaction (suction) wave, the conditions may become favorable to the formation of the cloud-chamber effect (§ 2.19). This is illustrated by the dome-shaped cloud formed over Bikini lagoon almost immediately after the underwater ("Baker") burst (see Fig. 2.39).

2.41   Following the appearance of the slick, a mound or column of broken water and spray, called the *spray dome* (Fig. 2.41), is thrown up directly over the point of the burst by the reflection of the blast wave at the surface.   The initial velocity of the water is proportional to the pressure of the incident shock wave, and so it is greatest di-



Figure 2.41.   The spray dome following the "Baker" explosion.

rectly over the explosion.   Consequently, water thrown up over 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.   Its upward motion is terminated by the effects of gravity and the resistance of the air.   The total time of rise and maximum height attained depend upon the energy of the explosion and upon its depth below the surface.   For a very deep burst the spray dome may not be visible at all.

2.42   If the depth of detonation of the bomb is not too great, the bubble of hot gases will remain essentially intact until it rises to the surface of the water.   At this point the gases, in the form of a jet, carrying some water by lateral entrainment, will be vented to the atmosphere.   As the pressure of the bubble is released water rushes into the cavity, and the consequent complex phenomena cause the

water to be thrown up as a hollow cylinder or chimney of spray known as the *plume* (Fig. 2.42).   The radioactive contents of the gas bubble are vented through this hollow plume and form a mushroom-shaped cloud at the top.
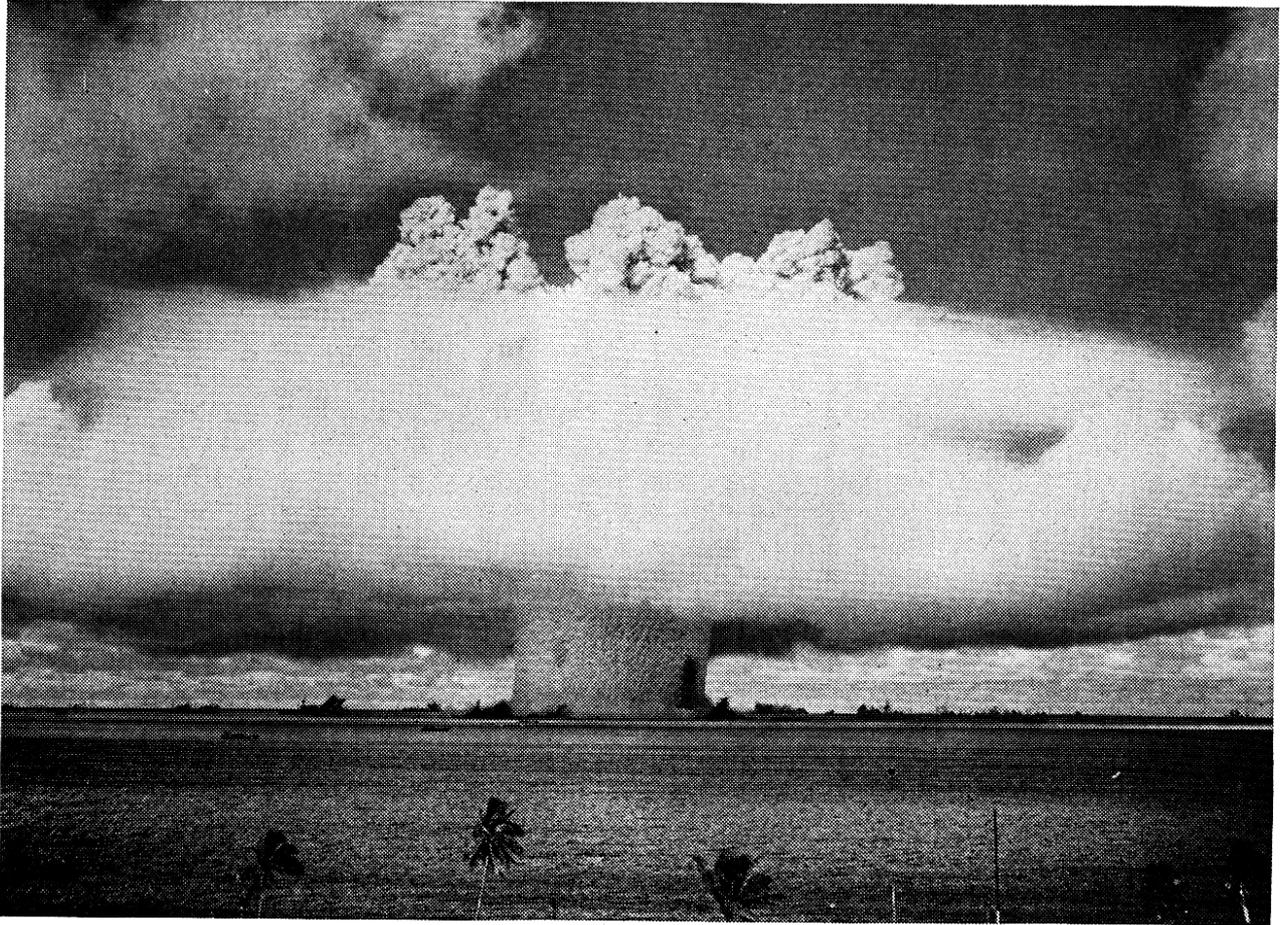


Figure 2.42.   Formation of the plume (column) in the "Baker" test.

2.43   In the shallow underwater burst at Bikini the conical spray dome began to form at about 4 milliseconds after the explosion; its initial rate of rise was some 2,500 feet per second, but this was rapidly diminished by air resistance   A few milliseconds later, the hot gas bubble reached the surface of the lagoon and the plume began to form, rapidly overtaking the spray dome at a height of a few thousand feet.   The maximum height attained by the hollow plume, through which the gases vented, could not be estimated exactly because the upper part was surrounded by cloud. (Fig 2.43).   It was probably some 8,000 feet, and the greatest diameter was about 2,000 feet.   It is estimated that the maximum thickness of the walls of the plume was about 300 feet, and that approximately a million tons of water rose in the plume.

2.44   The cloud, which concealed a large part of the upper portion of the plume, resembled a cauliflower, rather than a mushroom, in

shape. It contained some of the fission products and other bomb constituents, as well as water droplets. In addition, there is evidence that material sucked up from the bottom of the lagoon was also present, for calcareous sediment, which must have been part of the fall-out, was found on the decks of ships some distance from the burst.
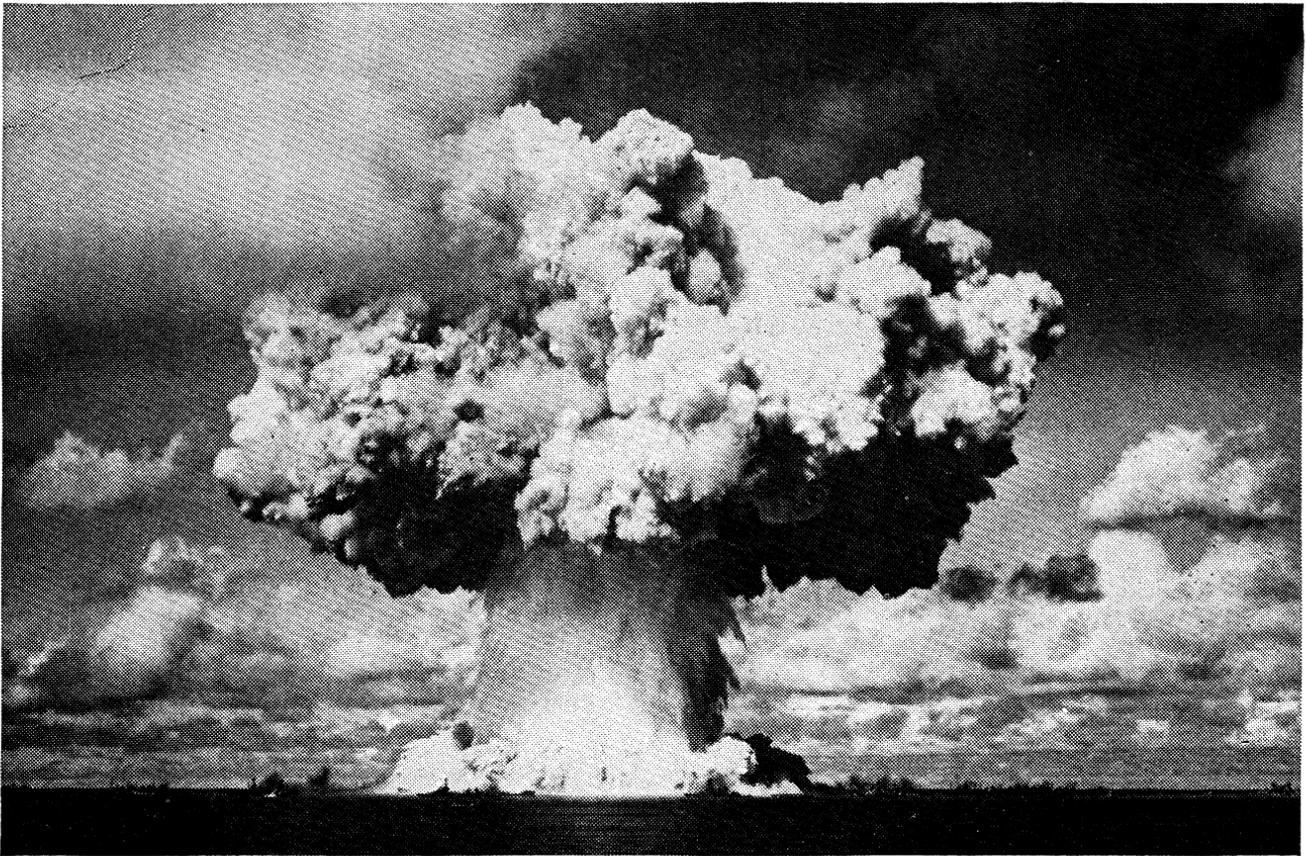


Figure 2.43. The mushroom cloud and first stages of the base surge (§2.45) following the underwater ("Baker") explosion at Bikini. Water is beginning to fall back from the column into the lagoon.

## THE BASE SURGE

2.45 In the Bikini "Baker" test, it was observed that as the column of water and spray constituting the plume fell back into the lagoon, there developed, on the surface at the base of the column, a gigantic wave or cloud of mist, approximately 1,000 feet in height, completely surrounding the neck of the plume (Fig. 2.43). This wave began to form within about 10 seconds of detonation, and traveled rapidly outward, maintaining an ever-expanding doughnut-shaped form. The wave or wall of dense mist, much like the spray at the base of Niagara Falls or other waterfall of considerable height, represents the initiation of what is known as the *base surge*. It is, in effect, a dense cloud of liquid droplets which has the property of flowing almost as if it were a homogeneous fluid (Fig. 2.45).
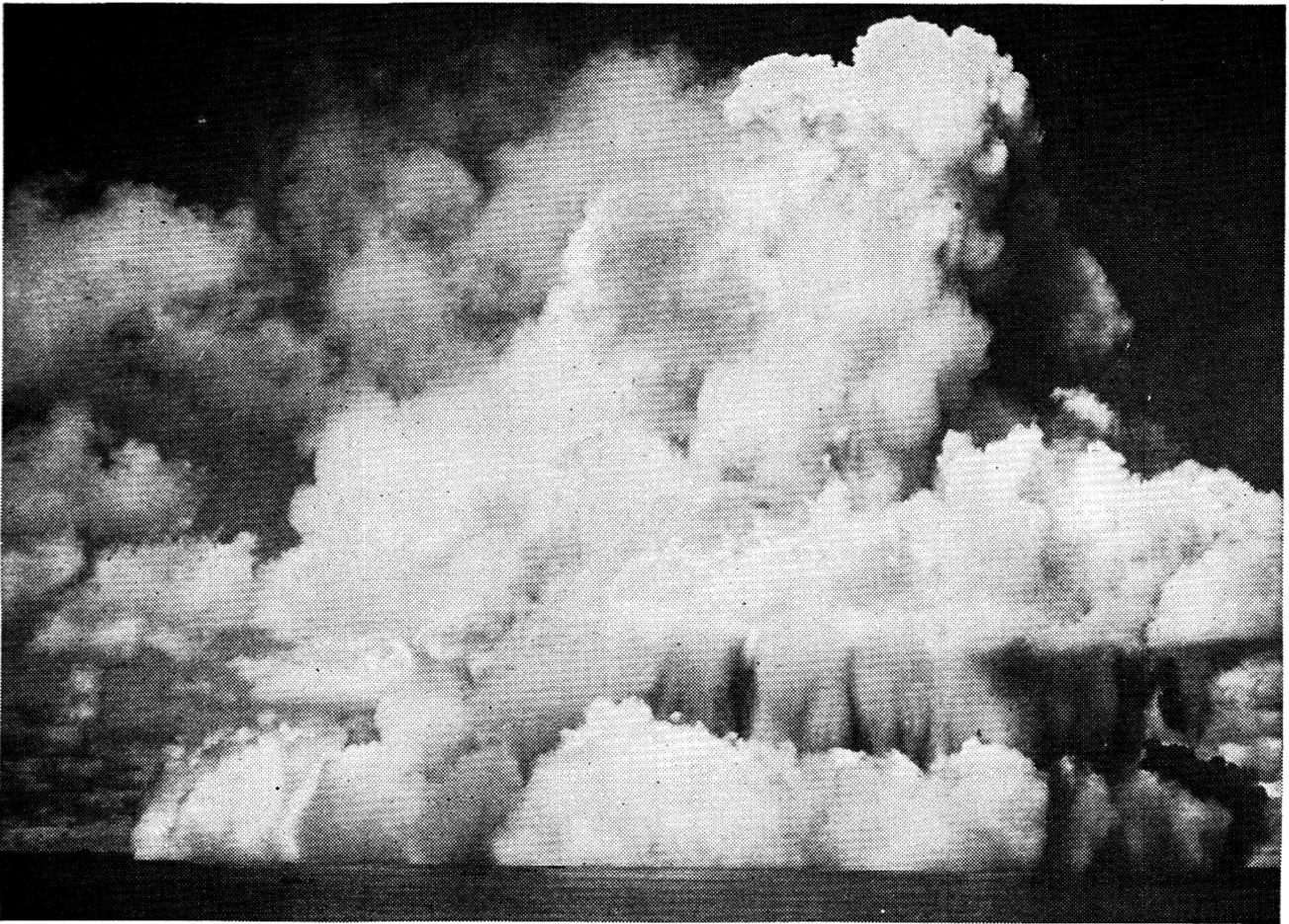
Figure 2.45.    The base surge developing after the "Baker" test.

2.46    As the base surge at Bikini traveled outward at high speed, it gradually lifted from the surface of the lagoon and after about 5 minutes it had assumed the appearance of a mass of strato-cumulus cloud, which eventually reached a thickness of some thousands of feet (Fig. 2.46).   A moderate to heavy rainfall, moving with the wind and lasting for nearly an hour after the atomic bomb explosion, developed from this cloud mass.   In its early stages the rain was augmented by the small water droplets, equivalent, in a sense, to the fall-out of an air burst (§ 2.29), still descending from the cloud.

2.47    Were it not for the fact that the base surge is highly radioactive, due to the presence of fission products, it would represent merely a curious phenomenon.   Because of its radioactivity, however, which is augmented by that of the water droplets in the fall-out, it may represent a serious hazard, for a distance of several miles, especially in the downwind direction (Chapter VIII).

2.48    It is of interest to note that there are reasons for believing that the base surge can be produced only in fairly deep water.   It may be significant that, except for the Bikini test, base surges have not been definitely observed in connection with large explosions in water,

such as that at Texas City in 1947. The conditions for the formation of a base surge, and the associated hazards will be considered more fully in later chapters.

2.49   In the event of a sufficiently deep underwater atomic burst, the hot gas bubble would lose its identity in a mass of turbulent water before reaching the surface and venting to the atmosphere. In this case, the spray dome would be relatively insignificant and no plume would be formed. Hence there would be no formation of a base surge and no appreciable fall-out. The disintegration of the gas bubble
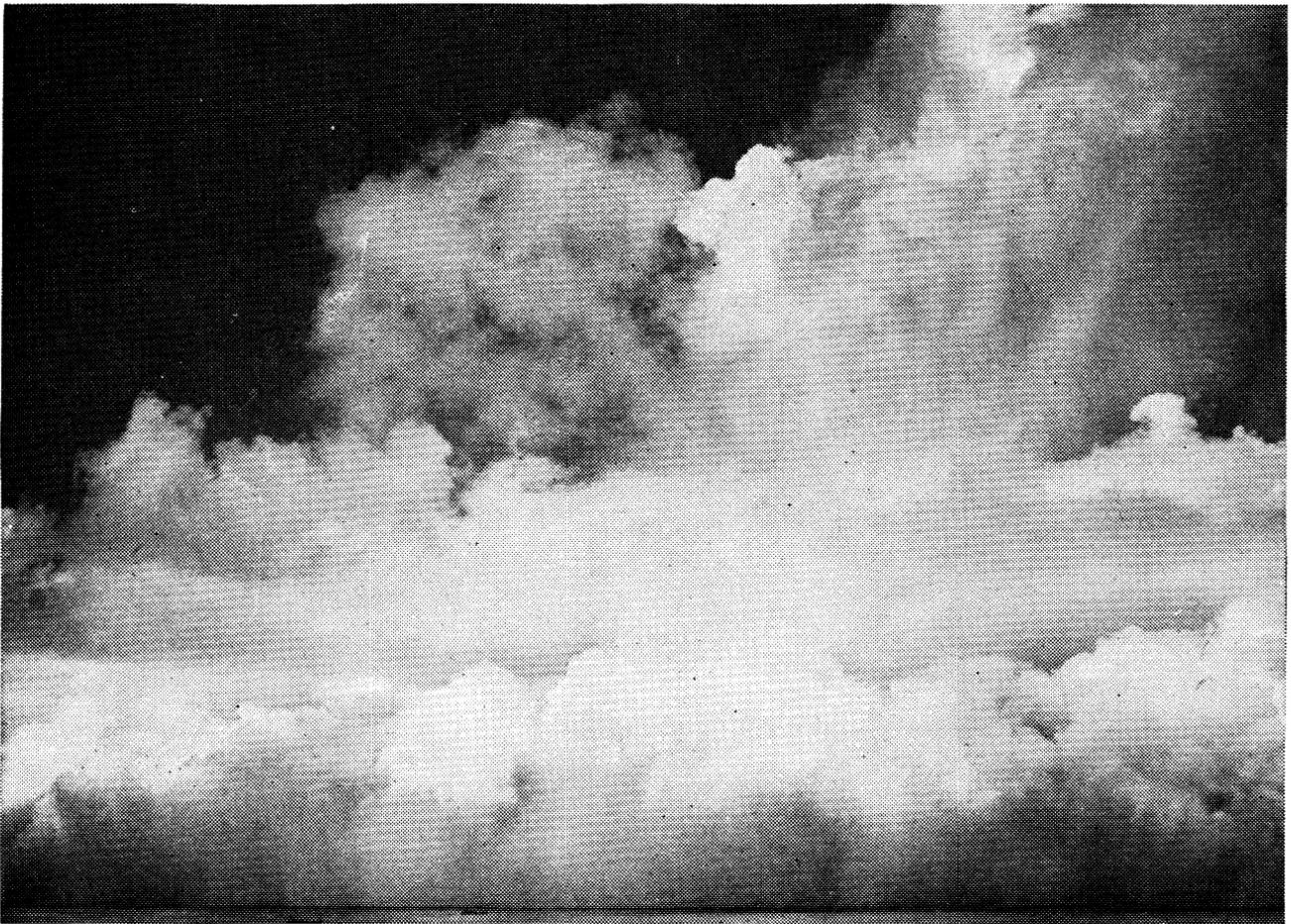


Figure 2.46.   Later stage in the development of the base surge cloud at Bikini.

into a large number of very small bubbles, which are churned up with the water, would produce a radioactive foam or froth. When this reaches the surface, a small amount of radioactive mist would be emitted, but most of the activity would be retained in the sea water. The deposition of the highly active foam on a nearby shore might, however, represent a hazard.

2.50   It seems possible that a base surge, made up of small solid particles, rather than droplets of water, but still behaving like a fluid, might result from an atomic bomb burst below a soft terrain, consisting of sand or mud. The debris would, of course, be very radioactive.

2.51   In considering the phenomena associated with an atomic bomb explosion, as described in this chapter, no mention has been made of the destructive effects of the shock wave when it encounters structures on land or ships on the surface of the sea.   Further, the harmful consequences of exposure to the radiations, both thermal and nuclear, emitted from the ball of fire, and the possible hazards due to fall-out and base surge have been no more than indicated.   These subjects will, however, be treated in some detail in subsequent chapters of this book.

# CHAPTER III[1]

# SHOCK FROM AIR BURST[2]

## A.  INTRODUCTION

3.1   The shock wave produced by an air-burst atomic bomb is, from the point of view of weapon delivery and disruptive effect, the most important agent in producing destruction.   This implies that the other characteristics of an atomic bomb which can be employed in warfare, such as the presence of thermal and visible radiations, neutrons, gamma rays, and fission products, are, at present, not serious competitors in the production of damage by a bomb which is burst in the air.   There are of course other applications, such as the possible use of an atomic weapon as an instrument for radiological warfare by exploding it in a conveniently located body of water, so as to produce a base surge (§ 2.45), or in restricting the escape of the fission products by means of a subterranean explosion.   The bomb might also be employed to produce earth or water shock through a subsurface explosion.   Such uses, although potent, must, because of the restrictive conditions placed on the delivery problem and the target location and configuration, be regarded as special applications of the varied destructive characteristics of the atomic bomb.

3.2   A reason for the superiority of air blast as a producer of damage is found in the low air shock pressures (from 2 to 15 pounds per square inch overpressure)[3] required to damage the majority of man-made structures.   Judging from observations made during tests of atomic weapons, it is in fact not very difficult to design atom bomb-proof structures which will enable life to survive directly below an air burst bomb set to explode at that altitude, about 2,000 feet, which will generally suffice to cause maximum area damage.   It is, of course, another matter to redesign cities to withstand these blasts.   Because of its primary importance in atomic warfare, the subject of air blast has received more intensive investigation and, in consequence, is better understood than the other characteristics of a nuclear explosion.

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[1] Material contributed by F. Reines.

[2] For a discussion of the theory of shock waves, see R. Courant and K. O. Friedrichs, "Supersonic Flow and Shock Waves," Interscience Publishers, Inc., N. Y., 1948.

[3] Ordinary atmospheric pressure at sea level is about 14.7 pounds per square inch (p. s. i.).   The *overpressure* is the pressure in excess of that due to the atmosphere.

3.3   The formation of the shock wave in an atomic explosion and its propagation, at first coincident with and then in front of the ball of fire, was described briefly in Chapter II.   It may be noted that the resulting air blast is still strong enough after 10 seconds, at about 12,000 feet from the explosion, to break windows, but after 30 seconds, at about 36,000 feet, almost all of its energy has been dissipated.   The behavior of the shock wave on the ground, during the half minute of its existence and when it exerts its destructive effect, is of great importance for both offensive and defensive purposes.   It is this aspect of the shock wave resulting from an air burst which will be considered in the present chapter.   The nature and type of destruction that might be expected as a result of the accompanying blast will be described in Chapter V.

## B.   CHARACTERISTICS OF THE SHOCK WAVE IN AN INFINITE HOMOGENEOUS ATMOSPHERE

### DEVELOPMENT OF SHOCK WAVE

3.4   No satisfactory detailed theory of the formation and evolution of the blast wave has been developed, although various approximations have been studied which, when coupled with experimental results, make up a reasonably complete description.   The qualitative discussion which follows is intended to give a picture of the development of a blast wave from an atomic bomb which is exploded in an infinite homogeneous atmosphere.   An examination of the effect of the proximity of the bomb to the ground will be reserved for a later section (§ 3.68).

3.5   Consider a small region in space which has been heated to a high temperature, say 100,000° C.   At the boundary of this region is a shock wave which propagates outward as the region expands. The flow of material through the shock front is described by the Rankine-Hugoniot conditions which result from the conservation laws for energy, momentum, and mass.[4]   These are important as boundary conditions in any analytical solution, and they also provide useful relationships between shock velocity, shock pressure, mass velocity, etc.

3.6   Initially, in the hot central region of the bomb the pressure exceeds atmospheric by perhaps a factor of many hundred thousand. As the shock front moves outward and the hot region grows in volume, it takes in air from outside of the shock front and drops in temperature

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[4] See R. Courant and K. O. Friedrichs, *op. cit.*

and pressure.   The pressure distribution behind the shock front in the very early stages is somewhat as illustrated in Fig. 3.6, which is a plot of the pressure against the distance from the center of the hot sphere at a given time.   It shows the pressure at the shock front, indicated by $p_s$, dropping rapidly in a relatively small distance to a
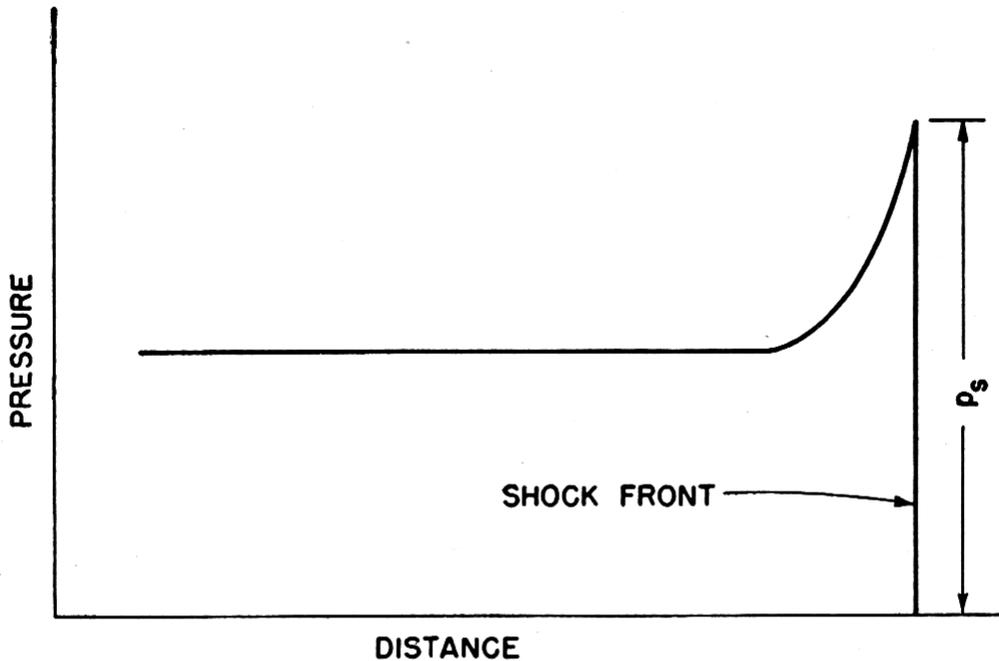


Figure 3.6.   Variation of pressure with distance in a shock wave at a given instant.

value about one-half the shock-front pressure.   The ratio of the shock pressure to that in the interior then remains constant throughout the hot region.

3.7   Because of the Hugoniot conditions and the change in the equation of state of air as the shock pressure decreases, the pressure distribution in the region behind the shock front gradually changes as the expansion proceeds.   The pressure ratio is no longer constant but drops off continuously as the center is approached.   Eventually at large enough shock radii, the rarefaction which develops at the center causes a drop in pressure below the initial preshock value and a suction phase develops.   The shock front weakens as it progresses outward and, as may be deduced from the Rankine-Hugoniot conditions, its velocity drops toward the velocity of sound in the initial cold air.[5]   At the same time the areas of the positive (compression) and negative (rarefaction) phases become more nearly equal because of conservation requirements imposed on the net outward movement of the shocked air.

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[5] For the change of shock velocity with distance, see Fig. 3.13c.   In general the shock velocity exceeds that of sound in the shock front by an amount approaching the material velocity, i. e., of the air in the present case.

3.8   The net outward motion of the air comprising the shock can at most be equal to the thermal expansion suffered by the air because of the irreversible shock heating it has undergone.   As an example, the surface of a sphere of 1,000 yards radius, i. e., about $4 \times 10^9$ cubic yards in volume, heated uniformly by a nominal atomic bomb (§ 2.1), would move outward 20 yards.   This value for the net thermal expansion is to be compared with the maximum outward excursion of about 100 yards for shocked air originally at this radius.   In other words, the shock drives the parcel of air out 100 yards, in the positive phase, and it returns in the negative phase to within 20 yards of its original position.

3.9   The sequence of events just described for increasing times from $t_1$ to $t_6$ is depicted in Fig. 3.9; this shows the pressure distribution
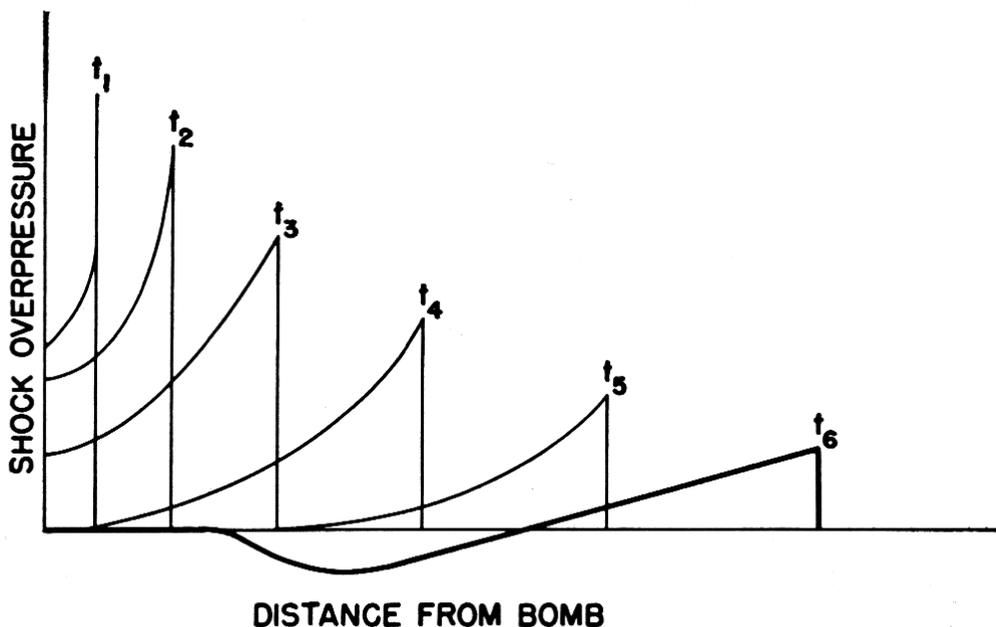


Figure 3.9.   Shock pressure-distance curves at successive times, increasing from $t_1$ to $t_6$.

in the shock as a function of the distance from the explosion at different stages in the expansion.   The absence of a negative phase out to a certain distance is apparent; however, it forms later and, as the shock weakens, approaches in area that of the positive phase.   At distances greater than 1,500 feet the negative pressure or the suction phase is well developed and the pressure distribution in the shock wave resembles the heavily-drawn curve in Fig. 3.9.

3.10   A more detailed description of the shock wave as it appears from this time on can be given in two different ways.   In Fig. 3.10, the heavy curve of Fig. 3.9, showing the variation of the shock over-pressure with distance at a given time, is redrawn.   The arrows above the curve show the direction of the air-mass movement, that is, of

the blast wind. The spatial extension of the positive phase is indicated by L; the magnitude of this extension is important in considering the damage caused. In general, the peak pressures reached in the positive phase, at the head of the blast wave, are higher than the pressures
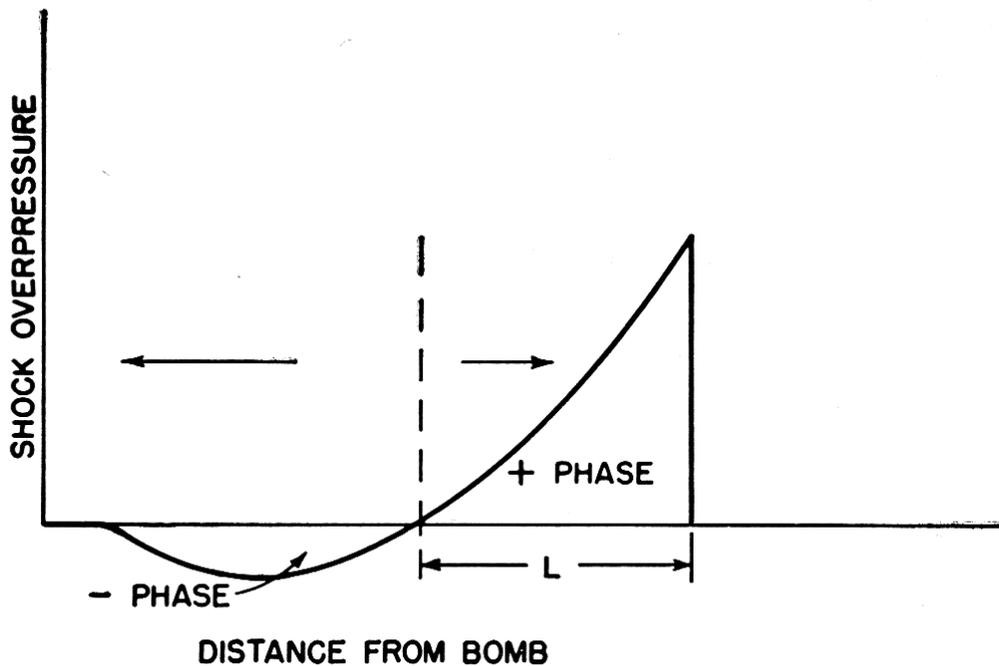


Figure 3.10. Shock pressure-distance curve at a given instant, showing positive and negative phases.

reached anywhere during the negative phase. Consequently, the blast wind is of higher velocity and shorter duration in the positive phase than in the negative or suction phase.

3.11 The same shock wave may be considered, alternatively, by plotting the variation of the overpressure with time, at a fixed location, as in Fig. 3.11. The symbol $\tau$ represents the time taken for the shock wave to travel from the explosion to the chosen location, and $t_+$ is the duration of the positive phase. Because the velocity of the shock is
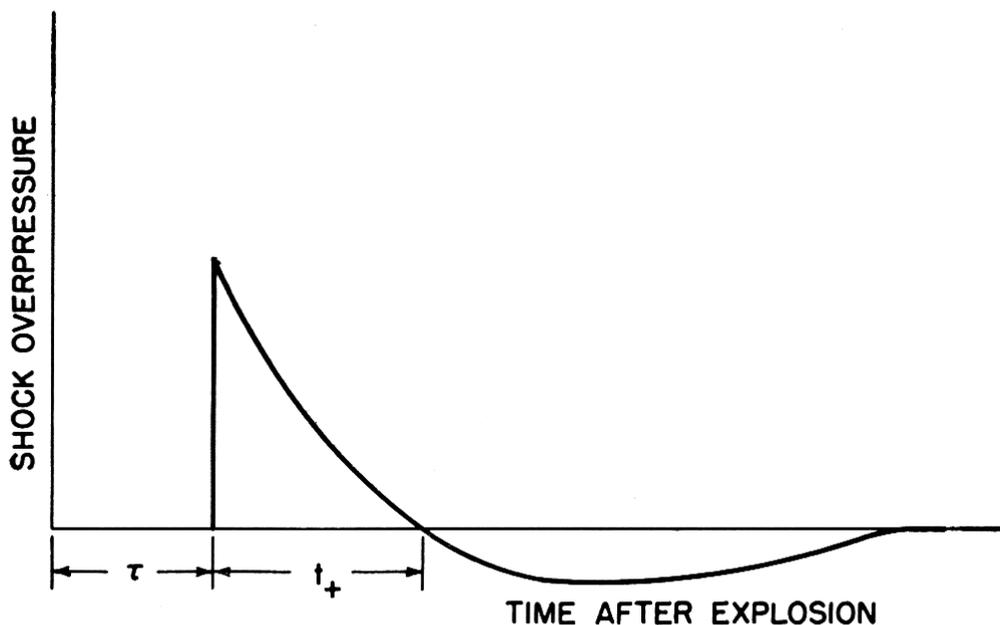


Figure. 3.11. Shock pressure-time curve showing positive and negative phases.

related to the peak overpressure by the Rankine-Hugoniot conditions, the time of arrival $\tau$ may be derived from a curve which gives the variation of peak overpressure with distance. At the 10 pounds per square inch overpressure level the spatial extent of the positive phase is in the neighborhood of 1000 feet, and its duration is something of the order of 0.5 second; the negative phase, however, lasts a few seconds.[6]

3.12  Certain other characteristics, for example, the temperature variation of the air at a given location as the shock wave passes through (see Fig. 3.12), are also of interest. When the shock front strikes the air, its temperature rises practically discontinuously to a value related to the pressure by the Rankine-Hugoniot conditions. An adiabatic expansion occurs behind the shock front so that the temperature-time sequence at a fixed location is related to the pressure-time-distance characteristics. An examination of Fig. 3.12
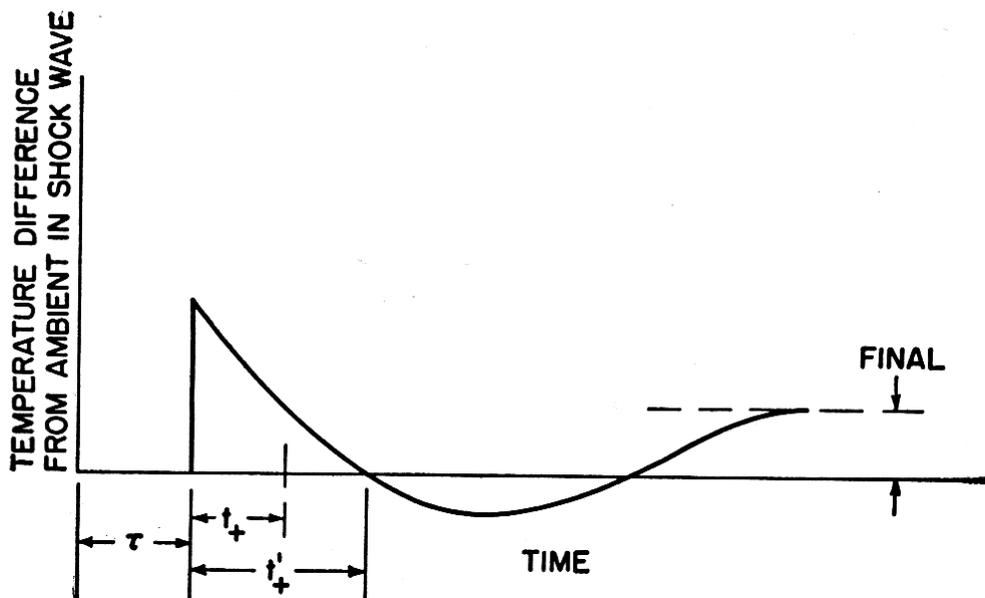


Figure 3.12.   Temperature-time curve in shock wave.

shows, first, that the temperature returns to its preshock value (time $t'_+$) after the pressure has done so (time $t_+$); and, second, that the minimum in temperature does not coincide in time with the minimum of pressure. It will be seen, too, that after the shock wave has passed, i. e., after the pressure has returned to normal, the temperature is slightly above its preshock value. The latter result is a consequence of the irreversible heating which occurs in the shock front. Because of the decrease of temperature below ambient in the

[6] As in an underwater explosion, successive secondary shocks might be expected as the air mass oscillates (§ 4.22). Such shocks should be much weaker and have in fact not yet been observed.

that $d < d_{max}$. The advantage gained by basing $h$ on $Y$ is that the pressure is increased, not only on the ground but over a vertical region coinciding with the Mach Y as well. In this way, the average pressure exerted by the blast on a structure is increased, resulting in increased destruction in regions where the pressure is marginal.

3.67 The situation is somewhat complicated by the variation of pressure along the stem of the Y. A 15 to 25 percent decrease in pressure occurs in traversing the stem of the Y from the ground to the triple point. Because of this variation the mean pressure along a chosen vertical strip is not rigorously maximized by making the stem of the Y just tall enough to cover it. As a working approximation, the height of burst will be chosen so as to achieve a desired stem height at a specific peak overpressure on the ground. By using an appropriate $W^{1/3}$ scale factor, it is possible to derive tables from the above experiments for bombs of various energy yields.

### HEIGHT OF BURST AND BLAST DAMAGE

3.68 In the concluding portion of this chapter, brief consideration will be given to the bearing of some of the results derived above on the damage caused by an atomic bomb. First, there is the question of the relationship between the height of burst and the area of blast damage. There are two arguments, as explained earlier, which favor an air burst, quite apart from the influence of oblique reflection. First, a bomb burst close to the ground is accompanied by cratering and melting of the ground, and hence there is a loss of energy from the blast. Second, an air burst avoids much shielding of one structure by another. An undesirable feature of an air burst is the fact that the bomb is further removed from the target than it would be if it were burst on the ground. To compensate, there is the fact that the high-pressure region of a bomb burst on or close to the ground would overdestroy the target in the near vicinity of the bomb (§ 3.31). This local overdestruction represents an unnecessary expenditure of energy on nearby parts of the target region, thus decreasing the destruction inflicted on more remote structures.

3.69 The reduction in blast pressure due to elevating the bomb is, of course, more pronounced for parts of the target which were in immediate contact with the ground-burst bomb, since they become removed by at least the height of burst. For more distant parts of the target the effect of increasing the height of burst is less important,

and at distances which are two or three times greater than the height of burst the change in distance from bomb to target, as a result of increasing this height, is completely unimportant.

3.70   Directly under the bomb, i. e., at ground zero, reflection from the ground partly compensates for the loss in overpressure due to the increase in distance from the bomb to the target area which accompanies an air burst.   The gain in overpressure occasioned by the head-on reflection of a normally incident shock is a factor which would be two if the shock were weak, and between two and eight if the shock is of finite strength (see Fig. 3.51).   For shock overpressures in the region of interest, i. e., 5 to 10 pounds per square inch, this factor is only a little above two.   At increasing distances from ground zero, the increase in the overpressure becomes even larger because of the properties of oblique reflection mentioned previously.   The highest amplification occurs soon after Mach reflection sets in.   After this it drops again as incidence becomes more and more glancing.   Since the blast decays with distance and the free air peak overpressure drops, maximum destruction will occur when the greatest reflection factor is at the point where the blast pressure is just marginal for the particular type of damage.

3.71   Actually, when the target, for example the wall of a house, is struck, it receives two blows if there is regular reflection by the ground in its vicinity: one by the direct and one by the reflected blast wave.   If these two waves are close together they both act as one blast.   If they are far apart, i. e., the angle of reflection is far from 90°, then these two shock waves hit the larger part of the wall with a considerable lag between their times of arrival.   As seen in § 3.37 as long as the reflection is regular the two shocks would arrive simultaneously at the ground but would be separate at all points above the ground, the separation between shocks increasing with distance from the ground.   In this case dissipative and other unfavorable effects may act between the two shocks.   Clearly, the most destruction occurs when the two shocks are merged together, a situation which obtains in the stem of the Mach Y.   If the height of burst of the bomb is such that the stem is about as high as, or perhaps slightly higher than, the target at the distance the pressure starts to drop below the destructive level, the extent of damage should be maximal.

3.72   In Fig. 3.72 the estimated peak overpressure on the ground is given as a function of the distance from ground zero for atomic
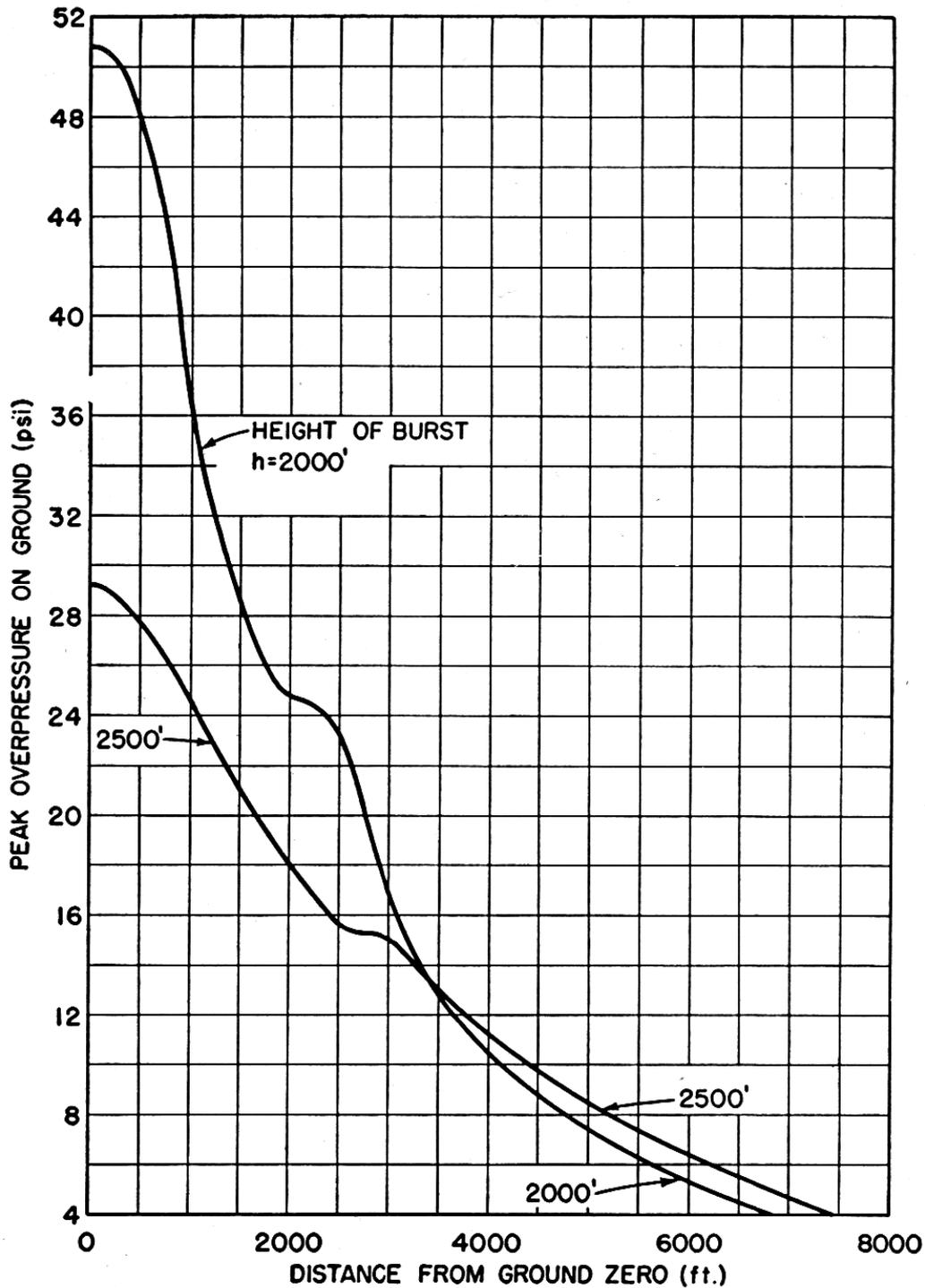
Figure 3.72.   Peak overpressure on ground as function of distance from ground
zero for heights of burst of 2,000 and 2,500 feet of nominal atomic bomb.

bomb bursts at altitudes of 2,000 and 2,500 feet above a rigid plane.
Irregular (Mach) reflection sets in around 2,000 to 2,500 feet from
ground zero, and the Mach stem height at the 10 pounds per square
inch peak overpressure is about 50 feet.

resulting in tension in the water. Sea water cannot withstand appreciable tension, the upper limit for natural sea water being of the order of atmospheric pressure. As a result, the tension is relieved by the formation of many small bubbles which prevent a further increase in tension. This phenomenon is called *cavitation*.

4.19  The form of the pressure-time curve observed at a point near a free surface is shown in Fig. 4.19; this curve is modified in its later
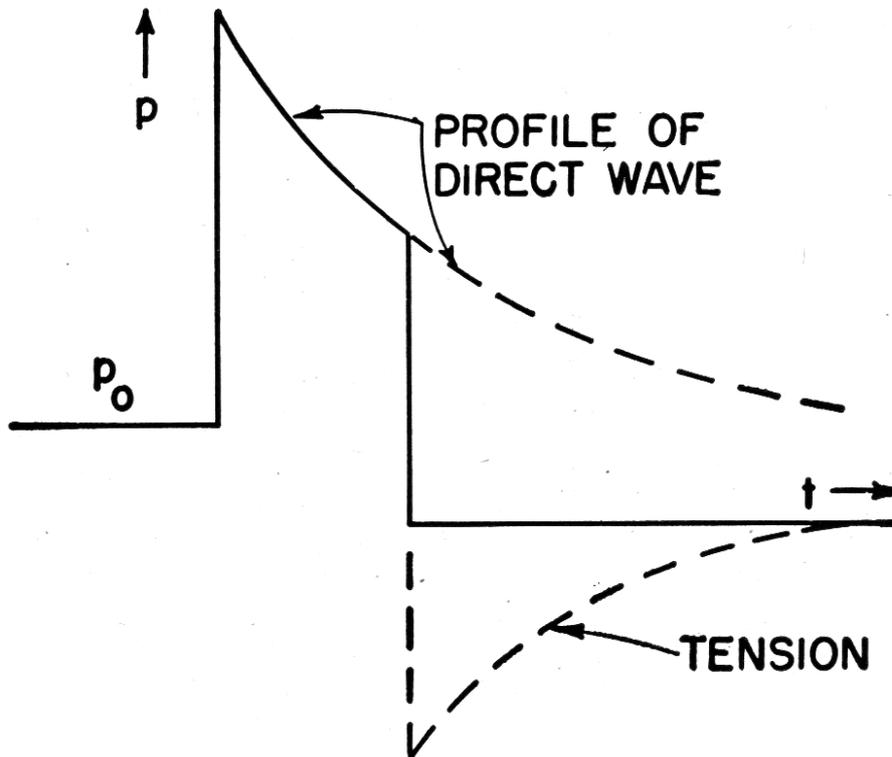
Figure 4.19.  Effect of surface reflection on a shock wave below a free surface.

portions by the reflected rarefaction wave from the surface. The broken line shows the region of tension to be expected as a result of the reflected wave and the solid line shows the result of cavitation. This effect of the rarefaction wave on the pressure wave is called the *surface cut-off*. The phenomenon of cavitation and the effects of a free surface on shock waves of finite amplitude have not been adequately described theoretically, in spite of the great importance of these effects on the surface phenomena accompanying an underwater explosion.

4.20  If the water is shallow, pressure waves reflected from the bottom may further complicate the over-all picture. The description of the pressure field resulting from the superposition of the reflected shock waves from both rigid and free surfaces then becomes very difficult.

4.21  In the description of the surface of the water as a free surface, the density of air is assumed to be negligible compared to that of

water.    Actually, the density of air is finite, and there is transmission of a relatively weak shock wave across the air-water interface into the air.    At the underwater ("Baker") test at Bikini, such a transmitted blast wave was in fact observed.

## MOTION OF THE GAS BUBBLE

4.22    After the shock wave has been emitted by an ordinary high explosive, nearly half of the initial energy of explosion remains in the gaseous detonation products.    Although the pressure in the gas bubble is then much lower than its initial value, nevertheless it is higher than the equilibrium hydrostatic pressure.    The gas bubble thus expands rapidly, and the residual energy of the gas is imparted to the water as potential energy.    The water in the neighborhood of the bubble has a high outward velocity, due in part to the excess of pressure existing within the bubble and in part to the afterflow which is characteristic of a spherical pressure wave.    Because of the inertia of the water, the expansion of the bubble continues until the gas pressure falls well below the equilibrium hydrostatic pressure.    In time, the pressure deficiency brings the outward flow of water to a stop and the bubble begins to contract.    During the contraction, the gas pressure is increased, and because of the inertia of the water, the contraction phase of the motion continues until the gas pressure is again greater than the equilibrium hydrostatic pressure.    This process may be repeated, and the bubble may undergo repeated cycles of expansions and contractions.

