SECTION II
BLAST AND SHOCK PHENOMENA

2.1 Air Blast Phenomena

a. General. The shock wave which propagates through air as a consequence of a nuclear explosion is commonly referred to as a blast wave. The head of the blast wave, called the shock front, causes an abrupt rise in both overpressure and dynamic pressure as it passes a given point, as illustrated at point B in figure 2-1. In the case of overpressure, this abrupt rise is followed by a decline to a pressure below ambient and then a gradual return to ambient. The portion of the wave in which the overpressure is above ambient is termed the positive overpressure phase, while the remaining portion, where the pressure is below ambient, is called the negative pressure phase. The decrease in pressure below ambient in the negative phase is usually small in comparison with the increase in pressure in the positive phase.

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The dynamic pressure associated with mass motion of air has a positive duration somewhat...
greater than the overpressure positive duration. During this period the transient winds blow in the direction of shock motion. The wind velocity after decreasing to zero reverses direction and flows toward the direction of the nuclear explosion. The dynamic pressure associated with this reverse flow of air is insignificant. The pressure-time histories of the overpressure and dynamic pressure are shown schematically in figure 2-1.

b. Propagation in Free Air.

(1) General. As the blast wave moves out from the fireball region, various changes in its physical characteristics occur as a function of time and distance. In free air, i.e., in a homogeneous atmosphere where no boundaries or surfaces are present, these changes take place in a definite manner as a result of spherical divergence and irreversible energy losses to the air through which the blast wave propagates.

As previously noted in paragraph 1.4b(3), the shock front velocity and peak overpressure decrease with increasing distance, while the duration of the positive phase increases. Other blast wave parameters are affected in a similar way, so that the blast wave is said to be attenuated with distance. The manner in which these changes take place for the different blast wave parameters is described in succeeding paragraphs.

(2) Time of arrival. As the shock front travels away from an explosion under sea level conditions, its velocity of propagation at breakaway is approximately seven times the velocity of sound. As the peak overpressure approaches zero, however, the shock front velocity approximates sonic velocity. The time of arrival of the shock front as a function of distance in free air for 1 KT burst in a homogeneous sea level atmosphere is shown in figure 2-2. The time of arrival for other yields can be computed using the scaling procedure accompanying the figure.

(3) Overpressure.

(a) Peak overpressure. The term overpressure, expressed in pounds per square inch (psi), is used to describe an increase in pressure over ambient. Peak overpressure is the highest overpressure reached during the passage of the blast wave. The basic free air curve for the attenuation of peak overpressure with distance for a 1 KT explosion in a standard sea level atmosphere is given in figure 2-3. Standard sea level atmospheric conditions are given in appendix II. The distance to which a given peak overpressure extends for other yields may be computed by use of the scaling procedure accompanying figure 2-3.

(b) Duration. The duration of the positive overpressure phase of a blast wave from a nuclear detonation of a given yield increases as the peak overpressure decreases with distance. Also the duration of the positive overpressure phase for a given peak overpressure increases as the yield increases. The variation of positive phase duration with distance is illustrated in figure 2-4. Accompanying this figure is the scaling procedure for other yields.

(c) Impulse and wave forms. In many cases, the damage resulting from a nuclear detonation is more nearly a function of both the positive phase overpressure and its duration, specifically the overpressure impulse, than upon peak overpressure alone. The overpressure impulse \( (I_o) \) of the positive phase of the blast wave is the area under the positive portion of the overpressure-time curve as illustrated in figure 2-1. This curve or wave form varies in an exponential fashion, depending on the peak overpressure. Negative phase impulse is similarly defined in terms of the underpressure; however, it is usually less significant than the positive phase impulse. For a more detailed discussion of impulse and wave forms, refer to appendix I.

(4) Dynamic pressure.