4.23    As a result of the several dynamical conditions which determine the motion, the bubble spends most of its time in an expanded condition, and the pressure of the gas is less than the equilibrium hydrostatic pressure during the greater part of the cycle.    The reversal of the bubble motion at the point of greatest contraction occurs so rapidly as to be almost discontinuous in a time scale appropriate to the description of the whole cycle.    These features of the bubble motion are illustrated in Fig. 4.23.

4.24    In the case of an atomic underwater explosion, the bubble consists of the fission products and a large amount of vaporized water. It may be supposed that behavior of this bubble simulates that of the bubble formed by the underwater detonation of a chemical explosive. In the simplest case, where the effects of boundaries do not need to be considered, the period of oscillation is quite simply related to the depth and to the energy residual in the gas;[6] it varies as the one-

[6] C. Herring, "Theory of the Pulsations of the Gas Bubble Produced by an Underwater Explosion," NDRC Division 6, Report No. C4-sr20-010, OSRD Report No. D-236 (1941).

third power of the energy and the negative five-sixths power of the hydrostatic pressure. The residual energy is proportional to the charge weight or yield, that is, to the energy of the explosion.
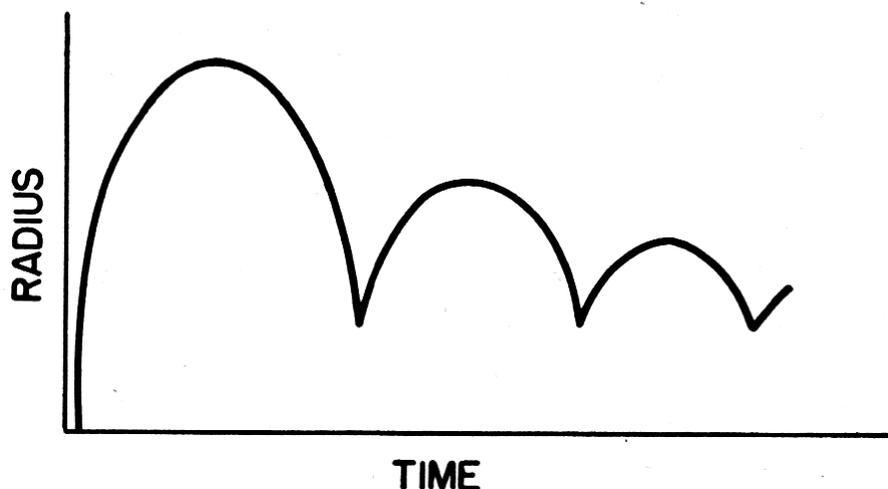


Figure 4.23.   Oscillation of gas bubble under water.

4.25   The theoretical expression for the period $T$ of the first bubble pulse is

$$T = 1.135 \rho^{1/2} p_0^{-5/6} E^{1/3}, \qquad (4.25.1)$$

where, using consistent, e. g., cgs, units, $\rho$ is the density of the water, $p_0$ is the total hydrostatic pressure at the level of the detonation, and $E$ is the energy which goes into the bubble pulsations, estimated at 0.4 of the energy of the explosion. For a nominal atomic bomb detonated at a depth of 2,000 feet, the predicted period is 1.9 seconds.

4.26   At the end of its first expansion, the radius of the bubble from an underwater explosion of TNT is given by [7]

$$R_m = 160 (W/p)^{1/3}, \qquad (4.26.1)$$

where $R_m$ is the maximum radius in feet, $W$ is the charge weight in tons, and $p$ is the total hydrostatic pressure expressed in feet of water. For 20 kilotons TNT, the depth at which the globe would just break the surface at its maximum size is 530 feet. At a depth of 1,000 feet the maximum bubble radius is 430 feet; at 1,500 feet the maximum radius is 380 feet; and at 2,000 feet the maximum radius is 340 feet.

4.27   About 40 percent of the energy of explosion, which remains in the gas bubble after the emission of the primary shock wave, is emitted in part in the form of spherical pressure waves generated by the oscillating bubble, and in part it is dissipated due to the effects of

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[7] C. Ramsauer, "Die Massenbewegung des Wassers bei Unterwasserexplosionen," *Ann. Physik*, *72*, 265 (1923). The relation has been verified by recent experimental work.

turbulence. The pressure in the water depends upon the square of the rate of bubble motion, and this is greatest near the point of greatest contraction. The excess water pressures due to bubble pulsation are, therefore, appreciable only near the time of greatest contraction. The amplitude of the pressure wave falls off with distance due to the spherical divergence of the wave. The bubble motion is radically affected by the proximity of the bubble to boundary surfaces; in consequence, the form of the pressure waves attributable to bubble motion depends upon these factors. The peak pressure of the first bubble pulse is much lower than that of the primary shock wave, being of the order of 10 percent of the latter. However, the duration of the pulse is much longer than that of the shock wave, and the impulses of the two waves are of the same order of magnitude. The pressure-time curve of the bubble pulse is shown schematically in Fig. 4.27. A considerable amount of the energy initially residual in the gas sphere is lost with each pulse, and generally only the first pulse is of appreciable magnitude.[8]
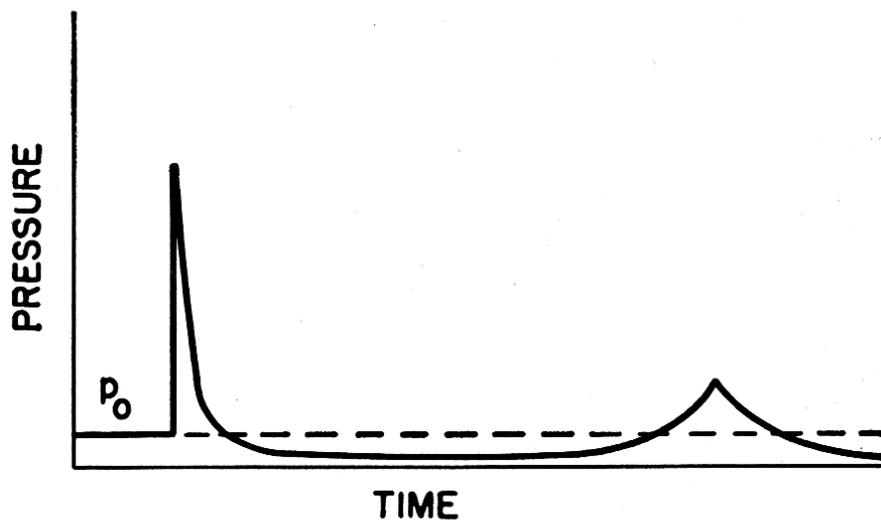


Figure 4.27. Pressure-time curve for shock wave and first bubble pulse.

4.28 A complete description of the motion of the gas bubble must include a consideration of the effect on the motion of the buoyancy of the bubble. The theoretical description given by Taylor[9] reproduces the characteristic features of the vertical migration. The bubble rises slowly during the initial period of expansion and with increasing velocity during the period of contraction; the rate of upward motion is a maximum at the point of greatest contraction. These characteristics are shown in Fig. 4.28.

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[8] A. B. Arons and D. R. Yennie, "Energy Partition in Underwater Explosion Phenomena," *Rev. Mod. Phys.*, *20*, 519 (1948).

[9] G. I. Taylor, British Report RC-235 (1941).
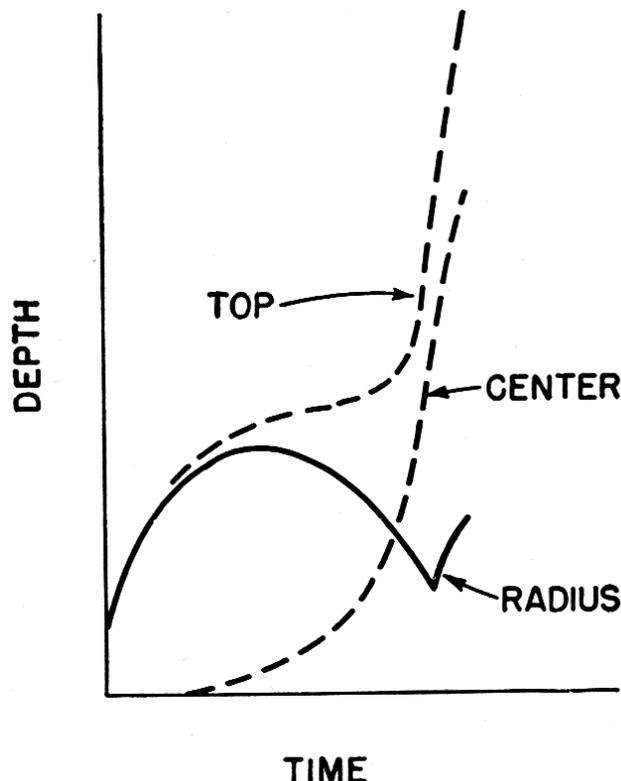
Figure 4.28. Characteristics of upward motion of gas bubble under water.

4.29 Because of the importance of the effect of gravity on the bubble motion, the simple scaling laws which pertain to the shock-wave phenomena are not applicable. Approximate scaling laws may be derived from the theoretical treatment of Taylor. However, these cannot be applied as confidently as in the case of shock-wave phenomena because the theoretical treatment neglects the additional factors affecting the bubble motion. The effect of varying hydrostatic pressure over the surface of a large bubble is to distort the bubble from a spherical shape into a mushroom shape, with the result that the theoretical estimates of migration velocity are too large. The bubble motion is also affected by proximity of the bubble to rigid surfaces, such as the ground-water interface, to the free surface at the air-water interface, and to deformable or rigid surfaces such as may be provided by a target. The exact description of these effects is a complicated hydrodynamic problem which must be considered in detail for each particular case.[10] It may be noted that the bubble is attracted toward a rigid surface and repelled from a free surface during the contraction phase of its oscillations.

4.30 One of the main reasons for interest in the vertical motion of the gas bubble is that for a charge exploded beneath a ship's hull the bubble will have approached the target during its first period. Consequently, the pressure pulse radiated at the end of the period will have a shorter distance to travel and will be more intense upon

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[10] A complete discussion is given by R. H. Cole, *op. cit.*, Chapter 8.

arrival at the target.   An approximate formula for the total rise during the first period for a bubble of the detonation products of TNT, based upon the assumption that the bubble remains spherical, is

$$\Delta y = 5900 \sqrt{W}/p_0, \qquad (4.30.1)$$

where $\Delta y$ is the rise in feet during the first period, $W$ is the charge weight in tons, and $p_0$ is the total pressure at the detonation level in feet of water.   For a 20 kiloton TNT bomb exploded at a depth of 2,000 feet, the predicted rise is 410 feet; at a depth of 1,000 feet, the rise would be 800 feet.   For depths significantly less than 1,000 feet, the bomb would not complete one oscillation before venting to the atmosphere.   Because of deviations from spherical shape, these figures represent an overestimate, as indicated above.

4.31   For very large charges, the effect of gravity predominates over the effects of the free surfaces.   Herring[6] has shown that the ratio of the velocities due to these causes is given by $(5\rho gh/p_0)\,(h/R_m)$, where $p_0$ is the total hydrostatic pressure at the detonation level, $h$ the depth of this level below the surface, $R_m$ is the maximum radius of the gas bubble, $\rho$ is the density of water, and $g$ is the acceleration due to gravity.   For a 20 kiloton TNT bomb detonated at a depth of 2,000 feet, the upward velocity due to gravity is of the order of 30 times that caused by neighboring surfaces.

## SURFACE EFFECTS

4.32   The most spectacular visible effects of an underwater explosion are the most difficult to treat theoretically.   They are intimately related to the geometry of the explosion, and depend in an involved manner on the depth of the burst.   A discussion of these effects must also consider the overall depth of the water and the contour of the bottom if the explosion has taken place in shallow water.   Since their theoretical interpretation is incomplete, only a qualitative discussion of surface effects can be attempted here.

4.33   It was stated in Chapter II that the first observed effect of the shock wave to reach the surface is the appearance of the slick, and this is soon followed by the spray dome.   The latter is thrown up directly over the charge by the reflection of the blast wave at the surface.

4.34   If the incident wave at the surface is exponential, the shock pressure decreases rapidly from its peak value.   The head of the reflected rarefaction wave falls progressively behind the head of the

[6] C. Herring, "Theory of the Pulsations of the Gas Bubble Produced by an Underwater Explosion," NDRC Division 6, Report No. C4–sr20–010, OSRD Report No. D–236 (1941).

direct pressure wave. The resultant pressure behind the rarefaction front would thus be less than the hydrostatic pressure $p_0$ at the detonation level if cavitation did not occur. Since the cavitation pressure of ordinary sea water is probably close to $p_0$, cavitation can be expected to result very near the surface in the area covered by the spray dome. According to the approximate formula of Pekeris,[11] the depth $\Delta$ at which cavitation occurs is given by

$$\Delta = \frac{p_0 R c_0 \theta}{p_m h (1 - 1.15 c_0 \theta / R)}, \tag{4.34.1}$$

where $R$ is the distance from an explosion at depth $h$, and $c_0$ is the velocity of sound. It is assumed that the incident wave is exponential, the time constant being $\theta$ and the peak pressure $p_m$ decaying as $R^{-1.15}$ (§ 4.11).

4.35 This expression indicates that cavitation occurs a fraction of a foot below the surface. Consequently, it appears that the thin layer of water becomes detached and rises with the velocity of the surface in the form of a spray rather than as a solid sheet. Kennard[12] has discussed in detail the structure of the region below the surface spray. It is concluded that the cavitation must spread rapidly downward for a distance that is appreciable but which is only a fraction of the charge depth. A mass of cavitated water with an upward velocity is thus produced, forming the spray dome.

4.36 The contour of the dome has been studied by a number of writers. If it is assumed that the peak pressure decays as $R^{-1.15}$, the initial velocity of the dome $u(r)$ at a distance $r$ from its center is related to the initial velocity at the center $u(0)$ by

$$u(r) = u(0) \left[ 1 + \left(\frac{r}{h}\right)^2 \right]^{-1.07}, \tag{4.36.1}$$

where $h$ is the depth of the explosion. The dome contour is thus steeper for a shallow explosion than for a deep one.[13]

4.37 As stated earlier, the bubble of hot gases formed in an underwater explosion reaches the surface essentially intact, provided the burst is not too deep. Here, the pressure of the bubble is relieved, and water rushes into the cavity forming a Monroe-type jet. This complex phenomenon gives rise to plumes of water spray.

[11] C. L. Pekeris, NDRC Division 6, Report 6.1-sr 1131–1433 (1944).
[12] E. H. Kennard, TMB Report No. 511 (1943).
[13] See R. R. Halverson, W. G. Schneider, and P. C. Cross, OSRD Report No. 6258 (1946).

4.38   The character of the plume depends upon the stage of the bubble motion at which venting takes place, and therefore upon the depth of the charge.  If the bubble reaches the surface before its contraction begins, it has a small upward velocity of migration and the venting is, therefore, largely radial.  At a greater charge depth, the bubble may reach the surface at its point of greatest contraction and greatest upward velocity of migration.  In this case, the water above the bubble is thrown up vertically to form a narrow, high plume.  At still greater charge depths, the vertical plume becomes increasingly less developed and radial plumes reappear.  As the charge depth further increases, this sequence can be repeated corresponding to different stages of the second bubble contraction, but on a smaller scale because of the decreased energy of the bubble.  After more than a few cycles, the bubble has an insignificant residual energy and loses its identity in a mass of turbulent water.

4.39   It is believed that the very large bubble from an atomic explosion does not survive more than about one oscillation.  For a relatively shallow burst, the bubble vents while expanding rapidly, and a vertical plume which rises to great heights appears almost immediately (§ 2.42).

## C. WAVES PRODUCED BY THE BIKINI UNDERWATER EXPLOSION

### Properties of the Waves

4.40   In the Bikini "Baker" shot, typical of shallow underwater atomic bomb explosions, the first wave to form was a positive crest, followed by a trough which descended as far below the still water level as the crest rose above it.  This trough was followed by a train of waves.  Near the explosion point the first crest was somewhat higher than the succeeding ones, both above the undisturbed water level and in total height above the succeeding trough.  At greater distances from the explosion the highest wave was frequently one of those in the train which followed the first wave.  The maximum height in this train passed backward to later and later waves as the distance from the center increased.  In almost all cases the height of the second crest was smaller than either the heights of the adjacent crests or the depths of adjacent troughs.

4.41   The number of waves measurable with the instruments used increased from 3 at 2,100 feet from the center to 6 at 10,000 feet, and

14 or more at 22,000 feet from the explosion. In an aerial photograph taken about 5 minutes after detonation over 20 waves can be seen, and the entire area of the lagoon discernible through the clouds is covered with concentric waves radiating from the bomb center. Most of these were apparently too low for instrumental measurement.

4.42   Within 8,000 feet, where the first wave is the highest wave, let $H$ be the maximum height in feet from crest to following trough and $R$ be the distance from the explosion in feet; the relationship $HR = 94,000$ can then be used to estimate maximum wave height at any given distance. Beyond 8,000 feet, the empirical equation $(HR)^{0.9} = 42,700$ should be employed. The following table [14] gives estimated maximum wave heights from crest to following trough at different distances:

| $R$, Distance (feet) | 1,000 | 2,000 | 4,000 | 6,000 | 8,000 | 10,000 | 12,000 |
|---|---|---|---|---|---|---|---|
| $H$, Maximum height (feet) | 94 | 47 | 24 | 16 | 13 | 11 | 9 |

4.43   The highest wave in the train following the first wave always had the same group velocity, which at Bikini was about 53 feet per second, and succeeding crests became highest as they attained this group velocity (and the corresponding wave length and period).

4.44   Many crests were present as appreciable waves at a considerable distance from the explosion (Fig. 4.44), but at a lesser distance there were only a few waves of measurable height. Since the wave energy travels with the group velocity, the only measurable waves present at any given distance were those that had attained or exceeded a minimum group velocity, determined by the size of the initial disturbance. At Bikini this group velocity was about 40 feet per second.

4.45   The observed times of arrival of the first wave crest are very well fitted by the equation for velocity of a solitary wave, namely,

$$\frac{dR}{dt} = C = \sqrt{g(d+h)},\qquad (4.45.1)$$

where $C$ is the wave velocity, $g$ is the acceleration due to gravity, $d$ is the depth, and $h$ is the height of the crest above the undisturbed water level.

4.46   The following values are obtained for the time of arrival of the first crest at different distances from the explosion:

| Distance (feet) | 1,000 | 2,000 | 4,000 | 6,000 | 8,000 | 10,000 | 12,000 |
|---|---|---|---|---|---|---|---|
| Arrival time (seconds) | 11 | 23 | 48 | 74 | 101 | 127 | 154 |

[14] These results may be assumed to apply to a nominal 20 kiloton TNT energy equivalent atomic bomb. In general, for an explosion in deep water the product $HR$ should be proportional to $W^{1/2}$, where $W$ is the energy release of the bomb. If the distance $R$ is proportional to $W^{1/3}$ (§ 3.16), then $H$ should vary as $W^{1/6}$.

Figure 4.44. Waves from test "Baker" reaching the beach at Bikini. The maximum wave height at the shore was about 7 feet.

4.47 Owing to the shoaling of the water in the direction toward Bikini, the velocity of the first wave markedly decreased beyond 12,000 feet and this wave arrived at Bikini, approximately 18,500 feet from the target center, about 306 seconds after the explosion. Thus the speed in the last 6,000 feet decreased to about half the value near the explosion point.

4.48 Times of arrival of the earliest measurable rise of the water surface due to the first wave, when plotted against distance, approximately fit a straight line with a slope of 80 feet per second, which intersects the axis of abscissas at about 1,000 feet. Theoretically the first rise traveled with acoustic velocity and was related to the shock wave itself. The measured first rise must therefore represent a sudden increase in an already existing slope of the sea surface and is probably related to the rate of travel of the wave energy. The point on the back side of the first crest at which the wave surface crossed the undisturbed water level traveled at about 70 feet per second.

4.49 The time interval between the first and the second crests was less than 20 seconds at 2,000 feet and increased to 40 seconds at 12,000 feet. That this interval continued to increase with increasing distance is indicated by the tower photographs from Bikini, which showed that the second major wave arrived at the beach more than 60 seconds after the first. It is probable that this apparent increase

of 20 seconds between 12,000 and 18,000 feet was due to the dying-out of the second wave, because of the difference between energy (group) velocity and phase velocity.

4.50   The distance between the first and second waves at 2,000 feet from the target center was 1,200 feet.  This distance increased with increasing range from the explosion point; at 12,000 feet from the target center it was 2,800 feet.

4.51   Wave length, period, and phase velocity for the second and subsequent waves all increased with time and distance from the center. At any point or time each wave had a period, wave length, and velocity less than that of the preceding wave.  The period of the second crest increased from 16 to 24 seconds between 2,000 and 12,000 feet, its wave length increased from 1,000 to 1,700 feet, and the phase velocity increased from 64 to 70 feet.  The phase velocity of all crests approached the value $C = \sqrt{gd} = 75$ feet per second as an asymptote.

4.52   In all its characteristics the first wave behaved differently from the succeeding ones.  It may be thought of as a long solitary wave, generated directly by the explosion, and receiving its initial energy from the high-velocity outward motion of the water.  The subsequent waves were generated impulsively by the collapse of the hole blown in the water.  The water rushing in to fill this hole built up a central mound.

4.53   According to the Cauchy-Poisson theory, the mound should have then subsided to the undisturbed level without further oscillation.  That this was at least approximately true is shown by the very small number of measurable waves near the explosion point, indicating that the amplitude of the central oscillation diminished very rapidly with time.

## Wave Shape

4.54   Twenty-three seconds after the explosion, when the first crest was 2,000 feet from the target center, the average slope from the undisturbed water at the leading edge of the wave to the crest was 1°51′.  At 140 seconds the first wave crest had progressed out to nearly 11,000 feet, while the fifth crest was at 5,500 feet.  The leading edge of the first wave was then at 12,000 feet and the average slope from this point to the first crest was 0°12′.  The highest average slope from trough to crest was 1°23′, on the forward side of the fourth wave.

4.55   From the present data, wave profiles prior to 20 seconds are uncertain.  Such a profile near zero time, drawn from the extrapolated positions of the first disturbance and the first crest and trough,

suggests that the outer side of the first crest had an average slope of about 15°, while the inner slope was apparently very much steeper. Waves are unstable and break when the average slope from trough to crest much exceeds 15°; hence the first wave was probably breaking as it left the central area.

4.56    At 140 seconds after the burst, there were present only five waves high enough to be recorded by the instruments.  Since wave energy is proportional to the square of the wave height, the major part of the total energy of the waves produced by the bomb must at this time have been contained in these five waves.  This energy was found to be between $2.6 \times 10^{18}$ and $3.4 \times 10^{18}$ ergs or between 0.3 and 0.4 percent of the total energy of a nominal atomic bomb.   More than half of the wave energy was in the first wave.

4.57    The first wave peaked up and broke 390 feet off Bikini in water 20 feet deep.   The height at breaking was 15 feet, i. e., 2.3 times the height which the wave would have had in deep water at the same distance from the explosion center.   This increase in breaker height over deep-water height agreed exactly with the well-known expression for wave behavior in shallow water,

$$h_b = 1.3\, h_d \left(\frac{d_d}{d_b}\right)^{1/4}, \tag{4.57.1}$$

where $h_b$ and $h_d$ are wave heights at breaking and in deep water, respectively, and $d_d$ and $d_b$ are the deep-water depth and the depth at breaking.

## D.    GEOPHYSICAL EFFECTS OF THE BIKINI UNDERWATER EXPLOSION

### CHANGE IN BOTTOM TOPOGRAPHY

4.58    The explosion of the Bikini "Baker" bomb caused a measurable increase in depth of the bottom of the lagoon over an area roughly 600 to 1,100 yards across.  The greatest apparent depth difference was 32 feet, but this represents only the removal of a small hill and not a hole 32 feet deep in a previously flat surface.   Over an area of 165,000 square yards the bottom was between 20 and 30 feet deeper after "Baker" Day.   A deepening of 10 to 20 feet was observed over an area of 260,000 square yards, and of zero to 10 feet over 510,000 square yards.

4.59    The net volume of bottom material removed was estimated to be about 1,420,000 cubic yards, a volume equal to that contained

in a 112-yard cube. This volume represents only the *net* amount of bottom material removed from the bomb site, and spread in a thin layer over an area more than a mile in radius. The total, or gross, amount of material originally placed in suspension or blasted out by the bomb is estimated to be 3,680,000 cubic yards. Of this amount, 2,260,000 cubic yards settled back into the crater, partially refilling it.

4.60    Before "Baker" Day, sediment samples collected at the bomb site consisted of coarse-grained algal debris mixed with less than about 10 percent sand and mud. The sand and mud probably resulted from the chemical or bacterial breakdown of the calcareous algal debris. Bottom samples taken after 'Baker" Day near the explosion point were entirely different in character. Instead of algal debris, thicknesses up to 10 feet of mud were found. This "target area mud" had a median diameter of 7.5 microns; 75 percent of the material was less than 20 microns and 25 percent less than 2.5 microns [15] in diameter.

## BEACH EROSION FROM WAVES

4.61    A minor amount of erosion of the beach was plainly evident from an examination on the afternoon of "Baker" Day. Some beach material was also carried inland, the farthest debris line in the region of the photographs being about 200 feet from the shore.

4.62    In the process of eroding the beach, the waves set up by the bomb shifted large blocks of beach rock measuring up to $9 \times 5 \times 1$ feet in size. Many of these slabs showed fresh scars several inches across; some were overturned, some broken across, but none, so far as could be determined, were carried more than a few feet from their original positions.

## E.    DESCRIPTION OF THE BASE SURGE AT BIKINI [16]

### OBSERVED SEQUENCE OF EVENTS

4.63    Immediately after the "Baker" burst at Bikini, the water moving upward formed a conical dome above the previous water level. This soon became a virtually straight-sided column forming the plume (§ 2.42), which continued to expand in diameter until at least 10 seconds after the explosion. On the basis of extrapolation from sur-

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[15] A micron is $10^{-6}$ meter or $10^{-4}$ cm.

[16] The following discussion is based largely upon study and measurements of still photographs taken with automatic recycling aerial cameras at 1 second and 3 second intervals from towers on Bikini, Amen, and Enyu Islands.

face wave measurements it is probable that at its maximum size, the column was considerably larger in diameter than the cavity blown in the lagoon waters.    Above 2,000 feet in altitude, the top of the column was concealed by a roughly equidimensional "cauliflower cloud" which extended up to more than 6,000 feet.

4.64    After the condensation cloud had disappeared, large spike-like jets were seen thrusting out through the sides of the plume.    Photogrammetric measurements show that these jets fell at rates of 32 to 80 feet per second.    It was at first thought that the jets were nearly entirely water because their velocities of fall were considerably greater than the terminal velocity of the largest stable water drop (about 25 feet per second for a drop 0.6 centimeter diameter).    Closer examination showed that after falling 5 to 7 seconds, many of the jets apparently broke up into spray without much increase in volume, and the visible rate of fall greatly diminished.

4.65    Evidently the jets, and therefore also the entire plume, consisted of a relatively small weight of water suspended as drops in air. The suspension of water drops behaved at first like a homogeneous fluid of somewhat higher density than the air outside the column. Exactly similar phenomena have been observed in laboratory studies of the rate of fall of aerosols and liquid suspensions conducted at Stanford University under the direction of P. A. Leighton.    In these experiments, drops of an aerosol or of a liquid suspension were introduced at the top of a glass cylinder into a fluid of very slightly lower density.    The aerosol drops settled at rates up to 10,000 times greater than the velocities of fall of the individual suspended particles they contained, as computed from Stokes's law.    This phenomenon was called "bulk subsidence".    It is an example of the more general class of flow which has been designated as a density current, that is, the flow of a fluid under the action of gravity through another fluid of slightly different density.

4.66    After 10 to 12 seconds, the suspension of water and air over the entire periphery of the column constituting the plume began to fall rapidly.    As this fall continued, the diameter of the water column decreased.    At a height of 450 feet, for example, the diameter changed from 2,050 to 1,500 feet, between 15 and 33 seconds.    Photographs taken 30 to 35 seconds after the explosion seem to show definitely that at this time the remaining part of the column, which was all inside 1,500 feet, was only a tenuous mist.    From this observation, together with the existence of the spike-like jets, and the rapid lateral expansion of the column, in the first 10 to 15 seconds after the explosion, over an area much larger than that of the cavity blown in the

water, it is difficult to avoid the conclusion that the plume was an essentially hollow cylinder with walls approximately 300 feet thick. This conclusion is supported by the "hollow" appearance of the cauliflower cloud, as seen from above in some of the aerial photographs.

4.67  As the falling suspension of water in air from the outer part of the column reached the sea surface, it billowed outward and upward as the base surge (§ 2.45).  This was first evident between 10 and 12 seconds after the burst.  At first the front of the base surge moved outward in all directions with a very high velocity, in excess of 100 feet per second, but this velocity rapidly diminished.  Thus, one minute after the explosion, the radial velocity in the cross wind direction was only 47 feet per second; between 2 and 3 minutes later the outward motion had ceased, and the whole mass of the surge was moving slowly down wind at about 10 feet per second, i. e., about 7 miles per hour.

4.68  The front of the base surge at first sloped inward from the water surface.  By 60 seconds, the front had assumed the typical rounded profile of a dust cloud or moving fog bank.

4.69  At 12 seconds, the suspended material in the cauliflower cloud began to fall back to the lagoon in large mamillary masses, which attained high settling velocities of more than 50 feet per second.  In some cases an abrupt decrease of velocity occurred after an interval, and the plume broke up into a rain curtain.  Evidently the same mass subsidence phenomena occurred in the cloud as in the column.  The first material from the cloud reached the surface about 1 minute after the detonation, and after 2.5 minutes the cauliflower cloud had dropped nearly all its suspended load into the base surge so that only remnants of it remained aloft.  Most of this material fell in an annular area with inner and outer radii of 1,950 and 2,850 feet, respectively. The aerial photographs show part of the lagoon surface inside this annular area after 45 seconds, indicating that at this time there was little suspended material either from the cauliflower cloud or the base surge in the central region.  Beyond the annular ring of fall-out from the cloud, the base surge extended over a very large area, with an average outer radius at 3.5 minutes of 8,400 feet.

4.70  For the first 2.5 minutes, the height of the top of the base surge increased irregularly but continuously up to about 1,800 feet. Large irregularities, due to turbulence, in the motion of both the upper surface and the advancing front of the base surge are apparent from the photographs.  After 2.5 minutes the top remained stationary in height for nearly a minute while the radial expansion of the surge diminished and finally ceased.  Between 3 and 4 minutes the surge

began to lift from the lagoon, and after 4.5 minutes its base had lifted 1,500 feet off the water. During and after the lifting process, the surge also thickened, so that its upper surface eventually rose to nearly 6,000 feet. This thickening must have been due to condensation of water in the adiabatically-cooled air pushed up by the base surge as it lifted. Because of this condensation, rain fell from the surge cloud for nearly an hour after the detonation.

## VARIATION OF VELOCITY AND DIMENSIONS WITH TIME

4.71   In Fig. 4.71 measured values of the mean crosswind horizontal velocity, mean surface radius, inner radius, and mean height of the base surge are plotted against time for the first few minutes after the detonation. Some of these values, and other data, expressed in metric units are also given in Table 4.71. Over the period from 10 to 200

TABLE 4.71

## RADIAL VELOCITY AND DIMENSIONS OF THE BASE SURGE

| Time (sec.) | Velocity (cm./sec.) | Outer radius (cm.$\times 10^4$) | Area* (cm.$^2\times 10^{10}$) | Height (cm.$\times 10^4$) | Volume** (cm.$^3\times 10^{15}$) |
|---|---|---|---|---|---|
| 10  | 3, 660 | 3. 7  | 0. 4  | 1. 3 | —      |
| 20  | 2, 650 | 6. 6  | 1. 4  | 1. 8 | 0. 15  |
| 30  | 2, 135 | 9. 2  | 2. 6  | 1. 9 | . 25   |
| 40  | 1, 830 | 11. 0 | 3. 8  | 2. 1 | . 40   |
| 50  | 1, 620 | 12. 8 | 5. 1  | 2. 6 | . 55   |
| 60  | 1, 430 | 14. 4 | 6. 5  | 3. 0 | . 79   |
| 80  | 1, 160 | 17. 1 | 9. 1  | 3. 7 | 1. 81  |
| 100 | 945    | 19. 2 | 11. 6 | 4. 5 | 3. 16  |
| 120 | 795    | 21. 4 | 14. 3 | 4. 8 | 4. 78  |
| 140 | 700    | 22. 6 | 16. 1 | 5. 5 | 6. 28  |
| 160 | 580    | 23. 8 | 17. 8 | 5. 5 | 7. 69  |
| 180 | 490    | 24. 9 | 19. 5 | 5. 5 | 9. 16  |
| 200 | 365    | 25. 6 | 20. 6 | 5. 5 | 10. 43 |

*Total area encompassed by base surge, including central clear region.
**In computing the volume of the base surge cloud, an attempt has been made to take the central clear area into account.

seconds, the crosswind velocity $V$ varied approximately with the inverse square of the time $t$, being fairly well fitted by the equation

$$V = \frac{C}{(K+t)^2} = \frac{3.3 \times 10^7}{(90+t)^2} \text{ cm./sec.} \qquad (4.71.1)$$
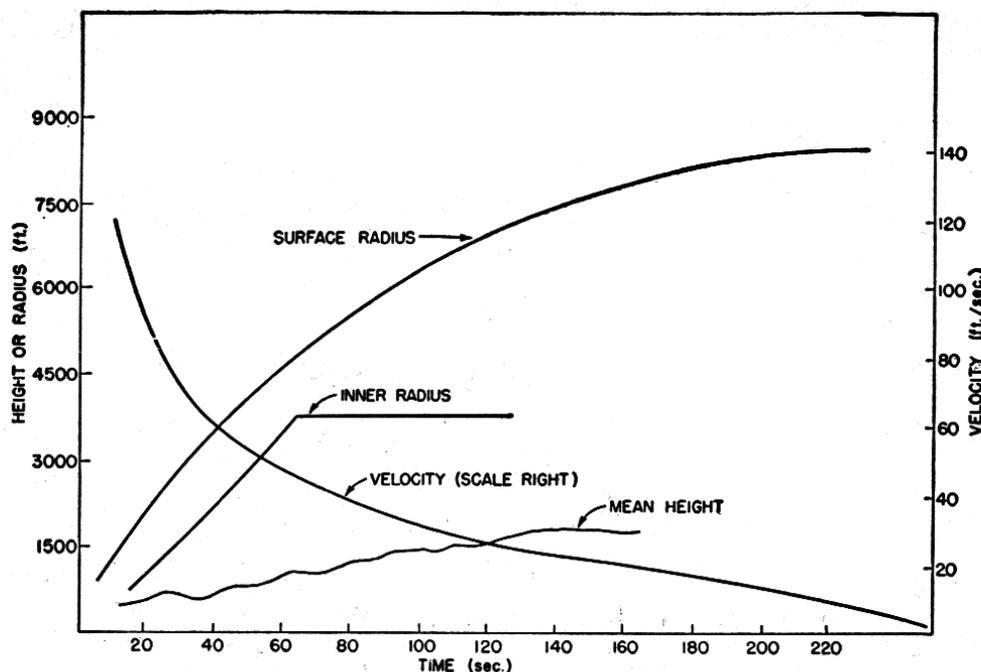
Figure 4.71.   Dimensions and velocity of base surge as functions of time.

4.72   For velocities in the upwind or downwind directions, the wind velocity of 300 centimeters per second must be subtracted from or added to the value for $V$ given in equation (4.71.1).   After 200 seconds, the radial velocity diminished rapidly to zero which was attained at about 240 seconds.

4.73   The mean outer radius corresponding to equation (4.71.1) is given by

$$R=\frac{aK^2+aKt+Ct}{K^2+Kt},\tag{4.73.1}$$

where $a=4\times10^3$.   Introducing numerical values for $K$ and $a$, it is found that

$$R=\frac{3.6\times10^5+3.7\times10^5t}{90+t}\text{ cm.}\tag{4.73.2}$$

Beyond 3 minutes the radius did not appreciably increase and these equations no longer held.

4.74   If $R_t$ is the surge radius at time $t$, and $U$ is the wind velocity, the distance from the explosion point to the upwind edge of the base surge at any time $t$ will be given by

$$X_{ut}=R_t-Ut,\tag{4.74.1}$$

and in the downwind direction by

$$X_{dt}=R_t+Ut.\tag{4.74.2}$$

4.75    Up to 180 seconds, the area swept by the base surge—including the central region which was apparently clear after the first minute—was, in accordance with equations (4.73.1) and (4.73.2),

$$A = \frac{\pi(aK^2 + aKt + Ct)^2}{(K^2 + Kt)^2} = \frac{\pi(3.6 \times 10^5 + 3.7 \times 10^5 t)^2}{(90 + t)^2} \text{ sq. cm.} \quad (4.75.1)$$

4.76    After 200 seconds the area underneath the surge at any instant did not increase, but the total area over which the surge cloud had passed gradually lengthened as the surge traveled downwind (see § 4.79 on probable effects of higher wind speed).

4.77    The height of the base surge at the point of intersection with the plume column remained at about 450 feet throughout the period during which the major fall-out from the plume occurred, that is, between 15 and 33 seconds. As shown in Table 4.71, however, the average height of the top of the base surge increased continuously up to 140 seconds. After 140 seconds it remained constant until the entire mass started to lift from the lagoon, at about 210 seconds.

4.78    The apparent volume and mass of the base surge increased continuously from 10 seconds onward (Fig. 4.78). This increase was
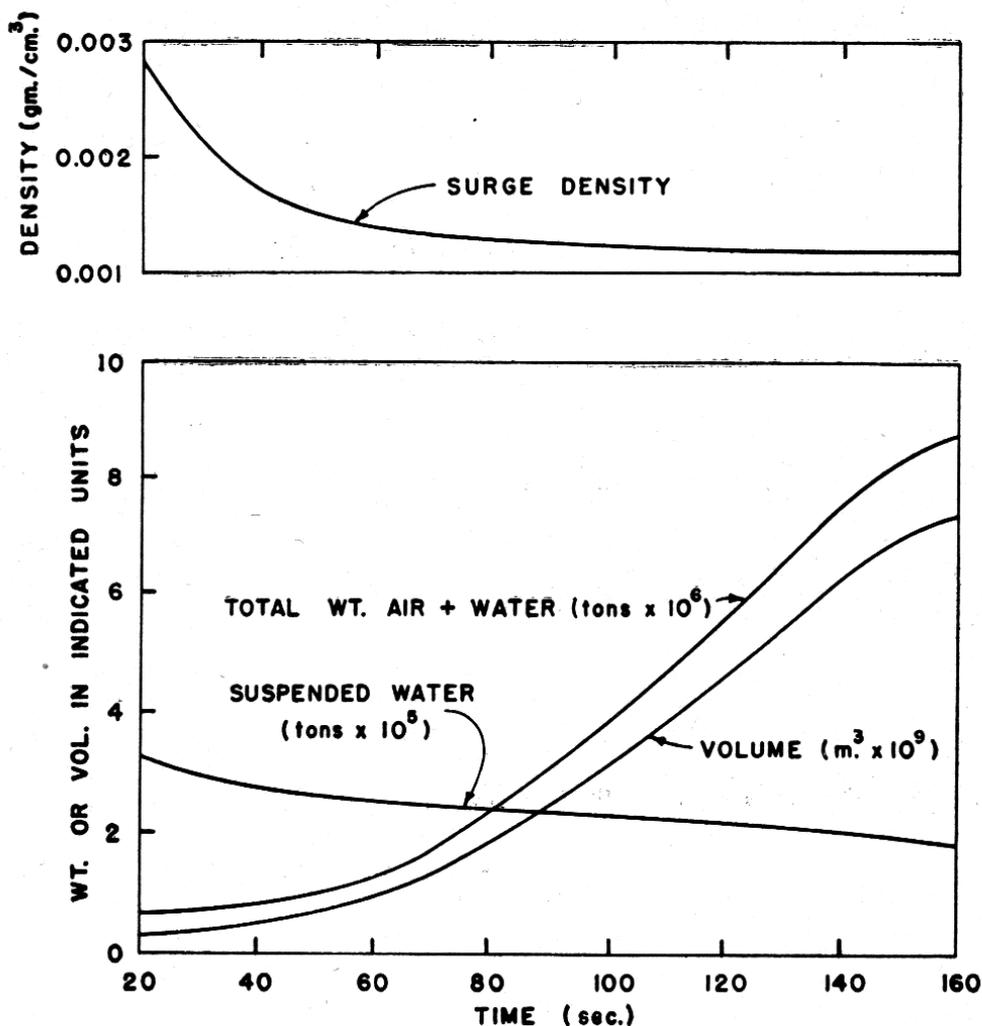


Figure 4.78.    Weight, volume, and density of base surge as functions of time.

due to different causes at different times. Up until 33 seconds, new material was being added as the falling column was transferred into the base surge. Throughout the period of outward expansion from 10 to 200 seconds enormous quantities of air were being engulfed by turbulence at the surface of the surge. Finally, after 200 seconds, condensation took place above the original surge cloud, in the adiabatically cooled air which was forced aloft as the surge rose.

## EFFECT OF WIND SPEED

4.79 At Bikini, the wind velocity near the surface was very low, only 5 or 6 miles per hour. An onshore wind of 10 to 15 miles per hour is a more usual daytime situation in a harbor, and winds up to 25 or 30 miles per hour are not uncommon. Such higher wind speeds would have several effects:

(a) The surge would not extend as far upwind at any time.
(b) The surge front would arrive at any downwind point sooner after the explosion, and therefore with higher radiation intensity and higher rate of fall-out.
(c) The area and volume of the surge cloud would be increased by turbulence due to the wind, particularly after the first few minutes when the initial rapid outward expansion of the surge has ceased. Experience with the behavior of smoke over water indicates that

$$R_{wt} = R_{bt} + 0.2Ut, \qquad (4.79.1)$$

where $R_{wt}$ is the actual radius of the surge cloud at any time, $t$, $R_{bt}$ is the radius it would have had in the absence of wind, and $U$ is the wind velocity.

(d) The total area swept by the surge cloud from its beginning up to any time, $t$, increases with increasing wind speed. If the total swept area is $A_{\Sigma t}$, then

$$A_{\Sigma t} = \pi R_{bt}^2 + 1.3\,R_{bt}Ut + 0.13\,(Ut)^2. \qquad (4.79.2)$$

## EFFECT OF ATMOSPHERIC CONDITIONS

4.80 The view has been expressed that the base surge phenomenon as observed at Bikini was, at least partly, dependent on the very moist, tropical air-mass prevailing at the time of the explosion. As seen in § 4.65, it is probable that the aerosol constituting the base surge has a somewhat greater density than the surrounding atmos-

phere. Consequently, the aerosol acted as a meteorological cold-front, and in its outward travel pushed into the ambient air causing this to ascend over the surge front. The tropical air-mass had great thermal instability and its moisture content was such that an ascent of about 1,000 feet would cause sufficient adiabatic cooling to produce cloud condensation. This would explain the steadily increasing volume of the surge as it migrated outward from the center of the explosion.

4.81 At the point where the base surge began to rise off the water, its density, as an aerosol, must have been equal to or less than that of the surrounding air. The ascent then continued as a result of its lower density and was comparable to the rise of an unstable, moist air-mass along a warm front. The development of the strato-cumulus cloud at this stage (Fig. 2.46) is in harmony with the suggestions concerning cloud formation made above.

4.82 Even if the full development of the cloud mass requires a moist atmosphere, it is probable that the initial formation of the base surge, which moves forward at high speed, would be independent of the meteorological conditions. However, it is possible that all the phenomena, exactly as observed in the "Bikini" test, would not occur if an atomic bomb were exploded under water when a dry air-mass is present, or when the atmospheric condensation level is significantly above the height of the initial base surge.

## F. SHOCK FROM UNDERGROUND BURST

### UNDERGROUND SHOCK PROPAGATION

4.83 The preceding sections of this chapter have dealt with underwater bursts; in this final section some of the characteristics of underground explosions will be considered.

4.84 The detonation of an atomic bomb under the surface of the ground would produce an earth shock which, in its effects, would be somewhat similar to that of an earthquake of small focal depth.[17] The magnitude of the energy release in the underground burst of a nominal atomic bomb would, in fact, be comparable to the energy

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[17] Some of the seismic effects of the Alamogordo "Trinity" atomic bomb air burst and of the Bikini "Baker" underwater explosion are described by B. Gutenberg, *Bull. Seism. Soc. Amer.*, *36*, 327 (1946) and by B. Gutenberg and C. F. Richter, *Trans. Amer. Geophys. Union*, *27*, 776 (1946), respectively.

developed in a damaging earthquake of scale 5.0 on Richter's logarithmic scale.[18]

4.85 There is, however, a considerable difference in the depths of the focal point of the disturbance beneath the surface of the earth in the two cases. This depth is, in general, very large, of the order of miles, scores or even hundreds of miles in the case of an earthquake, while it would be effectively on the surface for an atomic bomb. These differences are reflected in the period of the seismic waves, their amplitudes, and their decay of intensity with distance from a spot directly above the center of disturbance. The period would be shorter, and the decay with distance somewhat more rapid, for the waves generated by an atomic bomb. Since profound differences exist in the mechanism of propagation of air shock waves and seismic waves generated by explosion, a brief description of the process occurring in an underground explosion will be given.

4.86 The initial stage of an air, water, or underground explosion is the same, namely, the sudden creation of a mass of highly heated and compressed gas which exerts tremendous pressure. This high-pressure gas immediately begins to expand, imparting a high radial velocity to the earth particles adjacent to the charge and producing a large transient pressure in the medium.[19] The high initial velocity of the earth carries it past the point of pressure equilibrium due to inertia, so that after a certain time the motion is arrested and a reverse motion is imparted. If the pressure in the gas bubble were not relieved, the pressure at remote points would decrease to a value equal to the permanent stress in the medium due to the presence of this sphere of high-

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[18] Richter's magnitude scale, which is based on the logarithm of the amplitude of motion, is related to the energy by the formula

$$M = \frac{1}{1.8} \log\left(\frac{E}{E_0}\right),$$

where $M$ represents the magnitude of the earthquake of energy $E$, and $E_0$ is the energy of an earthquake of zero magnitude (taken as $2 \times 10^{11}$ ergs). The smallest earthquakes felt are of magnitude 1.5, while those of magnitude 4.5 will cause slight damage near the epicenter. Those of magnitude 6 are destructive over a limited area, and magnitude 7.5 is the lower limit of major earthquakes. The results in the appended table give an approximate relationship between the energy and the type of earthquake. The total energy release of a nominal atomic bomb is about $8 \times 10^{20}$ ergs.

| | Energy range ergs | Magnitude of mean |
|---|---|---|
| Great earthquakes | $10^{26}$ | 8.5 |
| Major earthquakes | $10^{24}$–$10^{26}$ | 7.5 |
| Destructive earthquakes | $10^{22}$–$10^{24}$ | 6.5 |
| Damaging earthquakes | $10^{20}$–$10^{22}$ | 5.5 |
| Minor strong earthquakes | $10^{18}$–$10^{20}$ | 4.5 |
| Generally felt small earthquakes | $10^{16}$–$10^{18}$ | 3.0 |

For further discussion, see K. E. Bullen, "Introduction to the Theory of Seismology," Cambridge University Press.

[19] See Appendix B.

pressure gas. There are two factors tending further to reduce the final pressure: one is the cooling of the gas in the bubble due to thermal conduction to the medium, and the other is the relief of pressure due to the break-through of the gas bubble to the surface of the earth, or to the leakage of gas into the surrounding earth. If the charge is buried at such a depth that the gas pressure is quickly relieved by motion of the medium above the charge, the peak pressure will be reduced.

4.87    The effect of progressively greater depths of burial of an explosive charge is to increase the magnitude of the compressive wave until a depth is reached at which the relief of pressure due to the surface break-through comes after the time of maximum excursion of the adjacent particles in the medium. Subsequently, relief of pressure exerts no influence on the maximum value of the pressure, and greater depths of burial have little influence on the propagated effects. This result is found experimentally and is consistent with the mechanism described. The critical depth in earth is predicted to be about 600 feet for a nominal atomic bomb, which is much greater than any practical depth of penetration that could be achieved by bombs or guided missiles.

4.88    The rate of change of the magnitude of the compressive wave with depth of burial of the bomb is such that at practical depths of penetration of a heavy bomb about 35 percent of the maximum potential pressure in the propagated wave will be developed. The remainder of the potential mechanical energy will be spent in producing air blast, fusing the ground, forming a crater, and in dispersing material from the crater into the air. A detonation just on the surface would reduce this figure to about 20 percent for propagated seismic effects, leaving about 80 percent of the energy for air-blast production, cratering, etc.

### Effect of Soil Characteristics [20]

4.89    The variability of the soil characteristics and the proximity of underlying rock strata introduce additional variables into the underground damage problem over those encountered in air-blast phenomena. The presence of underlying rock strata relatively close to the surface is a condition which can enhance very appreciably the propagated effects in an underground explosion. This enhancement comes about in at least two different ways. The first is a consequence of the reflection of the pressure wave from the rock strata. Crude calculations show that in normal incidence not more than 50 percent of

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[20] For further discussion, see Appendix B.

TABLE 5.45

| Wind velocity (mph) | Duration (sec) | Overpressure (psi) | Miles | Feet | Damage |
|---|---|---|---|---|---|
| | | | | | Limit of light damage at 8 miles. |
| 50 | 1.25 | 1.5 | | 12,000 | Light damage to window frames and doors, moderate plaster damage, complete window damage. |
| | | | 2.25 | | |
| 60 | 1.23 | 1.7 | | 11,000 | Flash charring of telegraph poles. Roof and wall covering on steel frame building damaged. |
| | | | 2.0 | | Partial damage to structures in area. |
| 70 | 1.20 | 2.0 | | 10,000 | Blast damage to majority of homes. Severe fire damage expected. Flash ignition of dry combustible materials. |
| | | | 1.75 | | |
| 80 | 1.15 | 2.4 | | 9000 | Heavy plaster damage. |
| | | | | | Moderate damage to area. |
| 100 | 1.12 | 2.9 | 1.50 | 8000 | Severe damage to homes, heavy damage to window frames and doors, foliage scorched by radiant heat. |
| 125 | 1.06 | 3.6 | | 7000 | |
| | | | 1.25 | | Structural damage to multistory brick buildings. |
| 160 | 0.98 | 5.2 | | 6000 | Severe damage to entire area. Severe structural damage to steel frame building. 9-inch brick walls moderately cracked. |
| | | | | | Electrical installations and trolley cars destroyed. Multistory brick building completely destroyed. |
| 200 | 0.90 | 7.4 | 1.0 | 5000 | 12-inch brick walls severely cracked. |
| | | | | | Steel frame building destroyed (mass distortion of frame). Light concrete buildings collapsed. |
| 270 | 0.77 | 10 | 0.75 | 4000 | Reinforced concrete smoke stack with 8-inch walls overturned. Roof tiles bubbled (melted by heat). |
| | | | | | 18-inch brick walls completely destroyed. |
| 380 | 0.62 | 16 | | 3000 | |
| | | | 0.50 | | Virtually complete destruction of all buildings, other than reinforced concrete aseismic design. |
| 550 | 0.45 | 24 | | 2000 | Limit of severe structural damage to earthquake-resistant reinforced concrete buildings. Reinforced concrete building collapsed, 10-inch walls, 6-inch floor. |
| | | | | | Mass distortion of heavy steel frame buildings. Loss of roofs and panels. |
| | | | 0.25 | | |
| 800 | 0.37 | 36 | | 1000 | Decks of steel plate girder bridge shift laterally. |
| | | | | 0 | Air Burst of an Atomic Bomb. |

## LONG-RANGE BLAST DAMAGE

5.52   One of the curious features of blast damage caused by a large explosion, not necessarily that of an atomic bomb, is that appreciable effects are sometimes observed at considerable distances from the bomb burst, while some intermediate regions are largely unaffected. It appears that under suitable meteorological conditions, there is a focusing of incident and various reflected shock waves which may result in causing blast damage at certain points as far as 50 miles from the explosion.   Some of the necessary conditions appear to be temperature inversion (§ 2.27, footnote) at a relatively low altitude, surface winds of low velocity, and a region of high atmospheric pressure.