(a) General. As mentioned in (a), above, a wind of high velocity blowing in the
direction of shock motion exists immediately behind the shock front. Dynamic pressures are a measure of the drag forces associated with these winds and are a function of the density and particle velocity of the air behind the shock front. Dynamic pressure is usually denoted by "q" and is expressed in pounds per square inch. Examples of the maximum winds or peak particle velocities expected for various free air peak overpressures in a homogeneous sea level atmosphere are shown in table 2-1. The wind velocities shown therein coincide with the onset of the shock front, but thereafter diminish as the blast wave overpressure decreases. It is emphasized that wind velocities following the shock front exist only for short periods of time, and the effects cannot be compared directly with steady winds of the same velocity. However, the duration of the blast wind for a given dynamic pressure increases with increase in yield. The relation between free air peak dynamic pressure and distance for a 1 KT burst in a homogeneous sea level atmosphere is given in figure 2-5. The distance to which a given peak dynamic pressure extends for other yields may be computed by use of the scaling procedure accompanying this figure. During the negative overpressure phase, the transient winds reverse and blow at reduced velocities; the resulting values of dynamic pressure are small and act in the opposite direction.

(b) Duration. The time during which dynamic pressure acts in the direction of shock motion at a given distance from the detonation is somewhat longer than the positive phase duration of the overpressure at the same distance. The wind velocity does not go to zero at the same time the overpressure becomes zero due to the inertia of the air in motion. This "overshoot" is usually not significant because of the very rapid decay of the dynamic pressure behind the shock front. As shown by figure 2-1, the dynamic pressure is very small at the end of the overpressure positive phase.

c) Impulse and wave forms. The dynamic pressure impulse is the area under the dynamic pressure-time curve. This curve or wave form varies in an exponential fashion, depending upon the peak dynamic pressure. For a more detailed discussion of impulse and wave forms, refer to appendix I.

<table>
<thead>
<tr>
<th>Peak overpressure (psig)</th>
<th>Peak particle velocity (ft/sec)</th>
<th>Dynamic pressure (psig)</th>
<th>Peak density (slugs/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>72</td>
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<td>1,180</td>
<td>75</td>
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<tr>
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<td>2</td>
<td>103</td>
<td>70</td>
<td>0.1</td>
</tr>
</tbody>
</table>

(1) General. When an incident air blast wave strikes a more dense medium, such as the earth's surface, it is reflected as shown in figure 2-6. The reflected wave near the earth's surface moves faster than the incident wave because the former travels through a region which, as a result of the passage of the incident shock front, is hotter and more dense than the ambient atmosphere. Therefore, under appropriate conditions, that portion of the reflected shock near the surface overtakes and merges with the incident shock to form a single shock front called the Mach stem. Due to the reflection process, higher peak overpressures and higher peak dynamic pressures are realized at or near the surface than would be obtained at the same distance in free air.
The characteristics of the blast wave at or near the surface, as well as the formation of the Mach stem, are dependent upon yield, height of burst, and the boundary or reflecting surface conditions. The region where the incident and reflected shocks have not merged to form a Mach stem is often referred to as the region of regular reflection; the region where they have merged is referred to as the region of Mach reflection. As the Mach stem travels along the surface, the triple point (the point of intersection of the incident wave, reflected wave, and the Mach stem) rises. The estimated height of the Mach stem as a function of height of burst and distance from ground zero is given in figure 2-7, for a 1 KT burst. The procedure for scaling to other yields is illustrated in the example accompanying this figure. In addition to the fusing of the reflected and incident blast waves to form a Mach stem as just described, that portion of the reflected wave passing through the fireball of a burst in the transition zone will also fuse with that portion of the incident wave directly above the fireball. This fusion is primarily a result of the increased velocity of the reflected wave as it passes through the fireball, and as a consequence, is relatively narrow in lateral extent. As the height of burst varies from the surface to about 160 W'13, the peak overpressures in the fused wave above the fireball vary from those ex-
pected from a particular weapon burst at the earth's surface to those expected from a free air burst of the same weapon. This is primarily the consequence of the spherical divergence of the reflected shock together with the dissipative effect of passing through a heated region.

(a) *Good surface conditions.* The preceding description of the reflection process considers the earth's surface as if it were an ideal reflector. For bursts over real target areas, however, the condition and nature of the surface must be considered, since it has been determined that under certain circumstances severe modifications of the blast wave may occur. These modifications are due to the physical characteristics of the surface, which result in thermal and mechanical effects on the blast wave. These effects will be discussed further in d(4) below. In a practical sense, the surfaces which most closely approach the ideal are ice, snow and water. These surfaces are considered as “good,” since the influence of such surfaces in altering the blast wave is expected to be a minimum. The air blast characteristics for nuclear detonations over such “good” surfaces are presented in figures 2-8A, 2-9, and 2-11A.

(b) *Average surface conditions.* As noted above, the characteristics of the blast wave can be appreciably influenced by the type and condition of the surface over which it passes. In many target areas, it is expected that a significant thermal layer will form near the surface prior to shock arrival. The interaction of the incident blast wave with this thermal layer may affect the reflection process to a considerable degree, depending on the intensity of the thermal layer. Thus individual blast wave parameters such as shock velocity, peak overpressure, particle velocity, peak dynamic pressure and duration, as well as arrival times, wave forms and impulse values, will be affected. The nature of these perturbations depends on the height of burst and ground range involved, and to a lesser extent on the yield. They are important for surface bursts, bursts in the transition zone, and air bursts over such surfaces as desert sand, coral, wooded and agricultural areas. In general, severe thermal effects on the blast wave may be expected over such surfaces for burst heights up to 650 W^{1/3} feet, while moderate to light thermal effects may be expected for burst heights between 650 W^{1/3} and 800 W^{1/3}. However, these thermal effects are not expected in regions where pressures are below 6 psi for bursts over any surface. Mechanical influences on the blast wave may be present for any pressure level, but their relative importance is considerably less than the thermal effects previously mentioned. A detailed discussion of thermal and mechanical effects is given in d(4) below. The air blast characteristics for nuclear detonations over the real surfaces described above are presented in figures 2-8B, 2-10, and 2-11B. These figures should be used as representative for all target areas where surface conditions cannot be considered as good.

(2) *Time of arrival.* The time of arrival of the shock front on the surface is given in figure 2-8 as a function of height of burst and ground range for a 1 KT burst in a homogeneous sea level atmosphere. For other yields, cube root scaling applies to burst heights, ground range and time. Figure 2-8A applies to good surface conditions while 2-8B applies to average surface conditions.

(3) *Peak overpressure.*

(a) *General.* For given surface conditions, the variation of peak overpressure with distance as a function of the height of burst is presented in "height of burst" curves. Curves for good surface conditions are shown in figure
of burst and yield, as well as the extent of perturbation of the wave form as noted above. The classical wave form previously discussed for free air overpressures (characterized by an instantaneous rise to a peak value at shock arrival, followed by an exponential decay in some manner dependent upon shock strength) is seldom found along the surface for overpressure levels above 6 psi. Only for such specialized surface conditions as snow, ice and water, where thermal effects on the blast wave are expected to be at a minimum, do the wave forms for higher overpressure levels approach the ideal. Even then, minor mechanical effects may be present; for example, over water the rise time may not be instantaneous and there may be a slight rounding of the peak value of the overpressure wave form.

In general, non-ideal overpressure wave forms which reflect precursor action will result for those bursts over such real surfaces as desert sand, coral, wooded and agricultural areas where significant thermal effects on the blast wave may be expected. The variation in the overpressure wave shape depends on height of burst and ground distance. For a detailed discussion of wave form types and overpressure impulse to be expected under various conditions, refer to appendix I. A detailed discussion of the precursor is given in d(4) below.

4) Dynamic pressure.