5.53   Long-range blast damage was observed, to some extent, as a result of the atomic bombing of Japan.   For example, the barracks sheds at Kamigo, nearly 5 miles south of ground zero in Nagasaki, collapsed to ground level, although other buildings close by remained completely intact.   In Hiroshima, the general limiting radius for the displacement of roof tiles was about 8,000 feet from the bomb burst, but some cases of displacement occurred as far out as 5 miles.

## MULTISTORY REINFORCED-CONCRETE FRAME BUILDINGS

5.54   In the preceding paragraphs the discussion of damage has been somewhat general in nature.   Consideration will now be given to the kind of damage inflicted on specific types of structures.   There were many multistory, reinforced-concrete frame buildings in Hiroshima and a smaller number in Nagasaki (Figs. 5.54 a and b).   They varied in resistance to blast damage according to design and construction, but generally suffered remarkably little damage, particularly those designed for resistance against earthquakes.   After the severe earthquake of 1923 a code was established for all new construction to reduce earthquake damage.   The height of buildings was limited to 100 feet and design for a lateral load of 0.1 times gravity was required.   In addition, the recognized principles of stiffening by diaphragms and improved framing to provide continuity were specified. The more important buildings were well designed and constructed according to the code, but some were built without much regard for its requirements.

5.55   Close to the explosion the vertical component of blast was more important so that there was heavy damage caused by the downward force exerted on the roof.   Depending upon its strength, the roof was pushed down and left sagging or failed completely.   The
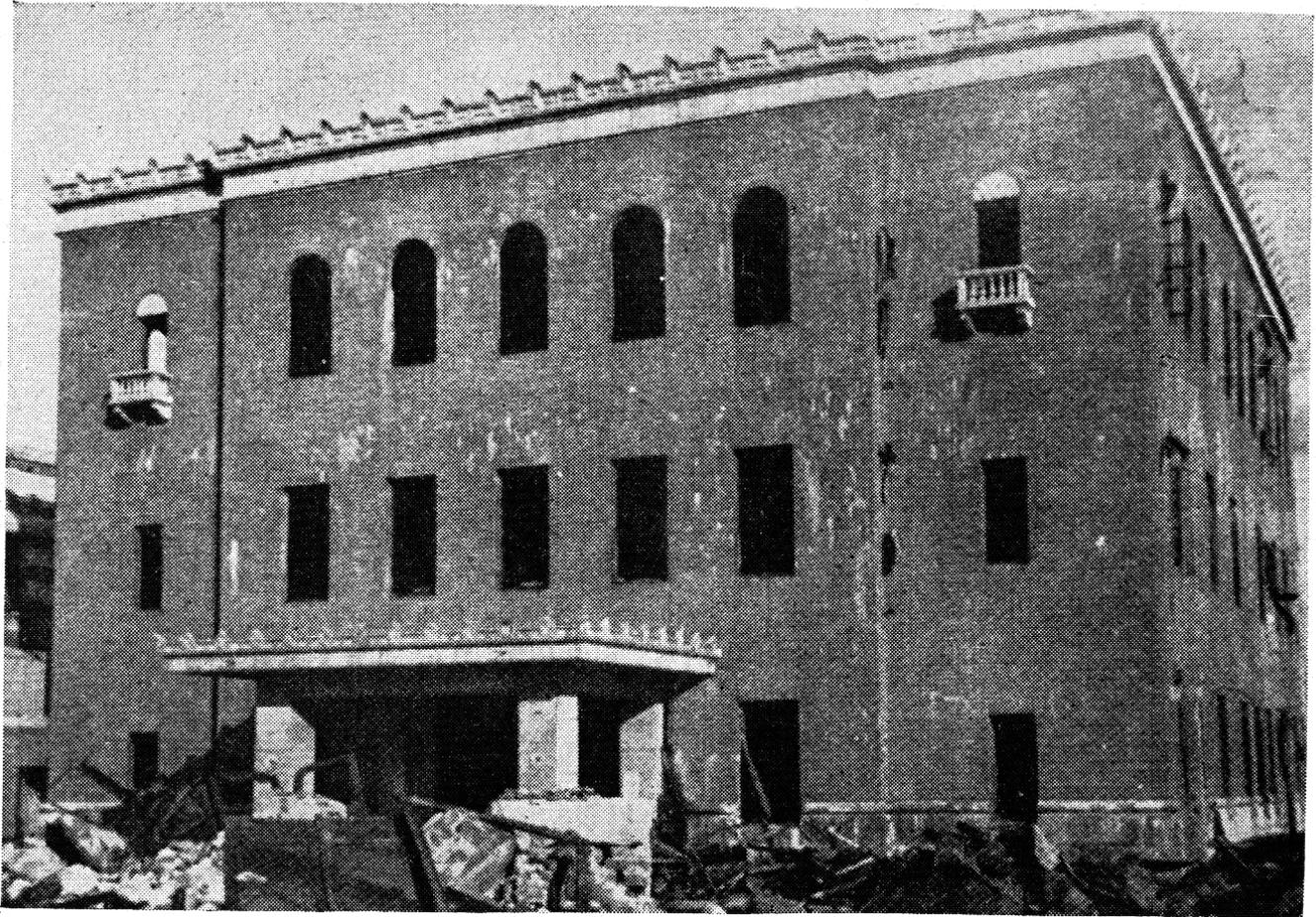
Figure 5.54a.    *Upper photo:* Reinforced-concrete frame building, **700** feet from
ground zero, 2,100 feet from point of explosion; external walls intact.    *Lower
photo:* Interior of above burned out; note sagging of roof and spalling of plaster
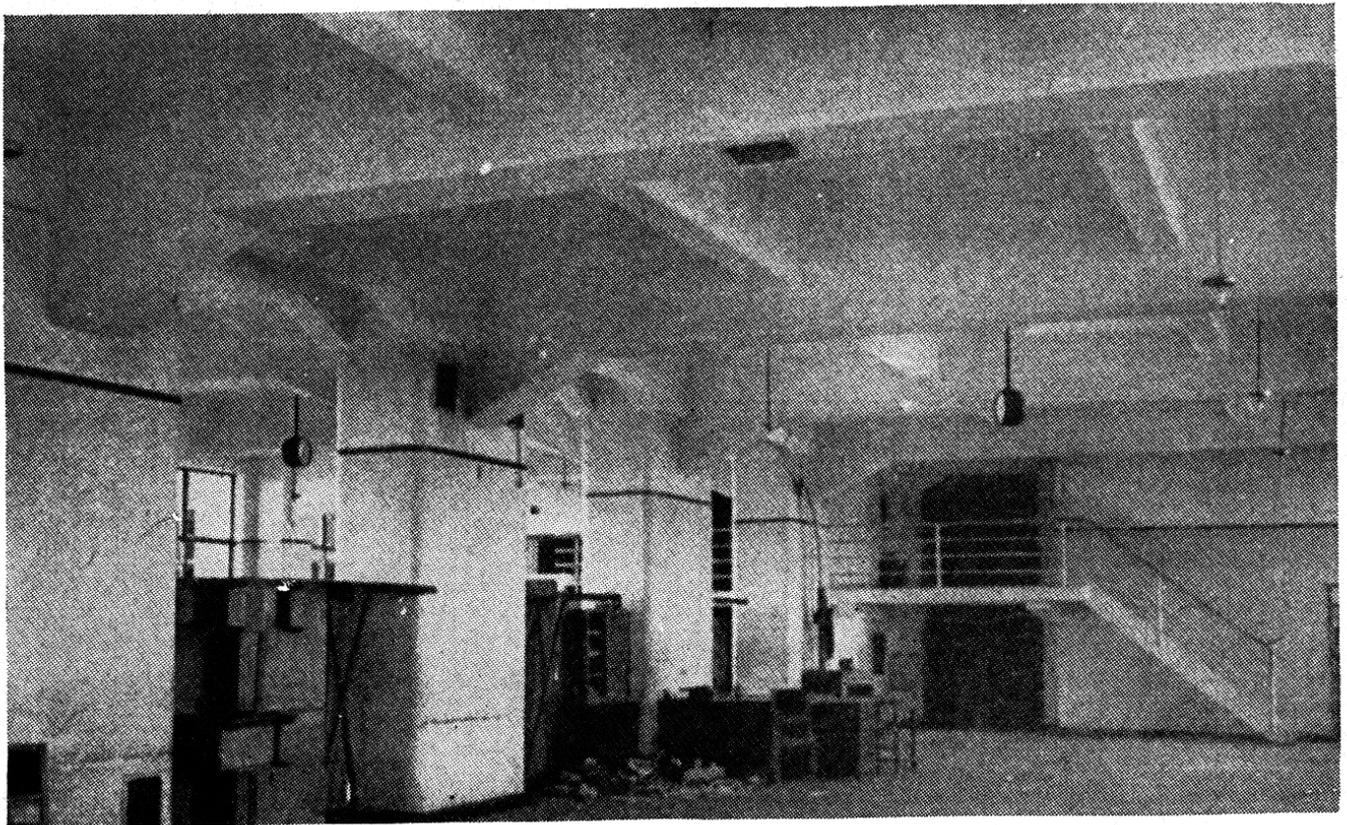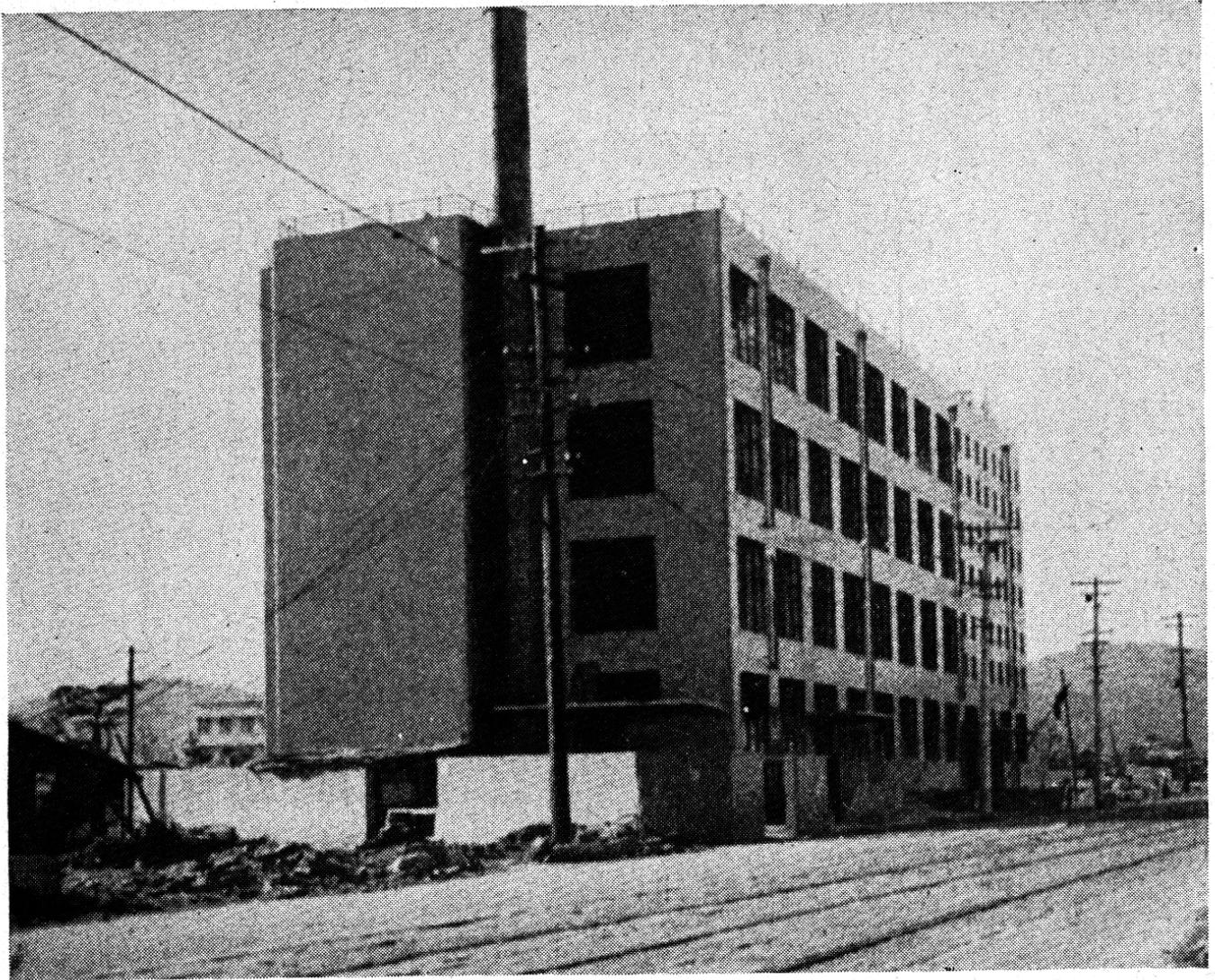by fire.

Figure 5.54b. *Upper photo:* Reinforced-concrete frame building, 5,300 feet from ground zero. *Lower photo:* Interior of above practically undamaged, except for windows.

remainder of the structure was less damaged than similar buildings further from ground zero because of the smaller horizontal force.

5.56    At greater distances the lateral force was proportionately greater and produced the following effects:

(a)  *Failure of the roof slab by lateral compression causing it to buckle.*— This was apparently caused by the force applied to the side of the building which in turn was transferred to the roof tending to push it back.   Since the roof was restrained by connections to less affected portions of the building, it failed in compression (Fig. 5.56a).
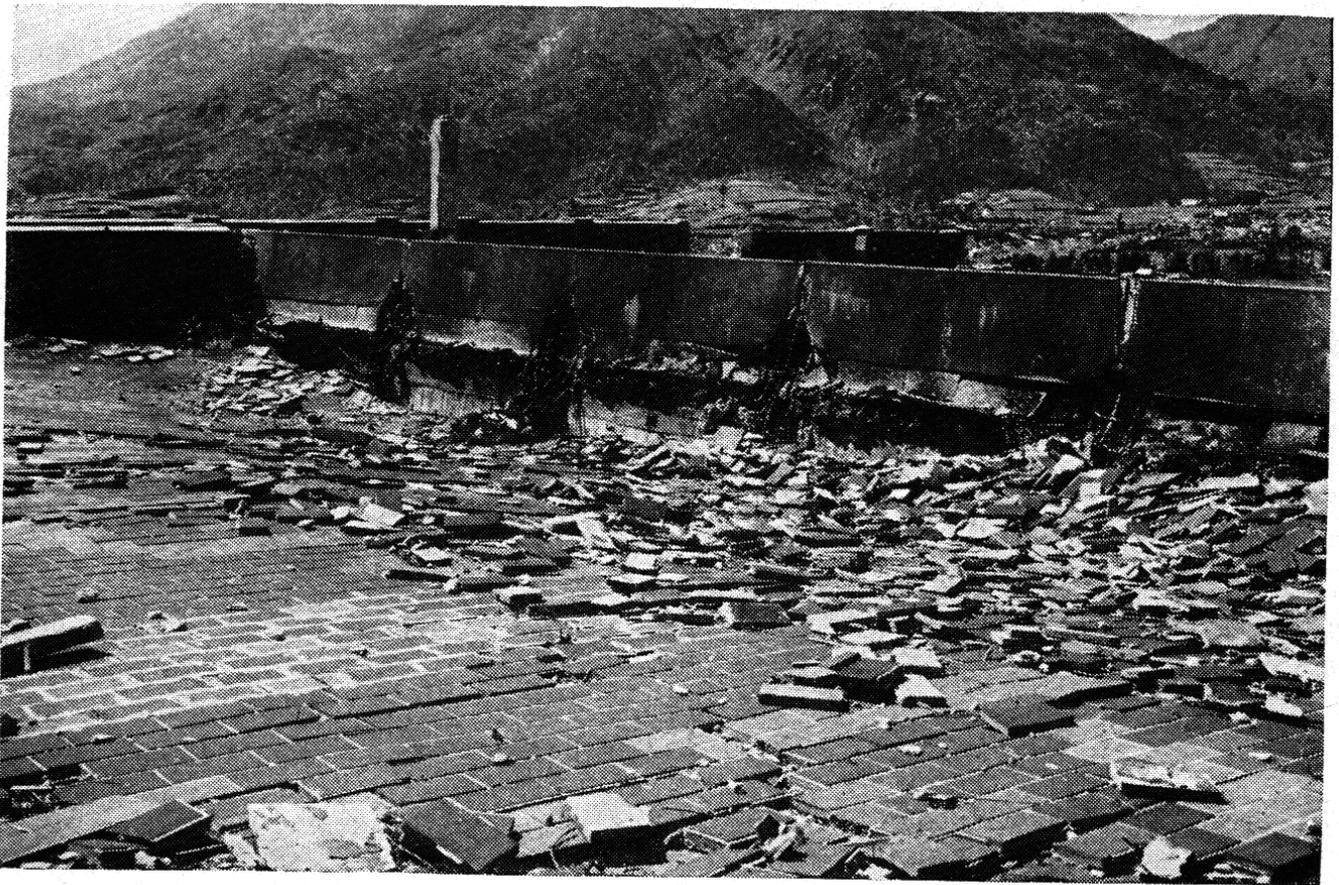


Figure 5.56a.    Reinforced-concrete building, about 1,700 feet from ground zero, showing cracked roof slab and parapet walls.

(b)  *A similar failure in floor systems.*—Failure usually occurred in the bay between the first row of interior columns and the affected wall (Fig. 5.56b).   Buckling was usually upward.

(c)  *Cracking of concrete and overstressing of concrete and steel at haunches and connections.*—This effect was apparent in a large number of buildings and is readily explained by the tremendous lateral force applied (Fig. 5.56c).
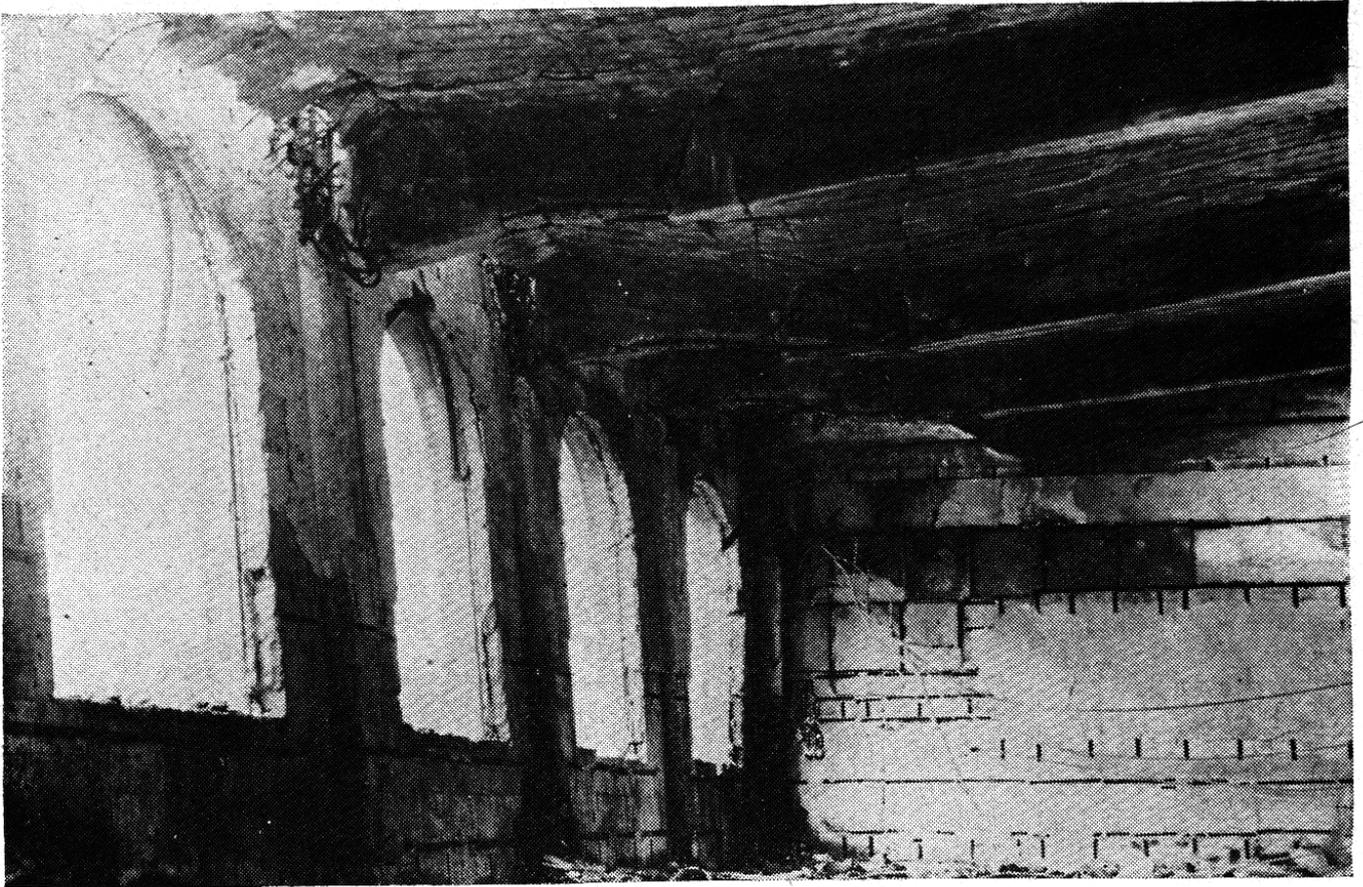
Figure 5.56b.   Buckling and cracking of beams in reinforced-concrete building, about 1,700 feet from ground zero.
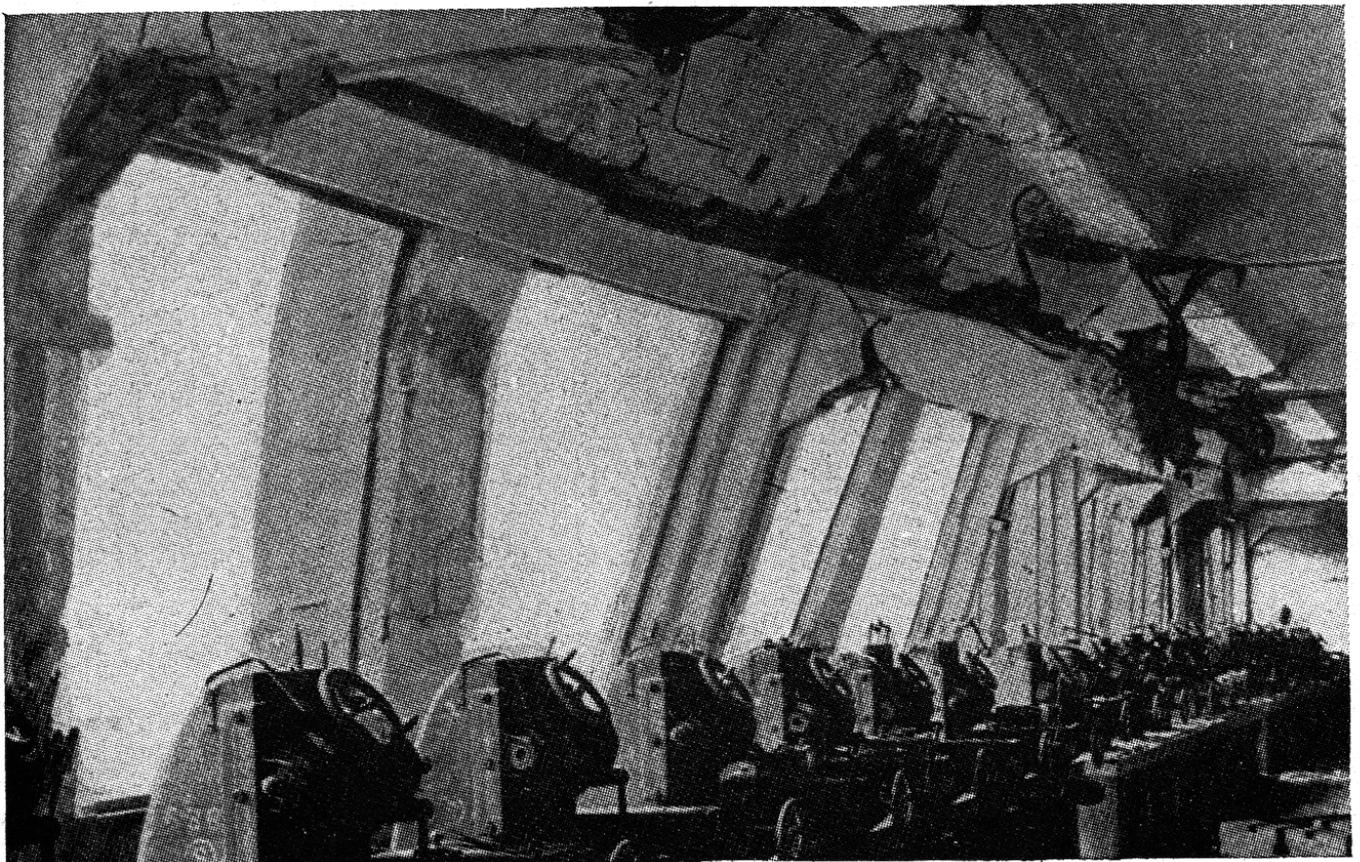


Figure 5.56c.   Second floor of reinforced-concrete frame building, 1,900 feet from ground zero, showing fractured third-floor beams, and failure of columns at windows.

## MULTISTORY STEEL-FRAME BUILDINGS

5.57 There was only one building of this type on record (Fig. 5.57). This was in Nagasaki at a distance of 4,500 feet from the bomb burst. The only part of the structure not classified as being of heavy construction was the roof which was of thin concrete supported by unusually light steel trusses. The downward failure of the roof, which was dished 3 feet, was the only structural damage in the building. Reinforced-concrete buildings at the same distance were also undamaged, but there is insufficient evidence to permit conclusions to be drawn as to relative resistance of the two types of construction.

## INDUSTRIAL BUILDINGS AND EQUIPMENT

5.58 In Nagasaki there were many steel buildings used for manufacturing, and these were generally of the shed type, with some of the sawtooth design (Figs. 5.58a and b). Roofs and siding were of corrugated sheet metal or of asbestos cement. In some cases there were rails for heavy gantry cranes, but generally cranes were of low capacity. Construction was generally comparable to that in the United States. The first effect of blast was to strip off the siding and roof material, but since this did not occur instantaneously, a large impulsive force was applied to the frame. Severe damage occurred up to a distance of 6,000 feet.

5.59 There were several types of failure of such structures. Close to the explosion the buildings were pushed over bodily, and at greater distances they were in many cases left leaning away from the source of the blast (Fig. 5.58a). The columns being long and slender offered little resistance to the lateral force. Sometimes columns failed by a combination of lateral force, causing flexure, at the same time that an increased downward load came from the vertical component of blast on the roof. This caused buckling and collapse. Roof trusses were buckled by compression resulting from blast on the exposed side of the building.

5.60 A difference was noticed in the effect on the frame depending upon whether a frangible material, like asbestos cement, or a material of high tensile strength, such as corrugated sheet iron, was used for roof and siding. Asbestos cement broke up more readily and transferred less force to the steel frame with less structural damage.

5.61 Fire produced heavy damage to unprotected steel members so that it was impossible to tell exactly what the blast effect had been. In general, the steel frames were badly distorted and would have
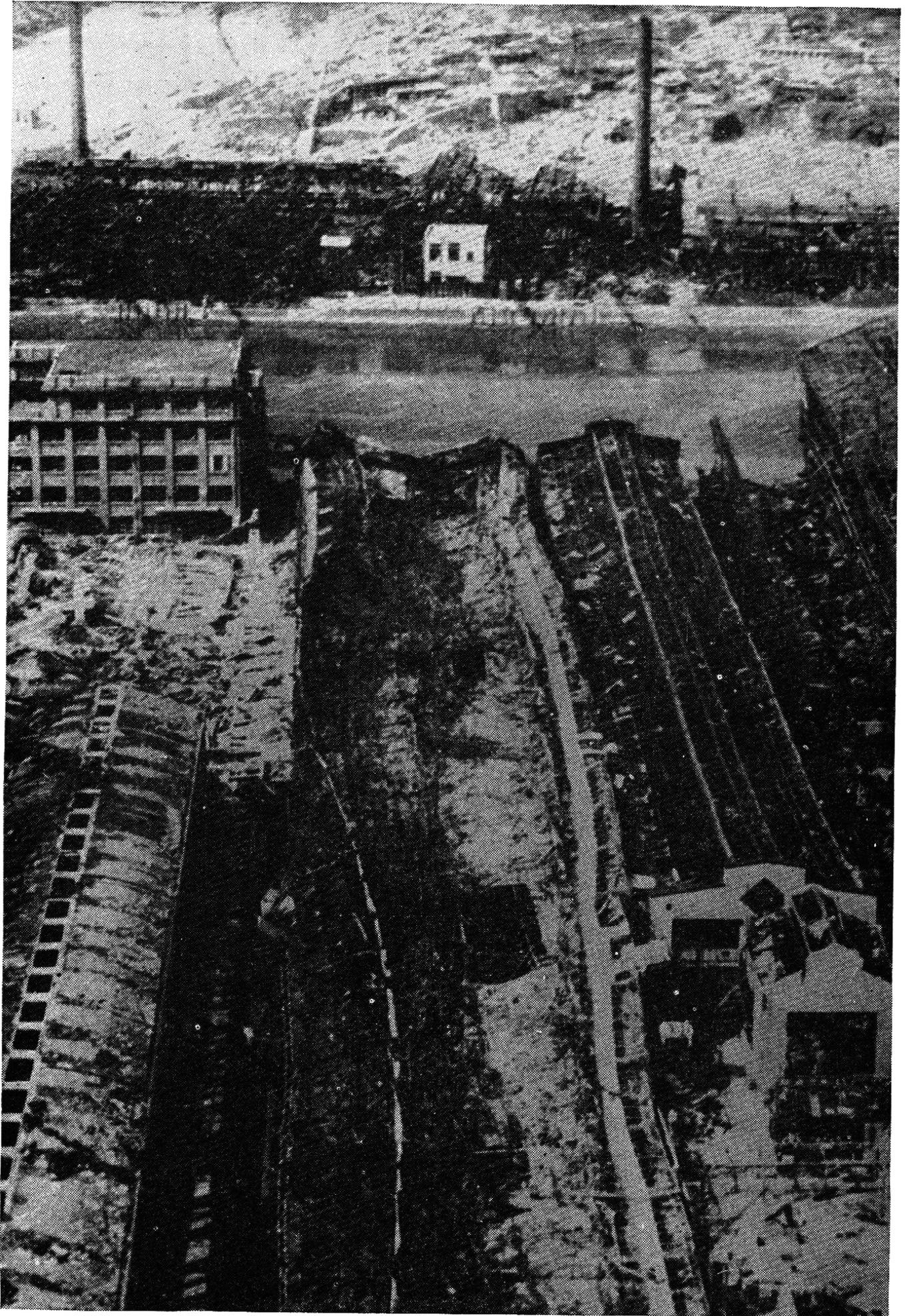
Figure 5.57.   At left and somewhat back of center is shown the only multistory steel-frame building exposed to atomic bombs.   It was in Nagasaki, 4,500 feet from ground zero.
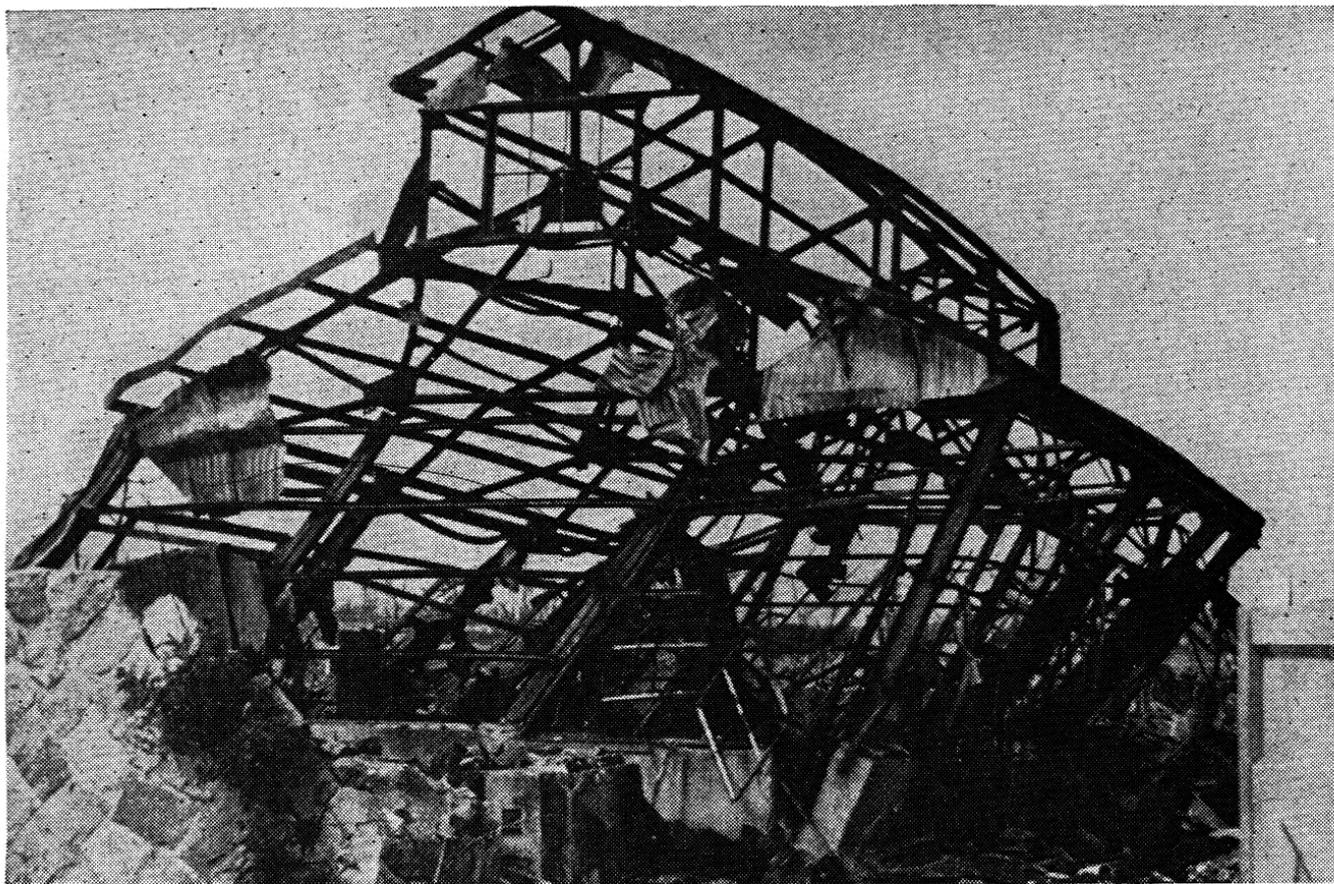
Figure 5.58a.  Light steel-frame industrial building, 1,800 feet from ground zero.  Corrugated iron roof and wall sheathing were stripped by the blast, and the combustible contents destroyed by fire.
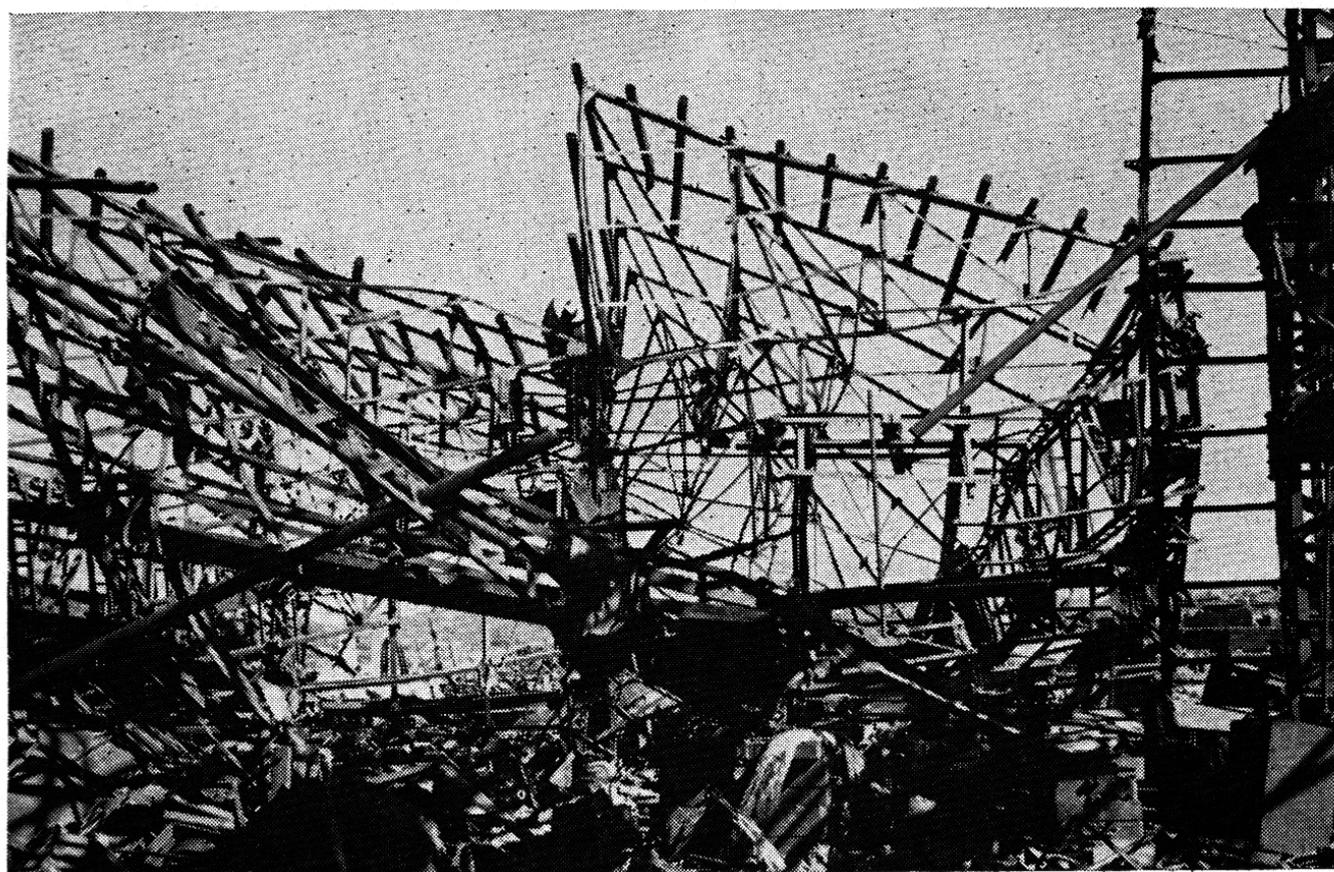


Figure 5.58b.  Industrial building with sawtooth roof truss, about 5,000 feet from ground zero.  Damage by blast and fire was severe.
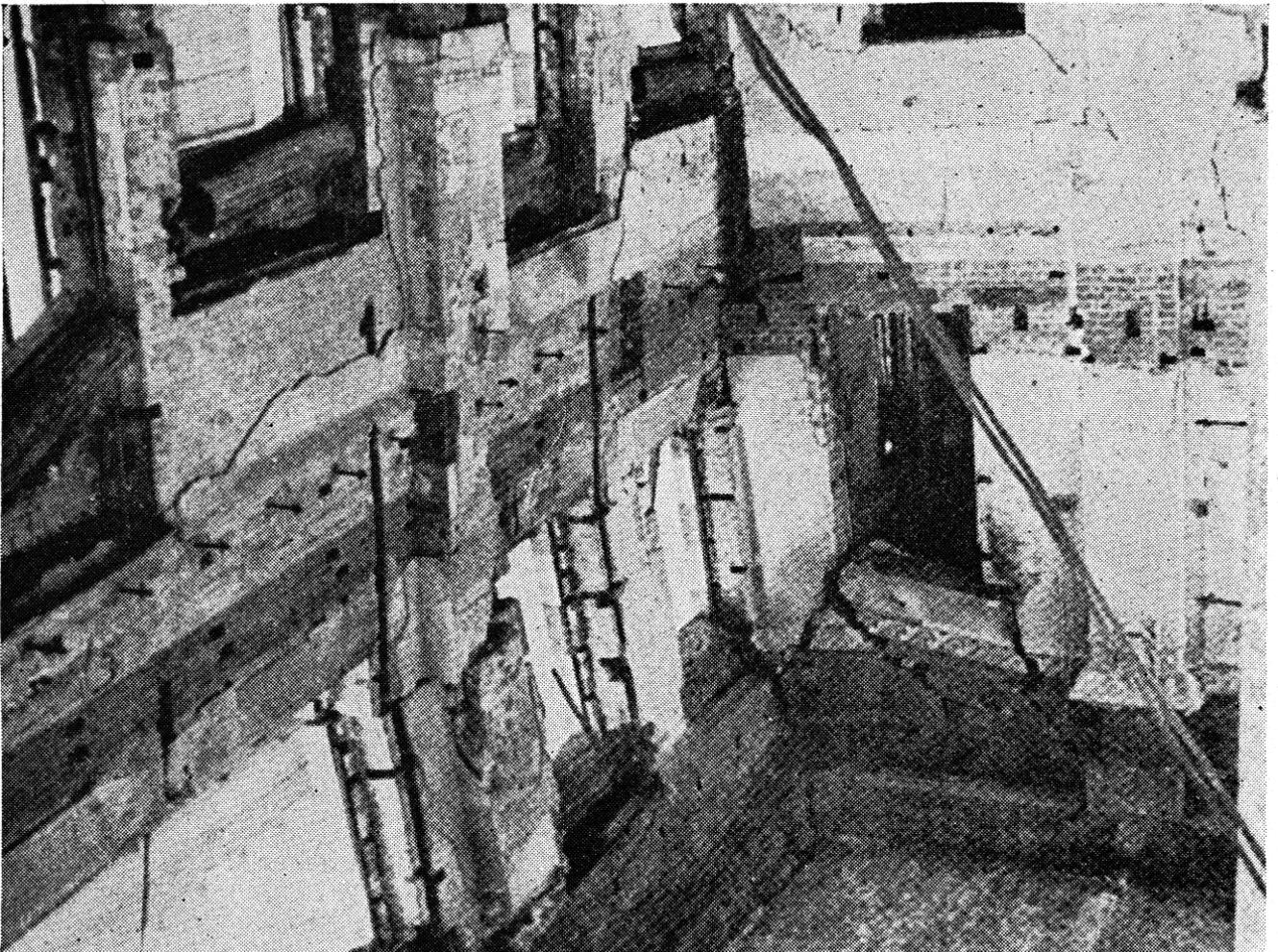
Figure 5.65a.  *Upper photo*: Building with load-bearing walls, 600 feet from ground zero, 2,100 feet from the point of explosion.  *Lower photo*: Interior of above, showing buckling of wall and combustible material burned out.
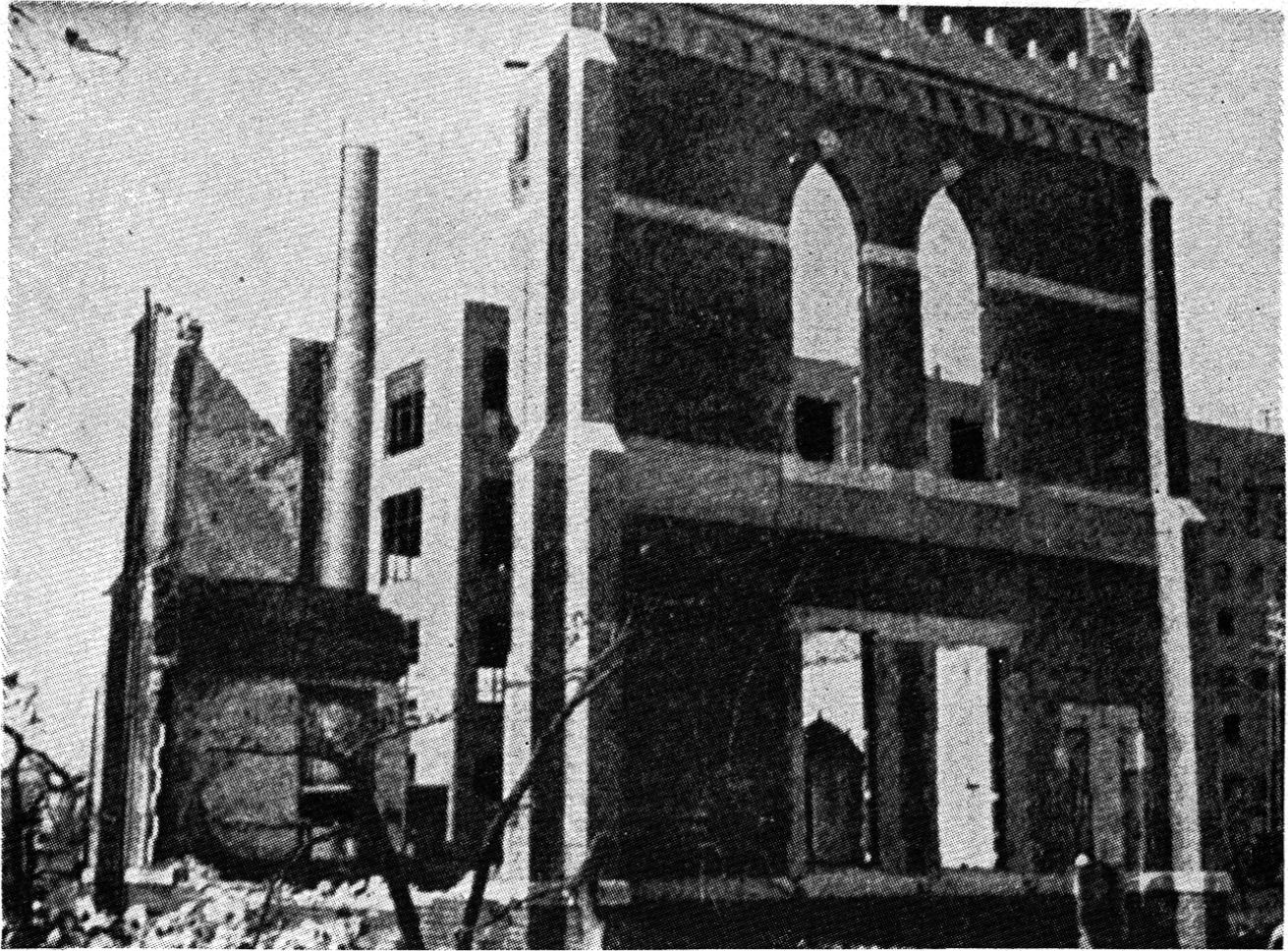
Figure 5.65b.   *Upper photo*: Building with load-bearing walls, 5,200 feet from
ground zero.   Load-bearing wall away from the blast collapsed.   *Lower photo:*
Interior of above, showing damage due to blast and fire.   (Compare with
Figure 5.54b for a reinforced-concrete building at about same distance from
ground zero; both buildings were in Hiroshima.)
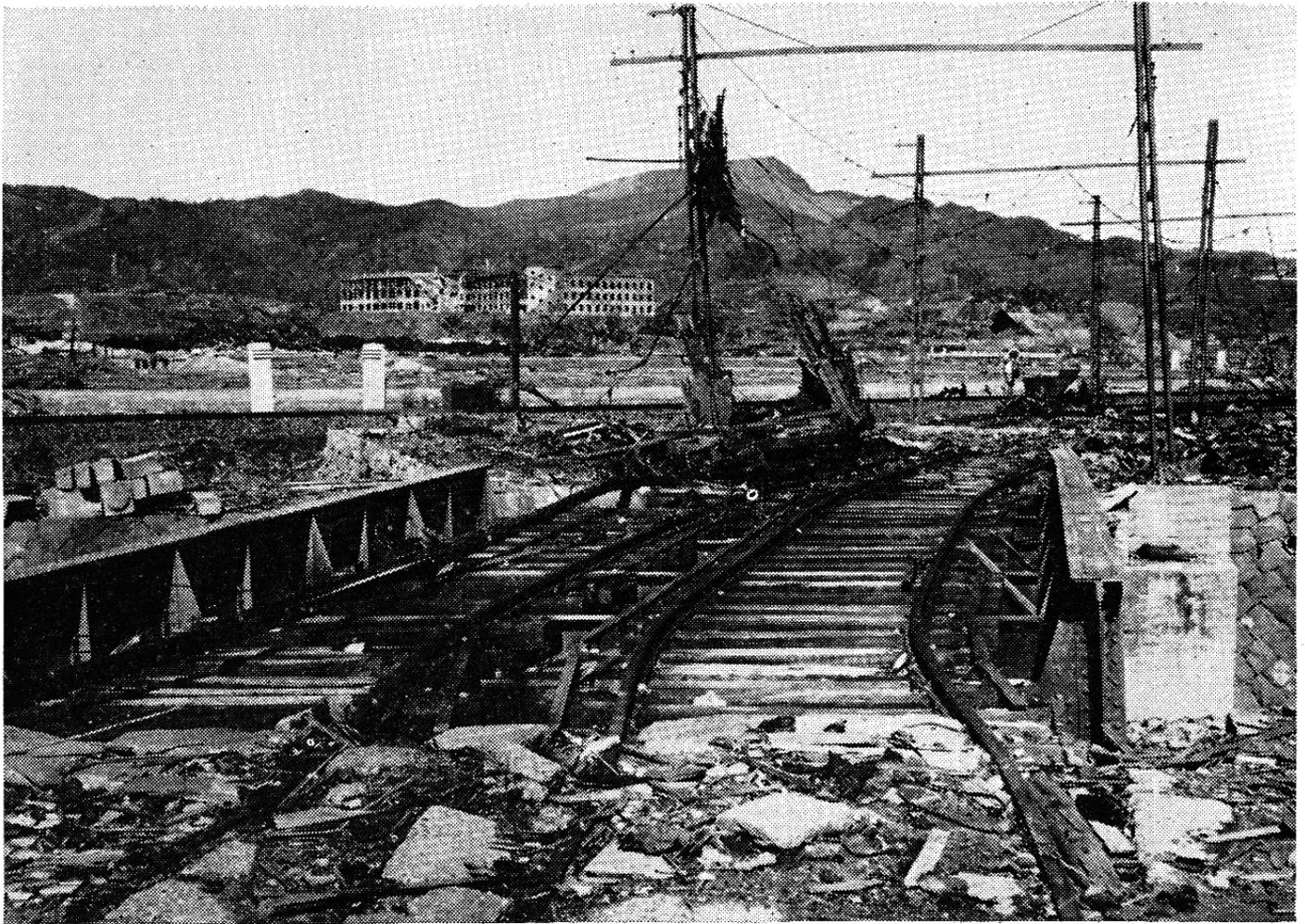
Figure 5.67b.  Steel-plate girder, double-track railway bridge, about 840 feet from ground zero, 2,150 feet from point of explosion.  The plate girders were moved about 3 feet by the blast; the railroad tracks were bent out of shape and trolley cars were demolished, but the poles were left standing.