(a) General. For given surface conditions, the variation of peak dynamic pressure at the surface with range depends on the yield and height of burst. This dependence is shown in the form of height of burst curves, such as those presented in figure 2-12 for 1 KT in a homogeneous sea level atmosphere for good surface conditions. These curves approach the ideal situation where thermal effects on the blast wave are
considered to be at a minimum over such surfaces as ice, snow and water. Under these conditions, wave forms are more nearly ideal. It should be noted that the curves in figure 2-12 show only the horizontal component of particle velocity, or the flow of air parallel to the surface. Consequently, all dynamic pressure levels fall to zero at ground zero, where the mass motion of the air has no horizontal component. However, peak overpressures in this close-in region of low horizontal dynamic pressures may be very high (see fig. 2-9). To scale to other yields, the height of burst and the distance to which a given dynamic pressure at the surface extends are multiplied by the cube root of the selected yield. This procedure is illustrated in the example which accompanies figure 2-12.

For average surface conditions, the variation of peak dynamic pressure at the surface with height of burst is presented in figure 2-13 for 1 KT in a homogeneous sea level atmosphere. This curve is based on limited empirical data which reflect both thermal and mechanical effects on the blast wave. As a result, wave forms above 1.5 psi are distorted in varying degree, depending upon the range and height of burst. Under such conditions, the classical shock front disappears, and peak values of the various air blast parameters occur at different times after shock arrival at a given range. The entire behavior of the blast wave in this region may be described as non-ideal. It is believed that the peak values of dynamic pressure reflect both increased particle velocities and dust loading in the precursor region. These effects are discussed further in d(4) below.

(b) Duration. As with the overpressure positive duration, the duration of dynamic pressure is dependent upon height of burst, ground range, yield and surface conditions. The limited data available indicate that dynamic pressure duration may be assumed equal to overpressure positive phase duration without serious error at the same range and height of burst. Therefore, dynamic pressure durations may be determined from figure 2-11A for good surface conditions and figure 2-11B for average surface conditions.

(c) Impulse and wave forms. Dynamic pressure impulse is the total area under the dynamic pressure-time curve. It is not possible at this time to establish a quantitative relation between height of burst, ground range, yield and surface conditions, due to the extreme variations in the limited full-scale data presently available. However, a few general statements concerning wave form variations with surface conditions are possible. For good surface conditions, that is, where thermal effects on the blast wave are minimized, wave forms for dynamic pressure approach the ideal or classical case. However, minor perturbations may sometimes occur for blast waves traveling over water due to the "pickup" of water near the surface. A further discussion of water loading of the shock wave is found under d(4)(d) below.

For bursts over such real surfaces as desert sand, coral, wooded and agricultural areas, where significant thermal effects on the blast wave may be expected, considerably disturbed non-ideal wave forms will be observed. Mechanical effects such as dust loading also contribute to wave form modification under such conditions. Measurements in this region often show high frequency fluctuations which indicate the extreme turbulence of the dusty air medium. For a more detailed discussion of dynamic pressure wave forms, see appendix I.

d. Other Influences on Air Blast Propagation.
(1) General. The material on air blast presented in previous sections is strictly
applicable only to standard homogeneous sea level conditions (app. II) and flat "open" terrain. Some modification of the data presented may be necessary under the following conditions:

(a) Heavy rains or fogs.
(b) Temperature inversions.
(c) Target or burst height at altitudes above sea level.
(d) Terrain with large hill masses, severe inclines or depressions, and obstructions.

The effects of these conditions are discussed in some detail below, together with an expanded discussion of the thermal and mechanical influences which cause the blast parameter curves for "average" surface conditions to differ from those representing the ideal situation, or "good" surface conditions.

(2) Atmospheric effects.

(a) Effects of rain and fog. The effects of atmospheric moisture on blast propagation are not completely known. An estimate of the effect on overpressure for moderate and heavy rains and fogs is given in figures 2–14A and 2–14B. Although the probability of encountering high concentrations of atmospheric liquid water is small, calculations indicate that for a high burst in very heavy rains or fogs a significant reduction may occur in the range to which overpressures less than 10 psi extend. Attenuation of air blast will be less severe in the higher overpressure regions, for lighter rains or fogs and for low heights of burst. Little is known about the effect of atmospheric moisture on other blast parameters such as time of arrival, positive phase duration, and dynamic pressure. No allowance for the effect of weather conditions on blast need be made if only hard targets (requiring greater than 15 psi overpressure) are being considered, since these targets require lower heights of burst and reductions in this overpressure range for low burst heights are small. Reductions for rain or fog effects should not be made unless it is definitely established that the extent of the rain or fog is large enough to cover a volume which includes the target and the burst.

(b) Effects of temperature inversions. A temperature inversion is a region in the atmosphere in which the temperature increases with increasing altitude, instead of decreasing. Temperature inversions tend to modify the blast wave on the ground because they are mild reflecting surfaces. An enhancement of surface or near surface overpressures at large ground distances may result when a burst is below a temperature inversion. The overpressures on the ground may be lessened somewhat if the explosion takes place above a temperature inversion. Since the corrections at close-in ground distances are small, quantitative adjustments to blast data to correct for the effect of a temperature inversion are usually unnecessary. However, the enhancement of lower overpressures at or near the surface produced by bursts below inversions may increase the possibility of damage to blast sensitive structures and equipment at greater distances.

(c) Effects of altitude.

1. Blast yield reduction with altitude.

For burst altitudes up to 50,000 feet the total blast energy available from a given size weapon is essentially the same as that produced when the weapon is burst in a sea level atmosphere. In the less dense atmospheres at higher altitudes, and at times and ranges of importance to military targets, more of the weapon energy is emitted as thermal energy and less is available in the form of blast. An estimate of this variation of blast yield as a function of altitude is presented in figure 2–15.
As indicated, the estimated reduction in blast yield is probably of minor significance up to altitudes of 100,000 feet. Until additional information is available, it is recommended that no correction be made for blast yield variation with altitude.

2. Blast propagation at altitude. The overpressure, distance and time relationships describing the propagation of a blast wave in air depend on the ambient atmospheric conditions. Blast wave propagation data presented for the standard sea level atmosphere may be converted to the atmospheric conditions of other altitudes by a procedure presented in appendix I. For targets at mean sea level altitudes of 5,000 feet or less, the altitude scaling corrections are small and are usually of no practical importance.

3. Effects of topography.

(a) General. In addition to the effects on blast wave propagation caused by atmospheric conditions, the characteristics of the blast wave along or near the surface may be modified by various natural and artificial, or man-made, factors. These modifications are generally regarded as topographic effects. They include such non-local effects on the individual parameters of the blast wave as are caused by gross terrain features, cities or forested areas; and such local effects as are caused by small areas which are significantly different from the general surroundings and should therefore be considered separately.

(b) Terrain. Small-scale high explosive tests and limited full-scale nuclear tests indicate that in the Mach reflection region steep slopes may significantly affect the overpressure wave shape of the blast wave. Depending
upon the effective slope, positive or negative slopes may result in respective increases or decreases in peak overpressures by a factor of as much as two. The former is attributable to the reflection of the blast wave from the positive slope, whereas the latter is attributable to the diffraction of the blast wave as it moves over the crest of the hill and down the rear slope. In the Mach region, the qualitative changes in pulse or wave shape which occur for a positive slope are the formation of a spike on the front of the pulse at the base of the slope, and the gradual widening of this spike as the blast wave progresses up the slope. The peak pressure ratio (the ratio of the peak pressures on the slope to those which would exist in the absence of the slope) increases as the positive slope angle increases and the incident pressure decreases. On a negative slope, the qualitative changes in pulse shape which occur are a rounding of the front of the pulse at the beginning of the negative slope with a return to the normal shape as the blast wave moves down the slope. The peak pressure ratio in this instance is reduced as the negative slope angle increases and the incident pressure decreases. These changes in the pressure pulse apply to the gross terrain features only, and not to local accidents of the terrain. There is no known procedure for relating local terrain accidents to gross terrain features.