Figure 5.67c.  Reinforced-concrete bridge with T-beam deck, 2,330 feet from ground zero.  Part of deck was knocked off the pier and abutment by the blast, causing one span, 35 feet long, to drop into the river.  The remainder of the bridge was almost undamaged.

TABLE 5.84

EARTHQUAKE DAMAGE SCALE*

*Grade A.*—Very violent (greater than 0.4 gravity).**

*Grade B.*—Violent (0.3–0.12 gravity).
>     Fissuring of asphalt; destruction of foundation walls and under-
>     pinnings of structures; the breaking of sewers and water mains; dis-
>     placement of street car tracks

*Grade C.*—Very strong (0.12–0.08 gravity).
>     Brick wall or masonry badly cracked with occasional collapse; frame
>     buildings lurched or listed on fair or weak underpinning; general de-
>     struction of chimneys and masonry, cement or brick veneers; consider-
>     able cracking or crushing of foundation walls.

*Grade D.*—Strong (0.08–0.02 gravity).
>     General but not universal fall of chimneys; cracks in masonry and
>     brick walls; cracks in foundation walls; a few isolated cases of lurching
>     or listing of frame buildings built up on weak underpinning.

*Grade E.*—Weak (less than 0.02 gravity).
>     Occasional fall of chimneys and damage to plaster, partitions, plumb-
>     ing, etc.

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*Physics of the Earth, Part VI: Seismology, Bulletin of the National Research Council, No. 90 (1933).
**The accelerations given in the table are those in a horizontal direction.

so that inertial forces are negligible, could stand very large displace-
ments if every part received the same amount of movement. But
if either or both of these conditions is not met, then damage may result.
Failures of the foundation walls may occur due to earth pressure alone
acting hydrostatically, but it is the differential earth pressures, which
are in turn functions of the shape and length of the pressure wave,
that are responsible for the accelerations imparted to the building sub-
structure.[12]   It is seen that the quantities are so interlinked that any
real separation of the effects is impractical. Nevertheless, since
inertial forces, differential movements and hydrostatic pressures are
agents that act to produce failures of the structure in different ways,
it may not be too unrealistic to attempt to set up criteria of damage
based on these three quantities, and to compare them with such in-
formation as is available to see if they are consistent.

5.86   From Table 5.84 it is seen that appreciable damage corre-
sponding to that from a strong (grade D) earthquake, which is ap-

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[12] Because of the great length of the shock wave in an atomic bomb burst, many buildings have dimensions
which are small compared with the positive part of the wave (§ 5.23).  The motion of the earth and the back
and front of a structure will thus be much the same, and the differential earth pressures may be small.

becomes so low that the air is no longer incandescent; this represents the breakaway point (§ 2.11).

6.9    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 seen. Thus, the apparent, or surface, temperature, having reached a minimum, commences to increase. The shock now ceases to play any further part, as far as radiation is concerned, and the rise of surface temperature continues until that of the hot core of the isothermal sphere is attained. This gives the second maximum which subsequently falls, due to cooling of the hot gases by radiation and expansion.

6.10    The formation of oxides of nitrogen in the air surrounding the ball of fire is of interest in connection with the optical properties described above. For temperatures between 2,000° and 5,000° K the equilibrium concentrations of nitric oxide and nitrogen dioxide in the air are between 1 and 5 percent. Below 2,000° K, the equilibrium concentration is negligible, and above 5,000° K, the oxides are dissociated into atoms. Thus, if the air is heated by the shock wave to this temperature range, the oxides of nitrogen are formed. Nitrogen dioxide is a brown gas which is opaque to visible radiation, and it is possible that the presence of this substance in the shock front contributes to the low surface temperature near the breakaway. It is estimated that in the explosion of a nominal atomic bomb something of the order of 100 tons of nitrogen dioxide are formed, and this was believed to be responsible for the peach color of the rising cloud observed in the Bikini "Able" test (§ 2.18).

## Transport of Radiation

6.11    Before proceeding to a more detailed consideration of the radiation emitted by an atomic bomb, brief reference will be made to a matter of some interest. It has been mentioned (§ 6.5) that the reason why the ball of fire becomes separated from the isothermal sphere is that at a certain temperature transfer of energy by shock is faster than by radiation. Since radiation consists of photons [3] traveling with the speed of light, it is not obvious why transport of energy as radiation should be slower than by the shock wave.

6.12    A simplified explanation of the situation may be developed by considering an isothermal sphere of air at a temperature of 30,000° K

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[3] According to the quantum theory, electromagnetic radiation is propagated in the form of *photons*, each carrying energy $hc/\lambda$, where $h$ is Planck's constant (§ 6.15), $c$ is the velocity of light, and $\lambda$ is the wave length of the radiation.

expanding by radiative transport alone into cold air.  By means of Planck's quantum theory, which is considered below (§ 6.15), it can be shown that in such a sphere as much as 70 percent of the radiation is concentrated in the region of wave length less than 1,860 Å.  In cold air the average mean free path of the photon for this radiation emitted by the hot sphere is of the order of 0.01 cm. or less.[4]

6.13  Now, the process of radiative transport proceeds somewhat in the following manner.  On the average, each photon travels with the velocity of light for a distance of one mean free path and then it is absorbed by a molecule, atom, or gaseous ion present in the air which becomes excited.  This entity remains in the excited state for a certain time, before returning to its ground state and emitting another photon.  After this photon is emitted it moves off in a random direction, and the adsorption and emission of photons by the air molecules, etc., is repeated.

6.14  Because of the short mean free path of the photons of radiation of wave length less than 1,860 Å, and also on account of the fact that the photons move in a random path—the so-called "random walk"—the effective rate of diffusion is very small.  In other words, the velocity of transport of radiation is low for the bulk of the radiation from the hot sphere; therefore, the rate of transport through cold air will be relatively small.  However, on account of its much greater mean free path, the small fraction of the radiant energy of longer wave length, i. e., in excess of about 1,860 Å, will be propagated with the velocity of light.

## B.  RADIATION FROM THE BALL OF FIRE

### RADIATION LAWS

6.15  The spectrum of the thermal radiation from the ball of fire, assuming it to be a black body radiator,[5] is related to the surface temperature by Planck's radiation law.  If $\epsilon_\lambda d\lambda$ denotes the energy density of radiation in the wave length interval $\lambda$ to $\lambda+d\lambda$, the law states that

$$\epsilon_\lambda = \frac{8\pi hc}{\lambda^5} \cdot \frac{1}{e^{hc/\lambda kT}-1},\qquad (6.15.1)$$

---

[4] The mean free path of a photon, i. e., the mean distance it travels before absorption by a molecule, is equal to the reciprocal of the absorption coefficient.  Radiations of wave length less than 1,860 Å are strongly absorbed (§ 6.17), and so the mean free path is very short.

[5] The assumption that the ball of fire radiates as a black body is made from theoretical considerations only, for the spectral distribution of the radiation has not been determined.  It may be mentioned that it is known from experiment that the continuous background in the radiation from the sun follows the black body distribution law, and there are reasons for believing that the conditions in the ball of fire are even more favorable for the emission of black body radiation.

where $c$ is the velocity of light in vacuo, $h$ is Planck's quantum of action, $k$ is Boltzmann's constant, i. e., the gas constant per molecule, and $T$ is the absolute temperature.   The values of the energy density, in ergs per cm.³ per Å, as calculated from equation (6.15.1) for three different temperatures, are plotted in Fig. 6.15 as a function of the
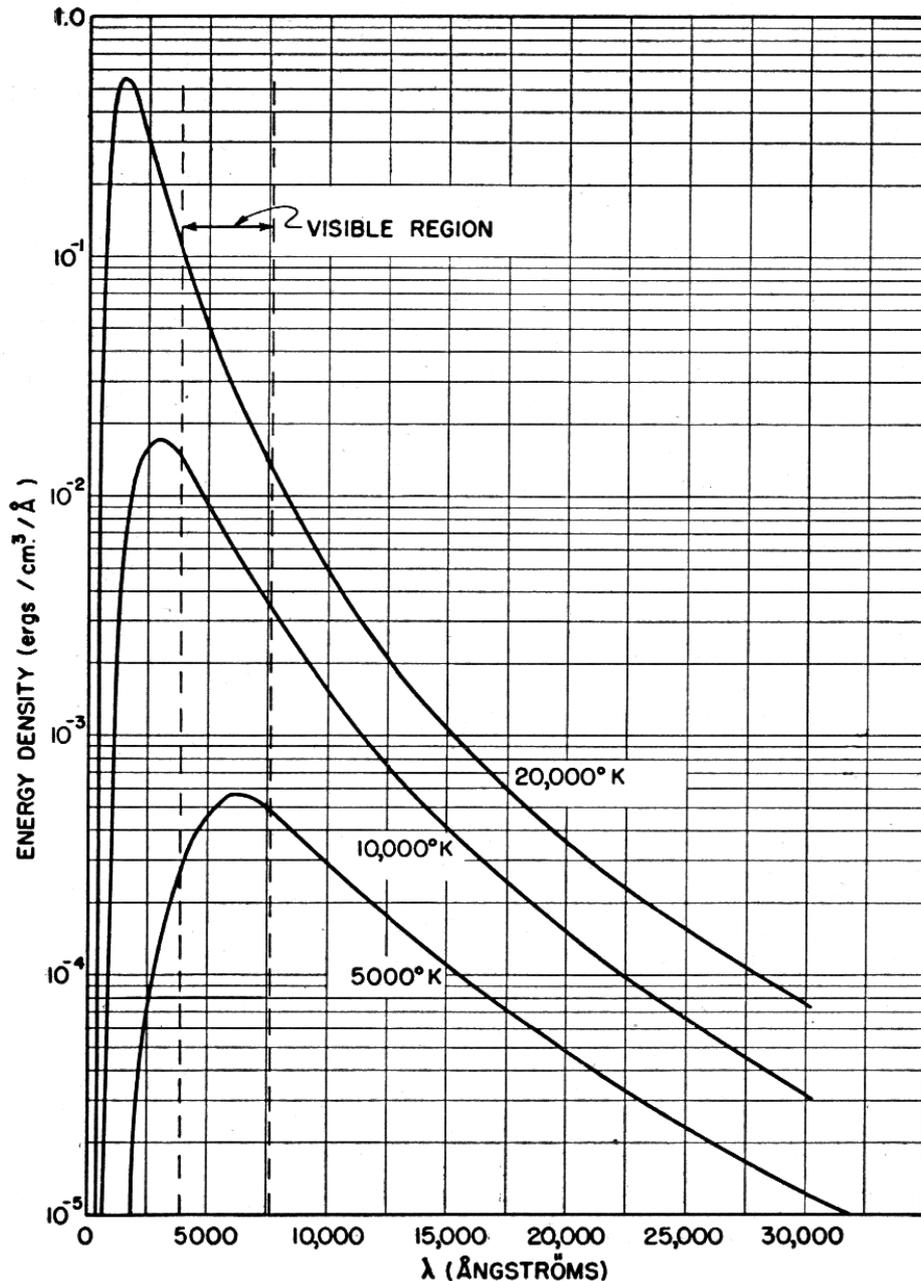


Figure 6.15.   Energy density of black body radiation as function of wave length for different temperatures according to Planck's equation.

wave length.   The curves show how markedly the radiant energy is concentrated into the short wave length region of the spectrum.

6.16   A second law of the black body radiation is required at this point.   When a black body is heated to an absolute temperature $T$, each unit area of its surface radiates energy at a rate proportional to the fourth power of the temperature.   This law, the Stefan-Boltzmann law, then states that the flux of radiant energy, that is, the rate

at which the energy passes through 1 square centimeter of the surface of a black body, is given by the expression

$$\Phi_b = \sigma T^4, \tag{6.16.1}$$

where, according to the Planck theory,

$$\sigma = 2\pi^5 k^4 / 15 h^3 c^2 \tag{6.16.2}$$

$$= 5.67 \times 10^{-5} \text{ erg cm.}^{-2} \text{ sec.}^{-1} \text{ deg.}^{-4}.$$

## RADIATION FLUX AND ILLUMINATION

6.17   From the two radiation laws stated above, it is possible to calculate the flux of radiant energy into an absorbing surface located



Figure 6.17.   Absorption coefficient of radiation by air as function of wave length.

at any distance from the ball of fire, provided the transmission characteristics of the air are known. On the basis of ultraviolet

absorption measurements in air, it can be stated that, for present purposes, cold air is opaque to radiations of all wave lengths shorter than 1,860 Å and is transparent for longer wave lengths. This is apparent from Fig. 6.17 which gives the absorption coe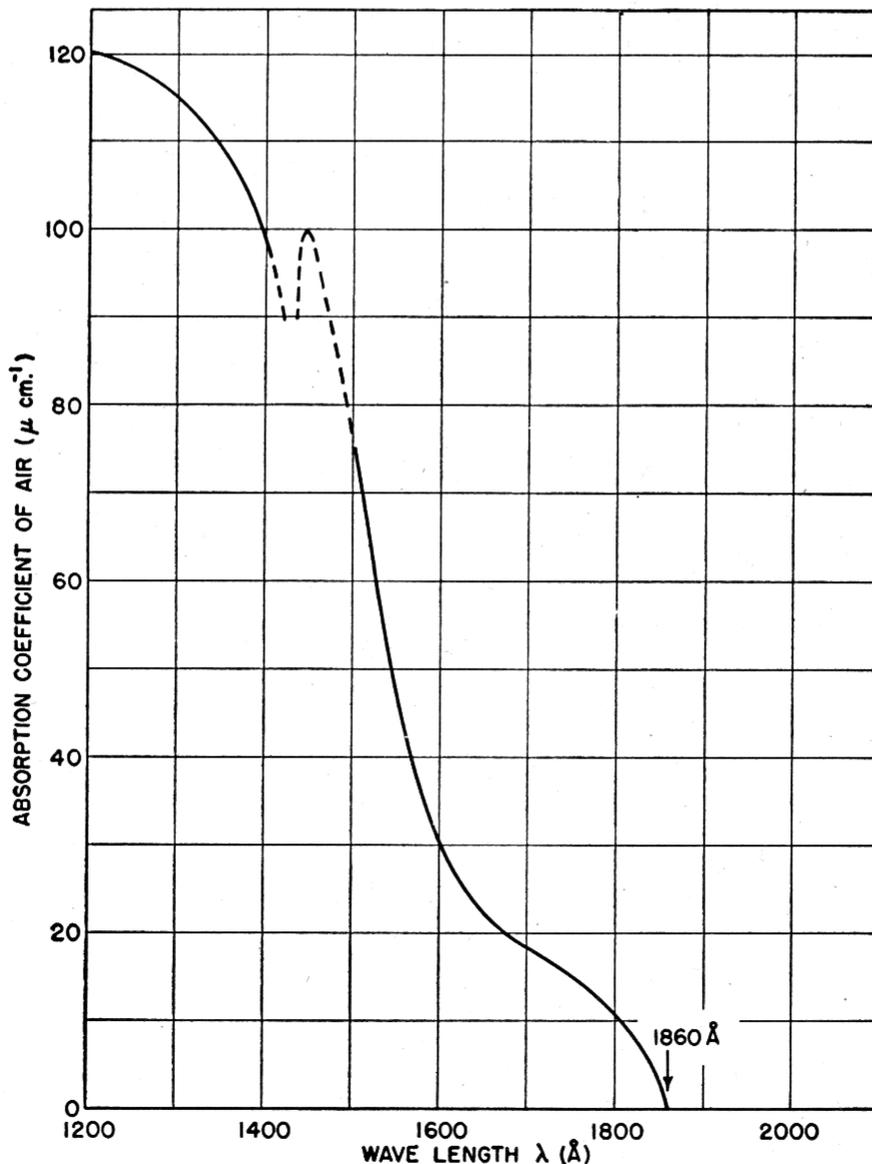fficient as a function of the wave length;[6] it is seen that at 1,860 Å the coefficient has decreased almost to zero, the actual value being 0.0044 cm.$^{-1}$.

6.18 The fraction $f_0$ of the total radiation emitted which can penetrate a significant distance in air can therefore be defined by

$$f_0 = \frac{\int_{\lambda_0}^{\infty} \epsilon_\lambda d\lambda}{\int_{0}^{\infty} \epsilon_\lambda d\lambda}, \qquad (6.18.1)\,[7]$$

where $\lambda_0$ is 1,860 Å, and $\epsilon_\lambda$ is the Planck function. Since $\epsilon_\lambda$ is given by the Planck equation (6.15.1), the indicated integrations can be performed, and the values of $f_0$ for different temperatures can be calculated. The results so obtained are shown in Fig. 6.18; they may
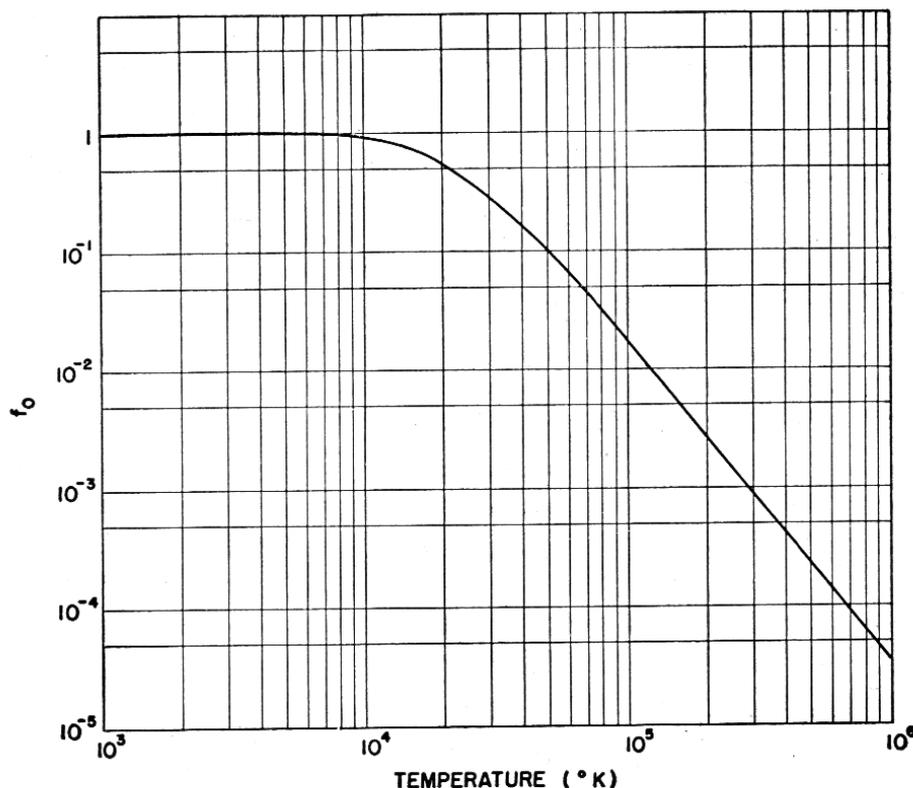


Figure 6.18. Fraction of radiation penetrating the air as function of temperature of ball of fire.

be taken as representing $f_0$ as a function of the surface temperature of the ball of fire. It will be noted from this figure that for temperatures

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[6] Absorption data given by E. G. Schneider, *J. Opt. Soc. Amer.*, *30*, 128 (1940).

[7] Because cold air is not completely transparent to wave lengths greater than 1,860 Å, this equation may be applied only for distances of a few meters from the ball of fire. The corrections necessary for greater distances are considered below (§ 6.24 *et seq.*)

less than 10,000° K, that is, for times greater than about $10^{-3}$ seconds after the explosion, the value of $f_0$ is essentially unity.

6.19   The rate at which energy passes through the whole of the spherical surface of the ball of fire, that is, over a solid angle of $4\pi$, is given by equation (6.16.1) as $\sigma T^4 \times 4\pi R^2$, where $R$ is the radius of the ball.   Since only the fraction $f_0$ of this penetrates the air, the rate at which the radiant energy reaches all points on a spherical area at a moderate distance from the point of detonation is $f_0 \sigma T^4 \times 4\pi R^2$. The radiant energy flux $\phi$ per unit area at a distance $D$ is then obtained upon dividing by the total spherical area $4\pi D^2$, so that

$$\phi = f_0 \sigma T^4 \left(\frac{R}{D}\right)^2. \qquad (6.19.1)$$

6.20   From equation (6.19.1) the illumination or flux at a given point, distant $D$, can be computed for various times after an atomic explosion, using the values of $R$ and $T$ from Fig. 6.5 and of $f_0$ from Fig. 6.18.   In order to avoid plotting values for individual distances, the quantity $\phi D^2$, which is equal to $f_0 \sigma T^4 R^2$, is given in Fig. 6.20



Figure 6.20.   Illumination of ball of fire as function of time after explosion.
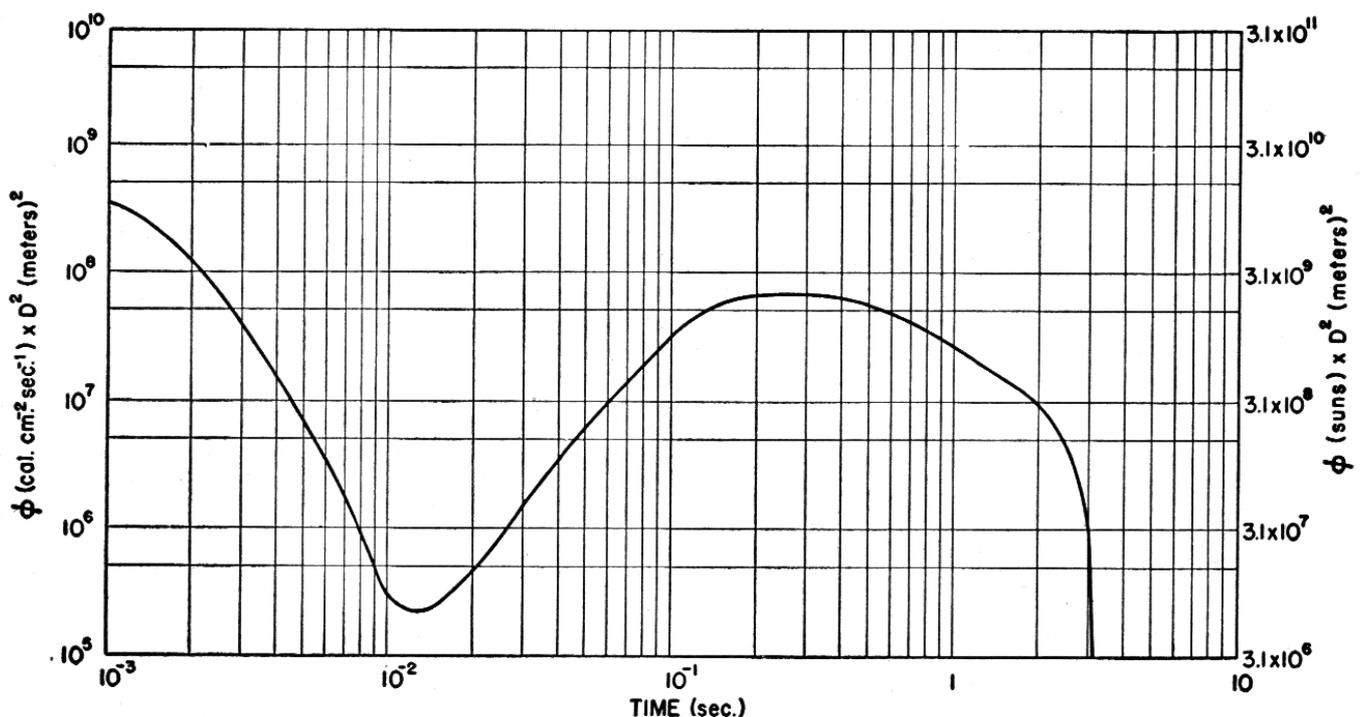
as a function of the time; the energy flux is in calories per square centimeter per second, and the distance is in meters.   From the curve, the energy flux at any given moderate distance at a specific time can be readily determined.   These values, with some modification for transmission of the radiation over long distances, can be used to calculate

the total thermal energy from an atomic bomb falling on unit area as a function of distance.

6.21    It will be observed that the smallest time interval after the explosion for which data are given in Fig. 6.20 is $10^{-3}$ second, and hence the values of $f_0$ are effectively unity, as stated in § 6.18. Therefore, the ordinates in this figure actually represent $\sigma T^4 R^2$. As seen above, the total rate at which energy is radiated from the ball of fire is $\sigma T^4 \times 4\pi R^2$ and, consequently, the ordinates in Fig. 6.20 give its radiation flux (or illumination) per unit solid angle after various time intervals.

6.22    In order to obtain some indication of the magnitude of the illumination, it is convenient to introduce a unit called a *sun*; this is defined as a flux of 0.032 calories per square centimeter per second, and is supposed to be equivalent to the energy received from the sun at the top of the atmosphere. The ordinates at the right of Fig. 6.20 give the values of $\phi D^2$, with $\phi$ in suns and $D$ in meters.

6.23    At the luminosity minimum, the value of $\phi D^2$ is about $6.8 \times 10^6$ sun-meters$^2$, so that at this point the ball of fire, as seen at a distance of about 2,600 meters, i. e., 1.6 miles, should appear about as bright as the sun. Actually, it will be somewhat less bright, to an extent depending on the clearness of the air, because of atmospheric attenuation to be considered below.

## SCATTERING AND ABSORPTION

6.24    The discussion so far has referred to the behavior of the radiation in the interior and in the immediate vicinity of the ball of fire. For this purpose it was justifiable to consider cold air as being transparent to all wave lengths longer than 1,860 Å, as the mean free path of such radiation is many meters. This simplified treatment of atmospheric transmission fails, however, when the radiant fluxes to be expected at great distances are required. It is necessary, therefore, to inquire into the transmission characteristics of air for radiation in the neighborhood of the visible region of the spectrum, i. e., for wave lengths exceeding 1,860 Å.

6.25    There are essentially two processes by which a beam of light may lose energy in penetrating air, namely, scattering and absorption. Two different types of scattering are important: scattering by individual air molecules, and scattering by dust or water droplets which are suspended in the air. The molecular, or Rayleigh, scattering is always present and is a function of the air density (or molecular concentration), to which it is in fact proportional; that is, it depends on the

## CRITICAL ENERGIES

6.48   The most important physical effects of the high temperatures due to the absorption of thermal radiation are, of course, ignition or charring of combustible materials and the burning of skin. The ignition of materials involves a large number of factors, and it is, in general, very difficult to establish definite conditions under which such burning will or will not occur. Somewhat similar considerations apply to skin burns. However, it seems to be established, at least as far as wood charring and skin burns are concerned, that if the heat is supplied at a rapid rate, as would be the case for the absorption of radiation of high intensity, the essential criterion is the total energy received per unit area.

6.49   The general nature of the results obtained for the charring of wood is shown diagrammatically in Fig. 6.49. The ordinates
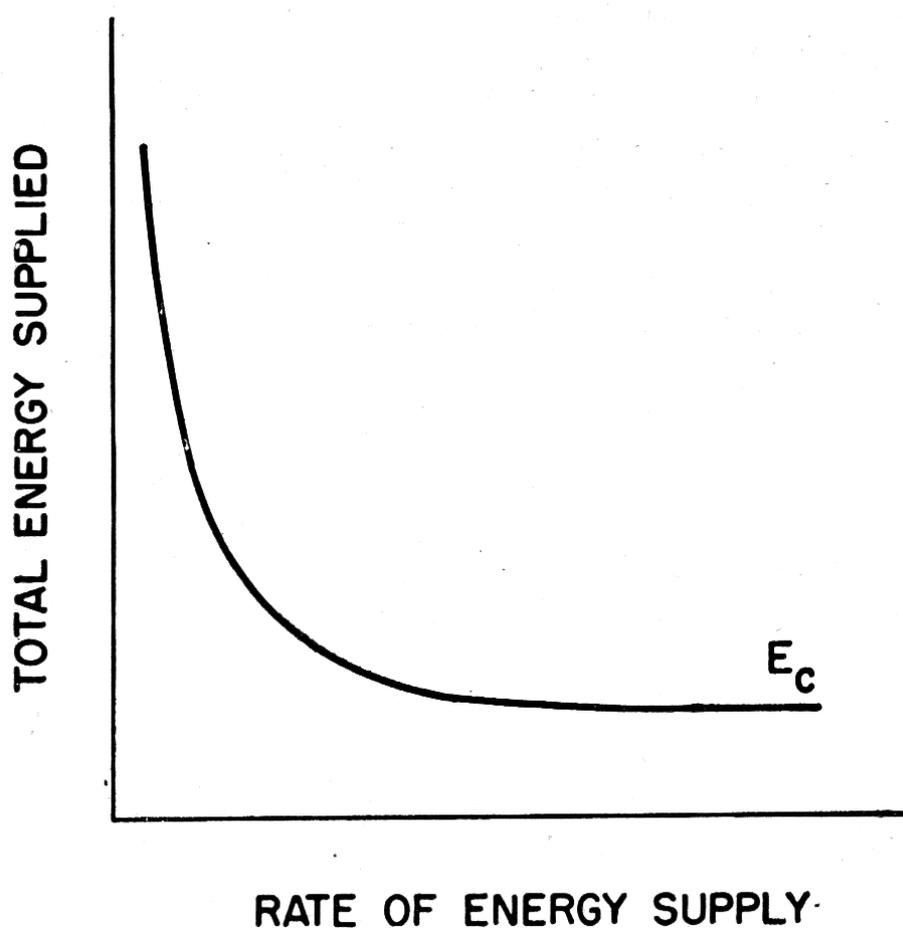


Figure 6.49.   Total energy necessary for ignition of wood as function of rate of supply.

represent the total amount of energy supplied as heat per unit area of the wood, and the abscissas give the rate of heat supply per unit area. It is seen that as the rate of heat supply increases, the total energy necessary to produce charring at first decreases, and then

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 was such as to place them in partial shadow.

6.55 Although thermal radiation 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 were observed only near the center of the explosion. Where burns did occur through clothing, these tended to involve regions where the clothes were tightly drawn over the skin, at the elbows or shoulders, for example, while areas where the clothing



Figure 6.55a. 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.

fitted loosely were unharmed (Fig. 6.55a). Finally, because white or light colors reflected the thermal radiations, they generally afforded better protection than dark clothing. Thus, it was not unusual to find burns through black clothing, but not through white material worn by the same individual (Fig. 6.55b).



Figure 6.55b. The patient's skin is burned in a pattern corresponding to the dark portions of a kimono worn at the time of the explosion.

## RELATIVE IMPORTANCE OF INFRARED AND ULTRAVIOLET RADIATIONS IN SKIN BURNS

6.56    In the foregoing treatment the influence of the total absorbed radiation has been considered as being due to its conversion into heat. The resulting high temperature then presumably causes chemical changes to take place which manifest themselves as skin

features.   In principle, the same result, as regards destruction by fire and blast, might be achieved by the use of conventional high-explosive and incendiary bombs.   It has been estimated, for example, that the physical damage to buildings, etc., equivalent to that at Hiroshima could be produced by approximately 325 tons of high explosive and about 1,000 tons of incendiary bombs.   It can be seen, however, that the atomic bomb is unique in the overwhelming nature of its destructiveness, and this is particularly true as far as incendiary effects are concerned.
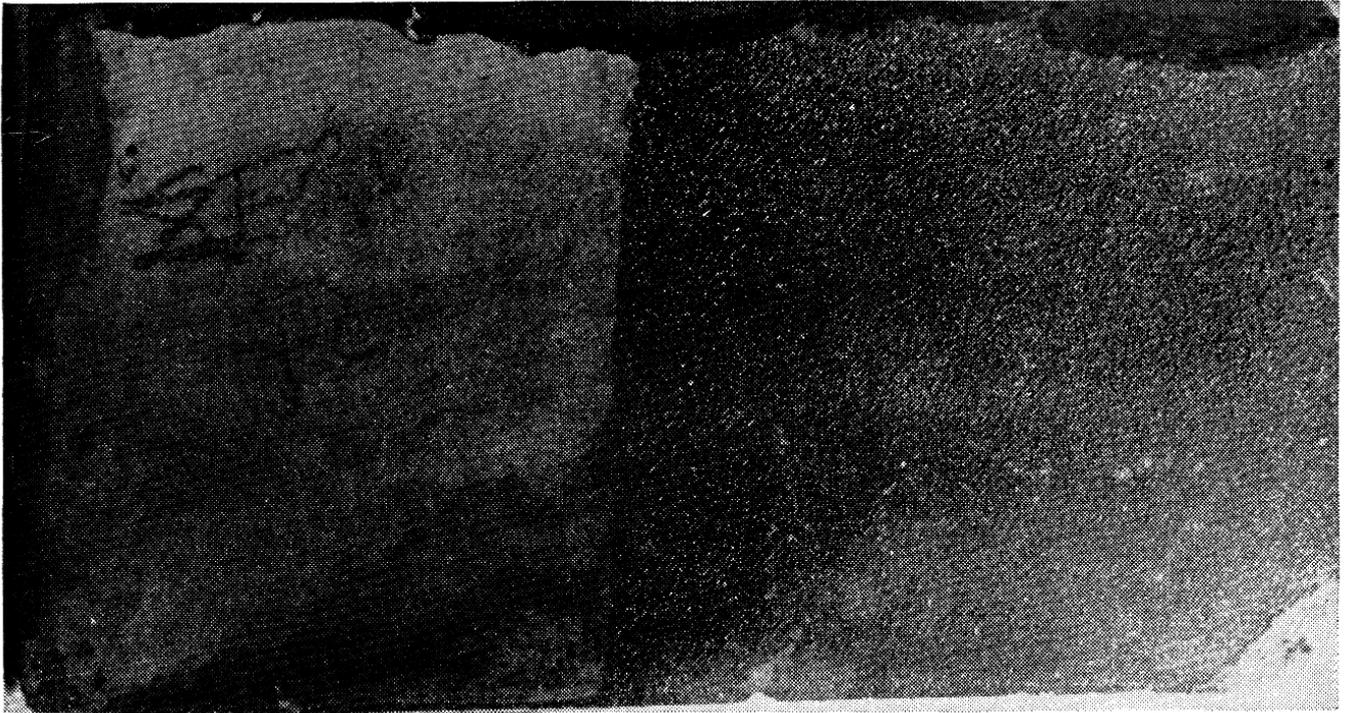


Figure 6.66.   Blistered surface of roof tile near ground zero, about 2,000 feet from the point of the burst.   Left portion of the tile was shielded by an overlapping one.

6.69   Whereas the blast damage caused by any bomb, atomic or otherwise, is largely determined by its energy release, the same is not true for destruction due to fire.   Some evidence for this is the fact that at Hiroshima and Nagasaki similar blast effects were experienced in each case at equal distances from the center of the explosion.   On the other hand, the total area severely damaged by fire at Hiroshima, about 4.4 square miles, was about four times as great as in Nagasaki.   Probably the main reason for this difference lay in the nature of the terrain, Hiroshima being relatively flat while Nagasaki was hilly.   This reflected the distribution of combustible buildings and the opportunity for the spread of fire (cf. § 6.82).

6.70   It is generally true, for any incendiary weapon, that the ultimate results are greatly dependent on a variety of conditions. Some of these are related to the characteristics of the particular

7.21 As the photoelectric effect and pair production involve destruction of photons, the latter are completely removed from the gamma-ray beam. It will be assumed, for the present, that the photons undergoing Compton scattering are also lost, a situation which, it will be seen later, applies in certain circumstances only. However, if this assumption is made, the quantity $n(\sigma_c+\sigma_{pe}+\sigma_{pp})N\,dx$ obtained above may be regarded as the decrease $(-dn)$ per second in the number of photons in the gamma-ray beam in its passage through a distance $dx$ over 1 square centimeter of matter; that is to say,

$$-dn=n(\sigma_c+\sigma_{pe}+\sigma_{pp})N\,dx \qquad (7.21.1)$$

or

$$\frac{dn}{n}=-(\sigma_c+\sigma_{pe}+\sigma_{pp})N\,dx. \qquad (7.21.2)$$

Upon integration this gives

$$n(x)=n_0 e^{-(\sigma_c+\sigma_{pe}+\sigma_{pp})\,Nx} \qquad (7.21.3)$$

as the relationship between the incident flux $n_0$ in the gamma-ray beam and the flux $n(x)$ after it has penetrated a depth $x$ into matter. The quantity $(\sigma_c+\sigma_{pe}+\sigma_{pp})N$ in the exponent of equation (7.21.3) is generally represented by the symbol $\mu$, called the *absorption coefficient* of the material for the particular homogeneous gamma rays under consideration. The photon flux may be replaced by the intensity $I$, to which it is proportional[5], and equation (7.21.3) then takes the familiar form of the exponential attenuation law, namely,

$$I=I_0 e^{-\mu x}, \qquad (7.21.4)$$

where $I_0$ is the intensity of the beam of gamma rays falling on the medium of thickness $x$, and $I$ is the intensity of the emergent beam.

7.22 Since the distance $x$ is usually given in cm., the absorption coefficient is expressed in cm.$^{-1}$ units. The values as calculated for a number of common materials, namely, air, water, aluminum, iron, and lead, for gamma rays of several energies are recorded in Table 7.22. The figures for air refer to 1 atm. pressure and 0° C.

7.23 The data in Table 7.22 give the total absorption coefficients, for Compton scattering, photoelectric effect, and pair production. It is, of course, possible to divide this value into three separate parts,

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[5] The intensity of an electromagnetic radiation, such as gamma rays, is strictly the amount of energy that flows in 1 sec. across unit area (1 sq. cm.) of a plane perpendicular to the propagation of the rays. Since each photon carries a definite amount of energy, the intensity or energy flux for homogeneous radiation, which is a measurable quantity, is proportional to the photon flux.

TABLE 7.22. ABSORPTION COEFFICIENTS ($\mu$) FOR GAMMA RAYS

| Gamma ray energy (Mev) | Absorption coefficients in cm.$^{-1}$ | | | | |
|---|---|---|---|---|---|
| | Air | $H_2O$ | Al | Fe | Pb |
| 0.5 | $1.11 \times 10^{-4}$ | 0.096 | 0.23 | 0.63 | 1.5 |
| 1.0 | .81 | .070 | .16 | .45 | .72 |
| 2.0 | .57 | .049 | .12 | .33 | .50 |
| 3.0 | .46 | .039 | .090 | .28 | .46 |
| 5.0 | .35 | .030 | .075 | .24 | .48 |
| 10.0 | .26 | .022 | .061 | .23 | .62 |

each being equal to the value of $\sigma N$ for the particular process. The separate partial absorption coefficients obtained in this manner for air and lead, taken as examples of extreme cases, are in fact the data which were plotted in Figs. 7.17a [6] and 7.17b. It is seen that for air, the Compton effect makes essentially the sole contribution to the absorption coefficient, at least for energies up to 3 or 4 Mev. This is generally true for materials consisting of light elements, e. g., animal tissues, water, etc.

7.24   The results given above show that the (total) absorption coefficients decrease, at first, with increasing energy of the gamma rays. This is due, as already mentioned, to the diminishing contributions of the Compton and photoelectric effects. At energies in excess of 1.02 Mev, pair production begins to play an increasingly significant part, so that at sufficiently high energies the absorption coefficient begins to increase, after passing through a minimum.[7] This is apparent in Fig. 7.17b and in the last column of Table 7.22 for lead. For elements of lower atomic weight, the increase does not set in until very high gamma-ray energies are attained, e. g., about 17 Mev for aluminum and 50 Mev for water.

7.25   As a very rough approximation, it may be stated that the absorption coefficient for gamma rays is proportional to the density of the material. In other words, the ordinary (or linear) absorption coefficient divided by the density, giving what is called the *mass absorption coefficient*, for gamma rays of a particular energy, is approximately independent of the nature of the absorbing material. This is especially true for light elements, i. e., those of low atomic weight, where the Compton effect makes the major contribution to the absorption coefficient.

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[6] The photoelectric effect in air is so small that it cannot be shown in the figure.

[7] Pair production is accompanied by gamma radiation due to mutual annihilation of a positive and a negative electron. This effect is probably of small significance for the present discussion.

of water, concrete, iron, and lead are given in Table 7.37, for gamma rays of 4.5-Mev and 0.7-Mev energy.[9]

TABLE **7.37**

SHIELDING THICKNESSES FOR 4.5-MEV AND 0.7-MEV GAMMA RADIATION

| Attenua- tion fraction | Thickness of shield in inches | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 4.5-Mev gamma | | | | 0.7-Mev gamma | | | |
| | Water | Concrete | Iron | Lead | Water | Concrete | Iron | Lead |
| 0. 2 | 30 | 11 | 3. 8 | 1. 6 | 12 | 5. 1 | 1. 8 | 0. 7 |
| . 1 | 40 | 15 | 5. 2 | 2. 3 | 16 | 6. 8 | 2. 4 | 1. 0 |
| . 02 | 70 | 25 | 8. 3 | 3. 9 | 25 | 11 | 3. 9 | 1. 7 |
| . 01 | 80 | 30 | 9. 5 | 4. 6 | 29 | 13 | 4. 5 | 2. 0 |
| . 001 | 110 | 40 | 14 | 6. 7 | 41 | 19 | 6. 4 | 3. 1 |

TRANSMISSION FROM SOURCE

7.38   In the foregoing discussion, no account has been taken of the source of the gamma rays or of its distance away. All that has been considered is the relationship between the intensity of the radiation falling on a thickness of material, which acts as a shield by attenuating the radiation, and the amount which penetrates the shield. The connection between the incident intensity $I_0$ and the properties of the source, e. g., an atomic explosion, require two factors to be taken into account; first, the inverse square law for the decrease of intensity with distance, as used in Chapter VI, apart from absorption, and second, the attenuation due to scattering and absorption in the atmosphere. The latter aspect of the problem is, however, not essentially different from that considered in connection with shielding, with the thickness of the material greater than the mean free path of the photon.

7.39   If a point source of gamma rays emits $n_0$ photons per sec., each carrying a quantum $\epsilon_0$ of energy, the intensity of radiation, i. e., the energy flux, at a distance $D$ will be $n_0\epsilon_0/4\pi D^2$, apart from attenuation due to scattering and absorption. Allowance for the latter may now be made by using equation (7.33.1), so that the intensity of the incident radiation falling on a shield at a distance $D$ from the

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[9] The values for these two energies are of special interest because the energy of some of the initial gamma radiation is 4.5 Mev, while the residual radiation, to be considered in the next chapter, has a mean energy of 0.7 Mev.

source, e. g., an atomic explosion, may be written as

$$I_0 = \frac{n_0 \epsilon_0}{4\pi D^2} B(\epsilon_0, \mu_c D) e^{-\mu_c D}. \qquad (7.39.1)$$

As before, the approximation has been made of neglecting the contributions of the photoelectric effect and of pair production in a medium, such as air, consisting of elements of low atomic weight.

7.40   Since $\mu_c$ and $B(\epsilon_0, \mu_c D)$ are known for air, it is possible to calculate $I_0/n_0$, that is, the energy received per photon emitted, at various distances from an atomic explosion, for gamma rays of specified energy $\epsilon_0$.   However, since the numbers of photons of various energies emitted are not known, the results are of little practical value, although they might have some interest when further information becomes available.   For the present, the best procedure to adopt is to make use of actual measurements of radiation intensity, or of an equivalent quantity, as will be described below.

### GAMMA RADIATION DOSAGE FROM ATOMIC BOMB

7.41   It was stated in § 7.18 that the physiological damage caused by gamma radiation is due to the ionization brought about by the high-energy electrons which are ejected or produced by the rays in their passage through matter.   For this reason, radiation dosage is measured in terms of a unit called the *roentgen*, symbol r, defined as the amount of gamma (or X) radiation which produces in 0.001293 gram of dry air, i. e., 1 cubic centimeter at 0°C. and 1 atm. pressure, electrically charged particles carrying a total of 1 electrostatic unit of charge of either sign.[10]   The conversion of gamma-ray energy values into roentgens is carried out somewhat in the following manner.   The energy absorbed per cubic centimeter of air at 0° C. and 1 atm. pressure due to the passage of gamma radiation is equal to the product of the cross section of the energy absorption per electron for the particular radiation, as derived from the Klein-Nishima formula,[11] the number of electrons per cubic centimeter of air at S. T. P., and the energy of the gamma radiation per square centimeter.   On the average, the production of 1 ion-pair (§9.2) in air requires 33.2 electron-volts so that the absorption of 1 Mev of gamma-ray energy produces $3.01 \times 10^4$ ion-pairs, which is equivalent to $1.44 \times 10^{-5}$ roentgens, if it is absorbed in 1 cubic centimeter of air.   If the total energy absorption per cubic

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[10] The measurement of radiation in terms of roentgens is described in Chapter IX; see also Appendix C.

[11] W. Heitler, *op. cit.*, pp. 149–157.

centimeter of air has been determined, by the method just described, the number of roentgens produced can be calculated.

7.42   The results obtained in this manner when combined with equation (7.39.1) might be used to determine the dosage in roentgens at a specified distance from an atomic bomb, provided the energy
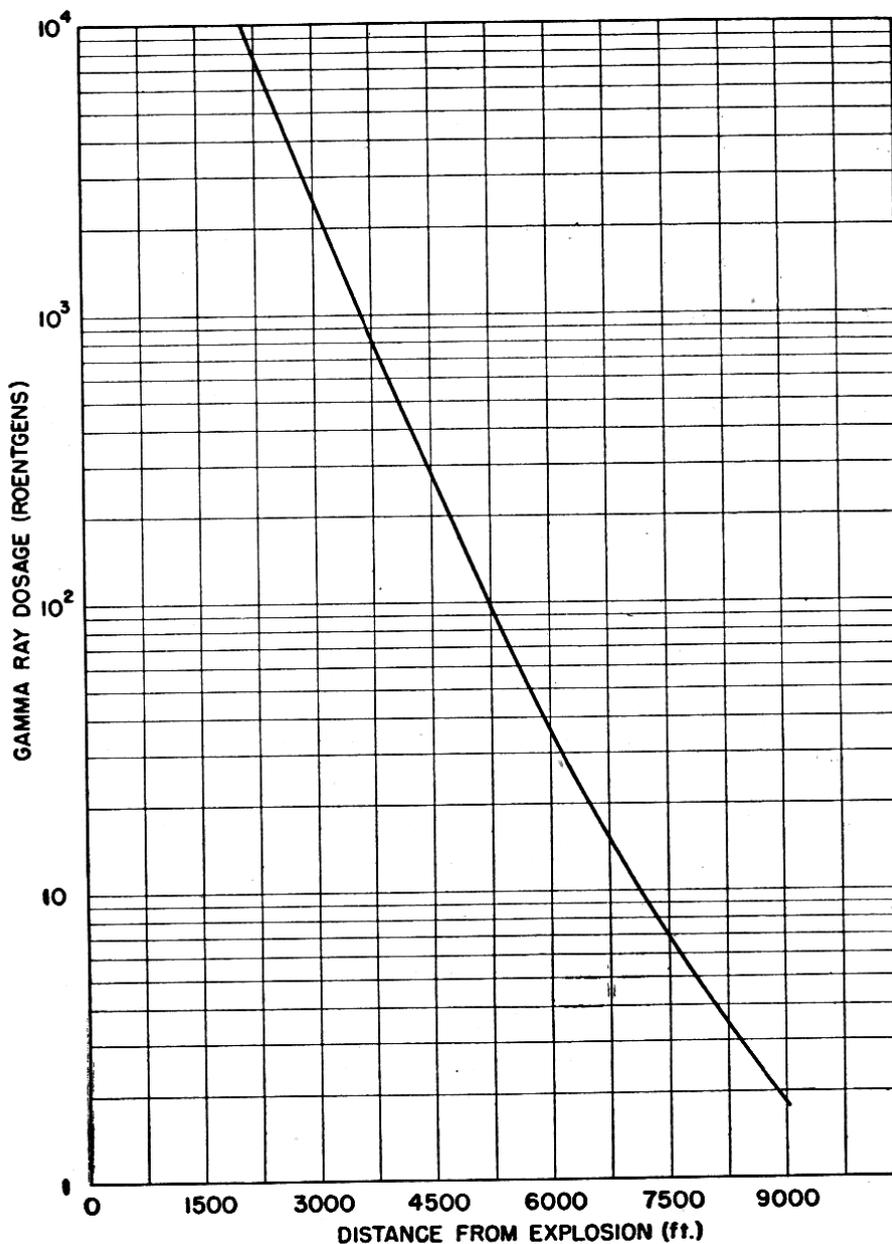


Figure 7.42.   Total dosage of initial gamma radiation as function of distance from explosion.

distribution were known in terms of the respective numbers of photons emitted.   As indicated above, this is not yet possible and so recourse must be had to calculations based on experimental results obtained at the time of an atomic explosion.   The dosage, in roentgens, due to the initial gamma rays, at various distances from about 2,100 to 9,000 feet from the explosion of the nominal atomic bomb are given in Fig. 7.42.[12]   Distances outside this range are of no interest, since at

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[12] The dosage in roentgens can be expressed with fair accuracy by means of the expression $3.8 \times 10^{11} e^{-D/1026}/D^2$, where $D$ is the distance from the explosion in feet.

less than 2,100 feet physical and thermal destruction are so serious in unprotected regions that radiological injury does not need consideration. At distances greater than 9,000 feet, the dosage is, in general, too small to be of serious consequence, unless it is repeated at short intervals.

7.43 It is usually accepted that a dose of 400 r of radiation received over the whole body in the course of a few minutes represents the median lethal dose which would be fatal to about 50 percent of human beings (see Chapter XI). From Fig. 7.42 it can be seen that the median lethal range of the gamma radiation from the nominal atomic bomb is about 4,200 feet. Thus a large proportion of human beings exposed to the initial gamma rays within 4,200 feet of an atomic explosion would die from radiation sickness. If part of the body were protected by a suitable shield, it is probable that a larger dose than 400 r would not prove fatal. However, it must be realized, in view of the great penetrating power of the gamma rays, that ordinary clothing can in no sense be regarded as protective.

7.44 The next matter for consideration is the shielding that would be necessary to reduce the gamma-ray intensity or dosage, which may be taken as being roughly proportional to one another, to amounts below the lethal value at various distances. In order to make reasonably accurate calculations, the gamma-ray spectrum, that is, the distribution of energies, from an atomic explosion should be known. However, this detailed information is not available, but an approximate estimate indicates that the average energy, at distances greater than about 3,000 feet from the explosion, is about 3 Mev, although the values for some components are as high as 4.5 Mev. In this event, the data in Table 7.37 may be used as a rough guide to calculate the thickness of shield that would be required to produce a particular degree of attenuation.

7.45 At the minimum distance of 2,100 feet from the explosion, for which Fig. 7.42 provides information, the dosage in an unprotected location would be 10,000 r. To reduce this to below the median lethal dose of 400 r would require something like 20 inches of concrete or about 3 inches of lead. The attenuation of gamma rays by tightly-packed soil is about 0.6 times that for concrete,[13] so that a layer of somewhat over 30 inches of soil would be equally effective. Underground shelters could thus provide adequate protection against the radiation hazard. An outside shelter of the type used in World War II as a protection against blast bombs, covered with about 20 inches

[13] The value varies somewhat with the nature and condition of the soil, but the factor 0.6 is probably a safe average.

of packed soil, would decrease the radiation dosage below the median lethal value at distances greater than about 3,000 feet from the explosion.[14] The thickness of concrete which would produce the same effect is roughly 12 inches, that of iron 4 inches, and that of lead about 2 inches. The thicknesses of concrete and iron which would be required to decrease the radiation dosages to 400 r, 100 r, and 25 r, respectively, at various distances from an atomic explosion, are indicated by the curves in Figs. 7.45a and 7.45b. The corresponding data for soil can be obtained upon multiplying the values for concrete by 1/0.6, i. e., by 1⅔.
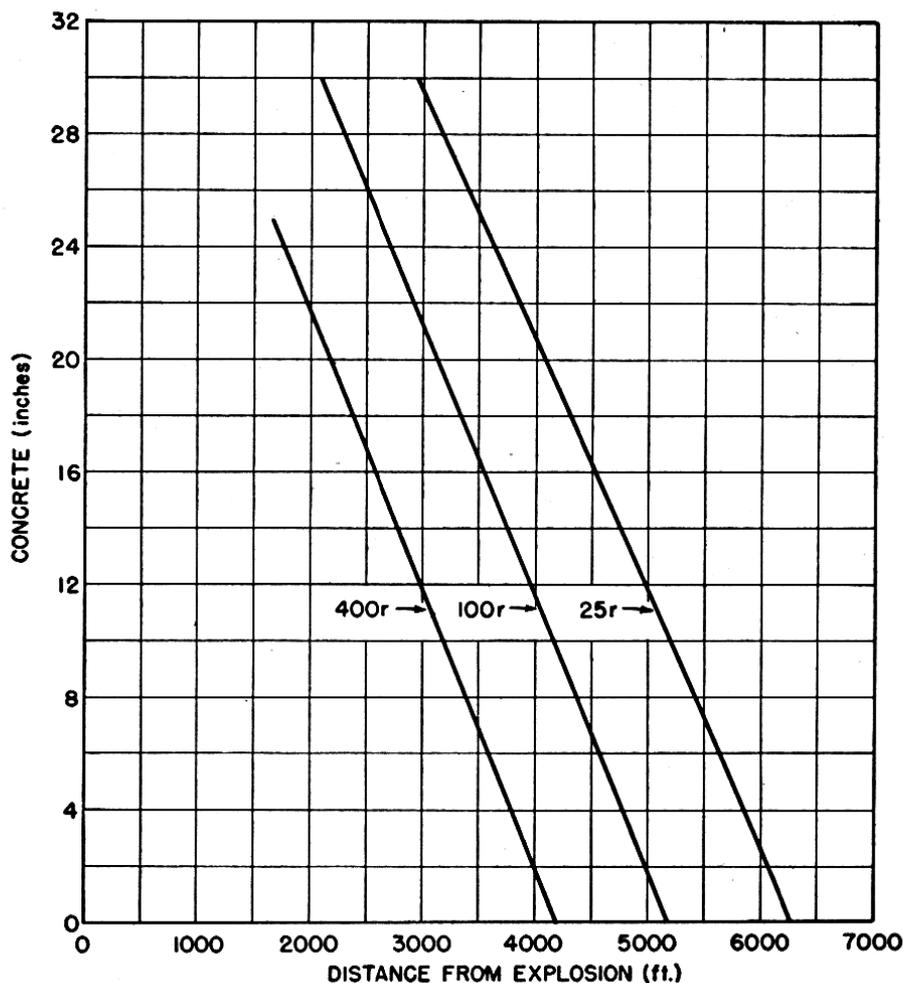


Figure 7.45a. Thicknesses of concrete required as function of distance from explosion to reduce initial gamma radiation to various amounts.

7.46 It was recorded above that an unprotected person within 4,200 feet of an atomic explosion would receive a median lethal dose of initial gamma rays from an atomic bomb. This statement is based, of course, on the supposition that the exposure lasts for the whole minute which was arbitrarily set as the period in which the "initial" radiation was emitted. It is of interest to inquire, therefore, into the time distribution of the radiation immediately following the explosion.

[14] For a height of burst of 2,000 feet, this would represent 2,250 feet or more from ground zero.
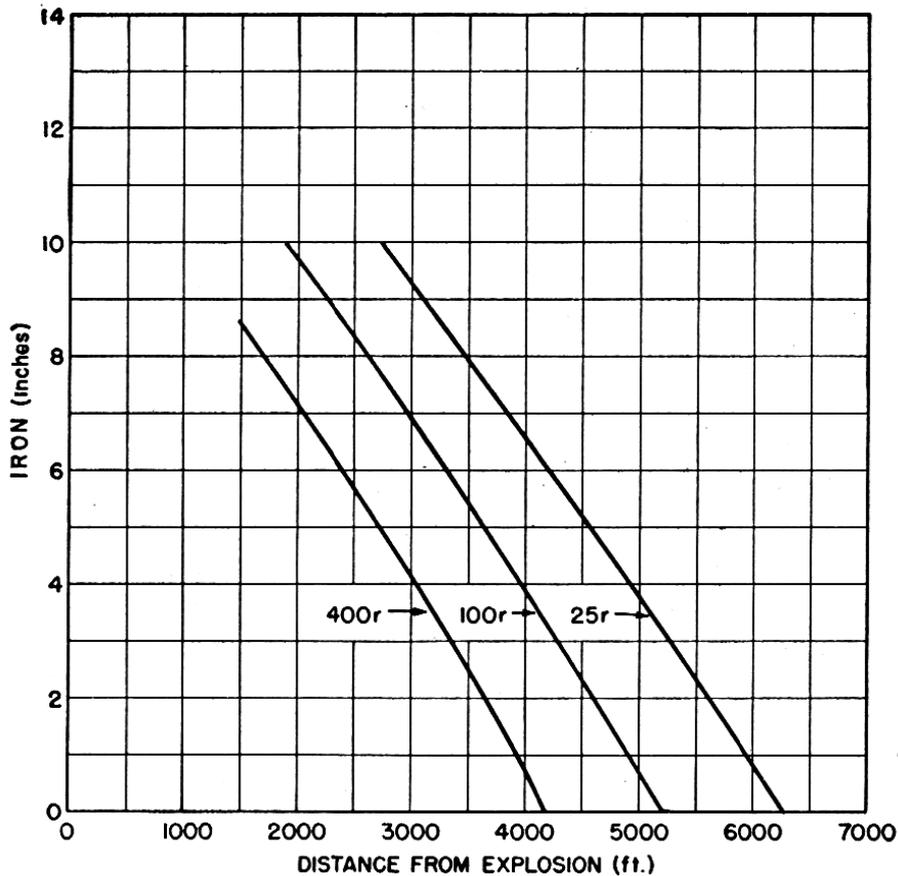
Figure 7.45b.   Thicknesses of iron required as function of distance from explosion
to reduce initial gamma radiation to various amounts.

Results based on actual observations are depicted in Fig. 7.46. The
recorded values depend to some extent on the distance from the atomic
explosion, and data in this figure apply to the distance at which the
mean lethal dose of 400 r would be received, i. e., 4,200 feet. It is
seen that at this distance about a half of the gamma-ray dosage is
received during the first second. Taking shelter quickly behind a
convenient building or in a slit trench, an act which is conceivable
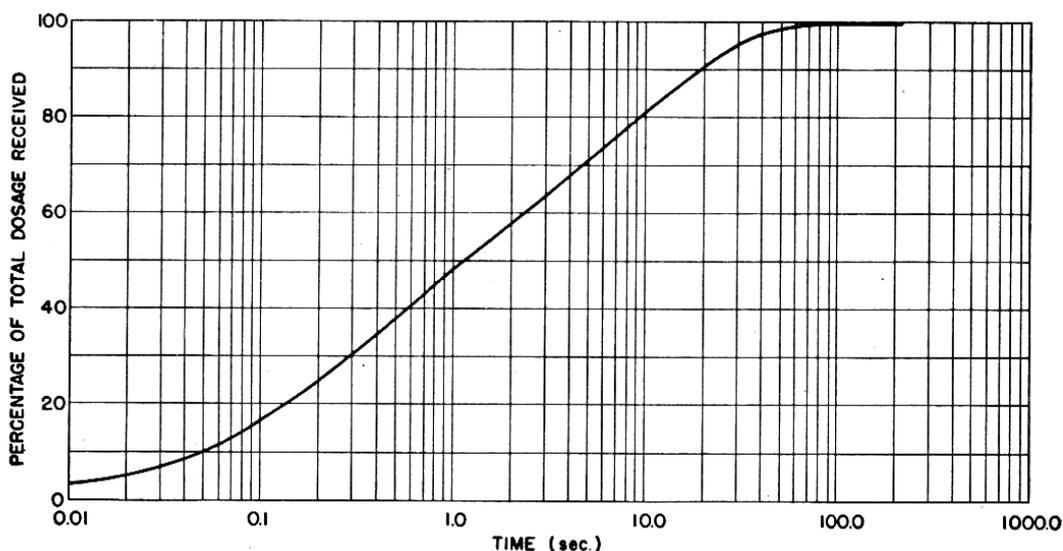


Figure 7.46.   Proportion of total dosage of initial gamma radiation received as
function of time after explosion.

within a second of seeing the bomb flash, might thus mean the difference between life and death to a human being at a point where the unprotected dosage would be near the median lethal value.

7.47  The discussion thus far has been concerned with the nominal, 20 kiloton TNT energy equivalent, atomic bomb.  In concluding this section on the initial gamma radiation, reference will be made to the scaling laws applicable to bombs of various energy releases.  It is probably sufficiently accurate to assume that the total gamma-ray emission is proportional to the number of fissions, and hence to the energy release.  The dosage in roentgens received at any given distance from the explosion is also approximately proportional to this quantity, and hence to the TNT equivalent.  Consequently, for an atomic bomb of $W$ kilotons TNT energy equivalent, the ordinates in Fig. 7.42 would all be multiplied by $W/20$.

7.48  If the energy release of the bomb were doubled, for example, from 20 to 40 kiloton TNT equivalent, the median lethal range, at which the dosage is 400 r, would be increased from 4,200 feet to 4,750 feet.  This means that the lethal area of the initial gamma radiations would be much less than doubled.  Consequently, the thickness of shielding necessary to attenuate the radiation to less than the lethal value at any point would not have to be increased greatly.  For a 40 kiloton equivalent bomb the dosage at 2,100 feet would be 20,000 r, and about 25 inches of concrete would reduce it to 400 r, the median lethal dose.  This may be compared with about 20 inches required at the same distance for the nominal 20 kiloton TNT energy equivalent bomb.

## C.  NEUTRONS

### SOURCES OF NEUTRONS

7.49  The neutrons emitted in the fission process carry about 3 percent of the energy of the atomic explosion.  Of this amount, perhaps less than 1 percent appears outside because of the loss of energy to the components of the exploding bomb.  Consequently, the escaping neutrons bear about 0.03 percent of the energy of the bomb, which is of the same order as that of the prompt gamma rays (§ 7.4).  Like the gamma rays, neutrons can penetrate considerable distances through air, and since they are a physiological hazard, they are a significant aspect of an atomic explosion.

7.50  More than 99 percent of the total number of neutrons accompanying the fission of uranium 235 or plutonium 239 are released almost immediately, probably within $10^{-8}$ second of the explosion.

These are referred to as the *prompt neutrons*. In addition, somewhat less than 1 percent, called the *delayed neutrons*, are emitted subsequently. The latter are actually expelled from certain of the fission fragments, following beta decay. The half-life periods of these fragments with respect to the emission of delayed neutrons range from about 0.5 second to nearly 1 minute. Because of their relatively small number, the delayed neutrons are of little importance in the present connection, although they may play a highly significant part in the control of nuclear reactors. Another source of neutrons from an atomic bomb are those produced by the action of gamma rays, i. e., by reactions of the $(\gamma, n)$ type, on the atomic bomb materials, etc. But the number of such neutrons is very small and may also be ignored.

7.51 Although the prompt neutrons are actually all liberated within less than a millionth of a second of the explosion, as noted above, they are somewhat delayed in escaping from the environment of the exploded bomb. It was thought at one time that these were actually the delayed neutrons referred to above, but this view has been shown to be incorrect. From experimental observations, it appears that the number of neutrons emitted is greater than the expected delayed neutrons by a factor of twenty or more. The neutrons leaving the bomb are thus mainly the prompt neutrons, the delay in their escape being due to interaction with the various atomic nuclei present in the exploded bomb.

7.52 In order to estimate the neutron hazard following an atomic explosion, it is necessary to know something of the energy spectrum; in other words, the distribution of energy values among the neutrons should be ascertained. It has just been seen that the prompt neutrons are the most important, and their energies are fairly well known; hence it should be possible, in principle, to calculate the energy spectrum of the neutrons after penetrating the bomb materials. However, since the latter are not completely dispersed when the neutrons are emitted, the neutron spectrum is dependent to a considerable extent on the detailed geometry of the bomb components at an extremely complex stage of the explosion. Because of these and other circumstances, the calculation is virtually impossible and recourse must be had to experiment.

## DIFFUSION OF NEUTRONS

7.53 Even if the detailed spectrum of the neutrons emitted from an exploding bomb were known, it would still be necessary, for the present purpose, to determine the energy distribution at the surface

# CHAPTER VIII [1]

# RESIDUAL NUCLEAR RADIATIONS AND CONTAMINATION

## A. INTRODUCTION

### CAUSES OF RESIDUAL RADIATIONS

8.1. The residual nuclear radiations, that is to say, those which are emitted after 1 minute from the instant of an atomic explosion, would arise mainly from the fission products, to a lesser extent from the uranium 235 or plutonium 239 which has escaped fission in the atomic explosion, and, in certain circumstances, from activity induced by neutrons in various elements present in the earth or in the sea. Any of the radioactive material which is dispersed in and considerably diluted by the atmosphere may be ignored. But that reaching the inhabited surface of the earth in appreciable amounts, for example, as a result of the fall-out (§ 2.29), a base surge (§ 2.45), or an underground explosion, may represent a serious physiological hazard. In addition, there is the possibility which, although not highly probable, must nevertheless not be ignored, that radioactive material might be used deliberately, apart from an atomic explosion, for the purpose of making certain areas uninhabitable.

### PERMISSIBLE RADIATION DOSAGE

8.2 Before proceeding with a more detailed discussion of the various sources of residual nuclear radiations and of their properties, further reference will be made to the matter of radiation dosage. In the preceding chapter, interest was centered on the radiation emitted in a very short period of time. The problem of dosage, sometimes called a "one-shot" dose, was then quite different from that arising in the case of the residual nuclear radiations which might persist for days, weeks or months.[2] A human being receiving a total of 400 r of the initial nuclear radiation, that is, over a period of a minute or so, would have a 50 percent chance of survival, but, if the same amount of

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[1] Material contributed by S. T. Cohen, L. R. Donaldson, E. S. Gilfillan, S. Glasstone, J. H. Hinds, B. Holzman, M. S. Plesset, H. Scoville, Jr., R. C. Smith, J. H. Webb.

[2] For the definition of the dosage unit, the roentgen (r), see § 7.41.

TABLE 8.10

TOTAL GAMMA ACTIVITY OF FISSION PRODUCTS IN MEGACURIES

| Time | Activity | Time | Activity |
|---|---|---|---|
| 1 minute | $8.2 \times 10^5$ | 1 month | 2.3 |
| 1 hour | $6.0 \times 10^3$ | 1 year | .11 |
| 1 day | 133 | 10 years | $.8 \times 10^{-2}$ |
| 1 week | 13 | 100 years | $.6 \times 10^{-3}$ |

8.11　The rate of emission of gamma-ray energy at any of the times given in the table may be readily obtained by making use of the fact that the mean energy of the gamma rays from the fission products is 0.7 Mev. For example, at 1 hour after the explosion, when the gamma-ray activity is $6.0 \times 10^3$ megacuries, gamma photons are being expelled at the rate of $6.0 \times 10^3 \times 3.7 \times 10^{16}$, i. e., $2.2 \times 10^{20}$, per second. Taking the average energy per photon as 0.7 Mev, the rate of emission of gamma-ray energy is then $0.7 \times 2.2 \times 10^{20}$, i. e., $1.5 \times 10^{20}$, Mev per second. The rates at other times may be obtained in a similar manner.

8.12　The mixture of radioisotopes constituting the fission products is so complex that the total rate of disintegration does not follow the usual decay law applicable to a single species (§1.18). Nevertheless, it has been found experimentally that the over-all rate of gamma-ray emission, at any instant $t$ second after the explosion of a nominal atomic bomb, can be represented to a fair degree of accuracy, by the relatively simple expression

$$\text{Rate of emission of gamma-ray photons} = 4.1 \times 10^{24} t^{-1.2} \text{ per second.} \tag{8.12.1}$$

Since the mean energy per photon is 0.7 Mev, it follows that

$$\text{Rate of emission of gamma-ray energy} = 2.9 \times 10^{24} t^{-1.2} \text{ Mev per second.} \tag{8.12.2}[5]$$

8.13　The rate of emission of beta particles from the fission products is roughly twice that of gamma-ray photons; hence, at a time $t$ sec. after the detonation,

$$\text{Rate of emission of beta particles} = 8.2 \times 10^{24} \, t^{-1.2} \text{ per second,} \tag{8.13.1}$$

for the whole of the fission products produced in the explosion of a nominal atomic bomb. The average maximum energy of the beta particles expelled in fission is 1.3 Mev, but most of the particles have

[5] For references see K. Way and E. P. Wigner, "The Rate of Decay of Fission Products," *Phys. Rev.*, **73**, 1318 (1948).

smaller energies, so that the over-all mean is about one-third of this value (§ 8.43), namely, about 0.4 Mev. Hence,

$$\text{Rate of emission of beta-particle energy} = 3.3 \times 10^{24} t^{-1.2} \text{ Mev per second.} \tag{8.13.1}$$

The total energy of the beta particles produced in fission is thus similar in magnitude to that of the gamma radiation. However, because the beta particles do not penetrate to such great distances as do the gamma rays, the energy of the former would, as a general rule, only be of significance in border-line cases.

8.14   The equations given above represent the decay of the total activity of the whole of the fission products from a nominal atomic bomb, but relationships of the same type apply to the rate of decay of any quantity of fission product, provided there has been no separation, by chemical or other means, of the several elements present. Thus, the activity, expressed either as the number of gamma-ray photons or of beta particles, or as the corresponding energies, emitted per second at a time $t$ sec. after the explosion, is given by

$$\text{Activity} = A_1 t^{-1.2}, \tag{8.14.1}$$

where $A_1$ is the appropriate activity of the particular fission product specimen at 1 second after the explosion. The time units need not be in seconds, for if $A_1$ is the activity in any chosen units at 1 minute or 1 hour after the detonation, then equation (8.14.1) will give the activity in the same units with $t$ in minutes or hours, respectively.

8.15   For practical purposes it is useful to express the activity of a quantity of fission products in terms of the dosage rate in roentgens per unit time. This dosage rate, whether due to gamma rays or to beta particles, or to both, will be proportional to the activity, i. e., to the rate of emission of the rays or particles or both, respectively. Consequently, the dosage rate in roentgens per unit time, due to any quantity of fission products, will be given by an expression analogous to equation (8.14.1); thus, the dosage rate at any time $t$ can be represented by

$$\text{Roentgens per unit time} = I_1 t^{-1.2}, \tag{8.15.1}$$

where $I_1$ is the dosage rate at unit time. The quantity $I_1$ can refer to the dosage rate, due to fission products, in roentgens per unit time at any unit of time, e. g., second, minute, hour, etc., after the explosion; equation (8.15.1), with $t$ in the same time units, will then give the dosage rate after the lapse of that time. As indicated above, this result applies to gamma rays, to beta particles, or to both.

## WORLD-WIDE CONTAMINATION BY RADIOACTIVITY

8.52   Fears have been expressed in some quarters concerning the danger of world-wide contamination by radioactivity resulting from atomic explosions.   That such fears are groundless can be shown by estimating the number of bombs which would have to be detonated to produce enough activity to cover the earth.   Such calculations may be made for external gamma radiation from the fission products, on the one hand, and for the internal hazard due to plutonium which has escaped fission, on the other hand.[11]

8.53   If the whole surface of the earth is to be contaminated, with a minimum number of bombs, they would have to be exploded within a short period of time.   Further, since contamination from fission products would be due essentially to the fall-out, sufficient time must be allowed for all the particles to settle out.   On the basis of these postulates, it has been calculated that in order to constitute a world-wide hazard, something like a million atomic bombs, of the nominal size, would have to be detonated, roughly one to each 200 square miles of the earth's surface.   This clearly represents a highly improbable situation.

8.54   An estimate of the possibility of world-wide contamination by plutonium is more difficult, because of the uncertainty concerning the proportion which escapes fission.   In order to take the extreme case it is supposed that the whole of the plutonium originally present in the bomb is uniformly distributed in the top centimeter of soil.   This plutonium may then be presumed to be absorbed by plants and thus find its way into the human body in the form of food.   Inhalation of dust represents another possibility which is taken into consideration. It appears from the calculations that for plutonium to constitute a world-wide hazard millions of atomic bombs would have to be exploded.

8.55   World-wide radioactive contamination would thus appear to be extremely unlikely, but local contamination due to a relatively small number of bombs might be a serious problem over a large area. The fact that the fall-out may be so widely dispersed means that radioactive particles will descend hundreds and even thousands of miles from the point of detonation.   Although they may not necessarily do any physiological harm, the particles may cause trouble.   An illustration is the case reported in § 8.73, where the radioactive dust from the Alamogordo explosion appeared in strawboard manufactured over a thousand miles away and, as a result, spoiled sensitive photographic film which was wrapped in this material.

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[11] See Appendix E.

8.56   It is important at this point to distinguish clearly between world-wide and local contamination.   To be a serious menace, the former would require, as seen above, the explosion of a very large number of bombs, but the explosion of a single bomb in appropriate circumstances might cause a hazard in a limited area.   It is this latter aspect of the problem of residual nuclear radiation from atomic explosions of various types which will be considered in the following sections.

## C.  RADIOACTIVE CONTAMINATION DUE TO AIR BURST

### CAUSES OF CONTAMINATION

8.57   In the case of an air burst of an atomic bomb, the radioactivity at the earth's surface would depend essentially on two factors, namely, neutron-induced activity and fall-out, since the direct deposition of fission products is negligible.   There would also be contamination of the air by the radioactive cloud which would be a hazard to aircraft. As far as the induced activity is concerned, this would probably be somewhat localized in character and would be appreciable only near ground zero.   There is a possibility, of course, that the radioactive material formed close to the position of burst may be carried over a fairly large area by the secondary winds created by the updraft of the rising cloud.   A special case is that of an air burst over salt water because of the presence of relatively large amounts of sodium chloride (§ 8.25), and because of the fairly rapid diffusion of the activity in the water.

8.58   The relative importance of the sources of radioactive contamination following an air burst will depend on a variety of circumstances, for example, the nature of the terrain and the meteorological conditions.   From a general point of view, however, the height of burst is perhaps of most significance, since this has a considerable influence on the more or less local contamination as well as on the fallout.   For convenience, heights of burst may be described as high or low, and although it is not possible to make a sharp demarcation, it will be taken here to be about 500 ft.   This figure is chosen because it is approximately the maximum radius of the ball of fire (§ 2.12), so that in an atomic explosion above this altitude the ball of fire will not touch the ground.   Thus a high burst will imply a detonation at an altitude greater than 500 feet, and a low burst will refer to a lower level.

### EFFECT OF HIGH AIR BURST

8.59   Typical examples of high burst atomic bombs were those exploded over Hiroshima and Nagasaki at altitudes of about 2,000

feet.   There seems little doubt that the height of the detonation was too great to permit an appreciable neutron flux at the earth's surface. Consequently, the amount of induced activity was small.   Since the ball of fire did not touch the earth, and most of the fission products were carried upward in the rapidly rising column of smoke, the extent of local contamination was small.   At Nagasaki, about 0.02 percent of the fission products were left on the ground within a radius of some 2,000 feet of ground zero; however, even a few minutes after the explosion, the area did not present a radiation hazard.

8.60   It was mentioned in Chapter II that the fall-out depends on debris of various kinds sucked up from the earth's surface after the atomic explosion.   It is believed that for a sufficiently high burst relatively little extraneous material would be taken into the cloud, and the fall-out would be negligible.   This is in general agreement with experience from the atomic explosions over Japan.   Since the fall-out is liable to be more significant for low bursts, it will be referred to again below.

8.61   If the air burst occurred at such an altitude that no appreciable debris was sucked into the cloud, the fission products would remain in a finely divided state for a long time, during which period they would be undergoing decay.   Eventually, the particles would descend to earth, but they would be so widely dispersed and their activity so much decreased that they could be ignored, as far as a danger to health was concerned.   Of course, special meteorological conditions, such as abnormal winds or perhaps rain clouds, might cause a large deposition of radioactive material in a particular area, but it is improbable that this would be at all general.

8.62   As already indicated, a not too high air burst over the sea would result in the formation of neutron-induced activity in the water, due mainly to sodium 24.   The evidence from the Bikini "Able" detonation, which took place several hundred feet above the level of the lagoon, indicates that almost all the fission products were carried upward in the atomic cloud.   Such activity as remained above the surface of the water, amounting to a maximum rate of 25 r per day at about 2 hours after the explosion, was due largely to gamma rays from the radioactive sodium.   This dosage rate, which decreases fairly rapidly because of the 14.8-hour half life of the sodium 24, would never result in a lethal dose.

8.63   The general conclusion to be drawn is that if an atomic bomb is detonated at a high altitude, so as to cause maximum blast damage in a city, the hazard due to radioactivity on the ground after the explosion is small.

## EFFECT OF LOW AIR BURST

8.64  Atomic bombs were exploded experimentally at low altitudes at Alamogordo and at Eniwetok. Radioactive contamination of the ground was many times greater than for the high-altitude bursts, due to the fact that the ball of fire touched the earth's surface. The radioactivity near the center of the explosion resulted partly from condensation of fission products upon contact with the ground, and partly from radioactivity induced by neutrons. The approximate radiation dosage rates, in roentgens per hour, measured on the ground at Alamogordo, 1 hour after the detonation had taken place at a height of 100 feet, are given in Table 8.64 for various distances from ground zero.

TABLE 8.64

### RADIATION DOSAGE RATE ON GROUND ONE HOUR AFTER EXPLOSION

| Distance from ground zero (feet) | Dosage rate (r. per hr.) |
|---|---|
| 0 | 8,000 |
| 300 | 5,000 |
| 600 | 600 |
| 900 | 150 |
| 1,200 | 30 |
| 1,500 | 10 |
| 2,250 | 5 |
| 3,000 | .3 |
| 3,750 | .07 |

8.65  It is apparent from these figures that after an air burst at low altitude an area, small compared with the damage area due to the bomb, near the explosion center would be uninhabitable because of the radiation hazard. Nevertheless, calculations show that a vehicle traveling at a moderately high speed could cross the contaminated ground about 15 minutes after the explosion without the occupants being greatly harmed. It would probably be 6 hours or more before it would be safe to walk across the area; but to stay for any length of time would, of course, be out of the question, unless proper shielding were available. The great amount of radioactive dust remaining in the air after a low-altitude explosion would require special precautions to prevent entry of the active material into the system.[12]

8.66  The disturbance of large quantities of earth and other material in the formation of a crater, which accompanies an air burst at low altitude, results in the deposition of contaminated debris at some distance away. In addition, much of the dust is carried aloft into the atomic cloud, but it eventually settles to the earth as the fall-out,

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[12] Masks such as are used for chemical warfare protection are suitable for this purpose.

after picking up fission product particles (§ 2.23), to contaminate areas much further from the center of the explosion. After the Alamogordo test, for example, high concentrations of radioactivity were detected on the ground several miles north and east of the site of the explosion. The integrated dose was, however, not dangerous to human life.[13]

8.67 Most of the dust particles which are contaminated with fission products in a radioactive cloud rise to a considerable height before beginning to descend. The fall-out thus extends over an appreciable time after the explosion. According to Stokes's law, which is especially applicable to particles of from 5 to 300 microns, i. e., $5 \times 10^{-4}$ to $3 \times 10^{-2}$ centimeters, in diameter, the rate of fall of a particle in the air under the influence of gravity is equal to $0.35 \, d^2 \, \rho$ feet per hour, where $d$ is the diameter of the particle in microns and $\rho$ is its density.

TABLE 8.67

TIMES FOR PARTICLES TO FALL 40,000 FEET

| Particle diameter (microns) | Time of fall (hours) | Particle diameter (microns) | Time of fall (hours) |
|---|---|---|---|
| 840 | 0. 37 | 33 | 40 |
| 250 | . 69 | 16 | 170 |
| 150 | 1. 95 | 8 | 680 |
| 75 | 7. 90 | 5 | 1, 700 |

In Table 8.67 are given the calculated times, based on this relationship, required for dust particles of various sizes to descend from 40,000 feet, this being taken as the height attained by the atomic cloud. The density of the particles is assumed to be the same as that of silica (sand). Particles with diameters less than 5 microns are seriously affected by Brownian movement and remain in the air for very long periods.

8.68 It has been found experimentally that the size distribution of any dirt raised by the wind is approximately the same regardless of the material. Consequently, it may be assumed, for purposes of calculation, that the size distribution of the particles in an atomic cloud is the same as observed at the Alamogordo "Trinity" test, which was similar to that for dust over the Sahara desert. Assuming this distribution of particle size to apply to the fall-out, it is possible to

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[13] A number of cattle, about 10 to 15 miles from the "Trinity" explosion at Alamogordo, New Mexico, were inadvertently exposed to the radioactive dust from the fall-out. In the course of a few weeks, loss of hair and blisterlike lesions were apparent. The latter soon healed, however, and the hair, originally red in color, grew again, although it was white or gray in color. Continued observation of the animals has shown that the cows have produced normal calves, irrespective of whether they were mated with bulls which had or had not been exposed to the radioactive dust. There was, by the end of 1949, no evidence of any effects of the radiation, other than the graying of the hair.

calculate the proportions by weight of the fission products falling during certain intervals of time after an atomic explosion. Using the results in Table 8.67, and supposing the particles to be raised to

TABLE 8.68

PROPORTION OF ACTIVE MATERIAL DEPOSITED FROM ATOMIC CLOUD

| Period (minutes) | Diameter of dust particles (microns) | Proportion deposited (percent) |
|---|---|---|
| First 22 | 840 | 3. 8 |
| 22–42 | 840–250 | 12. 6 |
| 42–117 | 250–150 | 14. 5 |
| 117–480 | 150– 75 | 18. 1 |

40,000 feet before they descend, the values in Table 8.68 have been obtained. These figures account for 49 percent of the activity present in the fall-out; the other 51 percent remains suspended for a very long time.

8.69    From the standpoint of radioactive contamination, the important factor is the surface area of the dust particles. The finely divided fission products deposit on the surface of these particles, and hence the proportion of the total radioactivity carried by dust particles of a particular size depends on the percentage of the total area associated with that size group. The results in the third column of Table 8.68 actually give the calculated percentages of the total area of the dust in various size ranges, and these are assumed to represent the proportions of the initial fission-product activity carried down, during various periods of time.

8.70    It should be noted that in deriving these results no allowance was made for the natural decay of the fission products during their ascent with the atomic cloud and their descent with the fall-out. However, because of this decay, the material deposited at increasing intervals from the time of burst will be less and less active. Thus, Table 8.68 indicates that in the period from 117 to 480 minutes after the atomic explosion, about 18 percent of the fission products will reach the earth's surface. But if allowance is made for the natural radioactive decay, it is probable that this would represent no more than about 0.1 percent of the original radioactivity of the atomic cloud.

8.71 . While the particles are descending, they are subjected to the action of the prevalent winds and to diffusion, which tends to spread them out over a large area. It is evident that even for a wind velocity as low as 10 miles per hour, many of the particles of the fall-out would reach the earth at some distance from the explosion, in spite of changes of wind direction with time and altitude. Even the largest

particles mentioned in the table, which are nearly 1 millimeter in diameter, would descend nearly 4 miles from their point of origin if the wind velocity remained constant at 10 miles per hour; many of the smaller particles would, of course, travel much further before descending.

8.72   Evidence for the great distances traveled by dust particles has been obtained in many instances, the outstanding example being the Krakatao eruption.[14]   After this disturbance the dust was detected thousands of miles away.   In fact, residual volcanic ash remained suspended in the atmosphere for approximately three years.   Further, the brown coloration of the snow observed in New England in February 1936, was due to soil raised by a dust storm in Texas nearly 2 days earlier.

8.73   Of more direct interest is the fact that radioactive dust produced in the atomic bomb ("Trinity") test at Alamogordo, New Mexico, on July 16, 1945, was detected by its presence in strawboard produced at Vincennes, Indiana, on August 6, 1945.[15]   The source of the contamination was undoubtedly the water from the Wabash River, which drains a large area.   In spite of the fact that the activity was adsorbed by the straw from large amounts of water, used for washing, the total radioactivity was actually very small, and it would have undoubtedly escaped notice completely were it not for the fact that the strawboard was used for packing very sensitive X-ray films. Fogged spots were found on the film due to action of the radiations. It may be mentioned that at the "Trinity" test, the bomb was exploded on a tower about 100 feet above the ground, so that a large amount of debris was sucked into the atomic cloud (see Fig. 2.11).

8.74   Although the lateral transport of most of the particles in the fall-out will be due to the action of winds, a proportion will be dispersed by eddy diffusion.   It is expected that this factor is significant only in the lowest levels of the atmosphere, and then the roughness of the terrain may lead to an unequal deposition of particles.   If there is a very stable thermal stratification of the lowest layers of air, a greater concentration of activity may occur in a valley than at higher altitudes.   Even under conditions of turbulence, it is possible, as a result of eddy diffusion, for activity to be deposited in one area yet for it to be completely absent from neighboring areas.

8.75   The foregoing considerations tend to support the general conclusion that in most circumstances the fall-out from an air burst

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[14] This eruption, of course, involved considerably larger amounts of energy, and much larger quantities of debris were raised, than for an atomic bomb explosion.

[15] J. H. Webb, *Phys. Rev.*, 76, 375 (1949).

will not be a serious radiological hazard. A special case might perhaps arise if the air were moist; in this event, the radioactive, metallic (fission product) oxides would attach themselves to the water droplets, which might subsequently fall as radioactive rain. In a warm front rainfall situation,[16] such as frequently occurs in temperate latitudes, the rain-bearing clouds may have a thickness of 20,000 feet. The radioactive particles, from an atomic bomb burst taking place a few hundred feet above the earth's surface, might ascend into the rain-bearing clouds. In a short time the atomic cloud within the rain-bearing cloud could possibly attain virtual equilibrium with the latter, and so become an integral part of the rain-producing system. The radioactive material might then be expected to deposit with the rain in a surface pattern dependent on the winds at the cloud level.

8.76  In the considered opinion of many who have made observations of atomic explosions, the fall-out in the case of a low air burst might be an inconvenience, but it would not, in general, represent a real danger. It would probably rarely be enough to prevent passage across an area, although it might necessitate suspension of operations for a few days within the area.

8.77  Special circumstances might, of course, arise, as indicated above, that would result in excessive contamination in certain localized regions. If there were a persistent wind in a particular direction, for example, a larger proportion of activity would probably be found in downwind areas. With the aid of a meteorological trajectory analysis,[17] it might even be possible to predict the location of these areas, provided sufficient data concerning wind directions and velocities were available.

## SURFACE EXPLOSION

8.78  The extreme case of an atomic explosion at low altitude would be represented by a burst taking place at the surface of the earth. Since there has been no detonation of this type it is possible only to speculate as to what the results might be. It is reasonably certain that the contamination due to neutron-induced activity in the vicinity of the explosion would be very high. Further, the probable formation of a large crater would, no doubt, be accompanied by considerable amounts of dust contaminated with fission products and with radioactive isotopes formed by neutron capture. This airborne activity,

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[16] A warm front type of rainstorm is associated with thick-layered clouds extending over an area of hundreds or thousands of square miles. The rain is usually gentle but continues to fall steadily for some time.

[17] See Appendix F.

which would produce a significant fall-out, might constitute a serious hazard in areas directly downwind at some distance from the explosion.

8.79 It is to be expected that in the event of a surface burst, a larger proportion of the fission products would remain on or near the ground than in the case of an explosion taking place in the air. On the whole, therefore, it may perhaps be anticipated that a surface burst, although less destructive in other ways, would result in greater radioactive contamination, especially at not too large distances from ground zero, than the other types of detonation already considered.

## Radioactive Cloud

8.80 One further aspect of an atomic air burst may be mentioned, namely, the question of how much radiation to which a crew of an airplane flying through a radioactive cloud would be exposed. Some computations have been made, using certain simplifying conditions. The assumption is made that the cabin is hermetically sealed and the air intake is closed, so that none of the active fission products enter the airplane. In actual practice such internal contamination could not be avoided, so that the estimates will inevitably be too low. This is in agreement with the result of observations made during atomic explosions.

8.81 The case considered is that of an aircraft flying on a line through the center of a radioactive cloud, assumed to be spherical in shape. This line of flight gives the maximum cumulative radiation dosage. The additional postulates are that the motion of the atomic cloud in ascent and expansion is small compared with the speed of the aircraft; that the radioactivity of the cloud remains constant during its passage; and that the cloud has risen to an altitude where its density is essentially that of the atmosphere.

8.82 The results of the calculations, for an airplane flying at the rate of 300 miles per hour, assuming the radiation to consist only of gamma rays arising from the fission products, and that the dosage is due to external exposure, and not direct contact or inhalation of the fission products, are recorded in Table 8.82.[18] Because of the necessary simplification mentioned above, the values given are to be recognized as being very approximate. The altitude, in the first column, is that of the cloud center at various times after the explosion, given in the second column; the dosage, in roentgens, is almost entirely derived from inside the cloud, for the contribution from outside is only 5 r at 15,000 feet and is essentially negligible above 25,000 feet.

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[18] Based on calculations made by M. S. Plesset and S. T. Cohen.

TABLE 8.82

ESTIMATED RADIATION DOSAGE OF AIRCRAFT AT 300 M. P. H. IN RADIOACTIVE CLOUD

| Altitude (feet) | Time after explosion (seconds) | Radius of cloud (feet) | Dosage (r) | Dosage rate (r per hr.) |
|---|---|---|---|---|
| 15, 000 | 90 | 3, 100 | 550 | 140, 000 |
| 20, 000 | 140 | 3, 800 | 260 | 55, 000 |
| 25, 000 | 200 | 4, 500 | 130 | 24, 000 |
| 30, 000 | 300 | 5, 300 | 70 | 11, 000 |
| 35, 000 | 430 | 6, 100 | 40 | 5, 600 |
| 40, 000 | 600 | 7, 100 | 25 | 3, 000 |

8.83    The calculated dosage rates, in roentgens per hour, are plotted in Fig. 8.83, as a function of the distance from the center of the cloud, for various cloud heights. It should be emphasized that, as stated above, the results are approximate; the actual accumulated dosage rates will probably be higher.   It is seen that outside the cloud the gamma-ray dosage falls off rapidly with increasing distance from the center.   Further, with the lapse of time, i. e., for increasing height of the cloud, the activity extends over increasing areas from the point of burst.

# D.   RADIOACTIVE CONTAMINATION FROM UNDERWATER BURST

## CAUSES OF CONTAMINATION

8.84    For an underwater burst at moderate depths, the initial gamma and neutron radiations can be ignored, since they are almost completely absorbed in a few yards of water.  Some radioactive sodium 24 and chlorine 38 may be produced as a result of reaction with neutrons, but it appears that most of the latter will be captured by the hydrogen of the water to form the nonradioactive isotope deuterium.  The neutron-induced activity evidently makes a relatively small contribution to the residual radiation, and this is largely due to the fission products which do not escape as easily as they do in the case of an air burst.

8.85    Of the types of atomic explosion the underwater burst at Bikini, that is, the "Baker" test, produced by far the greatest degree of radioactive contamination.  It was estimated that almost all of the fission-product activity either remained in the water immediately following the detonation, or fell back into the lagoon in the form of the radioactive base surge and rain (§ 2.45 et seq.).  The extent and degree of contamination following an underwater atomic explosion will

probably vary markedly with the conditions, such as the base surge, which in turn may well depend on the depth of the burst, the meteorological conditions, e. g., wind velocity and direction, rain clouds, etc., and the topography at the site of the detonation.



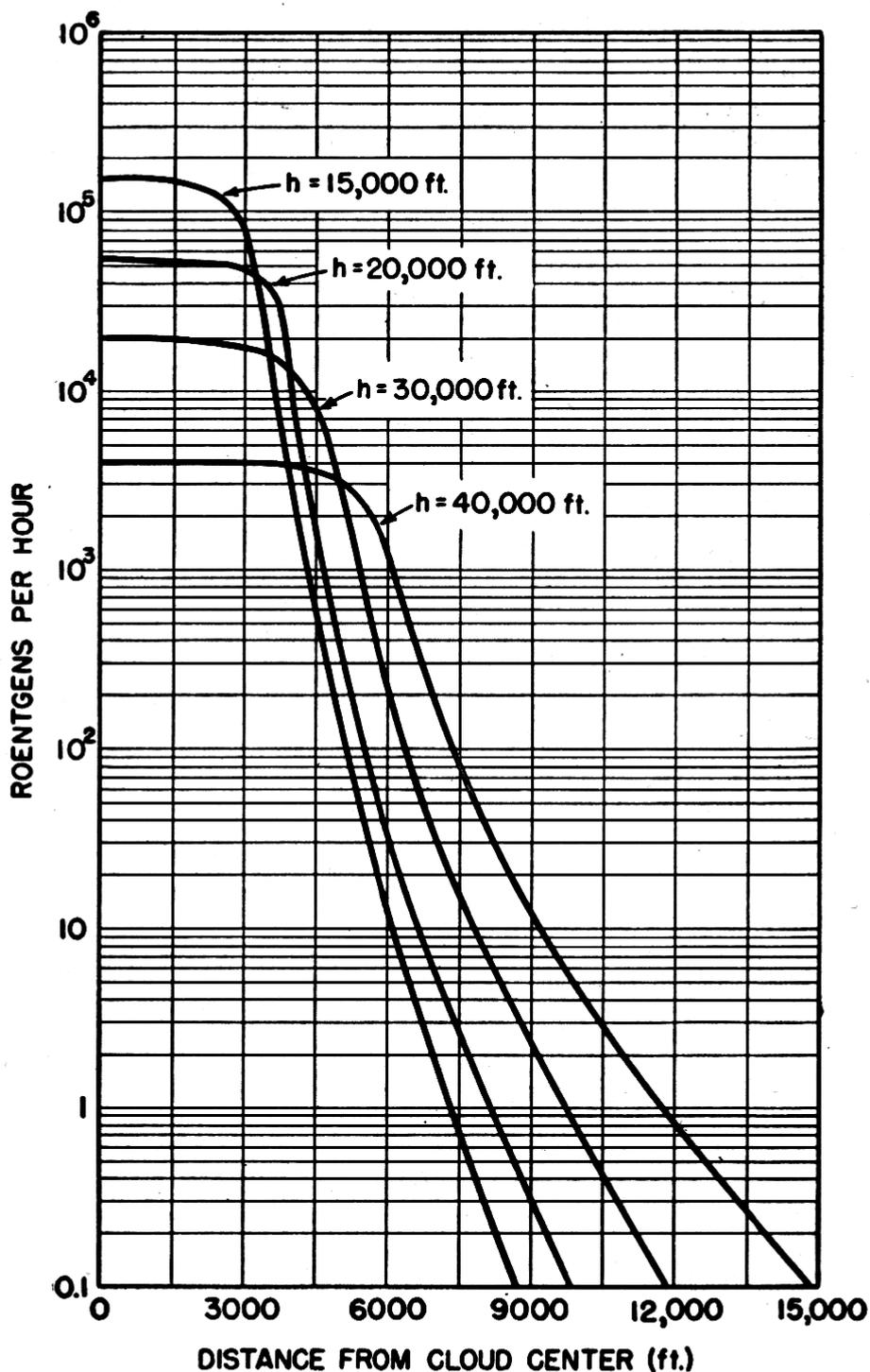Figure 8.83.   Dosage rates in atomic cloud as function of distance from center at various heights.

## BASE SURGE AND FALL-OUT

8.86   The phenomena, such as the formation of the plume, the base surge, and the mushroom (or cauliflower) shaped cloud, associated with an underwater atomic explosion were described in Chapters II and IV.   The present discussion will be restricted, therefore, essen-

tially to the radioactive contamination which can result from these effects. Partly because of the great weight of the water carried up in the plume, and partly because of the lower temperatures, the cloud does not ascend to such heights as in the case of an air burst. As a result, the fall-out, which is now in effect a radioactive rain, will commence to descend very soon after the explosion. At Bikini, for example, the first fall-out reached the surface of the sea at about a minute after the detonation. Consequently, instead of being dispersed, as it is for an air burst, a large proportion of the fission-product activity, aside from that remaining in the body of water, is precipitated in a short time within a radius of a few thousand yards of the point of detonation.

8.87  In the Bikini "Baker" test the base surge, consisting of a contaminated cloud or mist of small water droplets, which formed 10 to 12 seconds after the explosion and then moved rapidly outward, undoubtedly added markedly to the radioactivity deposited on ships in the lagoon. It is doubtful if any complete explanation of the base surge has yet been given, and, although several theories have been proposed, the subject is still a matter for controversy. One of the difficulties is, of course, that the phenomenon has been observed on one occasion only, and experimental tests of the various theories cannot be easily made. Although the development of the base surge into a cloud mass in the later stages may depend on the meteorological conditions, as indicated in § 4.80 et seq., it is probable that the initial formation and its rapid outward movement are determined solely by the nature of the underwater burst.

8.88  There has been some discussion, too, of the influence of the depth of the water in which the explosion occurs, and it appears possible that relatively deep water, or water and mud, would be necessary to produce a base surge. However, there is no certainty regarding this matter, and so until there is definite proof, one way or another, it must be assumed that an underwater burst of an atomic bomb will result in the formation of the radioactively contaminated mist called the base surge.

8.89  The base surge consists of a cloud of water droplets of various sizes, moving outward with high speed from the point of the explosion. As the base surge passes over an area, the latter receives a particular radiation dosage for the short interval of time while the cloud is in transit. In addition, a certain amount of radioactive rain will fall from the base surge during this period, leading to deposition of contamination; however, this contributes a relatively small proportion of the total dosage.

8.90    Apart from the effect of the base surge, radioactive contamination will result from the rain produced by the fall-out.   There has been some difference of opinion concerning the relative contributions of the base surge and the fall-out to the total radiation dosage.   The question is of practical significance, since some protection of personnel from ordinary rainfall, as from the fall-out, is possible in the open. But since the base surge is a cloud which moves laterally, protection from its radiation is not so simple.   There is no doubt that at Bikini, the base surge was very significant, and it appears that, in general, both base surge and fall-out will contribute to the radiation dosage, the relative amounts depending on the depth of burst, depth of water, and other conditions.

8.91    From measurements made at the time of the Bikini "Baker" test, it has been possible to draw some general conclusions with regard to the integrated or total radiation dosage received at various distances from surface zero.   Actually, about 90 percent of this dosage was attained within 30 minutes of the explosion.   The results are represented in the form of radiation dosage contours in Figs. 8.91a,
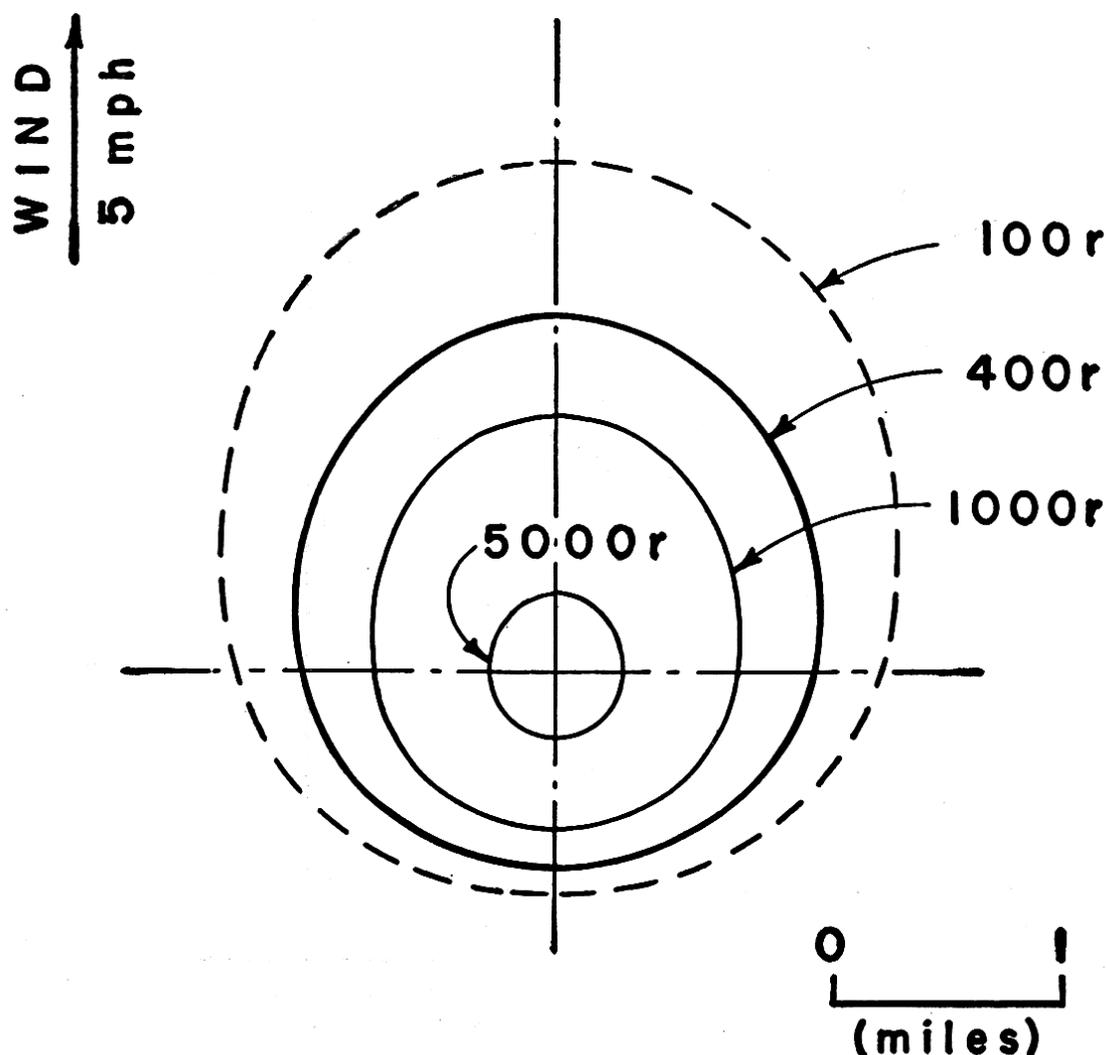


Figure 8.91a.   Contours for various integrated radiation dosages due to base surge from underwater burst.

b, and c.   The dosage due to the base surge mist as it passes over and through an area is shown in Fig. 8.91a.   The distortion from symmetry is due to the fact that a wind of about 5 miles per hour was blowing at and near the surface of the lagoon at the time of the detonation.   This results, of course, in the radioactive contamination extending much further downwind than in the upwind direction.[19]
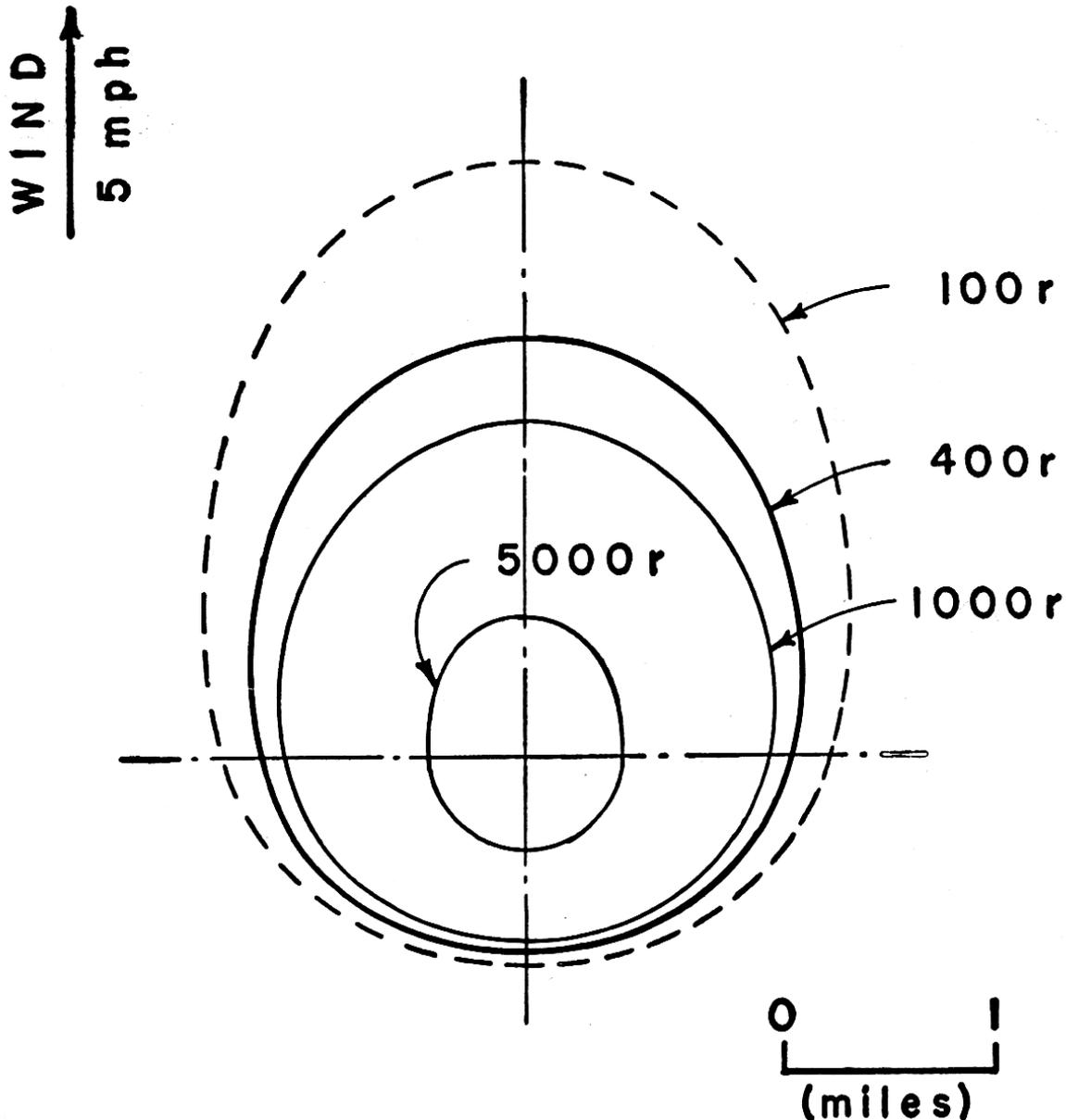


Figure 8.91b.   Contours for various integrated radiation dosages due to contamination from underwater burst.