Contrary to popular opinion, a "line of sight" concept does not apply to blast shielding by terrain features. However, severe local irregularities or terrain accidents may result in significant shielding from drag or dynamic pressure effects. In addition, the effects of an isolated terrain feature on the blast wave are essentially limited to the immediate vicinity of the terrain feature itself. The total energy of the blast wave is such that recovery from perturbations is quite rapid. The precursor effects on the blast wave, when coupled with the effects of terrain features, are unknown, but are believed to be significant.

(c) Cities. As with terrain features, the effect of a city as a whole on blast wave phenomena is limited essentially to the immediate vicinity of the city itself. This gross effect is usually less significant than localized changes in the characteristics of a passing blast wave. Although some local shielding similar to that afforded by terrain accidents is expected to result from intervening objects and structures, reflection and channeling phenomena may, in certain instances, result in increases in peak overpressures and peak dynamic pressures. These local effects cannot be quantitatively related to the gross effects of cities on blast wave phenomena. The general air blast characteristics in cities and urban areas are essentially the same as those for open terrain of average surface conditions.

(d) Forests. Forests may be effective in altering blast wave characteristics. However, non-local effects are less significant than localized effects. The extent of the alteration depends on forest area, tree size, state of foliation, distance from ground zero, and other variables. The shielding provided within a forest is not well known. Air blast characteristics in forested areas are essentially the same as those for open terrain, average surface conditions.

(4) Surface conditions.

(a) General. The nature of the surface over which the blast wave moves has been found to exert a considerable influence on the individual characteristics of the blast wave. For example, significant differences between the peak values of a given blast wave parameter may occur when considering the effects of a nuclear weapon burst over an
"average" surface as compared to those expected for the same weapon burst at the same height over a "good" surface. (See c(1) above for discussion of "good" and "average" surfaces.) These differences, as reflected in the iso-pressure height of burst curves, are a consequence of the thermal and mechanical influences of the earth's surface on the blast wave propagation.

(b) Thermal influences. For relatively low scaled heights of burst the earth's surface in the vicinity of ground zero absorbs sufficient thermal energy to reach a temperature of several thousand degrees in a relatively short period of time. If certain surface conditions exist, a hot layer of air or other gases, or a mixture of gases and solid matter, will form with explosive rapidity above the earth's surface. This layer may be no more than 10 feet thick, and is rapidly dissipated once the principal portion of the thermal energy has been emitted. If this thermal layer is sufficiently intense, a separate and distinct pressure wave forms and moves ahead of the incident and reflected blast waves. This detached wave, known as the "precursor," is illustrated in figure 2-16. The surface characteristics necessary for the formation and development of a precursor are not completely understood. However, precursors have been observed over coral and desert type soils, forest areas, and large artificial surfaces such as asphalt. In addition, they are expected to occur over other surfaces such as agricultural and urban areas. No precursor is expected to occur over water, snow or ice, or over ground covered by a white smoke layer. The criteria for precursor formation are shown graphically in figure 2-17.

(c) Precursor characteristics. As indicated in the discussion on impulse and wave forms in c(3) above, the precursor produces non-ideal wave forms. The rise in pressure above ambient at shock arrival is not nearly as instantaneous as in free air; instead, there is a relatively gradual and somewhat irregular increase to the peak value. There is also an increase in positive phase duration over that which is expected at a given range in the absence of a precursor. These degraded peak pressures, in combination with the increased positive phase durations at a given range, result in slightly larger impulse values. At ranges where the peak overpressure has fallen below about 6 psi, the precursor ceases to exist, and the blast wave form again becomes normal in shape. Although the reductions in peak pressure which may occur are on the order of one-third the ideal overpressure, reductions may be more or less than that value, depending upon the degree of development of the precursor. Overpressures in the precursor region, or where strong thermal effects on the blast wave are expected, may be obtained from figure 2-10.

The effect of the precursor on dynamic pressures is less well known than its effect on overpressures. It is known, however, that in the presence of a precursor, measured dynamic pressures over a dusty desert surface are considerably higher than those which are calculated from the peak overpressures over a "good" surface. Dynamic pressures to be expected where there are strong thermal influences on the blast wave are shown in figure 2-13.

A more detailed discussion of wave form variations reflecting precursor action is contained in appendix I.

(d) Mechanical influences. Mechanical influences of the earth's surface include air-to-earth or air-to-water coupling, reflectivity, surface roughness, and dust or water loading. Energy losses from air or surface bursts due to cou-
pling across the air-ground or air-water interface may be regarded as negligible. The reflectivity and roughness of the earth's surface exert only a minor influence on attenuation of pressure with distance, but may affect Mach stem formation and growth. Dust loading, however, may increase the peak dynamic pressure for a given peak overpressure over that which occurs in the absence of dust. Conditions for dust loading are maximized for bursts occurring over dry, fine-grained soils. The amount of dust produced will depend on the burst position, the type and moisture content of the soil, and the surface wind conditions. An effect similar to dust loading also occurs when water is picked up by the blast wave. With the possible exception of dust or water loading, mechanical influences on the blast wave are usually less significant than the thermal influences described in (b) above. In addition to the effects of dust on loading, dust also may limit visibility and movement in the target area for some time after a detonation.

e. Air Blast From a Subsurface Explosion.

(1) General. As discussed previously, there is no abrupt change in the air blast phenomena as the height of burst is varied. The changes occur gradually, as the earth's surface exerts a greater and greater influence on the air blast wave. The same is true for a subsurface burst. As the depth of burst increases, the magnitude of the air blast gradually decreases, until a depth of burst is reached at which any air blast effect is essentially nonexistent.

(2) Underground. Figure 2-18 gives the air blast peak overpressure at the ground surface for a 1 KT yield weapon detonated under sea level conditions, as a function of depth of burst and distance from surface zero. To scale to other yields, the depth of burst and distance at which a given peak overpressure occurs are multiplied by the cube root of the yield. The scaling procedure and an illustrative example accompany figure 2-18.

Thermal influences, discussed in (d) above, have little or no effect on air blast propagation resulting from a subsurface burst.

(3) Underwater. For shallow depths of burst, peak air overpressures from underwater explosions are expected to be approximately equal to those from underground explosions at the same depth of burst. Therefore, figure 2-18 may be used to determine peak pressure at the surface versus distance for a 1 KT detonation at the depths of burst represented. As the depth of burst is lowered below those depths given in figure 2-18, the shock wave transmitted across the water-air interface gradually becomes the predominate cause of the air blast, and the significance of changes in depth of burst becomes smaller. For example, it is predicted that a 1 KT burst at a depth of 180 feet would produce a peak air blast pressure of 1.5 psi at a range of 150 yards from surface zero. If the depth of burst were lowered to 360 feet, the 1.5 psi pressure would still extend as far as 150 yards.
Shock arrival time vs. distance in free air for a 1 KT burst in a homogeneous sea level atmosphere is given in figure 2-2.

**Scaling.** To calculate the distance and time of shock arrival for a yield other than 1 KT, use the following scaling:

\[
\frac{t_1}{t_2} = \frac{W_{1}^{1/3}}{W_{2}^{1/3}} = \frac{d_2}{d_1}
\]

where \( t_2 = \) time of arrival of shock front from explosion of yield \( W_2 \) KT at range \( d_2 \), and \( t_1 = \) time of arrival of shock front from explosion of \( W_1 \) KT at range \( d_1 \).