8.92   The integrated dosage contours resulting from contamination due to rain from both the base surge and the fall-out from the atomic cloud, are given in Fig. 8.91b, while Fig. 8.91c indicates the contours for total dosage, i. e., the sum of the base surge and contamination dosages.   It is probable that the data in Fig. 8.91b, and hence also in Fig. 8.91c, represent an underestimate, because a proportion of the contaminated water falling as rain ran off the decks of

[19] For the effect of wind on the area, etc., of the base surge, see § 4.79.

the ships and back into the lagoon, so that its activity was not included in the measured dosage.

8.93 It may be mentioned that the radioactive mist of the base surge is most hazardous within the first few minutes of its formation.
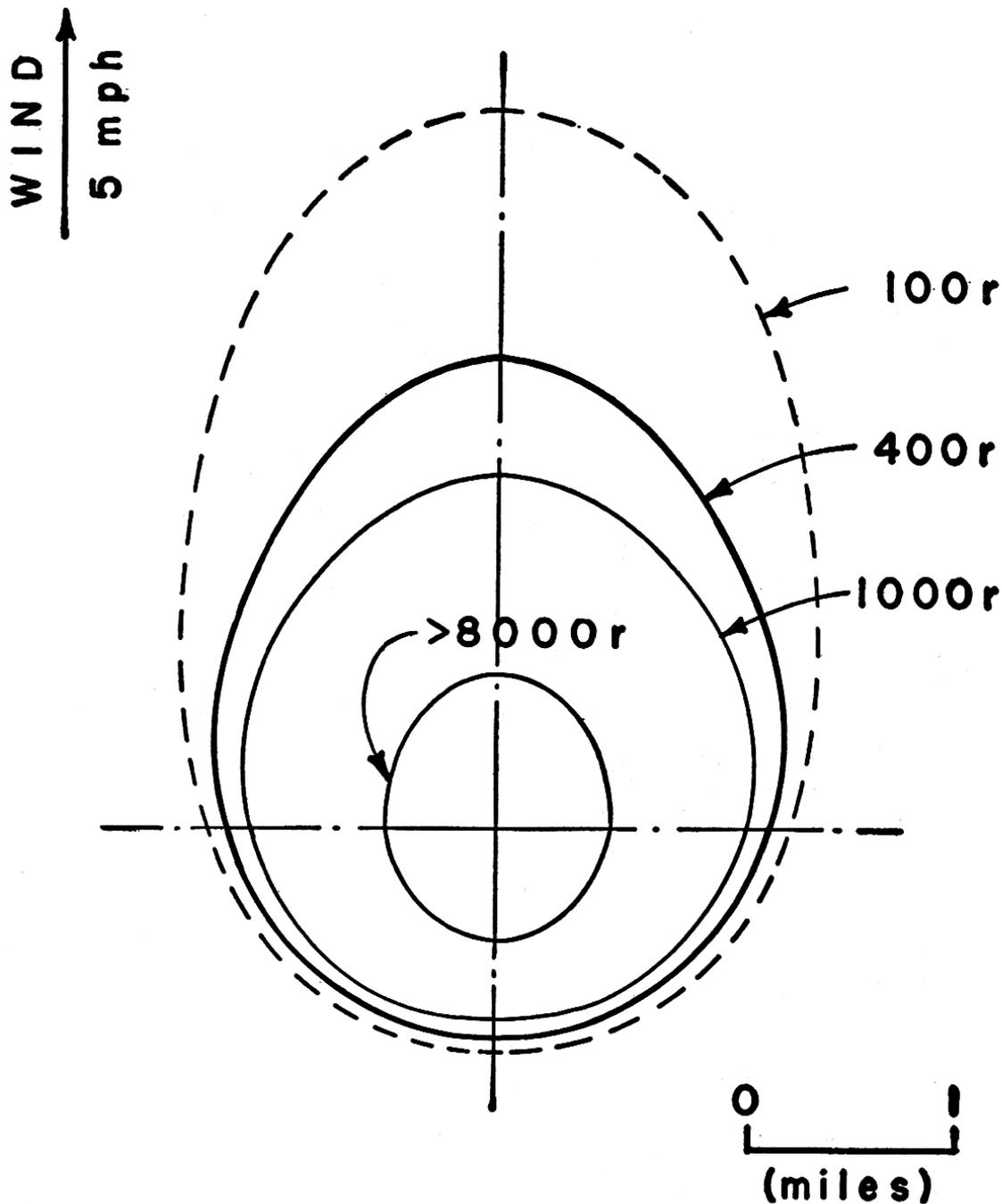


Figure 8.91c. Contours for total dosage due to base surge and contamination from underwater burst.

Its activity decreases rapidly in the course of a short time due to the operation of three factors, namely, dilution by increase of volume as a result of mixing with air, raining out of the active material as the droplets increase in size, and natural radioactive decay. Calculations which probably give a correct order of magnitude, at least, indicate that the dosage rate within the base surge decreases by a factor of about 400 in the interval between 1 and 4 minutes after the

underwater burst. This rapid decrease indicates the advantage of protection from the base surge mist during the 3 or 4 minutes immediately following an atomic explosion. At Bikini, contamination of the interior of the ships, due to the base surge, was minimized by closing down the hatches and stopping the ventilating systems. Attention to this point, especially in the early stages, would obviously prove well worth while.

### RADIOACTIVITY OF WATER

8.94 It was recorded earlier that in an underwater burst of an atomic bomb most of the radioactivity of the fission products ultimately appears in the water. Because of the large volume in which these substances are dispersed, the activity in the water is not as high as might be feared, except close to the explosion center and within a short time of the burst. As a result of diffusion of the active material, mixing with water from outside the contaminated area, and natural decay of the radioactivity, the dosage decreases with fair rapidity in a short time. In Table 8.94 are given the area and mean

TABLE 8.94

DIMENSIONS AND MAXIMUM DOSAGE RATE OF CONTAMINATED WATER IN BIKINI LAGOON

| Time after explosion (hours) | Contaminated area (square miles) | Mean diameter (miles) | Maximum dosage rate (r per day) |
|---|---|---|---|
| 4 | 16. 6 | 4. 6 | 75 |
| 38 | 18. 4 | 4. 8 | 10 |
| 62 | 48. 6 | 7. 9 | 5 |
| 86 | 61. 8 | 8. 9 | 1 |
| 100 | 70. 6 | 9. 5 | . 6 |
| 130 | 107 | 11. 7 | . 2 |
| 200 | 160 | 14. 3 | . 01 |

diameter of the contaminated portion of the lagoon after the Bikini "Baker" test, together with maximum observed dosage rates at various times after the burst.

8.95. It is evident that, although a ship would not wish to remain in the contaminated area for any length of time soon after the explosion, passage across the water would not be a great hazard. It is to be understood, of course, that condensers and evaporators would have to be closed down while the ship is in contaminated waters. Further, because of the decrease in activity with time, it seems unlikely that an underwater burst of an atomic bomb would prevent operation of a harbor for any length of time, at least as far as contamination of the water is concerned. However, it should be borne in mind that the

results in Table 8.94, although probably fairly representative, would be affected by the geophysical conditions of the harbor.

8.96   Another factor which contributed to the loss in activity of the water at Bikini was settling of the fission products to the bottom of the lagoon.   To judge from samples of bottom material collected 7 and 16 days after the explosion, a considerable proportion of the active material must have been ultimately removed in this manner. The results indicate that the major deposition had occurred within a week and that it covered an area of over 60 square miles.   On the assumption that the fission products had penetrated to a depth of 1 foot, it can be estimated that the total mass of the bottom material, in which the radioactivity was distributed, was about $1.4 \times 10^8$ tons. Consequently, even though the total initial activity of the fission products was high, about $2 \times 10^6$ curies measured a week after the explosion, its wide distribution at the bottom of the lagoon would mean that it did not represent a great hazard to marine life.   Observations made several months after the explosion indicated, too, that there was no tendency for the contaminated material to spread.

8.97   It is of interest in this connection to calculate the amount of radiation due to the radioactive isotope of potassium, mass number 40, in sea water.   This isotope is present to the extent of 0.012 per cent in all forms of potassium, regardless of its source.   It emits a beta particle, with a maximum energy of 1.3 Mev, and a gamma photon of 1.5-Mev energy.   Because of its long half life, about $1.5 \times 10^9$ years, the activity is normally of little significance, although it makes an appreciable contribution to the total background radioactivity of the body (§ 8.49).   Since sea water contains 0.4 gram of potassium per liter, the total weight of radiopotassium 40 in the Bikini lagoon is estimated to be $1.4 \times 10^9$ grams or $2.1 \times 10^{31}$ atoms.   From the known half life it can be calculated that there will be a total of about $4 \times 10^{14}$ disintegrations per second, which is equivalent to $10^4$ curies of activity due to the potassium 40 alone.   In other words, the normal background activity of Bikini lagoon, before the atomic bomb explosion, was at least $10^4$ curies.   This is not very different from the fission product activity collected at the bottom about 18 months after the detonation.

8.98.   There is a possibility that after an underwater burst of an atomic bomb, the radioactivity might be spread over a large area due to the action of marine life.   It is well known that land plants absorb and so concentrate mineral elements from the soil and that these are further concentrated in animals feeding on the plants. Similar circumstances arise in water environments; the simple plants, i. e.,

phytoplankton and algae, absorb the nutritive salts from the water, and they are then accumulated in the larger aquatic forms, e. g., fish, which directly or indirectly consume the simple plants.

8.99 In water containing radioactive materials, the latter are concentrated by the fish in the same manner and for the same length of time as are the stable forms of the corresponding elements. If the fish die, the radioactive isotopes are not lost, but they return to the water, as do the stable isotopes, to take part once again in the life cycle. Because of the landlocked nature of the Bikini lagoon, there is evidently little or no outward migration of the larger aquatic organisms so that, as mentioned above, there is no appreciable tendency for the radioactivity to spread. However, due to the behavior of the anadromous migratory fishes, e. g., salmon, shad, etc., which feed in the sea and then migrate upstream to die, or of birds that concentrate the minerals of the sea in guano, there might be some distribution of radioactivity in other cases following an underwater atomic explosion. The extent of such dispersion and its effects would depend greatly on circumstances and appears difficult to estimate.

### RADIOACTIVE CONTAMINATION OF LAND AREAS

8.100 The underwater burst at Bikini took place far enough from shore to prevent any appreciable contamination of land areas. Some radioactive rain fell at large distances from the explosion center (§ 2.36), but the activity was not serious. The possibility must be considered, however, of an underwater atomic explosion so near to the shore that significant amounts of the fall-out and the base surge will reach the adjacent land areas, and possibly affect dock facilities, warehouses, etc. As indicated earlier, because some of the radioactively contaminated water ran off the ships at Bikini, the values in Figs. 8.91b and 8.91c may represent an underestimate if applied to the shore. However, there may be compensating factors in the deposition of active material on the roofs or protruding portions of buildings, and also because of the shielding effects of various structures.

8.101 A rough attempt to assess the contamination, in terms of radiation dosage rates, of adjacent land areas from the underwater burst of a nominal atomic bomb, at 1 hour after the explosion is made in Fig. 8.101. The results are based on the assumption that the activity is due to fission products with a mean gamma-ray energy of 0.7 Mev (§ 8.11). Four contour lines are shown, representing radiation dosage rates of 400, 50, 10, and almost zero roentgens per hour, respectively. In the region outside the last contour line, the danger

due to radioactivity may, in general, although probably not always, be ignored.   It should be noted that the results are based on the assump-
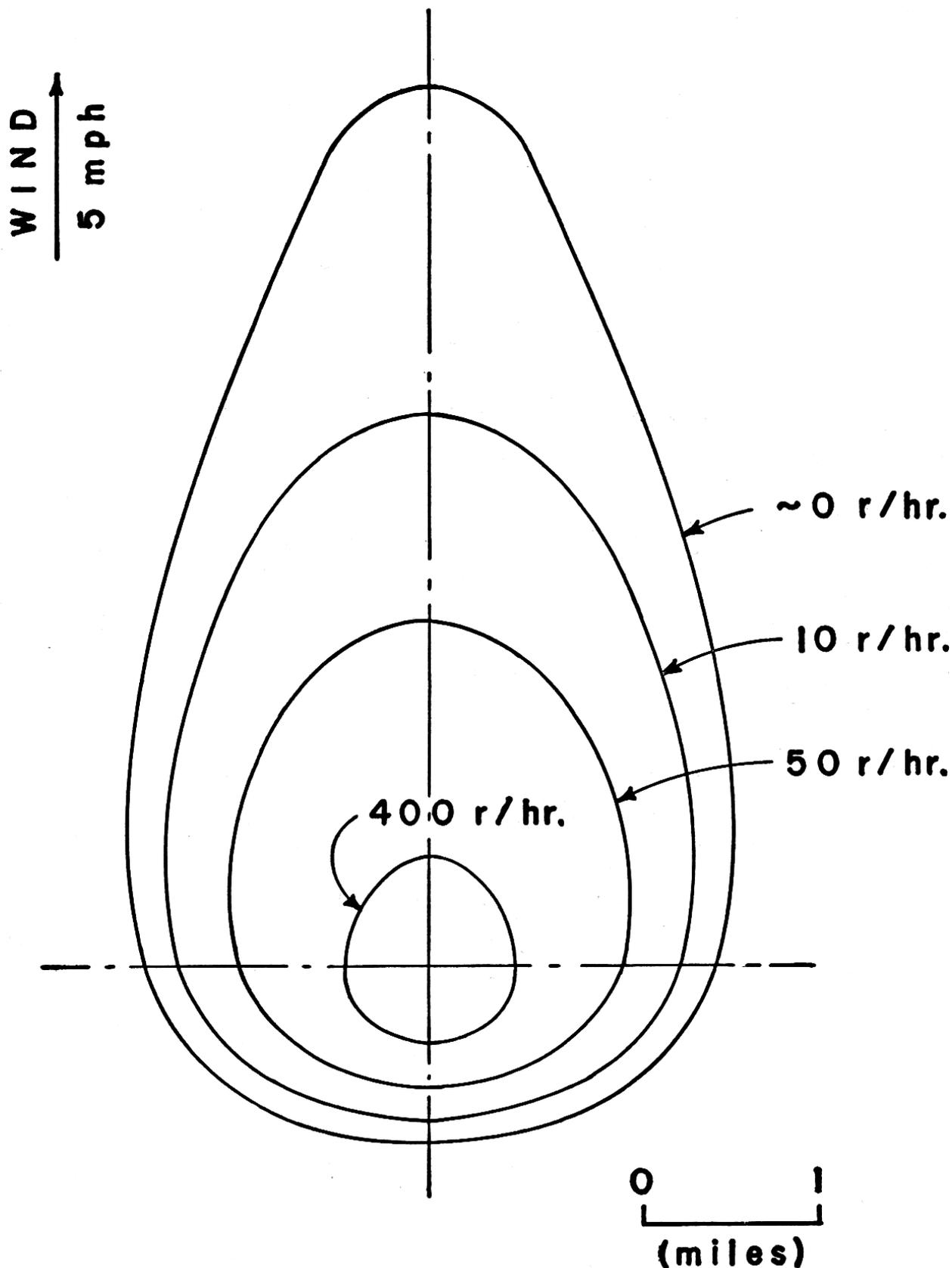


Figure 8.101.   Radiation dosage rate contours at 1 hour after explosion due to fission products from underwater burst.

tion that a 5-mile-per-hour wind is blowing, as was the case at Bikini. A difference in the wind velocity or a change in the direction or velocity within a short time after the explosion would, of course, alter the picture appreciably.

8.102 By combining the results of Fig. 8.101 with those in Figs. 8.16 and 8.17, some information can be obtained concerning the dosage rates and total dosage absorbed at various times after the explosion. The general method is the same as that indicated in § 8.18.

## E. RADIATION CONTAMINATION FROM UNDERGROUND BURST

8.103 Although there are no data available for the effects of an underground burst of an atomic bomb, it is possible to make some qualitative statements concerning the extent of radioactive contamination. The latter will depend markedly on the depth at which the bomb is exploded, for this will determine the proportion of the fission products that will be trapped and the extent to which they will be mixed with dislodged dirt. The formation of a crater and the amount of debris thrown into the air are factors which will influence the extent of radioactive contamination in the immediate vicinity of the explosion and at a distance. In a fairly shallow underground explosion, where the underlying material is a thick bed of sand or mud, but not rock, a phenomenon similar to a base surge might be possible. It would presumably consist of very fine particles of dirt contaminated with fission products.

8.104 Extrapolation of results obtained in studies with ordinary high-explosive bombs [20] indicates that if a nominal atomic bomb was exploded at a depth of 50 feet, the diameter of the crater would be about 800 feet, and its depth 100 feet. The volume of such a crater would be $10^6$ cubic yards, and its mass over half a million tons. If the fission product activity of the bomb uniformly contaminated the dirt from this crater, the activity an hour after the explosion would be about $6 \times 10^3$ curies per cubic yard. Probably a large part of this contaminated dirt would fall in the neighborhood of the crater and would constitute a serious hazard.

8.105 The crater itself would probably also be heavily contaminated, and supposing one-sixth of the activity of the fission products remained in the crater, the contamination density at 1 hour after the explosion would be 50,000 megacuries per square mile. Assuming a mean gamma-ray energy of 0.7 Mev, the dosage rate would be $5 \times 10^5$ r per hour at a point about 3 feet above the ground. Radiation intensities of this order of magnitude would not only make the crater area uninhabitable for a long time, but it would not be passable, to any degree of safety, even in a fast vehicle. The foregoing calculations do

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[20] Appendix B.

not take into account activity induced by neutrons in the elements, notably silicon and sodium, present in the earth. These would undoubtedly make a substantial contribution to the radioactivity in the region of the crater.

8.106 The general consensus at the present time is that the area highly contaminated by an underground explosion would be less than in the case of an underwater burst. One reason is that the density of soil is greater than that of water and so a smaller mass would be thrown into the air to descend at a distance from the explosion. However, although the area covered may be less, the radiation intensity might be correspondingly greater at small distances from the bomb burst.

## F.  RADIOLOGICAL WARFARE

### SOURCES OF RADIATION

8.107 An extreme case of contamination by radioactive isotopes would arise if such substances were used deliberately as an offensive weapon. This possibility is generally referred to as *radiological warfare*, the term being used to describe the employment for military purposes of radioactive material with the object of contaminating persons, objects, or areas. The atomic bomb may be described as an indirect weapon of radiological warfare, for its main purpose is to cause physical destruction, the radioactive contamination being a secondary consideration. It is of interest to examine various aspects of the use of radioactivity as a weapon, apart from its occurrence as a result of fission in an atomic bomb.

8.108 Radioactive materials can be obtained in quantity in two ways. First, fission products are always formed in the nuclear reactors (or "piles") used for the production of plutonium for atomic bombs (§ 1.47) or for power. Considerable quantities of radioactive material could thus conceivably become available as a by-product of the manufacture of atomic bombs. The complex mixture of fission products could be used directly, or certain constituents might be extracted by chemical means.

8.109 Second, the irradiation of many stable elements by the intense neutron flux of a nuclear reactor leads to the formation of radioactive isotopes, as a result of radiative capture reactions (§ 1.25). It appears that for the same power level of a nuclear reactor, it is possible to produce larger quantities of radioactive material, in terms of activity, by neutron capture than by fission. In the latter case, the product is a complex mixture with varying rates of decay, but in

the former case, a particular isotope, chosen as being suitable as a radiological warfare agent, could be made, if desired. However, it must be borne in mind that the formation of radioisotopes in a nuclear reactor, as a result of neutron capture, means that an equivalent amount of fissionable material, which can be used in a bomb, will be sacrificed.

8.110   It should be pointed out that, in any event, it would not be easy to produce large amounts of radioactive isotopes for radiological warfare. Under favorable conditions, a nuclear reactor operating for 100 days with a power output of a million watts would produce something of the order of a megacurie of activity. If this were spread out uniformly over a plane surface having an area of 1 square mile, the dosage rate 3 feet above the surface would be only 200 r per day for a 1.5-Mev gamma ray (Fig. 8.33). This rate would, of course, fall off with time, depending on the half life of the contaminating material.

8.111   As already seen, four types of nuclear radiation, namely, neutrons, alpha particles, beta particles, and gamma rays, produce harmful physiological effects. Apart from the atomic bomb, there does not appear to be any practical way of delivering and dispersing strong sources of neutrons, and so these need not be considered as possible radiological warfare agents. Because of their short range, alpha and beta particles would have little effect outside the body, but certain alpha and beta emitters when ingested can be lethal in relatively small quantities. A very high concentration of alpha-active or beta-active material would have to be placed over an area to insure that sufficient amounts entered the bodies of the inhabitants. Protection would be similar to that adopted against chemical warfare agents, and it seems unlikely that this form of radiological warfare would be worth while.

8.112   The caustic effect of beta-emitters on the skin (§ 11.78) might represent an important hazard, but this alone would hardly warrant employment of a pure beta-active substance as an offensive weapon. Nevertheless, it would represent an additional source of injury when a gamma-emitter is used.

8.113   On the whole it may be concluded that if radiological warfare is used as a weapon, it will be in the form of emitters of penetrating gamma radiation for which protective clothing and gas masks would be ineffective. With such substances it would be easier, than in the other cases, to achieve a level of radiation that would be lethal as the result of an appreciable exposure. However, it would appear to be a difficult matter to lay down such a concentration of gamma emitters over a large area as would cause serious injury from a short exposure.

## POSSIBLE ADVANTAGES OF RADIOLOGICAL WARFARE

8.114   Since the physiological consequences of nuclear radiations are not apparent for some time after absorption, radiological warfare could be used to prevent the occupation of a particular area without causing immediate casualties and destruction.   Contamination of a city, for example, might perhaps deny its use for habitation and close down its industries without causing the tremendous havoc produced by explosive and incendiary bombs.   It is doubtful, however, apart from exceptionally highly contaminated areas, if such denial would be completely effective.   By rotating the personnel, so that no individual received an excessive dose of radiation, the facilities of the city might be maintained, if on a reduced scale.   In any event, the natural decay of the radioactivity means that the hazard would decrease with time, unless additional material was deposited at the same place.

8.115   Another aspect of radiological warfare which might be turned to advantage is its compactness.   A few pounds of certain radioisotopes could produce millions of megacuries of activity.   An example is provided by the fission products of an atomic bomb; here the initial activity of about two pounds of material is about a million megacuries. If this material could be spread uniformly over a limited area, it would cause serious harm.   However, as may be seen from Table 8.10, the activity falls off rapidly with time, decreasing by a factor of nearly 10,000 by the end of the first day.

8.116   Perhaps the most important application of radiological warfare would be its psychological effect as a mystery weapon, analogous to the initial use of poison gas and of tanks in World War I. The obvious method to combat radiological warfare in this case is to understand and be prepared for it.   Although nuclear radiations cannot be directly detected by the senses, there are available instruments which are very sensitive to such radiations (see Chapter IX).   By the use of suitable devices their presence can be made apparent to the eyes and ears.   It would then be necessary to take appropriate steps to evacuate the contaminated area, as described in Chapter XII.

## DISADVANTAGES OF RADIOLOGICAL WARFARE

8.117   The natural decay of radioactive material means that the contamination hazard is one which diminishes with time.   This fact represents a disadvantage of radiological warfare in another sense: it is not possible to build up a stockpile of material for subsequent use,

as can be done with other weapons, for there is a continuous loss of activity. Consequently, the active substances must be manufactured continuously in order to maintain the stockpile even when the weapon is not being used.

8.118 It might be thought that the difficulty of decay could be overcome by using radioisotopes of long life, but this is not very practical because the activity in curies of a given mass of radioisotope is inversely proportional to its half life, and to its atomic weight. Relatively large quantities of material would have to be used, and it would be more difficult to achieve a high level of activity at any point on the ground. Of course, if a radioactive isotope of long half life could be used to produce considerable activity, it would mean that the area would remain contaminated for a longer time.

8.119 If gamma-ray emitters were to be used as radiological warfare agents, and these seem to be the only ones likely to be effective, the problem would arise of shielding personnel from the radiations during manufacture, storage, and delivery of the weapon. The use of adequate shields, presumably of concrete, iron, or lead, would add greatly to the weight of the munition and would complicate the mechanism of dissemination on the target. The uniform distribution of a relatively small amount of material over a large area would itself present a difficult problem, the solution of which might nullify the advantage of compactness.

8.120 Because its physiological effects would be delayed, radiological warfare could not be used as a tactical weapon, in the military sense of the term. Operations could be continued in the contaminated area, if the occupying force was either willing to accept the risk of probable future losses, or if there were periodic replacement of personnel to avoid overexposure.

8.121 While it is impossible to predict, as in the case of chemical warfare, whether radiological warfare will be used or not, it is necessary to understand and be prepared for it. Only in the event of being unprepared are the consequences likely to be as serious as the destruction caused by an atomic bomb.

# CHAPTER X

# DECONTAMINATION [1]

## A. INTRODUCTION

### TREATMENT OF CONTAMINATED MATERIAL

10.1   It was seen in Chapter VIII that radioactive contamination may be caused by the fission products formed in the detonation of an atomic bomb, by neutron-induced activity in soil and water, and by the deliberate use of specific radioisotopes, apart from their association with the bomb, as radiological warfare agents.   These sources would be largely responsible for external contamination.   In addition, there is the possibility that plutonium which has escaped fission may act as a contaminant representing an internal hazard.   It is now necessary to examine the problem of dealing with various objects which have become contaminated, in one way or another.

10.2   There are essentially three ways whereby the hazard associated with radioactive contamination may be minimized: first, to dispose completely of the material by deep burial in the ground or at sea; second, to keep it at a distance for a sufficient time to permit the radioactivity to decay to a reasonably safe level; and third, to attempt to remove the contaminant, that is, to decontaminate the material.   These three procedures were used, in one way or another, in connection with radioactive contamination suffered by ships and their equipment after the Bikini "Baker" test.

10.3   The particular method that is adopted in any case will depend on circumstances.   Large structures could not easily be disposed of, and decontamination could be attempted after the activity had decayed to some extent.   With smaller structures, decontamination might prove too costly if the activity is high, so that burial is the most economical plan.   If the radioactive contamination were not too great, however, decontamination could be attempted almost immediately.   On the other hand, in certain instances, it might prove more advantageous simply to set the article aside for the activity to decay.

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[1] Material contributed by E. S. Gilfillan, S. Glasstone, C. R. Schwob, W. E. Strope, W. H Sullivan.

10.4   At Bikini the U. S. S. *Independence,* a small aircraft carrier, received such a large radiation dosage that had there been any personnel on the hangar deck at the time they would have succumbed from external radiation, apart from the effects of blast.   Yet 2 weeks after the detonation the dosage rate was about 3 r per day, permitting short time access.   About a year later, the average dosage rate was only 0.3 r per day, and 3 years after the original contamination the *Independence* was in use at the San Francisco Naval Shipyard, where she housed the experimental engineering group of the Naval Radiological Defense Laboratory.   It was difficult at that time to find any areas on the ship where the radiation dosage would have exceeded the limit of 0.3 r per week adopted in installations of the Atomic Energy Commission (§ 8.4).

10.5   It should be noted that no decontamination of the *Independence* was attempted, primarily because the vessel was in a battered condition (see Fig. 5.79a), and it seemed unlikely that she could be returned to service as an aircraft carrier.   However, some of the other vessels at Bikini were decontaminated and reclaimed much sooner. Two submarines, thus decontaminated (Fig. 10.5), were used soon afterward in the Naval Reserve, with no risk to the operating personnel. Most of the other target vessels were destroyed, not because decontamination was not feasible, but mainly because they were damaged in other ways and decontamination would not have been economical.

10.6   Except where radioactive solutions, such as were present after the underwater burst at Bikini, soak into porous materials, like rope, textiles, unpainted or unvarnished wood, etc., or where neutrons have penetrated and induced activity to some depth, the decontamination will be largely restricted to the surfaces of materials, objects, and structures.   An outstanding exception would, of course, be the radioactive contamination of water supplies for drinking purposes.   The problem of decontamination is thus, to a considerable degree, a problem of removing sufficient of the surface material to reduce the activity to the extent that it is no longer a hazard.   The methods of surface removal may be divided into two main categories, namely, chemical and physical.   In the first case, the contamination is eliminated by making use of chemical reagents which, if sufficiently mild, will have a minor effect on the underlying material.   But in the second case, an appreciable thickness of the actual surface is removed.

10.7   It should be understood that the activity of a particular radioisotope is not changed in any way by chemical reaction.   All the latter can do is to convert the active isotope into a soluble compound, so that it can be detached and washed off as a solution.   Cer-

tain processes of decontamination, involving the use of detergents, represent a category intermediate between chemical and physical.



Figure 10.5.    Submarine U. S. S. *Skate*, damaged and radioactive after the Bikini "Able" explosion.

## B.    NATURE OF RADIOACTIVE CONTAMINATION

### IDENTIFICATION OF CONTAMINANTS

10.8    In order to devise suitable chemical decontamination procedures, it is necessary to know something of the nature of the radioactive material responsible for the contamination.    The composition of the fission products at various times after the atomic explosion is fairly well known, as will be seen below.    Consequently, if it is certain that the contamination is due to fission products, then appropriate chemical methods of treatment could be developed.    A

TABLE 10.15

MOST RADIOACTIVE CONSTITUENTS OF PRODUCTS AT VARIOUS TIMES AFTER FISSION

| 1 hour | 1 day | 1 week | 1 month | 6 months–1 year |
|--------|-------|--------|---------|-----------------|
| Rare Earths* | Rare Earths | Rare Earths | Rare Earths | Rare Earths |
| Tellurium | Iodine | Iodine | Barium | Columbium |
| Barium | Zirconium | Tellurium | Zirconium | Zirconium |
| Iodine | Columbium | Barium | Strontium | Strontium |
| Rubidium | Xenon | Molybdenum | Ruthenium | Ruthenium |
| Krypton | Strontium | Xenon | Rhodium | Rhodium |
| Strontium | Molybdenum | Zirconium | Columbium | Barium |
| Xenon | Tellurium | Strontium | Iodine | |
| Molybdenum | Rhodium | Ruthenium | Xenon | |

* Because of its chemical similarity, yttrium has been included with the rare-earth elements in every case.

Because of their similarity in chemical properties, the rare-earth elements and yttrium have been grouped together. The various elements are arranged in order of their decreasing contribution to the total activity.

10.16  It is an interesting and important fact that from an hour to a year, and probably longer, after fission has taken place, at least 30 percent of the fission-product activity is due to radioisotopes of the rare-earth elements and yttrium. The removal of these elements alone would thus reduce the degree of contamination by about a third or more. This has been achieved by the use of various substances which form soluble complex ions with the rare-earth elements (cf. § 10.51).

10.17  Any substance capable of forming complex ions in this manner is frequently referred to as a *complexing agent*. While salts of citric acid and other organic acids are perhaps the most important such agents in general use for decontamination purposes, it is possible that a concentrated solution of a chloride might prove to be a complexing agent for ruthenium and rhodium, and perhaps for some other important fission products.

10.18  Since one of the objects of decontamination is to prevent internal absorption of radioactive materials, brief mention may be made here of the hazards due to the ingestion of certain fission products. The subject will, however, be considered more fully in Chapter XI. Some elements, particularly iodine, strontium, barium, zirconium, and cerium, are strongly held in the body so that their consequences, when absorbed as radioisotopes, may be more serious

removal of the film will facilitate the action of the various agents used for more thorough decontamination.

10.34. In every attempt at decontamination, preliminary or final, the safety of personnel is an essential consideration. The immediate emergency measures must consequently be delayed, as stated above, until the activity has decayed sufficiently to permit operation without excessive risk. Those directly employed in the decontaminating work should wear suitable protective clothing, of rubber if necessary, and should be provided with rubber boots and gloves. If spray or dust is produced in the operation goggles, and masks must be worn (cf. § 12.79 *et seq.*).

10.35 Shielding, whether by distance, terrain, walls, structures, etc., must be used as advantageously as possible. For example, the decontamination of a building or a ship should be started from a suitable position in the interior, where the activity will probably be less than on the outside. In this connection it is recommended that installations of strategic importance, in a situation where contamination is a possibility, should be provided with hosing down equipment controllable from the interior.

10.36 It is not possible to give a general rule concerning the areas from which decontamination should be initiated. In some cases it would be advantageous to start in a region where the activity is low, for this will not only make the operation less hazardous but will allow time for decay of the more highly contaminated portions. On the other hand, in certain circumstances, it might be advisable first to carry out a quick, even if preliminary, decontamination of an area of high contamination in order to permit freedom of movement.

## SURFACE REMOVAL

10.37 The problems of thorough decontamination are so involved and so novel that a great deal of work will be necessary before the most effective procedures are developed. The information given here, based on limited experience, is the best available at the present time. But improved methods for the treatment of materials, structures, etc., which have become contaminated with radioactivity, will undoubtedly be developed in due course. At present, although certain general principles are apparent, it seems impossible to make predictions concerning the efficiency of a particular decontamination procedure in any given circumstances. It would be necessary, therefore, in actual practice, to use a succession of methods until the desired degree of decontamination is achieved.

10.38   For nonabsorptive substances, removal of the entire surface of the material is an obvious means of securing decontamination. While it cannot be applied to all surfaces, it is highly successful whenever it is feasible, except perhaps where capture of neutrons has induced activity at some distance below the surface.  In this, as in all decontamination procedures, it is necessary to exercise rigid control over the radioactive residues.  They must not be allowed to recontaminate newly exposed or adjacent surfaces, nor must they be permitted to become an inhalation or ingestion hazard in the form of dust.  During an operation, these requirements can be met by wetting down the surfaces with water or with solutions of certain chemicals which dissolve the solid particles, as mentioned below.

10.39   Physical methods of surface removal are often difficult because they involve much labor and sometimes special equipment. Methods employing abrasion are perhaps the most effective; wet sandblasting, for example, was used successfully in decontaminating large areas of the Bikini target vessels (Fig. 10.39).  The techniques



Figure 10.39.   Wet sandblasting for removal of radioactive contamination. (Note protective clothing worn by the operator.)

involved here are a part of normal ship maintenance, and the equipment and trained personnel are generally available at military and industrial establishments. The wet sandblasting method can also be employed for the decontamination of unprotected concrete. This procedure leaves large volumes of sand and water, containing the active material, and although their disposal may present a problem, the fact that the contaminant is thereby considerably diluted is some compensation.

10.40   Abrasives less radical than sand, and which effect removal of only a thin surface layer, have also been used. Soft materials like sawdust and other substances of a similar nature, have been suggested for the decontamination of delicate articles, such as instruments or bearing surfaces, that would be injured by sand. Similarly, scrubbing may be used for the removal of a thin outer layer. Steel wool, wire brushes, floor polishers, or various buffing or polishing machines, can be adapted to decontamination by surface removal in various circumstances.

10.41   Chemical means can also be applied to remove the surface, and with it the contaminating radioactivity. The action is rapid and certain, and in some instances it is the only practical method. The use of highly corrosive or other dangerous chemicals, although they might be effective, should be avoided if possible. The substances employed must be capable of being stored without danger, available in large quantities, and preferably of small bulk. Because of these requirements, primary consideration must be given to the use of aqueous solutions. Organic solvents are usually inflammable or toxic, or both, but most water-soluble chemicals can be stored easily, and dissolved quickly when desired. The heat evolved when some materials, such as caustic soda, are dissolved is often advantageous in that it hastens chemical action. Further, standard fire-fighting equipment, pumps, transport and mixing devices are particularly adapted to the handling of aqueous solutions.

10.42   Decontamination by chemical means usually results in the transfer of the activity to fairly large volumes of liquid, thereby presenting a disposal problem. Mere wetting of the surface by the solution of the chemical reagent is nearly as efficient as flooding for decontamination. If wetting only is used, the waste material can be confined and is controllable, but it will have a relatively high activity. On the other hand, with the flooding method the resulting solution is more dilute and the radioactivity is dispersed in a larger volume. Both procedures have advantages and disadvantages, and the particular method used must be determined by the circumstances.

10.43    Chemical methods of surface removal can be designed for each specific type of surface.  For example, alkalis have been found to be effective in removing contaminated layers of paint.  In special cases, drastic treatments using acids, caustic alkalis, and other corrosive agents have proved successful in removing surfaces, but they are liable to be destructive, since they erode and pit the base material while removing the surface.  Mild chemical means of surface removal, such as by the use of complexing agents, which will be mentioned below, have been employed in certain cases, for example, for paint containing titanium.

10.44    A combination of physical and chemical treatments is represented by live steam as a decontaminating agent, especially in conjunction with a detergent, as mentioned in § 10.33.  It has been found particularly valuable for cleaning up highly contaminated areas in laboratories and plants.  It appears to be especially efficient for painted surfaces, the action being based on the partial destruction of the paint by hydrolysis.  In addition, loose or mechanically held contamination is swept away, and the surface suffers some disintegration because of the sudden increase of temperature.  It is probable that the combination of live steam with a detergent may prove useful in decontaminating many types of surfaces and objects.

10.45    Heat by itself acts in a manner similar to live steam.  The contact of a blow-torch flame with a contaminated paint surface for a fraction of a second produces a marked reduction in activity.  This method of decontamination should not be attempted unless adequate ventilation is available for removal of the radioactive fumes.

## Removal of Lightly Held Material

10.46    In the examination of the naval vessels which had become contaminated with radioactivity at Bikini, it was observed that much of the activity was associated with dust, corroded areas, etc., which could be removed without difficulty.  In some circumstances, up to 90 percent of the radioactivity remaining on ship surfaces three years after being contaminated was removable by vacuum sweeping or brushing.

10.47    In the event of contamination due to radioactively contaminated water, following an underwater burst of an atomic bomb, water under high pressure can be used for removing loosely held contaminants (Fig. 10.47).  However, there is some evidence that radioactive dusts, such as might be produced from an underground burst or dry fall-out or might be used in radiological warfare, tend to

become attached to surfaces as a result of treatment with water or an aqueous solution. In such instances, dry physical methods, e. g., vacuum cleaning, brushing, application of adhesive, etc., are pre-
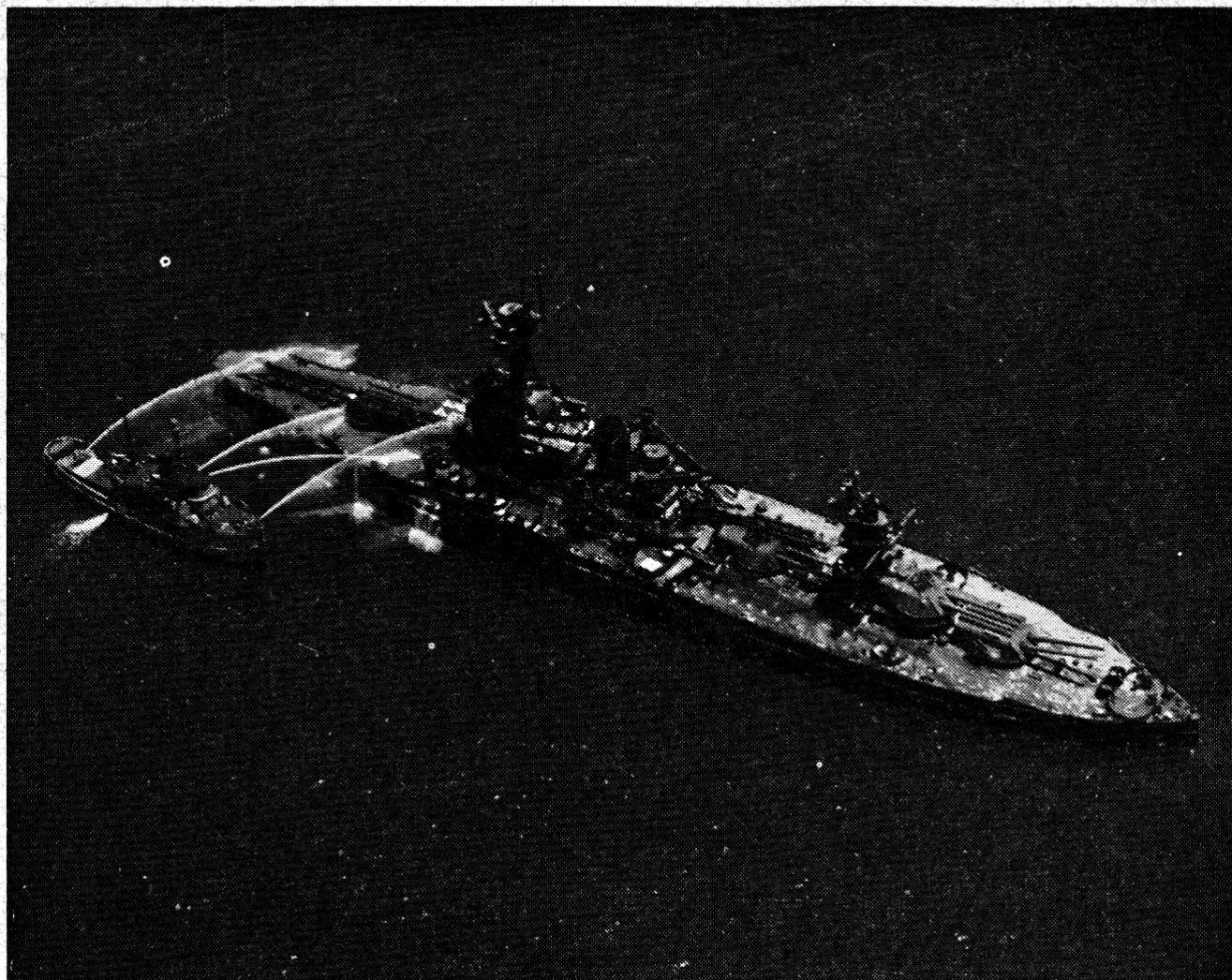


Figure 10.47.  Preliminary decontamination of U. S. S. *New York* after the "Baker" test at Bikini; the decks are being washed down with sea water by a Navy fireboat.

ferred as an initial step to prevent spread or strong attachment of the contamination.

10.48  Adhesives of various kinds have been found practical for removing loose dust and mechanically held contamination. An adhesive coating is applied to the contaminated surface, and is then stripped off; some of the radioactive material will be retained by the coating when it is removed. Sprayed strippable coatings, which can penetrate pores and crevices, are useful for decontaminating moderately rough surfaces. For smooth surfaces, adhesive tapes of different kinds have proved successful. Several types of putty have been tried, but the results have not been satisfactory.

10.49  In dealing with loosely held contamination, the obvious use of soap and water cannot be neglected. As indicated previously, not

only will soap and other detergents remove dirt, dust, grease, etc., which has become radioactively contaminated, but it is safe for most surfaces, nonhazardous, and does not call for particular experience in its application. As will be seen later, detergents and wetting agents have other valuable properties in decontamination.

### Removal of Tightly Held Materials

10.50 When the extent of decontamination resulting from the removal of lightly held radioactive material is not sufficient, further treatment will be necessary. Surface removal, as described above, may be employed, but the procedures are necessarily harsh and unsuitable for delicate equipment; further, after decontamination, the surface must frequently be renewed to provide protection against corrosion. The roughened surface is also liable to be more susceptible to subsequent contamination. The use of chemical methods can frequently avoid these disadvantages. By means of a solution of a chemical reagent, it may be possible to transfer the radioactivity to a liquid phase which is then washed off. In this connection three general principles have been employed; they are formation of soluble complexes, ion exchange, and solubilization.

10.51 Substances which have a greater affinity for the decontaminating element than for the surface, and which form water-soluble compounds with it, are suitable complexing or sequestering agents. Much research has been conducted with the object of finding compounds or ions which form complexes with the fission products and with the fissionable material constituting the atomic explosive. Sodium citrate solutions were used with some success in the clean-up operations after the Bikini tests, but other substances, such as the sodium salts of ethylenediamine-tetracetic acid, aminotriacetic acid, and pyrophosphoric acid, have been found to be more satisfactory and generally cheaper. It is of interest to mention that, contrary to theoretical expectation, strongly acidified citric acid solutions were more effective than neutral citrate in removing radioactive contamination. Apparently, the hydrochloric acid present dissolved rust and scale in which the contaminants tended to concentrate, and which were consequently difficult to decontaminate. Much research still remains to be done before a reliable complexing agent or a simple mixture of such agents can be recommended for general use.

10.52 The partial removal of radioactive ions from surfaces is rendered possible by application of the principle of chemical equilibrium. The undesirable ions of a radioisotope may exchange with ions

of nonradioactive isotopes of the same element applied in solution. The exchange will result in a decrease in the number of radioactive ions on the surface, even though the total number of ions, radioactive and stable, may actually increase. For decontamination due to fission products from an atomic explosion, this procedure would require, theoretically, 34 elements in a variety of valence forms. Some of these are prohibitively rare, while others, namely, technetium (atomic number 43) and promethium (atomic number 61), do not exist in nonradioactive forms. Possibly certain common ions of high valence, such as aluminum, iron, or cerium, may prove useful in this connection. Unfortunately, the exchange reactions are very slow, and laboratory results obtained so far have not been too encouraging.

10.53  Insoluble contaminants, such as oxides, basic salts, etc., may not furnish enough ions to permit rapid complexing or exchange action.  However, some of these will respond to the action of wetting agents and detergents.  The peptizing properties of these substances allows the particles of insoluble material to be washed away as a suspension.  The use of a detergent in any decontamination procedure is beneficial because, in addition to the so-called solubilizing effect just mentioned, it promotes more complete and rapid wetting of the surface, as well as facilitating, as noted earlier, removal of dust, dirt, etc., carrying radioactive material.

10.54  In considering the problem of decontamination, there is one fundamental point which must not be forgotten.  Decontamination procedures do not neutralize the radioactivity; they merely transfer the active material from one place to another.  Consequently, before undertaking decontamination it is necessary to arrange for the proper disposal of the material removed, to a location where it does not represent a hazard.  The method to be used must be determined by the circumstances existing at the time.

## City and Domestic Decontamination

10.55  In the event of serious radioactive contamination of a large part of a city, steps would have to be taken to make it habitable within a reasonable time.  The most important matter in this connection would appear to be the removal or coverage of loose material which might form dust that would be inhaled or ingested with food.  For paved streets flushing, perhaps with the aid of detergents, street cleaning or vacuum sweeping, if feasible, might be the first steps.  If the contaminant is on the surface or has not penetrated too deeply,

concrete, stone and brick buildings would perhaps have to be wet-sandblasted and reroofed. Painted wooden structures might be decontaminated by some of the methods given earlier in this chapter, but stucco buildings might have to be removed. The same could well apply to roofs, which would collect considerable amounts of radioactive material, but could not be easily decontaminated.

10.56   Soils have a fairly high specific surface and also have well-defined base exchange properties; as a result they will tend to concentrate radioactive material. This is fortunate, in a sense, because in the washing down of contaminated streets, buildings, etc., much of the water will be transferred to the surrounding soil, if special drainage facilities are not available. Because of the properties mentioned above, the radioactivity will remain in the uppermost few inches. The only scheme that seems to be practical for dealing with such topsoil, as well as that from parks and lawns in the contaminated city, is to remove it or to cover it with at least a foot of fresh soil. This could perhaps be done by turning the soil over, so that the lower uncontaminated soil covered that which had become contaminated. In any operations with such soil, standard wetting-down procedures would be required to minimize the hazard due to radioactive dust.

10.57   Badly contaminated clothing, as well as rugs, curtains, and upholstered furniture would have to be discarded and buried or burned in proper incinerators perhaps designed to prevent the escape of radioactive smoke. If the contamination is not too serious, laundering may be effective in reducing the activity sufficiently to permit reuse. In most cases, it is probable that interior walls and floors of houses and buildings, if still surviving after an atomic explosion, could be decontaminated by thorough washing. They could then be repainted, papered, or varnished according to circumstances.

### Decontamination of Food and Water

10.58   Properly covered foods should undergo little or no contamination. The same will be true of canned goods or any materials in impervious, dustproof wrappings. There appears to be no feasible means for salvaging unprotected food, either in the home, the store or in the fields, which has become radioactively contaminated.

10.59   The contamination of water supplies might arise in several ways, such as fall-out particles dropping into a river or reservoir, accumulation of radioactivity from fall-out particles deposited on the watershed, explosion of an atomic bomb in or near a reservoir, or the deliberate use of radioisotopes in radiological warfare. If the degree

of contamination is not too severe, then it is probable that, as a result of the operation of several factors, e. g., dilution by flow, natural decay, adsorption, etc., the water will not usually be rendered unfit for consumption, except perhaps for a limited time immediately following the contamination.

10.60   In surface waters, radioactive contaminants will tend to be adsorbed by the suspended and colloidal matter that is invariably present.   This matter will partly settle or be adsorbed by the walls and bottom of the reservoir.   In urban water systems radioactive material escaping adsorption in the reservoir itself may be picked up by the surfaces of the distribution system which usually consist of highly adsorbent brick or rusted iron.   When, in addition, the purification process includes coagulation, sedimentation and filtration stages, it is expected that very little radioactive material will normally reach the consumer.

10.61   Because of the adsorptive properties of soil, referred to above, underground sources of water are generally safe from contamination.   For the same reason, moderately deep wells, even under contaminated ground, can be used as sources of drinking water, provided surface drainage of contaminated material is prevented.

10.62   If a reservoir or river is seriously contaminated, and the water is not subjected to coagulation or filtration, as described above, the water may be unfit for consumption for several days.   However, because of dilution and natural decay of the radioactivity, the degree of contamination will decrease with time.   It would be necessary, in cases of this kind, to subject the water to careful examination for radioactivity and to withhold the supply until it is reasonably safe for human consumption.   It should be remembered in this connection that since the water is taken internally, alpha and beta activity, as well as gamma activity, is important.

10.63   In some cities water is taken directly from a river and merely chlorinated before being supplied for domestic consumption.   If no alternative source of water is available in case of emergency, consideration should be given to the provision of cationic and anionic exchange columns or beds to be used if the regular supply should become contaminated.   Home water softeners might serve the same purpose. In hospitals and on ships sufficient water for emergency purposes could be obtained by distillation.   It was found at Bikini, for example, that contaminated 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 radioactivity is of no value.

10.64   The suggestion has been made that algae and zoogleal bacteria, such as are used in the activated sludge process for purification of sewage, which absorb and concentrate mineral elements directly from water (cf. § 8.98), could be employed to remove radioactive contamination from reservoirs.   In order to be effective, the conditions would have to be such as to cause profuse growth of the organisms.   Once the activity is incorporated into the latter, the water could be drawn off, and the bacteria, etc., removed by mechanical filtration or by sludge beds and allowed to decay.   Whether this procedure will prove practical on a large scale is not yet known, although preliminary experiments indicate some success in the removal of plutonium from contaminated water.

10.65   The accepted safe tolerance level for water containing fission products is $4 \times 10^{-6}$ microcurie/cc.   Assuming the mean gamma-ray energy to be 0.7 Mev (§ 8.11), it can be shown by means of Fig. 8.37b that the dosage rate measured just above the surface of a body of water contaminated to this extent would be nearly $4 \times 10^{-6}$ r per hour. This activity in curies is appreciably lower than that of some radioactive mineral waters which are consumed in quantity without obvious deleterious consequences.   It would appear, therefore, that in an emergency, water with many times the accepted tolerance limit could be used for drinking in limited amounts.   Because of the rapid decay of the fission products with time, the activity of the water and the corresponding hazard, if any, would soon decrease.[4]

## Special Protective Methods

10.66   The ideal defense against radioactive contamination is to use, wherever possible, surfaces which are either resistant to such contamination or from which the active material can be readily removed.   It has been found, for example, that surfaces coated with certain plastic paints are relatively easily decontaminated.   Attempts are being made to classify materials according to their contamination and decontamination characteristics, but it will be some time before a clear understanding of the subject can be obtained.   In a general way, however, it can be stated that an ideal surface for the purpose in mind should have its specific surface area, i. e., area per unit mass, porosity, and chemical and surface activity as small as possible.   There are indications at present that certain materials, such as polyethylene,

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[4] The presence in a reservoir of appreciable amounts of plutonium, with its long half life and tendency to concentrate in the body (§ 11.93), would present a special problem.   For the accepted tolerance level of plutonium in water, see § 12.72.

have these desirable properties, and these substances could be used to form thin surface layers on various articles or equipment.

10.67  Structural materials, e. g., concrete, brick, and soft woods, present a special problem, since decontamination of porous substances is virtually impossible.  At the present time, it appears that well-maintained paint or other sealer is the only means of protection against radioactive contamination.  This matter should be borne in mind, especially in connection with new construction near bodies of water where an underwater explosion is a possibility.  In designing structures, efforts should be made to eliminate inaccessible spaces, sharp concavities, and poor drainage.

10.68  Another possibility in connection with protection against radioactive contamination, which has been found successful in laboratories handling high levels of activity, is to use strippable coatings.  A removable protection of this kind, consisting of adhesive tape or special sprayed or brushed coatings of a plastic material, is affixed directly to the surface to be protected.  In the event of radioactive contamination, the plastic surface is stripped off and replaced with a new one.

10.69  Where the foregoing procedures are not possible, vital equipment may be kept under cover, by means of tarpaulins or other movable protection.  Emergency access ways to installations should be protected in some manner, for experience at Bikini has shown that a simple shelter can be very effective in decreasing the extent of radioactive contamination.

# EFFECTS ON PERSONNEL

## A. TYPES OF INJURIES

### INTRODUCTION

11.1    The injurious effects to personnel resulting from an atomic explosion may be divided into three categories: these are, blast injuries, burns, and nuclear radiation injuries. Although it was estimated in Chapter VI that at least 50 percent of the fatal casualties due to the atomic bombings of Japan were caused by burns of one kind or another, it is virtually impossible to determine the relative importance of the various factors. Many people who were injured by blast were also burned, and this undoubtedly was also the fate of others who would have ultimately succumbed to the effects of radiation. Within about 2,500 feet of the center of the explosion, it is probable that blast, burns, and radiation could separately have been lethal in many cases. It should be pointed out, however, that not everyone within the 2,500 feet radius from the center of burst was killed. Among those who survived the immediate results of the explosions at Hiroshima and Nagasaki, a number died later from what was ascribed to radiation sickness; these were believed to represent from 5 to 15 percent of the total number of fatal casualties.[2]

11.2    In spite of the fact that no definite information can be obtained from Japanese experience concerning the relative contributions of the three causes of injury, some general conclusions can be drawn with regard to the type of burst. In the case of a high air burst, such as at Hiroshima and Nagasaki, most of the casualties will be due to burns and blast effects. There will be a small proportion of radiation injuries resulting from exposure to the initial nuclear radiations, but the effect of contamination by residual radiation will be negligible.

11.3    An explosion at low altitude or at ground level would produce somewhat fewer casualties from blast or burns, but a small area would be highly contaminated with radioactive material. If proper precautions are taken, the casualties due to this residual radiation should be a very small fraction of the total.

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[1] Material contributed by J. P. Cooney, R. D. Evans, A. C. Fabergé, G. M. Lyon, Shields Warren.

[2] A number of persons who were within 2,500 feet of the atomic explosions in Japan survived because they were sheltered in one way or another (cf. § 11.71).

11.4   After a shallow underwater burst the number of casualties from blast and burns will also be diminished.   However, some casualties might arise from exposure to the radiation from fission products and, to a lesser extent, material which has escaped fission, spread over an appreciable area by the base surge and the fall-out (§ 8.64 *et seq.*). During the first two months or more the primary danger would be due to the gamma rays, in particular, and the beta particles from fission products.   Subsequently, the ingestion of plutonium might in exceptional circumstances become a hazard.   In the event of serious contamination of this kind, it would be necessary to evacuate the population from the affected areas, until they could be adequately decontaminated, as described in Chapter X.

### BLAST INJURIES: DIRECT AND INDIRECT

11.5   Two types of blast injuries, namely, direct and indirect, may be considered.   Direct blast injuries result from the positive pressure phase of the shock wave acting on the body so as to cause injury of the lungs, stomach, intestines and eardrums, and internal hemorrhage. Such injuries occurred in World War II after large-scale air raids with conventional high-explosive bombs.   At Nagasaki and Hiroshima, however, the direct blast effect was not a significant primary cause of fatality, since those near enough to the explosion to suffer injury in this manner were burned or crushed to death.   A pressure of about 35 pounds per square inch or more is required to cause direct harm to a human being, and the peak pressure of the shock wave from a nominal atomic bomb would attain such values only at distances of 1,000 feet or less from ground zero, assuming a height of burst of 2,000 feet.

11.6   More important than the primary blast injuries in the Japanese bombings were the indirect or secondary effects due to collapsing buildings, and to timber and other debris flung about by the blast wave.   Persons were injured by flying objects, crushed or buried under buildings, and thrown against fixed structures.   Glass fragments penetrated up to an inch beneath the skin, and the light summer clothing worn at the time offered little protection.   Unless proper precautions are taken, as described in Chapter XII, glass thus represents a considerable hazard.

11.7   The nature of the indirect injuries from blast varied from complete crushing, severe fractures, and serious lacerations with hemorrhage, to minor scratches, bruises, and contusions.   Patients were treated for lacerations received up to 10,600 feet from ground

zero in Hiroshima, and out to 12,200 feet in Nagasaki. Shock, both physiological and traumatic, i. e., due to bodily injury, was a serious complication in many cases. It may be mentioned, too, that many burns were also, in a sense, an indirect effect of the blast.

11.8 The number of blast casualties of various kinds that might be expected from an atomic explosion will evidently be related to the type of building construction, and also to the height of the burst. However, on the whole, the indirect blast injuries due to the atomic bomb are similar to those caused by conventional bombs. The only important difference is the much greater number and variety of such injuries produced in a short interval of time in the former case. This fact is well illustrated by the figures in Table 11.8 [3] where the casualties

TABLE 11.8

COMPARISON OF CASUALTIES FOR ATOMIC AND CONVENTIONAL
BOMBS

| | Hiroshima | Nagasaki | Tokyo | Average of 93 attacks |
|---|---|---|---|---|
| Weapon_____ | Atomic bomb | Atomic bomb | 1,667 tons TNT and incendiary | 1,129 tons TNT and incendiary |
| Population per square mile_____ | 35, 000 | 65, 000 | 130, 000 | — |
| Square miles destroyed_____ | 4. 7 | 1. 8 | 15. 8 | 1. 8 |
| Killed and missing_____ | 70, 000 | 36, 000 | 83, 000 | 1, 850 |
| Injured_____ | 70, 000 | 40, 000 | 102, 000 | 1, 830 |
| Mortality per square mile destroyed_____ | 15, 000 | 20, 000 | 5, 200 | 1, 000 |
| Casualties per square mile destroyed_____ | 30, 000 | 42, 000 | 11, 800 | 2, 000 |

produced by the atomic bombs at Hiroshima and Nagasaki are compared with those in the attack on Tokyo with conventional bombs on March 9, 1945, and with the average results of 93 attacks on other Japanese cities with similar weapons. The high mortality and casualty rates per square mile destroyed by the atomic bomb are very apparent.

FLAME AND FLASH BURNS

11.9 As stated in Chapter VI, two types of burns were observed at Hiroshima and Nagasaki; these were generally differentiated as (a) fire or flame burns, and (b) flash burns due to thermal radiation.

[3] "The Effects of Atomic Bombs at Hiroshima and Nagasaki," U. S. Strategic Bombing Survey (1946).

When the area of the body not protected by clothing, e. g., the face and hands, was small, the latter were characterized by more or less sharp limitation of area, which suggested the appelation "profile burns" (§ 6.54); flame burns on the other hand, covered large portions of the body that were originally protected from thermal radiation. It may be noted, however, that where large parts of the body were exposed to the thermal radiation, the flash burns also covered considerable areas. Because of the numerous and extensive fires that developed after the atomic explosion, it is not surprising that the total number of casualties, fatal and otherwise, due to flame burns, was very large. The evidence indicates that burns of one kind or another occurred as far out as 14,000 feet at Nagasaki and 12,000 feet at Hiroshima.

11.10 Since flame burns due to an atomic explosion, apart from their frequency, do not present any features different from those caused by other conflagrations, they need not be considered in detail. A brief description will, however, be given of some of the major characteristics of flash burns.[4] In addition to being restricted in area to exposed parts of the body, the majority of flash burns show a much smaller depth of penetration of the skin. This is to be expected in view of the fact that the thermal radiation which is responsible is absorbed in such a very short time, during the first 3 seconds following the explosion. A very high surface temperature is thus produced in a small time interval. Within the depths to which the thermal radiations penetrate, the tissues appeared to be completely destroyed; in a radius of 3,600 feet from ground zero blackening indicated that actual charring had occurred.

11.11 According to the Japanese reports, marked redness of those portions of the skin exposed to thermal radiation from the atomic bomb appeared almost immediately, with progressive darkening and blistering taking place over a period of a few hours. As with flame burns, the subsequent development depended on the degree (or depth) of the burn. Uninfected first degree burns that were not irritated healed promptly without, apparently, any unusual features. However, it was noted, in many cases, that after healing, there were marked overgrowths of scar tissue, i. e., keloid formation. It was suggested, at one time, that this might have been due to nuclear radiations, e. g., gamma rays, but this view is not now accepted. The degree of the keloid formation was undoubtedly influenced by secondary infections, that complicated healing of the burns, and by mal-

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[4] Because of their importance in relation to the effects of an atomic explosion, a comprehensive study of flash burns is being sponsored by the U. S. Atomic Energy Commission.

nutrition, but more important is the known tendency for keloid formation to occur among the Japanese, as a racial characteristic. Thus, many spectacular keloids were formed after the healing of burns produced in the fire raids on Tokyo.

11.12   The margins of healed flash burns were usually sharply defined and were often accentuated by a narrow zone of pigment loss in the adjacent skin.   The edge of the scar, however, showed a denser pigmentation that tended to fade to a lighter color toward the center. This pigmentation is not necessarily an effect peculiar to thermal radiation, since other factors, such as ultraviolet light and certain chemicals, e. g., mustard gas, which stimulate the pigment layer of the skin produce similar results.

11.13   A form of thermal radiation or flash burn, sometimes distinguished as a contact burn, was caused by dark-colored clothing materials becoming hot and so burning the skin with which they were in contact.   This accounts for the fact, mentioned in § 6.55, that where burns occurred through clothing, the regions involved were those where the clothes were tightly drawn over the skin, e. g., the shoulders, elbows, waist, etc.

11.14   Hair exposed to thermal radiation from the atomic explosions in Japan was sometimes burned off or singed.   Occasionally the sweat glands and hair follicles were injured or destroyed in this manner. There is no doubt that sometimes the effects were due to the thermal, and not to the nuclear, radiations for where a cap provided a protective medium for the head, the area of hair loss was restricted by the cap. If gamma rays had been responsible, the cap would, of course, have offered no protection.

### Treatment of Burns

11.15   For practical purposes of diagnosis and treatment, it is not necessary to distinguish among burns caused by thermal radiation, by flame, or by contact.   Although there are differences with respect to extent of body surface involved, depth of the injury to the skin, and general reactions of the individual to burns of different types, the indicated treatment for burns due to an atomic explosion appears to be the same as for those encountered in large-scale incendiary raids and in civil disasters.   The unique feature of the atomic bomb burns is the great number of casualties produced in a very brief period of time, the variety of burns encountered, and the wide range of severity, depending on the distance from the explosion.

11.16   A great deal was learned during World War II concerning the treatment of burns, but the subject is still under investigation and

has not yet become stabilized. It may be recommended, therefore, that until there is more general agreement, the medical men in each community should employ the treatment for severe burns which they have found most efficacious.

## OPHTHALMIC EFFECTS

11.17 The effect of thermal radiation on the eyes was surprisingly small; even those who looked directly at the explosions at Hiroshima and Nagasaki, from some distance, of course, reported only temporary loss of vision. In one case a patient was so blinded by the flash that he was unable to distinguish light from dark for two days, but eventually his recovery was complete.

11.18 Temporary blindness of this type may be due to two known causes. First, the intense light results in the complete utilization of the visual purple of the retina. Blindness will then persist until such time, usually not more than half an hour, as sufficient of this substance is once more produced to permit vision. Second, temporary blindness may be due to the focusing of thermal, particularly infrared, radiation on the retina by the lens of the eye. An example of this type of injury is the so-called "eclipse blindness" experienced from gazing directly at the sun.

11.19 One reason why there were relatively few persons in Japan who suffered from burns of the eyeballs due to thermal radiation from the atomic bombs is that the structure of the eye is more resistant to heat than is the average skin. Further, in locations relatively near to the explosion, where the radiation was most intense, the recessed position of the eyes provided protection from the rays. In addition, the blink reflex of the eye acted as an effective protective mechanism; the thermal radiation is emitted during a period of about 3 seconds and this is quite appreciable compared with the time required to blink.

## B. NUCLEAR RADIATION EFFECTS

### RADIATION INJURY AND RADIATION SICKNESS

11.20 The injurious effects of radiation from an atomic bomb represent an aspect of an atomic explosion which is completely absent from conventional bomb bursts. For this reason the subject of radiation sickness will be discussed at some length in this book. It should be clearly understood, however, that the extended treatment is not meant to imply that radiation is the most important source of

casualties in an atomic explosion.   This was certainly not the case in Japan, where, as stated earlier, a maximum of 15 percent of the fatalities were attributed to radiation, compared with over 50 percent due to burns.   While nuclear radiation may definitely be a hazard, the extent of which will depend on the type of atomic explosion (§ 11.2 *et seq.*), it is by no means to be regarded as being of dominating significance.

11.21   It has long been known that excessive exposure to any radiation, for example, X-rays, alpha and beta particles, gamma rays, and neutrons,[5] capable of producing ionization in living tissues, can cause injury to the organism.   After the discovery of X-rays and radioactivity toward the end of the nineteenth century, serious and sometimes fatal exposure to the radiations were sustained by radiologists, before the dangers were fully realized.   With the passage of time, however, means for providing protection were developed and serious overexposure became less frequent, although occasional accidents have occurred with personnel operating radiographic equipment, powerful X-ray machines in industrial laboratories, cyclotrons, etc., or working with radioactive materials.

11.22   As a general rule, the exposures in these cases were limited to certain parts of the body, and the effects were referred to as *radiation injuries.*   These included local destruction of tissue, loss of hair, and temporary sterility.   In a very few instances there had been accidental exposure of large parts of the body to an overdose of radiation, and this led to systemic, rather than or in addition to a localized effect.   This systemic disease is called *radiation sickness.*

11.23   Before the bombings of Hiroshima and Nagasaki, radiation sickness was a rare occurrence, but in these attacks exceptionally large numbers of individuals were exposed to gamma rays of varying intensity.   There were consequently available for analysis a wide variety of forms and severities of the illness in a large group of people who had absorbed radiation dosages covering a considerable range, from insignificant quantities to amounts which proved fatal.   A complicating factor was the difficulty of differentiating casualties according to direct and contributory causes, for many victims of radiation also suffered burns or mechanical injuries, or both.   Nevertheless, certain general conclusions have been drawn with regard to the effects

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[5] Neutrons produce very little or no ionization directly.   However, as the result of collisions with hydrogen nuclei contained in the water or other constituent of tissue, fast neutrons produce recoil protons which cause ionization in their paths (cf. § 9.5).   Slow neutrons can suffer radiative capture (§ 7.7) by hydrogen nuclei accompanied by the emission of gamma rays of about 2.2 Mev energy.   The latter are capable of causing ionization in the usual way.

of nuclear radiation on the human organism; these will be discussed later in this chapter.

11.24 It has been established that all radiations capable of producing ionization directly, e. g., alpha and beta particles, or indirectly, e. g., X-rays, gamma rays, and neutrons, can cause radiation injury or radiation sickness of the same general types.[6] However, although the effects are qualitatively similar, the various radiations differ in their quantitative behavior. Thus, for the same amount of energy absorbed in tissue, an alpha particle is from 10 to 20 times, a slow neutron about 5 times, and a fast neutron about 10 times as effective biologically as a beta particle, while the latter has been found to be approximately equivalent to a gamma-ray photon. By making use of these relationships, it is possible to express radiation dosages in terms of the roentgen, although, as defined (§ 7.41), this unit is strictly applicable only to X-rays and gamma rays.

## RADIATION DOSAGES

11.25 The effects of radiation on living organisms depend not only on the total amount absorbed, but also on the rate of absorption, on whether it is chronic or acute, and on the area of the body exposed (cf. § 8.5). Some radiation phenomena, such as genetic effects (§ 11.96 *et seq.*), are apparently independent of the rate of delivery of the radiation, and depend only on the total dosage. In some cases it has been claimed that the effectiveness of the radiation has been increased upon decreasing the rate of delivery; this has been attributed to an increase in the sensitivity of the tissue as a result of continued irradiation.

11.26 In the majority of instances, however, the biological effect of a given dose of radiation decreases as the rate of exposure decreases; thus, to cite an extreme case, 600 r would certainly be fatal if absorbed by the whole body in one day, but it would probably have no noticeable consequences if spread over 30 years. The most reasonable explanation of this fact is that if the dosage rate, i. e., the amount of radiation taken per day, is very small, the damaged tissues have a chance to recover. If the intensity or rate of delivery of the radiation is increased, recovery cannot keep up with the damage, and an increased effectiveness is to be expected. It is apparently the recovery factor which makes it possible for human beings to accept limited

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[6] It will be understood that the term "radiation" as used in the present and succeeding sections of this chapter refers to any radiation which causes ionization directly or indirectly. Thermal radiation is, of course, not included, since it cannot produce ionization.

doses of radiation, at least 0.3 r per week (§ 8.4), for long periods of time without any apparent harmful consequences.

11.27  The foregoing considerations account for the necessity for distinguishing between acute exposure, i. e., occasional large doses, and chronic exposure, i. e., continued exposure to small doses, of radiation.  As far as the effects of the atomic bomb are concerned, the situation is simplified by the fact that the initial nuclear radiations are emitted for a short period, taken as about a minute or so, so that exposure to these radiations may be regarded as being of the acute type.  On the other hand, the residual radiations, due to fission products, etc., would represent a chronic hazard, either as internal or external radiation.

11.28  Because large acute doses have been accepted by human beings only as a result of accidents of one kind or another, it is not possible to state definitely that a particular amount of radiation will have certain consequences.  Nevertheless, from experiments with animals, whose sensitivity to radiation relative to that of human beings has been studied, certain general conclusions have been drawn.  These cannot be exact, in any event, since there are marked variations among individuals insofar as sensitivity to radiation is concerned.  The results given in Table 11.28 may therefore be regarded as an approxi-

TABLE 11.28

PROBABLE EARLY EFFECTS OF ACUTE RADIATION DOSES OVER WHOLE BODY

| Acute dose | Probable effect |
|---|---|
| 0–25 r | No obvious injury. |
| 25–50 | Possible blood changes but no serious injury. |
| 50–100 | Blood-cell changes, some injury, no disability. |
| 100–200 | Injury, possible disability. |
| 200–400 | Injury and disability certain, death possible. |
| 400 | Fatal to 50 percent. |
| 600 or more | Fatal. |

mate indication of the early effects on human beings of various acute doses of radiation, assuming exposure of the whole body.[7]  Somewhat larger doses may be accepted, with an equivalent likelihood of injury, if the exposure is protracted over several days or weeks, or if it is limited to a portion of the body.  For these extended or split-up exposures, however, it is not possible to give any satisfactory rules for estimating the risk factors.

[7] The possible delayed effects of radiation are being studied in Japan as part of a long-range program of the Atomic Bomb Casualty Commission of the U. S. National Research Council, sponsored by the Atomic Energy Commission.  Apart from cases of cataracts (§ 11.71), nothing significant has been observed 4 years after the atomic explosions.

11.29 Because of the variations among individuals, it appears that an acute dose exceeding 200 r may prove fatal to a human being, the probability increasing with the dosage. The general variation of the survival rate with dosage for rabbits and rats is represented in Fig. 11.29, and from the results the corresponding curve, shown dotted, for human beings has been inferred. It would appear that an acute dose of 200 r would prove fatal to about 5 percent of those exposed, while an almost equal proportion would be expected to survive a dose of 600 r.
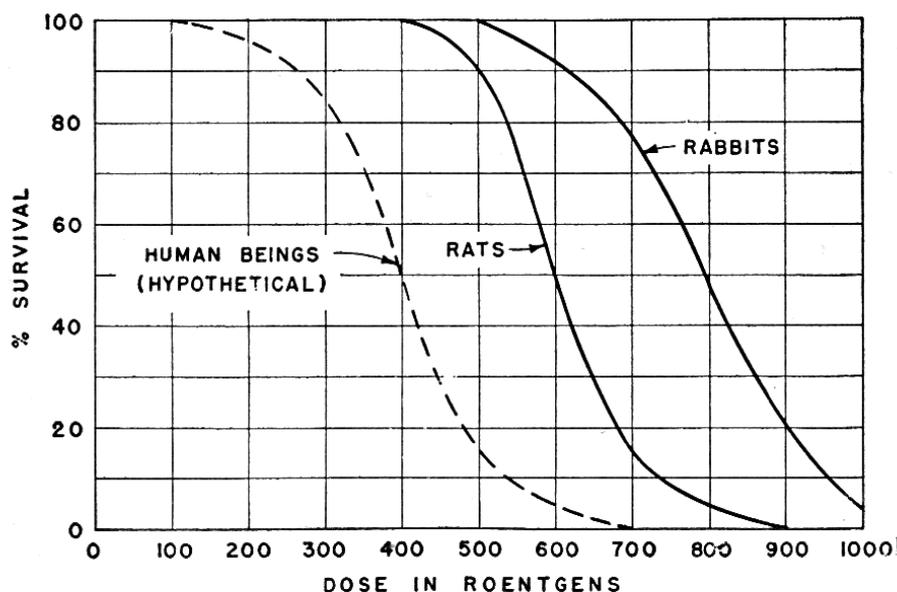


Figure 11.29. Percentage survival as function of acute radiation dosage.

11.30 Most of the victims of the initial nuclear radiations from the atomic bombings of Japan were exposed over a large part of their bodies, since clothes are no protection against gamma rays. From the observations made, much information has been obtained concerning the symptoms and development of radiation sickness of different degrees of severity. For convenience, the description given here will refer to three main degrees of exposure within a short period of time.[8] They are: (*a*) lethal dose, i. e., about 600 r or more, which is fatal in nearly all cases within 2 weeks of exposure; (*b*) median lethal dose, i. e., about 400 r, resulting in death to 50 percent of the patients from 2 to 12 weeks after exposure; and (*c*) moderate dose, i. e., from 100 to 300 r, which is generally not fatal.

11.31 It may be mentioned that in Japan deaths from radiation, in those protected from blast and burns, began about a week after exposure and reached a peak in 3 to 4 weeks; these were probably the

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[8] There are, of course, no sharp lines of demarcation between the three postulated types of exposure; the distinction, which is one of degree only (cf. Fig. 11.29), is made here for the sake of convenience in description.

individuals who had received doses of more than about 400 r. Subsequently, the death rate declined, and became very small after about 8 weeks.

## C. CLINICAL SYNDROME OF RADIATION SICKNESS (ACUTE RADIATION SYNDROME)

### LETHAL DOSE

11.32  In the most severe exposures, probably several thousand roentgens, death may occur within a few hours, but there are few reliable observations on the course of the radiation sickness in these circumstances. In cases of lethal, but not extreme, exposures, individuals were found to exhibit varying degrees of shock, possibly within a few hours. This was accompanied, or followed shortly, by nausea and vomiting, and then by diarrhoea, during the first day or two after exposure; subsequently, there was a development of fever. The diarrhoea was frequent and severe in character, being watery at first and tending to become bloody later.

11.33  The sooner the foregoing symptoms developed, the sooner was death likely to supervene. Although there was no pain in the first few days, patients experienced a feeling of discomfort or uneasiness (malaise), accompanied by marked depression and bodily fatigue. The early stages of the severe radiation sickness may or may not be followed by a so-called latent period of 2 or 3 days, during which the patient is free from symptoms, although profound changes are taking place in the body. This period, if it occurs, is succeeded by reappearance of the same symptoms and active illness, accompanied by delirium or coma, in many cases, terminating in death usually within 2 weeks.

11.34  Among other symptoms which have been observed are secondary infection and a tendency to spontaneous internal bleeding toward the end of the first week. At the same time, swelling and inflammation of the throat is not uncommon. Loss of hair, mainly from the head, may occur by the end of the second week. Examination after death revealed a decrease in size, and degenerative changes, in the testes and ovaries; ulceration of the tonsils and of the mucous membrane of the large intestine were noted in some cases. The development of the illness was accompanied by a characteristic increase of the body temperature; generally between the fifth and seventh days, sometimes as early as the third day, after exposure, there was a step-like rise usually continuing until the day of death. There were also

some striking changes in the blood of the patient, to which reference will be made below.

## Median Lethal Dose

11.35 The initial symptoms, namely, nausea, vomiting, loss of appetite, and malaise, of a person who has received a median lethal dose of radiation over the whole body will be the same as for a lethal dose; however, they will, in general, develop somewhat later and be less severe. After the first day or two the symptoms disappear and several days to two weeks may elapse ("latent period") in which the patient feels relatively well. This is followed by a recurrence of the illness, with the symptoms, including fever, severe diarrhoea, and the steplike rise of temperature, the same as for the lethal dose, as described above.

11.36 Commencing between 14 and 21 days after exposure, there is a marked tendency to bleed; blood spots under the skin, called petechiae, are common and are a manifestation of this tendency. Bleeding may occur into any organ or group of tissues, and from any mucous membrane. Particularly common are spontaneous bleeding in the mouth, and from and into the lining of the intestinal tract. There may be blood in the urine from bleeding into the substance of the kidney or into the urinary tract leading from the kidney. The hemorrhagic tendency apparently depends on injuries produced in tissues and cells, e. g., thrombocytes, involved in the very complicated blood-clotting mechanisms, and on capillary damage.

11.37 Other symptoms observed were loss of hair, and ulceration about the lips. These ulcers extended from the mouth through the entire gastro-intestinal tract in the terminal stage of the sickness. A contributory factor to ulcer formation was the loss of white blood cells, which allowed bacteria to multiply, so that an overwhelming infection ensued. Susceptibility to secondary bacterial infection was, in fact, one of the most serious complicating factors.

11.38 In the cases where the symptoms were most extreme, there was severe emaciation with fever and delirium, resulting in death within from 2 to 12 weeks after exposure. Those patients who survived for 3 or 4 months, and did not succumb to tuberculosis, lung diseases or other complications, gradually recovered. Whether the recovery was complete or whether after-effects will appear in the course of time is not known (§ 11.28, footnote).

## MODERATE DOSE

11.39    Moderate doses of from 100 to 300 r total-body radiation received within a brief period of time are generally not fatal.    Exposures of this kind were common in Hiroshima and Nagasaki, particularly among those persons who were some distance from the atomic explosions.

11.40    The illness resulting from moderate dosages of radiation presents much the same picture as in the case of more severe exposure, except that the onset is less abrupt and the symptoms are less marked. There may be a so-called latent period, up to 2 weeks or more, following exposure during which the subject has no disabling illness and can proceed with his regular occupation.    The usual symptoms, such as loss of appetite, malaise, loss of hair, diarrhoea, and tendency to bleed, then appear, but they are not very severe.    The changes in the character of the blood, which is typical of radiation sickness, are found, but neither their severity nor their persistence is as marked as with patients receiving larger doses of radiation.    If there are no complications, due to injuries or infections, there will be recovery in nearly all cases, with hair growth recommencing after about two months.

11.41    It may be noted that recovery may be hindered by changes in the intestinal tract that greatly hamper the assimilation of food, thus producing serious malnutrition.    The intractability of the diarrhoea may also be important in this connection.    With these factors to be considered, it is consequently not usually possible to predict a definite course of convalescence.    In general, however, the more severe the early stages of the radiation sickness, the longer and more difficult will be the process of recovery.

11.42    Single exposures of from 25 to 100 r over the whole body may produce mild and somewhat indefinite symptoms, or there may be nothing more than the characteristic blood-cell changes (§ 11.44 *et seq.*) to a minor extent.    Disabling illness is not common, and exposed individuals should be able to proceed with their usual duties.

11.43    A simplified summary of the clinical symptoms of radiation sickness, obtained from data collected in Japan, is given in Table 11.43.[9]

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[9] Adapted from "The Atomic Bombings of Hiroshima and Nagasaki," The Manhattan Engineer District, 1946, p. 32.

TABLE 11.43

## SUMMARY OF CLINICAL SYMPTOMS OF RADIATION SICKNESS

| Time after ex-exposure | Lethal dose (600 r) | Median lethal dose (400 r) | Moderate dose (300–100 r) |
|---|---|---|---|
| First week | Nausea and vomiting after 1–2 hours. | Nausea and vomiting after 1–2 hours. | No definite symptoms. |
| | No definite symptoms. | No definite symptoms. | |
| Second week | Diarrhoea. Vomiting. Inflammation of mouth and throat. | | |
| | Fever. Rapid emaciation. Death. (Mortality probably 100 percent.) | Beginning epilation. | |
| Third week | | Loss of appetite and general malaise. | Epilation. |
| | | Fever. | Loss of appetite and general malaise. |
| | | Severe inflammation of mouth and throat. | Sore throat. Pallor. Petechiae. |
| Fourth week | | | Diarrhoea. |
| | | Pallor. Petechiae, diarrhoea, and nosebleeds. | Moderate emaciation. |
| | | Rapid emaciation. Death. (Mortality probably 50 percent.) | (Recovery likely unless complicated by poor previous health or superimposed injuries or infections.) |

## DIAGNOSIS OF RADIATION SICKNESS

11.44  Of the biological consequences to exposure of the whole body to a large single dose of radiation, perhaps the most characteristic are the changes which take place in the blood.  Soon after exposure there is a drop in the number of lymphocytes, i. e., those white blood cells (leukocytes) which are formed in portions of the lymphatic tissues of the body, such as lymph nodes and spleen.  In some instances an increase in the total white blood cell count was reported in Japan following the atomic explosions; this was apparently due to a gain in the number of granulocytes, i. e., the white blood cells formed mainly in

the bone marrow.   But such an increase was soon followed, within a few hours, by a sharp decrease (Fig. 11.44a).   As a result, there was, after the first day, a rapid decrease in the total white blood cell count which continued for about 5 or 6 days (Fig. 11.44b).   The total number
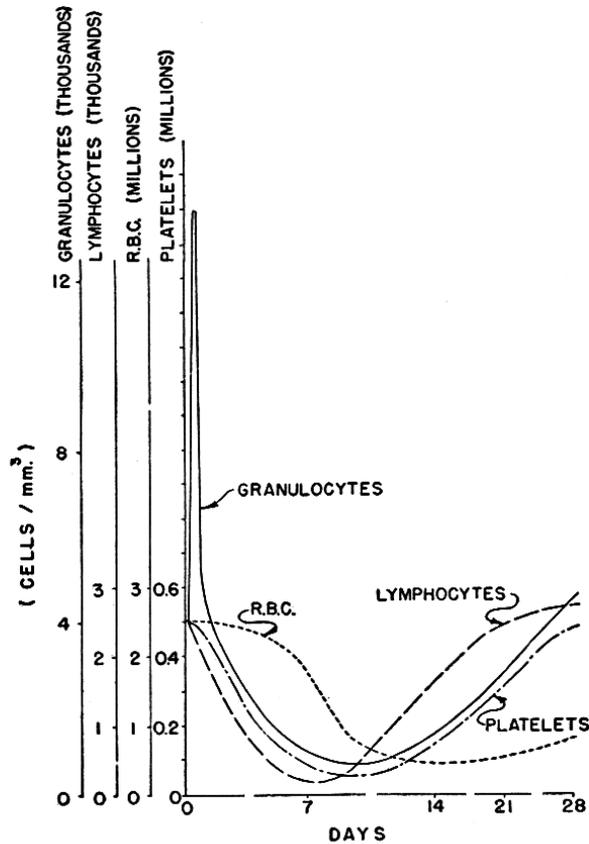


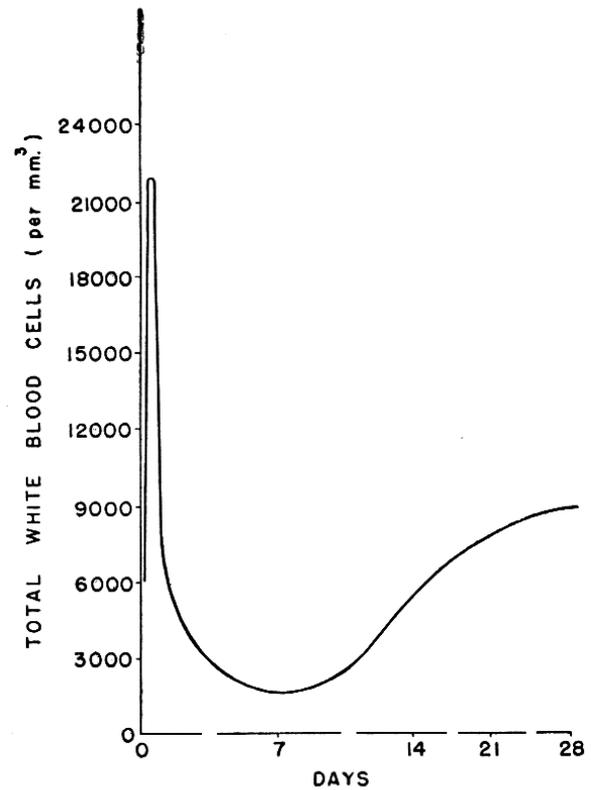Figure 11.44a.   Variation in blood cell counts with time in radiation sickness.

Figure 11.44b.   Variation of total white blood cells with time in radiation sickness.

of white blood cells had then decreased from the normal value of from 4,000 to 10,000 per cubic millimeter to something like 1,000 to 3,000 per cubic millimeter.   In severe cases, the white blood count dropped to 300 or less before death.

11.45   After about a week the lymphocytes had reached their low point, and then their number began to increase, in patients who were in process of recovery.   By the end of the third week, the lymphocytes may show considerable gain, while the number of granulocytes is also growing.   During this period the erythrocytes, i. e., the red blood cells, indicated by R. B. C. in Fig. 11.44a, formed normally in the bone marrow, may show a decline, especially where the radiation dosage has been high.

11.46   The main function of the leukocytes in the blood is to defend the body against infection and to remove injured tissue.   Most bacterial infections, whether localized or generalized, stimulate an out-

pouring of the white blood cells. These cells then restrict the infection and overcome it. The failure of the bone marrow and of the lymphoid tissues to produce granulocytes and lymphocytes, respectively, as a result of the action of radiation, means that an important defense mechanism of the body is rendered inoperative, and there is an increased susceptibility to infection, as mentioned above.

11.47 Although there are changes in the red blood cell count and in other factors of the blood, it is the net decrease in the total number of white cells soon after the exposure which is always observed in radiation sickness, particularly in severe cases. If the number of cells falls much below 2,000 per cubic millimeter, the chances of recovery are not good, and if it is less than 500 per cubic millimeter, the consequences are almost certain to be fatal. At present the white blood cell count is considered to be the most valuable and direct single index of radiation sickness. It can thus be used for establishing a diagnosis and in following the course of the illness.

11.48 It is important to note, however, that by itself the number of white blood cells cannot be taken as presumptive evidence of over-exposure to radiation. Various other diseases and infections, unrelated to radiation, can cause similar blood-cell changes. If it is suspected that a group of individuals have been exposed to radiation, from an atomic bomb, for example, and they all show a similar reduction in the white blood cells, then it is probable they will suffer from radiation sickness. Evidence from other symptoms must nevertheless be obtained before the diagnosis can be regarded as conclusive. The situation could be confused if there were an epidemic of some virus infection, such as acute influenza, at the time of the bomb explosion, for the white blood cell count would then be low in any event. On the whole, however, the combination of such circumstances may be discounted.

11.49 It should be emphasized that the white blood cell count can be used as an indication of radiation sickness only when the exposure has been at least moderately severe. Because of the occurrence of daily variations, of unobserved low-grade infections, and of differences in counting techniques, the count for an individual may be appreciably lower than his previously established normal without exposure to radiation. Consequently, the observed decrease in the white blood cell count must be appreciable if any importance is to be attached to it as a means of diagnosis.

# CHAPTER XII[1]

# PROTECTION OF PERSONNEL

## A. INTRODUCTION

### TYPES OF DAMAGE

12.1   In the preceding chapters of this book the destructive effects of an atomic bomb have been described and discussed.   These effects include damage due to air blast, ground and water shock, thermal radiation, initial nuclear radiations, and residual nuclear radiations. In addition, extensive fires, due to various secondary causes, will follow the atomic explosion.   Fortunately, the situation as regards protection from these hazards, although by no means simple, is not as complex as the existence of so many danger factors would imply. In general, it appears that proper protection against blast, shock and fire damage, could also minimize the danger to personnel from thermal radiation and the initial nuclear radiations.

12.2   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 materials, especially near windows.   The only known defense against the gamma rays and neutrons constituting the initial nuclear radiation is the interposition of a sufficient mass of material between the individual and the atomic bomb, including the rising ball of fire.   The use of concrete as a construction material, which is necessary to reduce air-blast and ground-shock damage, will, to a great extent, decrease the initial radiation hazard.

12.3   From the standpoint of physical damage, the problems of construction and protection from atomic bombs are not fundamentally different from those associated with bombs of the conventional type. It should not be forgotten, however, that the former are enormously more powerful, and the damage will cover an extensive area, probably several square miles (Fig. 12.3).   These facts are important in connection with planning for control of fire-fighting and rescue operations.

12.4   An attempt to indicate the magnitude of the consequences of the explosion of a nominal atomic bomb is illustrated in Figs. 12.4a,

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[1] Material contributed by E. A. Bemis, S. Glasstone, J. O. Hirschfelder, G. M. Lyon, S. B. Smith, W. E. Strope, D. W. Sweeney, T. N. White.
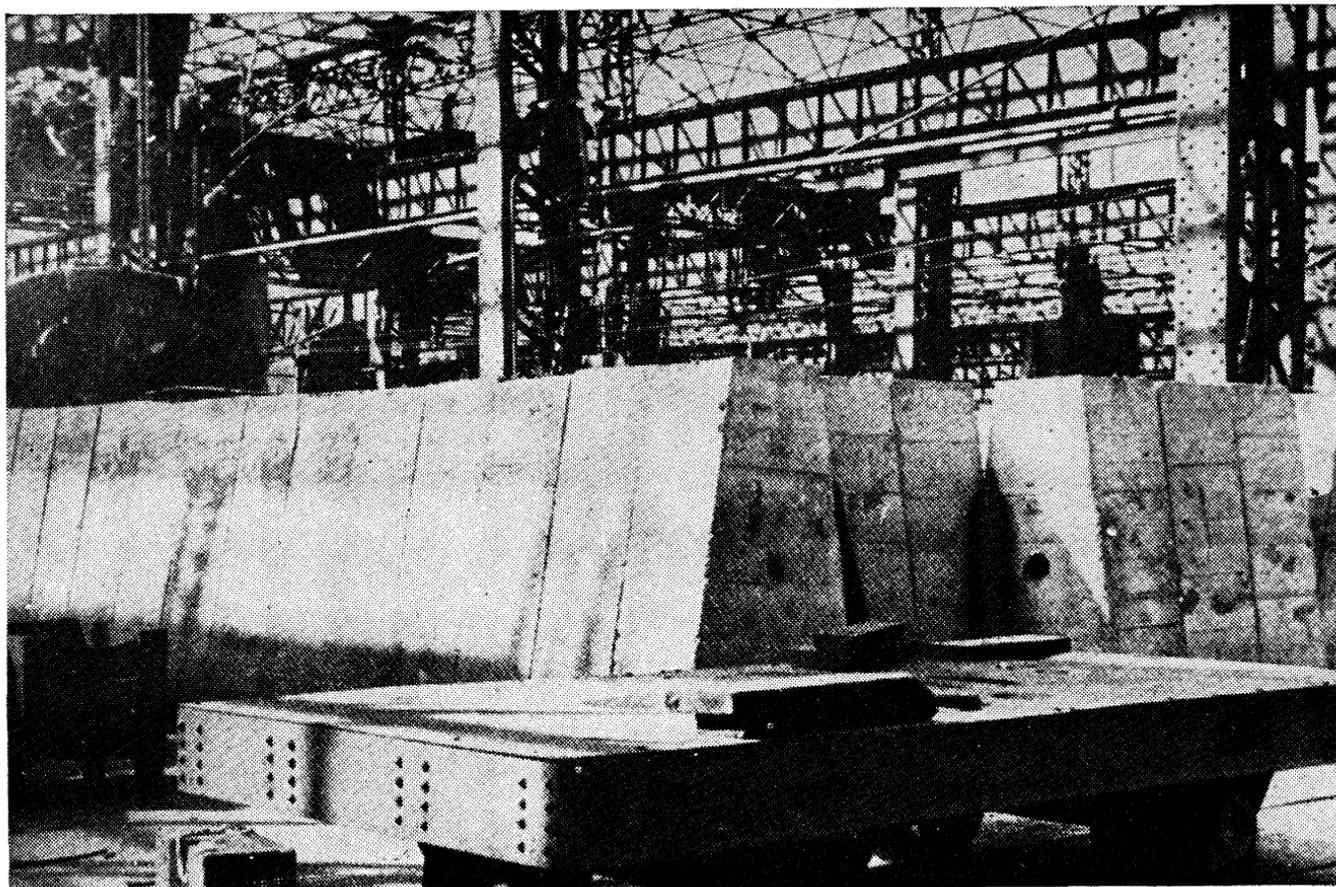
Figure 12.35a. Precast, prismatic reinforced-concrete blast walls, 4,500 feet from ground zero.
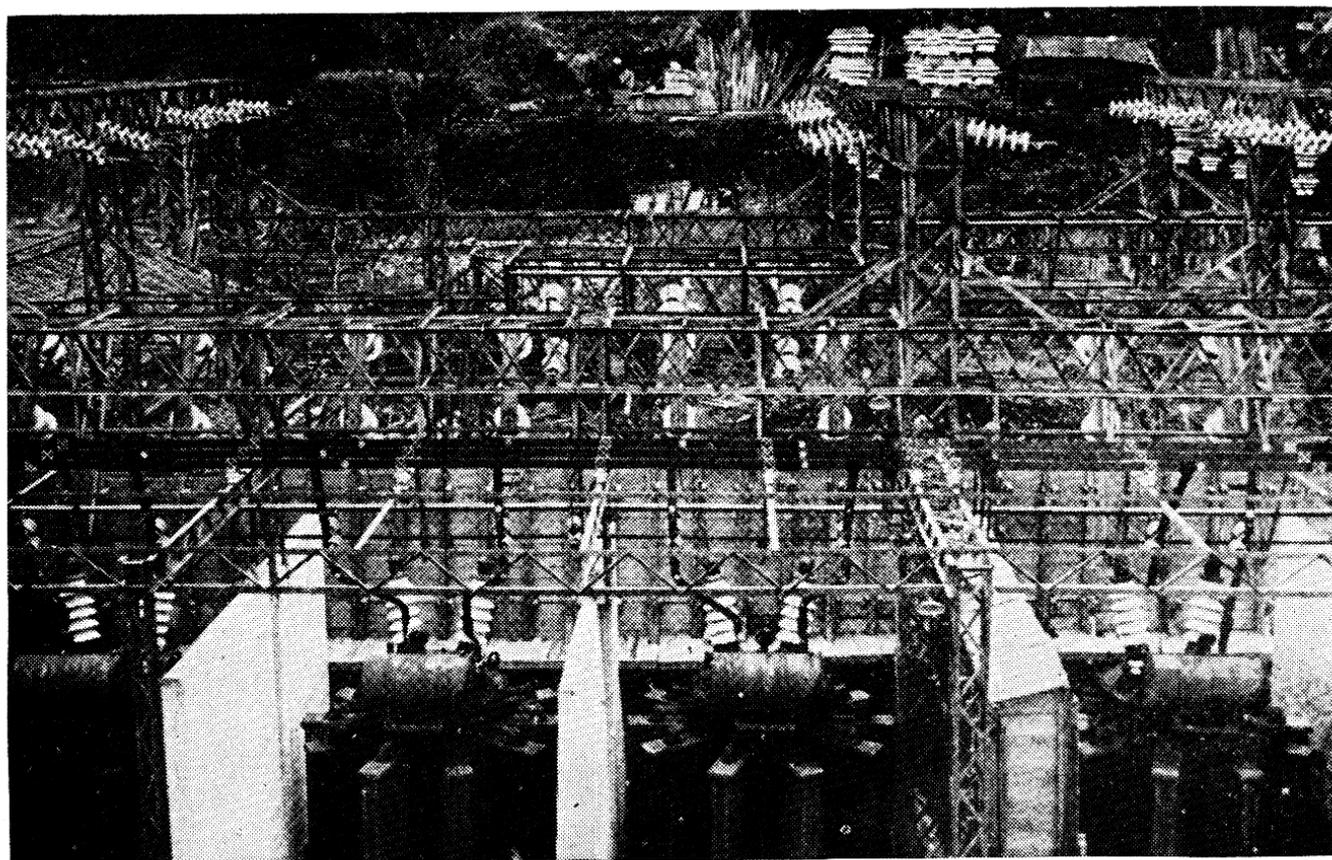


Figure 12.35b. Reinforced-concrete blast walls protecting transformers, 5,400 feet from ground zero.
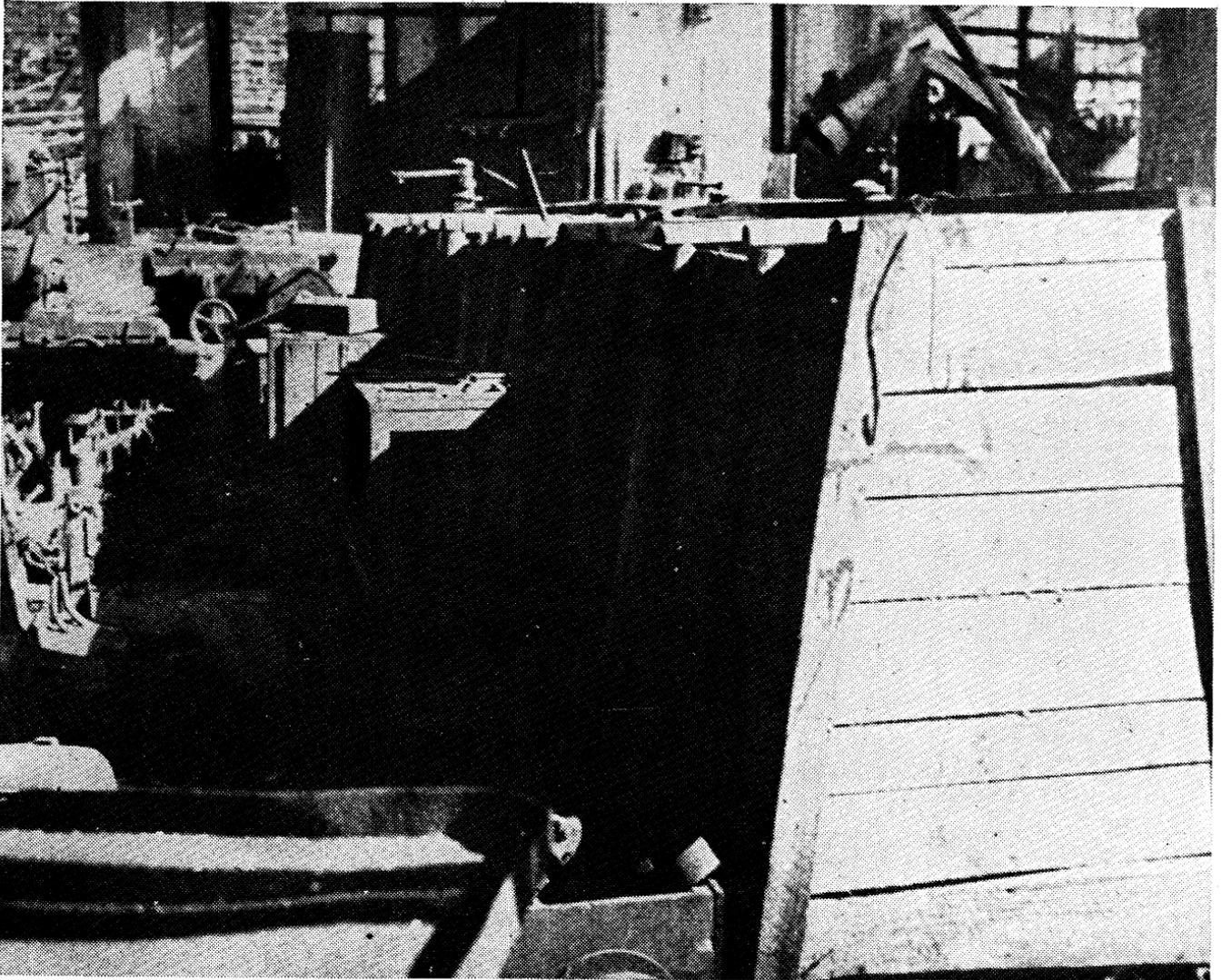
Figure 12.35c.    Earth-filled, wooden blast walls used to protect machinery, 4,600 feet from ground zero.

## UNDERGROUND EXPLOSION

12.36   Should an atomic bomb be employed so as to produce an underground explosion, there would be almost complete destruction within the crater area.   Beyond that area, there would be earthshock effects that are roughly comparable to those of an earthquake (see Chapters IV and V).   It appears, therefore, based on present information, that design for earthquake resistance is a requirement in probable target areas.   Such design should provide for a lateral loading of one-tenth the vertical load, which would be comparable with the wind load suggested in §12.22 for a multistory building to be resistant against air blast.   In this connection, while there would be some air blast in an underground explosion, it is not believed necessary to design for both earth shock and air blast as occurring simultaneously. Structures should be designed for the condition that is likely to cause most damage.

12.37   Houses should, in general, be reasonably resistant to earth shock from an underground explosion beyond the crater area, as these structures are relatively light.   Shifting of the house on its foundations would be likely, with overturning of piers in some cases.   Here also, the same design as for earthquake resistance should be considered if within 3 miles of any probable target.

12.38   The primary cause of damage to underground utility lines is differential earth displacement.   Sewers, especially those made of brick, large gas mains, and other shallow piping of low strength may also be damaged by the pressure from the explosion.   Primary consideration must be given to localizing damage by cut-out valves, loop systems, and protection against damage at points where differential displacement is likely to occur.

12.39   Tunnels and subways in earth would be seriously damaged by underground explosions if they are just outside the crater area, but might be quite resistant at greater distances, since they are generally designed to withstand heavy pressures.   An analysis of the time-pressure curves of the structures (see Chapter V) is recommended. Where below the water table, provision of mobile pumps to drain flooded sections might be indicated.   Consideration of means of limiting flooding by emergency gates would also be important where applicable.

### Underwater Explosion

12.40   In the event of an underwater atomic explosion taking place close to the shore, the actual harbor works are expected to suffer some damage (§ 5.114).   The blast effect on shore installations, warehouses, etc., must, of course, be taken into consideration, but the problems are essentially the same as those for an air burst.

12.41   A special case would arise in the event of an underwater explosion which succeeded in breaching a hydraulic dam.   Apart from the associated damage to penstocks and valves, the large-scale flooding might cause great damage to industrial facilities downstream.   In designing a dam or assessing probable damage to an existing dam, the theoretical calculations in Chapter IV, although not exact, may act as a guide.

### Fire Protection

12.42   As noted in Chapter VI, fires due to an atomic explosion are started by radiant heat (thermal radiation) and by secondary effects, such as overturning stoves and furnaces, rupture of gas pipes, etc. Fire-resistive construction and avoidance of fabrics and other light

materials of inflammable character are essential to reduce fire damage·
The methods of fire-resistive design of buildings and of city planning
are well known and there is no need to repeat such information here.[8]
A special requirement is the reduction of the chance of ignition by
thermal radiation of combustible, especially black, material that might
be exposed at windows and other openings.   It has been recommended,
in this connection, that all such openings be shielded from rays from
all directions.   Vital above-ground plants with combustible contents
should be housed in structures without openings.

12.43   To judge from Japanese experience, it would appear that
steel columns and other steel members should be protected from fire,
for the distortion by heat of exposed structural steel frames was evi-
dent.   Further, narrow firebreaks were found to be of little value,
so that it should be borne in mind 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 sug-
gested.

12.44   One of the most important lessons learned from the atomic
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 only 30 pounds per square inch at the time of the explosion and
because of breaks in mains and house service lines it soon dropped to
10 pounds per square inch; on the following day the pressure was
almost zero.   This drop in the water pressure contributed greatly to
the extensive destruction caused by fire.   The experience at Hiro-
shima was quite similar.

12.45   A large proportion of the fire devastation in Japan after the
atomic bomb attacks was due to the fact that the fire-fighting services
were incapacitated (Fig. 12.45).   It would seem to be advisable that
fire departments of strategic cities and industrial plants should be
housed in structures capable of withstanding the blast at about half
a mile from the explosion. Underground construction or concrete
walls 2 feet thick would provide this degree of blast protection.


## C.   ESSENTIAL DISASTER FACILITIES

### CONTROL AND FIRST AID CENTERS

12.46   Facilities for the direction of disaster-relief activities and
provision of first-aid in a city, require a protected area on one of the

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[8] For a discussion of this and related matters, see "Fire and the Air War," edited by H. Bond, National
Fire Protection Association, Boston, Mass., 1946.

wind, and steps should be taken to reduce to a minimum the inhalation of dust. This would require shutting down the ventilating system and closing all windows and doors in case of an emergency. At distances beyond 12,000 feet from ground zero, many windows would not be broken in an atomic burst, and occupants could remain in buildings with reasonable safety until directed to leave. Provided there were no leakage from outside, air-conditioning systems could remain in operation with advantage.

## OUTSIDE SHELTERS

12.52 Shelters outside of larger structures should, in general, be designed to resist the effects of blast and radiation from an atomic bomb at a reasonable distance, say one-half mile. They should be located well clear of buildings to avoid hazard from debris and fire. A buried or semiburied shelter will usually be the best choice for protection from an air burst, as the earth cover will act as a protection against radiation (Figs. 12.52a and b). In addition, blast effects will



Figure 12.52a. Tunnel shelters in hillside, very close to ground zero in Nagasaki, protected the occupants from blast and from thermal and nuclear radiations.

be less than on a surface shelter. Such buried shelters would, of course, be useless in the event of a nearby underground detonation of an atomic bomb.

Figure 12.52b.  Simple earth and pole shelter, undamaged by fire or blast at 5,000 feet from ground zero, although surrounding buildings were destroyed. (The debris was cleared from the roadway before the photograph was taken.)

12.53   The general aim in structural design of a shelter is to provide strength to resist blast and with sufficient cover to protect against the initial radiations from an atomic bomb.  Reinforced concrete is a good constructional material and can be made strong enough to resist the pressures involved.  Alternatively, corrugated sheet iron of the type used in culverts has strength and is capable of a high degree of distortion without failure.  Wood is also a suitable structural material, but it is less permanent.  In each case an adequate layer of soil or of sandbags would be necessary to make a total thickness equivalent to about 2 feet of concrete.

12.54   Tentatively, shelters may be designed for a static load of 500 pounds per square foot, with usual design stresses to provide an adequate factor of safety.  Additional allowance should be made for the dead load due to the earth cover, etc., and adequate drainage should be provided.  The survival of persons in shelters near ground zero in Japan shows that doors are not needed if a baffle or turn in the entrance shields from the direct heat rays of the bomb.  A ramp entrance is preferable to steps, and two means of exit are essential.

12.55   Although there would be little danger from airborne particles contaminated with radioactivity after a high burst, it might be

advisable to construct shelters so that they would provide protection in case of surface or subsurface bursts, in which the spread of radiation through the air might be a hazard. Hence, special consideration should be given to the problem of insuring suitable ventilation for shelters.

12.56 The most effective method for providing adequate ventilation is to use a pressurized installation in which the air is forced through special air filters which will remove radioactively contaminated particles.[9] The practicability of such extreme measures, however, is open to question. Air-conditioning and cooling systems where provided can be left in operation for cooling and otherwise improving inside air conditions. The length of time that any structure under these conditions can be occupied without addition of fresh air will depend upon many factors, including the number of people inside, heat transmission through walls, removal of carbon dioxide, etc.

## HOME SHELTERS

12.57 Basements of homes, especially if they extended beyond the main structure of the house, would offer reasonable protection against blast damage, provided they are not too near the center of the explosion. However, care must be taken to provide escapes to be used in case the house catches fire or collapses. A shallow rampart of soil or of sand bags outside the house would probably be advantageous. Semiburied shelters for individual families, of the type used in Europe during World War II, for protection against conventional bombs would also provide worthwhile protection against atomic explosions.

## EMERGENCY SHELTER

12.58 The discussion of shelters, given above, has been based on the tacit assumption that there is sufficient warning of air attack to permit people to take shelter. In the event of a surprise atomic explosion, immediate action could mean the difference between life and death. The first indication of an unexpected atomic burst 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 this light, but rather to do everything possible to cover all exposed parts of the body.

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[9] The Chemical Warfare Service No. 6 Filter is satisfactory for handling large volumes of air.

12.59   If a person is in the open when the sudden illumination is apparent, then the best plan is instantaneously to drop to the ground, while curling up so as to shade the bare arms and hands, neck, and face with the clothed body.   Although this will not protect against gamma rays, it may help in reducing flash burns (§ 6.53).   This is important since disabling burns can be suffered well beyond the lethal range for gamma rays (Fig. 12.13).   The curled-up position should be held for at least 10 seconds; the immediate danger is then over, and it is permissible to stand up and look around to see what action appears advisable.

12.60   If in the street, and some sort of protection, such as a doorway, a corner or a tree is within a step or two, then shelter may be taken there with the back to the light, and in a crouched position to provide maximum protection, as described above.   No attempt should be made to reach a shelter if it is several steps off; the best plan then is to crouch on the ground, as if completely in the open. After 10 seconds, at least, a standing position may be resumed, but it is strongly advisable to press the body tightly against the side of a building to avoid breaking glass or falling missiles, as far as possible.

12.61   A person who is inside a building or home when a sudden atomic bomb attack occurs should drop to the floor, with the back to the window, or crawl behind or beneath a table, desk, counter, etc.; this will also provide a shield against splintered glass due to the blast wave.   The latter may reach the building some time after the danger from radiation has passed, and so windows should be avoided for about a minute, since the shock wave continues for some time after the explosion.   The safest places inside a building are the interior partitions, and it is desirable to keep as close to these as possible.

## D. PROTECTION FROM RESIDUAL RADIATIONS

### INTRODUCTION

12.62   As stated earlier, protection of large numbers of people from the effects of the residual nuclear radiations, that might follow the explosion of an atomic bomb, represents an entirely new problem concerning which there has been no previous experience.   After the attacks on Japan the fission products were so widely dispersed as not to be an appreciable danger; at least, there is no evidence that such a hazard existed.   In special circumstances, however, for example, an underwater burst close to the shore or an underground or surface burst, or in the event of the use of radiological warfare weapons, pre-

cautions would have to be taken against the residual radiations. In the present section an outline will be given of the general lines of procedure that might be followed for radiological defense; in view of the lack of experience, these may be regarded as tentative and subject to improvement.

12.63   Since the possibility of combating radioactive contamination is bound up with the extent of the associated physical damage, it is desirable to make a rough classification of the possible combinations that might arise.   Three general types may be distinguished:

(a) *Heavy Physical Damage and Heavy Contamination.*—Such a condition might be due to a combination of an air-burst atomic bomb followed, or accompanied, by the use of a radiological weapon.   In view of the wasteful nature of such action, it may be regarded as not too probable, although it cannot be ignored. An underwater burst in a harbor of a large city, close to the shore, might cause both heavy damage and contamination over a limited area.   In this event, radiological safety measures might be delayed by the necessity of clearing away debris, establishing communications, etc.

(b) *Heavy Physical Damage and Light Contamination.*—This would arise from an atomic explosion of the type experienced at Hiroshima and Nagasaki.   The problem of protection against radioactivity would not be serious in this case.   It would be necessary for monitoring teams to follow the radioactive cloud downwind in case there were a marked fall-out in any particular area.   It is of almost equal importance to know definitely that there is no hazard.

(c) *Moderate or Little Physical Damage and Moderate to Heavy Contamination.*—Such circumstances could arise from a radiological warfare attack, from dry or wet fall-out, from base surge on a ship or on shore at some distance from an underwater explosion, or from an ineffective ("fizzle") explosion of an atomic bomb. The radioactive protection would be of the greatest significance, and to meet these conditions the radiological defense system must be especially prepared.

STAGES OF DISASTER

12.64   In considering the practical problems of a radiological hazard it may be supposed that there will be three stages, the duration and

severity of which will depend on circumstances described above. These are as follows:

(a) *Complete Disorganization.*—In the event of heavy and widespread physical damage, it may be presumed that roads will be blocked for some distance from the explosion, and that all normal communication systems will be out of commission. Emergency transportation and communication, except perhaps for self-contained radio equipment, will not be immediately in effect.

(b) *Emergency Control Stage.*—This phase will begin as soon as margin roads have been cleared, and transportation and communication has been reestablished, at least on an emergency scale, so that information can be transmitted to a control room. In the case of moderate physical disaster (§ 12.63 (c) ), the emergency control phase would start immediately, and might last a week or more.

(c) *Recovery Stage.*—The final phase would be reached when most people were out of immediate danger of injury, and there is time to start more thorough decontamination operations where necessary (Chapter X).

12.65    In the emergency control phase, an important factor in the operation of radiological defense is the rapid gathering of data regarding contamination. The radiations which may be encountered are gamma rays and beta particles from fission products, neutron-induced activity or other radioactive material, and alpha particles from plutonium or uranium. Of these, the gamma radiation can be measured most readily; this is perhaps the greatest immediate hazard because of its considerable penetrating power. Beta particles as such are not a serious menace unless the source enters the system or remains on the skin for some time.

12.66    Monitoring of suspected contaminated areas for gamma radiation should be carried out at the earliest possible moment after an atomic explosion in which such contamination is likely to have been produced. Initially, this might even be done by means of low-flying aircraft; from the gamma radiation dosage measured at a known height above the ground it will be possible to obtain an approximate indication of the area and intensity of contamination (see Fig. 8.35). However, ground monitoring for gamma radiation, with portable instruments, will be necessary at the first opportunity. The monitoring for beta radiation will, in general, be an auxiliary measurement, made in the later stages after the immediate emergency has passed.

12.67  It was pointed out in Chapter XI that while the danger from external beta and gamma radiation might exist, the hazard due to alpha particles, from plutonium or uranium, can be ignored.  This is fortunate, for measurement of alpha contamination is a laborious and time-consuming process.  The detection of surface contamination by a source of alpha particles requires that the instrument be held very close to the suspected surface on account of the short range of the particles.  In any event, the measurement would be extremely difficult, with portable instruments, in the presence of high concentrations of beta and gamma activity.

12.68  Because the specific danger from alpha particles will not arise for some weeks, search for alpha emitters is probably best carried out by taking samples to a laboratory for testing.  The amount of alpha active material suspended in the air can be estimated reliably only by collecting the active material from a large sample of air, using a suitable filtering device (Fig. 9.24b) and then measuring the activity of the deposit on the filter.

## Permissible Radiation Levels

12.69  The question of the amount of exposure to the residual nuclear radiation that is permissible for control and rescue personnel is one which is very difficult to answer exactly, for a good deal will depend on circumstances and the risks which must inevitably be taken. In the initial disorganization phase, when the radioactivity is also most intense, it will be important for emergency personnel to avoid overexposure to radiation except where it is necessary to carry out missions of the greatest importance.

12.70  It may be noted in this connection, however, that because of the rapid initial decay of the fission products, a person who is exposed to the radiation from this mixture for the first hour following an explosion will not suffer any further appreciable injury by staying for several hours more.  A situation of this kind might arise due to the immediate fall-out from an underground or an underwater burst.

12.71  During the emergency control phase the radiological defense system should be fully operable.  As indicated above, estimates of contamination will be based largely on measurement of gamma activity.  Every effort should be made to minimize the dose received by the general population.  If contamination is due to fission products, the actual value will be somewhat higher at the beginning and lower at the end of the period.

12.72   In the recovery stage, the main objective would be to achieve as effective decontamination as possible so as to reduce the general contamination level to that permitted for routine workers with radioactive material, e. g., 0.3 r per week (§ 8.4).   Although there is not complete agreement on the subject, because of the lack of adequate knowledge, the information given in Table 12.72 may

TABLE 12.72

PERMISSIBLE CONTAMINATION

| Contaminated material | Fission product | Alpha-emitter |
|---|---|---|
| Air | $2 \times 10^{-10}$ microeurie/cc | $2.5 \times 10^{-11}$ microgram/cc. |
| Water | $4 \times 10^{-6}$ microcurie/cc | $2 \times 10^{-5}$ microgram/cc. |

be taken as indicating a few approximate permissible contamination levels for continued exposure.   It is assumed that plutonium is the alpha emitter, since this is probably the most dangerous of those likely to be encountered.

12.73   It should be noted that the figures given in the table refer to permissible levels for personnel exposed to radiation every day, as a result of their peacetime occupation.

12.74   With regard to the internal radiation hazard, it is not possible to make any sound estimate of the amount of material which is likely to be ingested in various circumstances.   A person working under normal indoor conditions, for example, would absorb much less than one engaged in an occupation in which there was much dust. Children, because of their habits and closeness to the ground, would be expected to ingest more than adults.   These factors would greatly complicate a rehabilitation program, and make it almost impossible to attempt to assess universal permissible contamination levels.

## MONITORING EQUIPMENT

12.75   All emergency workers, no matter what their duties, who are sent into areas contaminated with beta or gamma radiation, should be provided with, or closely accompanied by, instruments for personnel monitoring (see Chapter IX).   During the disorganization phase and for part, at least, of the emergency control phase, these would have to be of the self-reading, pocket dosimeter type.   Instruments of various total ranges, in roentgens, are available, and it would be necessary to use the particular range appropriate to the work to be undertaken.   Provision must be made for recharging the dosimeters after each period of use, for otherwise they would be valueless.

12.76   Because of the high cost of the self-reading instruments, their number would presumably be limited, so that only one might have to be supplied to a group operating in close proximity.   With improving transportation, communication, and control, the pocket chambers, which require to be read by an electrometer device, could be used. The combined charger and reader could be available on a rescue truck or other similar vehicle.   The film badge is the simplest and cheapest of personnel-monitoring devices, but its disadvantage lies, as stated in Chapter IX, in the fact that time is required to collect, develop, and interpret the films.   This handicap might be overcome by the use of a transportable photographic laboratory with relatively simple equipment.

12.77   Some indication of the time which emergency workers could spend in a particular location in a contaminated area can be obtained from Fig. 12.77,[10] which gives the total accumulated dosage for various times spent in a contaminated area, divided by the dosage rate at the time of entry.   By taking a reading of the dosage rate in roentgens per hour at the time of entering a contaminated area, the total dosage acquired during any subsequent interval can be determined.   For example, if a person enters the area at 1.5 hour after the explosion and the dosage rate is found to be 15 r per hour, then if he stays for 2 hours the total dosage will be the ordinate, corresponding to the abscissa of 1.5 hour and the parameter 2 hours, multiplied by 15, i. e., $1.2 \times 15 = 18$ r.

12.78   Survey instruments (see Chapter IX) carried by teams operating during the first two phases should be of the area survey type for gamma radiation.   They should be able to measure at least 5 r per hour, and a certain number should be capable of responding to beta, as well as to gamma, radiation, as they will be required at a later stage.   Alpha-beta-gamma survey meters, reading up to 25 r per hour, will be useful in the emergency control stage if there are insufficient beta-gamma survey meters available.   However, as stated previously, it is important that no time should be wasted in a search for alpha radiation in the early stages.   This work should be left until considerably later, and is best carried out in the laboratory.   Where aerial monitoring is undertaken and measurements are made at some distance above the earth's surface, sensitive gamma-ray meters would be required.

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[10] The difference between Fig. 12.77 and Figs. 10.21a and b lies in the fact that the former requires a measurement of the dosage rate to be made at the time operation in an area is started; for the latter, the measurement can be made at any time.
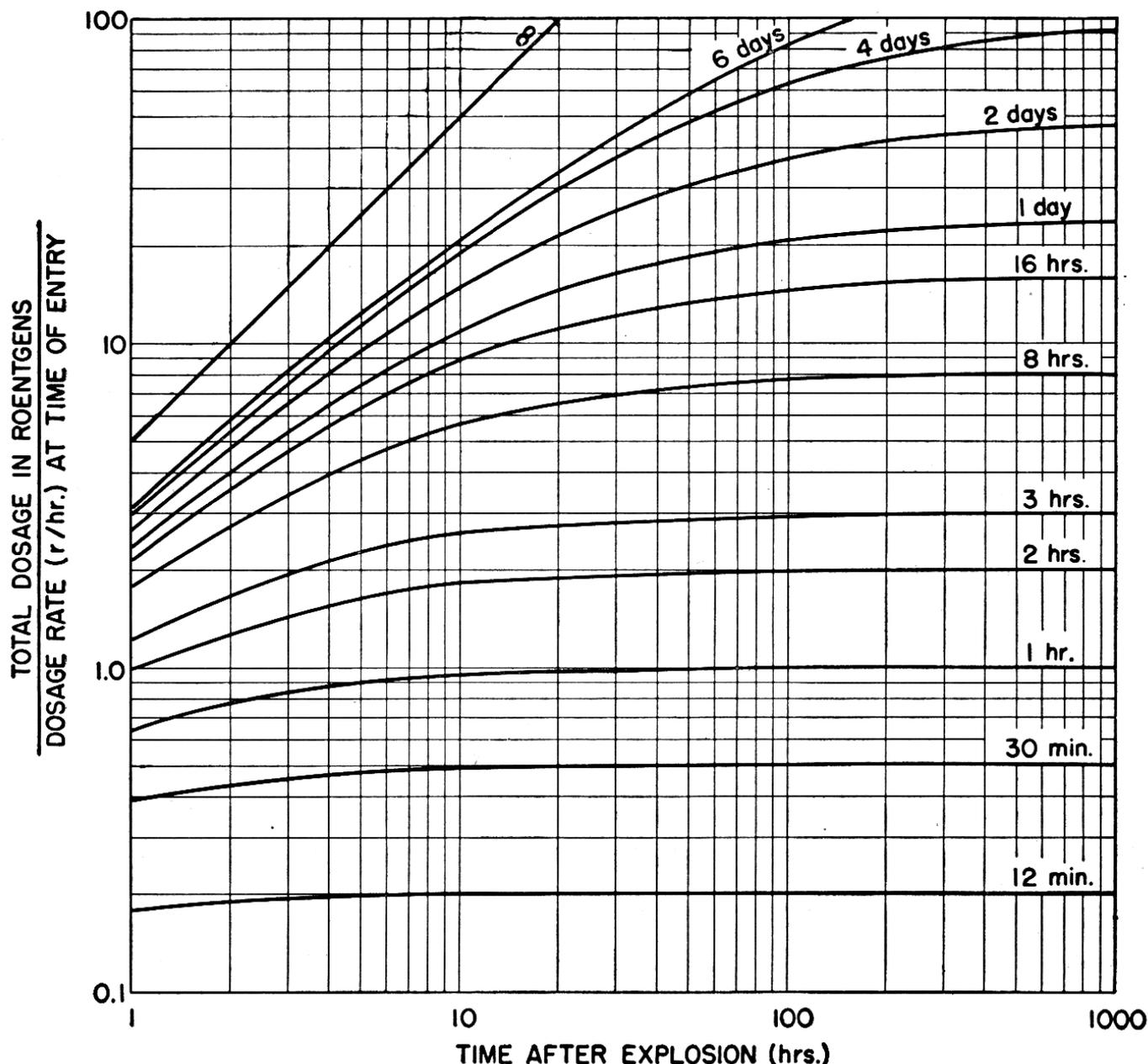
Figure 12.77.   Determination of total radiation dosage received in a contaminated area.

PROTECTIVE CLOTHING

12.79   Personnel entering a contaminated area, whether to perform monitoring or other emergency work, should wear protective clothing of some kind.   Actually ordinary clothing is adequate protection against alpha and beta radiation, but since it is likely to become contaminated it would have to be destroyed.   It is preferable, therefore, to make use of relatively cheap coveralls, worn over the clothing. These could be washed if not too badly contaminated, or discarded altogether.   Smocks, made of fabric or plastic, which protect a large part of the clothing, while not so effective as coveralls, will have some value.   As a general rule, rubber suits will not be necessary for work in a contaminated area.   But if there is any chance of the clothing becoming wet, either in a washing-down operation or in any other way,

such suits, which cover the whole body, should be provided (see Fig. 10.39). They can be cleaned with a stream of water and used several times.

12.80 Booties made of canvas and which slip over the shoes, should always be worn in a contaminated area; the bottoms of the trouser legs should be tied over the outside of the booties. Gloves of some kind should also be provided. Ordinary cotton gloves will afford good protection in most cases, although surgeons' gloves, made of rubber, may be preferable in some cases. Hard leather gloves should be used when rough handling is involved as, for example, when digging in rubble. Some sort of tight-fitting cap, preferably of the type used by surgeons, covering the hair as completely as possible, should be worn at all times.

12.81 Soon after an atomic explosion there is likely to be a large amount of dust in the air, especially in the regions of appreciable destruction. As stated in § 12.55, there is practically no danger in this dust being contaminated after a high air burst. However, other types of deliveries could spread radioactivity on the ground. Consequently, all members of emergency teams entering a contaminated area should wear respirators. Masks covering the nose and mouth, of the type developed as a protection against chemical warfare agents, have been found to be satisfactory in preventing the inhalation of dust particles. Where the amount of dust is very large, it might be necessary to use a respirator hood to give complete protection of the head.

## E.  CONCLUSION

12.82 It will be evident from the material presented in this chapter that adequate protection against the effects of an atomic bomb attack will require very comprehensive and detailed planning. Such planning will be necessary to avoid panic, for mass hysteria could convert a minor incident into a major disaster. It has been the purpose of this book to provide the essential scientific and technical information that will permit the necessary plans to be made for dealing with the new and unusual situations that would arise as the result of the explosion of an atomic bomb. The organization, preparation, and techniques designed to deal with these situations involve considerations beyond the scope of this book. Their precise nature depends upon many factors which must be evaluated nationally, and their application will vary with the patterns of regional and community development.

# *APPENDIX D* [1]

## SPECIAL PROBLEMS IN GAMMA RAY TRANSMISSION

CIRCULAR AREA OF RADIOACTIVE CONTAMINATION ON THE GROUND

D.1  The special case considered here is the evaluation of the ionization produced in the air as a function of distance $h$ above a circular area on the ground uniformly contaminated with radioactive material. This situation might arise from the deposition on the ground of fission products after the explosion of an atomic bomb. Let $j(\alpha_0)$ be the number of gamma rays of energy $\alpha_0$ (Mev) emitted per second and per cm.² from the contaminated area. The present interest is in distances $h$, which are so small compared with the mean free path of the photons in air that only the unscattered contribution to the radiation received need be considered. Further, the dosage rate will be calculated at a point $h$ above the center of the area. At this location, for given $h$, the maximum dosage rate is obtained; and, if the radius $R$ of the contaminated area is much greater than $h$, it may be shown that the dosage rate will be essentially constant at the height $h$ over all the area except near the boundary.

D.2  The unscattered gamma ray energy intensity in units of Mev per cm.² per second received at $h$ from the element of area $2\pi\rho d\rho$ (cf. Fig. D.2a) is given by the equation

$$dE(h) = \frac{2\pi\rho d\rho\, j(\alpha_0)\,\alpha_0 \,\exp\,[-\mu_c(\alpha_0)\,(\rho^2+h^2)]^{\frac{1}{2}}}{4\pi(\rho^2+h^2)}$$

$$dE(h) = \frac{j(\alpha_0)\,\alpha_0}{2}\, \frac{\exp\,[-\mu_c(\alpha_0)\,(\rho^2+h^2)]^{\frac{1}{2}}}{(\rho^2+h^2)}\,\rho d\rho, \qquad (D.2.1)$$

where $\mu_c$ is the Compton scattering coefficient. The integrated energy intensity coming from the entire contaminated area is

$$E(h)_R = \frac{j(\alpha_0)\,\alpha_0}{2}\,[Ei(-\mu_c\sqrt{h^2+R^2}) - Ei(-\mu_c h)]\,\frac{\text{Mev}}{\text{cm}^2}. \quad (D.2.2)$$

The dosage rate in roentgens/sec. is $1.45 \times 10^{-5}\mu_A(\alpha_0)E(h)$. Here $\mu_A$ is the Klein-Nishina coefficient for energy absorption in air at
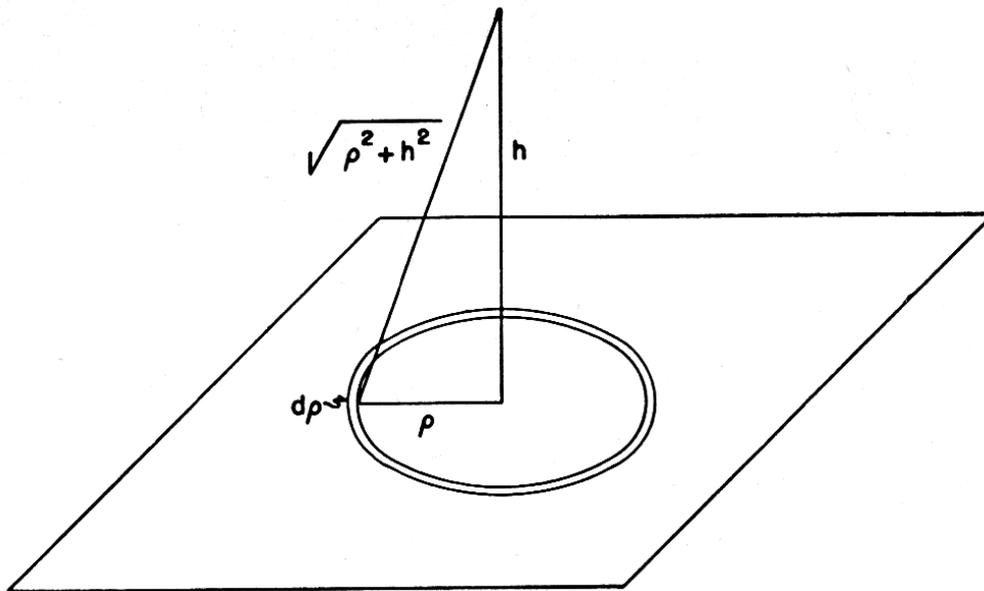
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[1] By S. T. Cohen and M. S. Plesset.

Figure D.2a.   Uniformly contaminated circular area.

standard conditions as given in Fig. D.2b.   For $R$ very large, there is a special case of equation (D.2.2), namely,

$$E(h)_\infty = \frac{j(\alpha_0)\,\alpha_0}{2}\,[-Ei(-\mu_c h)],$$   (D.2.3)
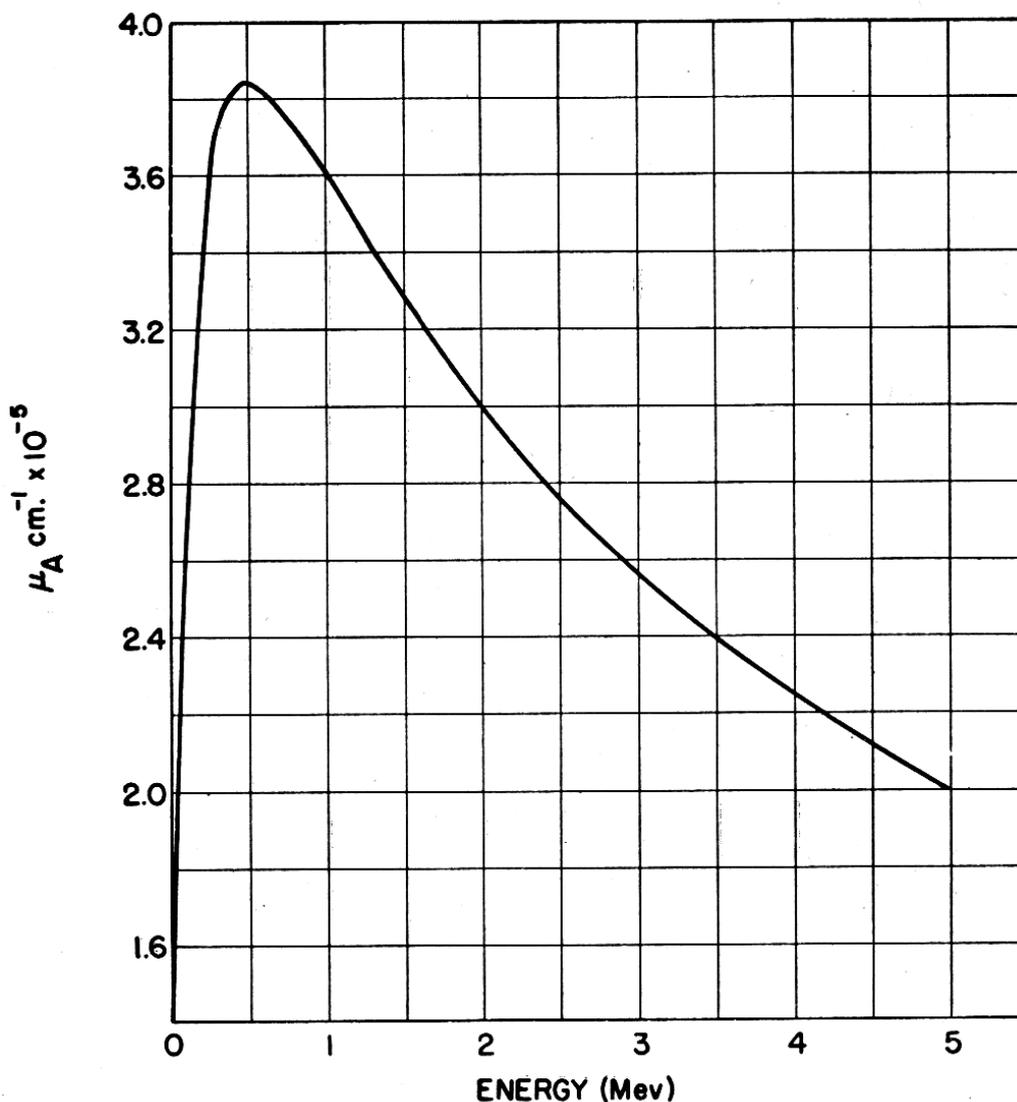


Figure D.2b.   Klein-Nishina absorption coefficient for air.

so that equation (D.2.3) corresponds to an infinite contaminated sheet. In Fig. D.2c, the ratio $E(h)_R/E(h)_\infty$ is shown, for various values of $h$, as a function of $R$. These curves apply to the case where the emitted gamma radiation has the energy 1 Mev. In Fig. D.2d, the ratio of the dosage rate, $E_\infty(h)$, at a height, $h$, in meters above an infinite contaminated area on the ground to the dosage rate, $E_\infty(1)$, at a height of one meter above the infinite contaminated area is
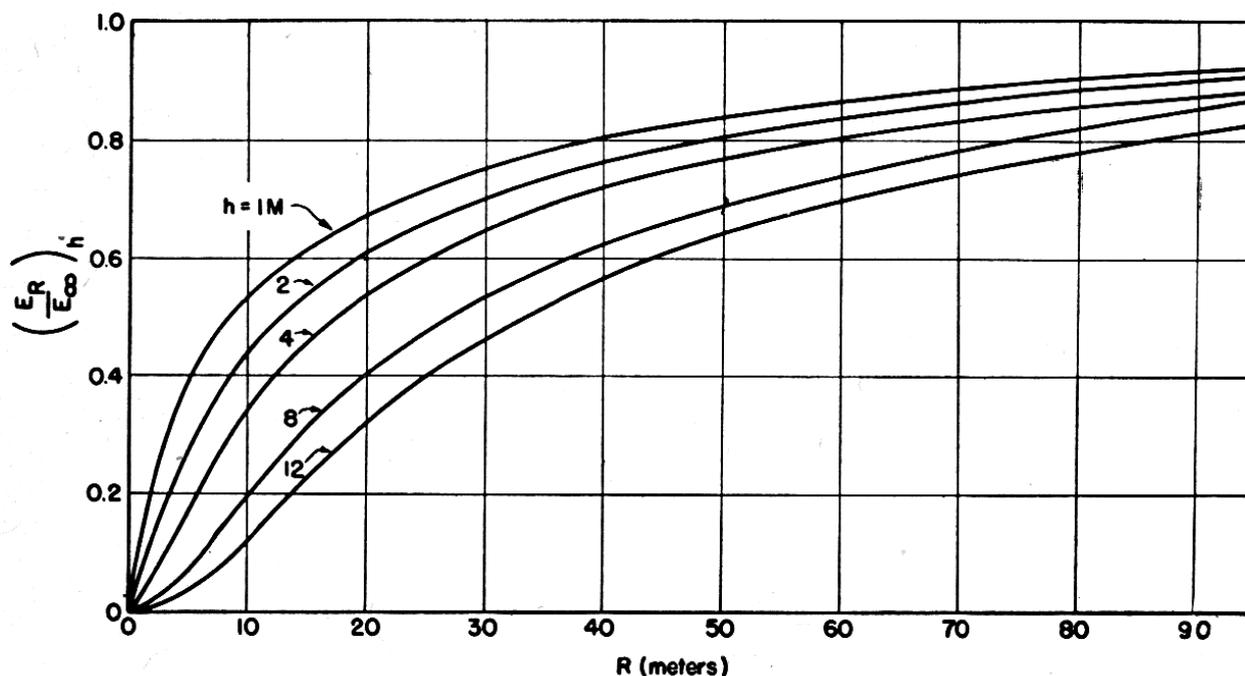
Figure D.2c. Relative dosage rate at various heights above a finite contaminated slab as function of the radius, for 1-Mev gamma radiation.
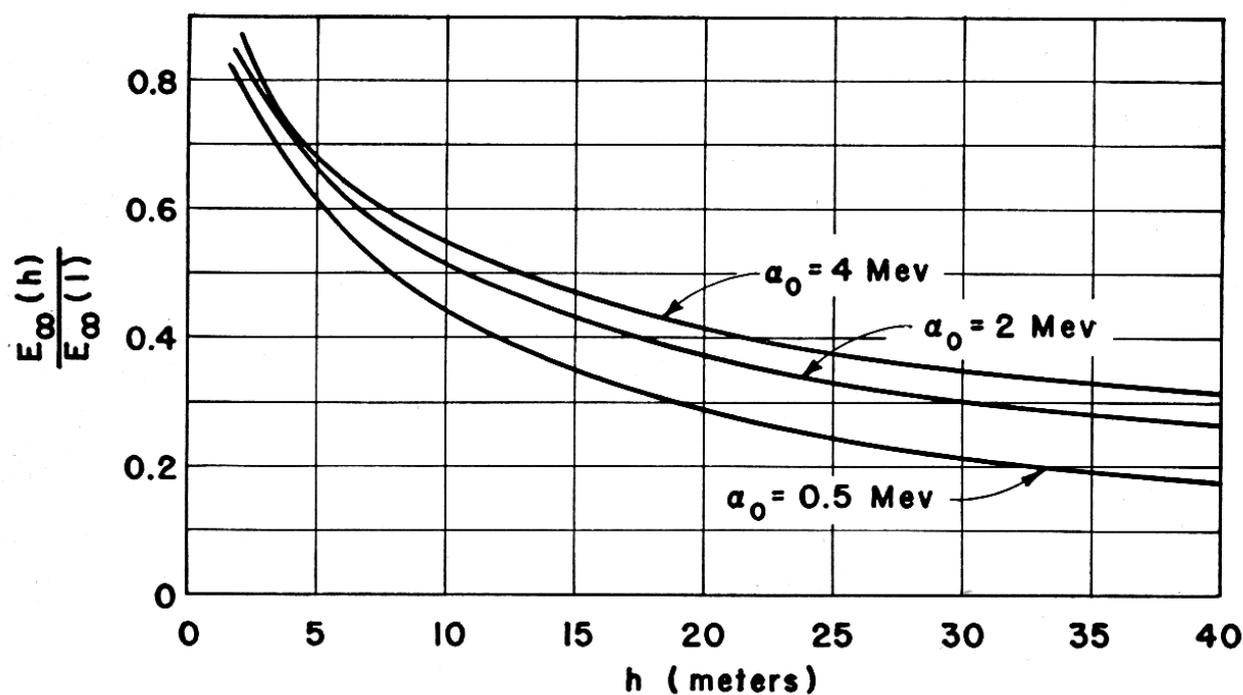
Figure D.2d. Relative dosage rate for various gamma-ray energies as function of the height above an infinite contaminated slab.

shown as a function of $h$ for three values of the emitted gamma ray energy.

## SEMI-INFINITE CONTAMINATED SLAB

D.3   This case could correspond to a large body of water contaminated from the surface to a depth large compared with the mean free path of the gamma rays in water.   The energy intensity of the emitted gamma radiation will be determined at a height $h$ in air above the water.   The number of gamma rays of energy $\alpha_0$ emitted per cc. per second will be taken as constant over the contaminated volume and equal to $i(\alpha_0)$.   If the gamma ray flux emerging from the water surface, as reduced by self-attenuation, is determined, this problem then becomes similar to the case discussed above.   The important contribution to the gamma ray flux emerging at the surface comes from the layer of water near the surface which is only a few mean free paths thick.   A slight underestimate of this emerging flux will be made by calculating it on the basis that only unscattered radiation makes an appreciable contribution.

D.4   With this approximation, the energy intensity (in Mev/sec. cm.$^2$) at the water surface is (cf. Fig. D.4)

$$d^2E_S = \alpha_0 i(\alpha_0) \frac{2\pi\rho^2 \sin\theta \, d\theta \, d\rho \, e^{-\mu_c(\alpha_0)\rho}}{4\pi\rho^2}, \qquad (\text{D.4.1})$$
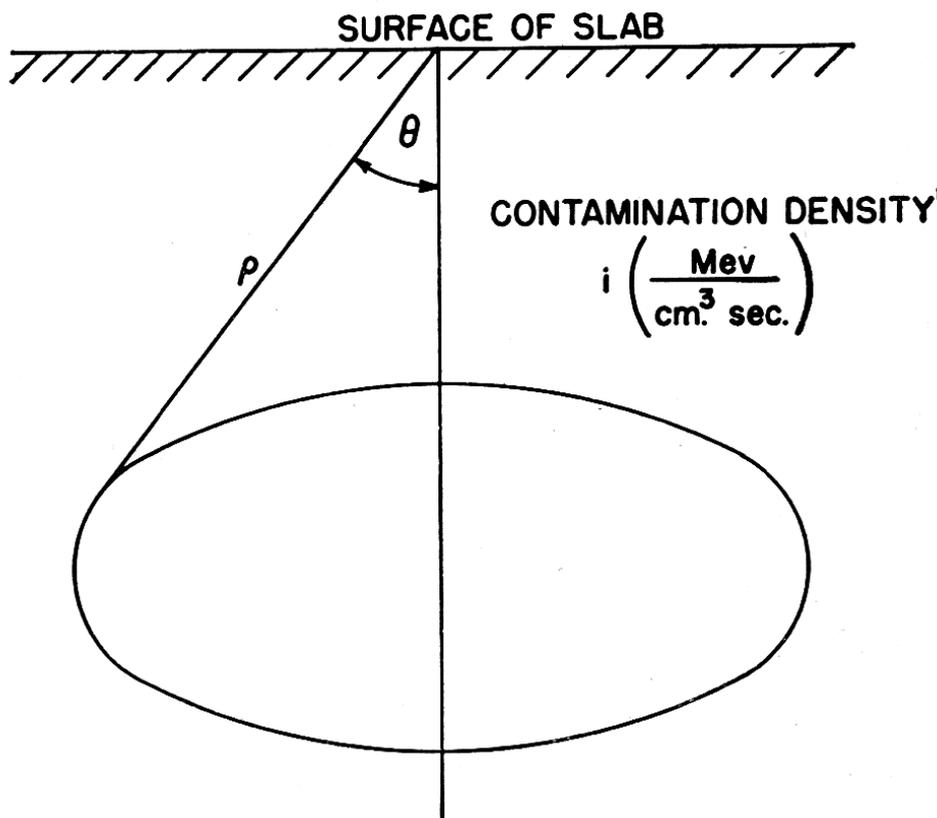


Figure D.4.   Semi-infinite contaminated slab.

where $\mu_c$ is the Compton scattering coefficient for water.   The equivalent isotropic energy intensity at the water surface is given by integration as

$$E_S = \frac{\alpha_0 \dot{i}(\alpha_0)}{2\mu_c(\alpha_0)}. \qquad (D.4.2)$$

If this value for $E_S$ is now used for $\alpha_0 j(\alpha_0)$ in equation (D.2.3), the value for the energy intensity in air at a distance $h$ above the water surface is found to be

$$E(h) = \frac{\alpha_0 \dot{i}(\alpha_0)}{4\mu_c(\alpha_0)} [-Ei(-\mu_c h)], \qquad (D.4.3)$$

where $\mu_c$ is the Compton scattering coefficient for air for the photon energy $\alpha_0$.   The dosage rate (roentgens per second) is again $1.45 \times 10^{-5} \mu_A(\alpha_0) E(h)_\infty$.

D.5   The dosage rate inside a volume of radioactively contaminated water, large compared with the mean free path in water, is given by

$$1.45 \times 10^{-5} \mu_A(\alpha_0) \dot{i}(\alpha_0) \alpha_0 \int_0^\infty e^{-\mu_c(\alpha_0) l} B(\alpha_0, l) \, dl.$$

# APPENDIX E[1]

## CALCULATION OF HAZARD FROM WORLD-WIDE CONTAMINATION

### I. PLUTONIUM

Assume:

1. A 20 kiloton TNT energy equivalent bomb leaves 100 pounds of plutonium.
2. The surface of the earth is $5.1 \times 10^{18}$ square centimeters.
3. The contamination is distributed uniformly over the surface of the earth.
4. Hazard to humans is from agricultural areas, in which contamination is uniformly mixed with the top 1 centimeter of soil.
5. Concentration of plutonium in the ash of food eaten is the same as in the soil. This assumption overrates the danger, as plants are known to select against plutonium.
6. A man eats 1,000 pounds of food per year, of which 1 percent is ash.
7. Of plutonium ingested, 0.007 percent is fixed in the body (J. G. Hamilton, *Rev. Mod. Phys.*, *20*, 718, 1948).
8. The safe rate of fixation of plutonium in the body is 0.07 micrograms per year.

From these assumptions it is readily calculated that: From one bomb there is $2.5 \times 10^{-6}$ microgram of plutonium in 1 pound of soil. From a man's yearly ration he absorbs $1.8 \times 10^{-10}$ microgram of plutonium from each bomb which has exploded up to that time; hence the number of bombs to endanger is 0.07 divided by $1.8 \times 10^{-10}$, or $4 \times 10^8$.

To calculate the hazard from respiration of plutonium, the following additional assumptions are required:

9. That, on the average, an individual retains 5 grams of dust per year in his lungs.
10. That all plutonium entrapped as dust in the lungs becomes fixed in the body.

From these assumptions it follows that the yearly rate of absorption is $10^{-9}$ microgram, and the number of bombs to endanger is 0.07 divided by $10^{-9}$, or $7 \times 10^7$.

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[1] Material supplied by E. S. Gilfillan, H. Scoville, Jr.

## II. Fission Products

Assume:

1. All fission products have settled uniformly over the surface of the earth and there remains no fission product activity in the air.
2. The surface of the earth is $5.1 \times 10^{18}$ square centimeters.
3. The fission product activity is $6 \times 10^9$ curies at 1 hour after detonation of a nominal atomic bomb and the fission products decay according to the $t^{-1.2}$ law.
4. All bombs are exploded at the same time and the time after detonation for which these calculations are made is 6 months.
5. The level of activity is 0.1 r per 24 hours.
6. One thousand curies per square mile will produce an exposure of 0.1 r per 24 hours.
7. There is no shielding.

Curies at end of 6 months (4,320 hr.)

$$= 6 \times 10 \times \frac{1}{(4,320)^{1.2}}$$

$$= \frac{6 \times 10^9}{23,040} = 2.6 \times 10^5 \text{ curies per bomb at 6 months after detonation}$$

Curies per square centimeter per bomb at 6 months

$$= \frac{2.6 \times 10^5}{5.1 \times 10^{18}} = 5.1 \times 10^{-14} \text{ c/cm}^2 \text{ bomb}$$

Curies per square centimeter for 0.1r/24 hours exposure

$$= \frac{1,000}{2.6 \times 10^{10}} = 3.85 \times 10^{-8} \text{ c/cm}^2 \text{ (1 square mile} = 2.6 \times 10^{10} \text{ cm}^2)$$

Number of bombs needed for 0.1r/24 hours

$$= \frac{3.85 \times 10^{-8}}{5.1 \times 10^{-14}}$$

$$= 7.55 \times 10^5 = 755,000 \text{ bombs for 0.1r/24 hours at 6 months after}$$
detonation.

# APPENDIX F[1]

## METEOROLOGICAL TRAJECTORY ANALYSIS

The fall-out trail can be estimated in the following manner if the wind velocities are known at a series of heights: $h_1 < h_2 < h_3 < \ldots < h_n$. Let $V_x(h_i; \tau)$ be the component of wind velocity at the height $h_i$ at the time $\tau$ from the north direction (a negative value of $V_x$ corresponds to a southerly component); $V_y(h_i; \tau)$ be the component of wind velocity from the east; $x$ is the distance north of ground zero; $y$ is the distance east of ground zero. Consider a particle which is located at a height $h_j$ at a point $(x_0, y_0)$ at a time $t = 0$ and require the time $t$ to reach the ground. This particle will land at a point $(x, y)$ given by the equations

$$x = x_0 - \frac{t}{h_j} \sum_{i=1}^{i=j} (h_i - h_{i-1}) V_x \left( h_i; \tau = t \left( \frac{h_i - h_{i-1}}{h_j} \right) \right)$$

$$y = y_0 - \frac{t}{h_j} \sum_{i=1}^{i=j} (h_i - h_{i-1}) V_y \left( h_i; \tau = t \left( \frac{h_i - h_{i-1}}{h_j} \right) \right)$$

If a rough initial distribution of the active material is assumed at a time $t = 0$, these equations suffice to map out the trail. For example, it might be assumed that initially all of the active material is located in a cylinder 1 or 2 miles in radius extending up to the base of the stratosphere. Calculations for a series of points on the surface of the cylinder and a series of assumed times of fall, $t$, will suffice to rough out the fall-out trail and the time of arrival of the activity. This type of analysis has been used successfully at Alamogordo and Bikini in connection with the experimental bomb tests.

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[1] By J. O. Hirschfelder.