**Example.**

**Given:** A 100 KT burst in free air.
**Find:** The time of arrival of the shock front at 40,000 feet.
**Solution:** The corresponding distance for 1 KT is,

\[
d_1 = \frac{d_2 \times W_{1}^{1/3}}{W_{2}^{1/3}} = \frac{40,000 \times 1}{(100)^{1/3}} = 8,600 \text{ ft.}
\]

From figure 2-2, the time of arrival \( t_1 \) for a 1 KT burst at 8,600 feet is 7 seconds. Thus, the time of arrival of the shock front from a 100 KT detonation at a distance of 40,000 feet is,

\[
t_2 = \frac{W_{2}^{1/3} \times t_1}{W_{1}^{1/3}} = \frac{(100)^{1/3} \times 7}{1} = 32.5 \ (\pm 4.8) \text{ seconds. Answer.}
\]

**Reliability.** Times of arrival obtained from this curve are considered to be reliable to \( \pm 15 \) percent (0.1 KT to 100 MT).

**Related material.**
See paragraphs 2.1.2(2) and I–3.
See also figures 2–3, 2–4, 2–5, and 2–8.
TIME OF ARRIVAL OF SHOCK FRONT VS SLANT RANGE IN FREE AIR
HOMOGENEOUS ATMOSPHERE OF STANDARD SEA LEVEL PROPERTIES
1 KILOTON YIELD

ARRIVAL TIME (seconds)

SLANT RANGE (feet)
A curve of peak overpressure vs. slant range in free air for a 1 KT burst in a homogeneous sea level atmosphere is presented in figure 2-3. This curve may be used to predict incident pressures near the surface from air bursts at heights up to 40,000 feet. Reflected overpressures at the surface for moderate bursts heights (up to 5200 feet for 1 KT) may be determined from the height of burst curve, figures 2-9 and 2-10. Reflected overpressures at the surface for high burst heights (above 5200 ft. for 1 KT) may be calculated by use of the reflection factors given on page I-31 in appendix I as a function of incident pressure and angle of reflection as explained in paragraph I.4. The above procedures should be used for predicting effects on surface targets. For predicting effects on air-borne targets, figure I-14 in appendix I should be used as explained in paragraph I.3b.

**Scaling.** In order to calculate the distance to which a given overpressure extends for yields other than 1 KT, use the following scaling:

\[
\frac{d_1}{d_2} = \left( \frac{W_2}{W_1} \right)^{1/3}
\]

where \(d_1\) = distance at which a given overpressure occurs from an explosion of yield \(W_1\) KT, and \(d_2\) = distance at which the same overpressure occurs for an explosion of yield \(W_2\) KT.

This scaling is often referred to as "cube root" scaling.

**Example:**

*Given:* A 100 KT detonation in free air.

*Find:* The distance to which 7 psi overpressure extends.

*Solution:* From figure 2-3 a 1 KT burst produces 7 psi at a distance of 1,000 feet.

Scaling to 100 KT:

\[
\frac{1,000}{d_2} = \frac{1}{(100)^{1/3}} \quad \text{or} \quad d_2 = \frac{1,000 \times (100)^{1/3}}{1}
\]

\[
1,000 \times 4.64 = 4,640 \text{ feet. Answer.}
\]

**Reliability.** For ranges less than 1,000 feet (overpressures greater than 7 psi) the values of peak overpressure obtained from the curve are considered reliable to \(\pm 5\%\). This portion of the curve is based largely on analysis of data obtained by high-speed photography. For overpressures less than 7 psi the curve is based on data obtained with pressure gages near the ground. The reliability of this portion of the curve is estimated to be \(\pm 30\%\).

**Related material:**


See also figures 2-2, 2-4, 2-5, 2-9, and 2-10.
PEAK OVERPRESSURE VS. SLANT RANGE IN FREE AIR

HOMOGENEOUS ATMOSPHERE OF STANDARD SEA LEVEL PROPERTIES

1 KT. YIELD

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FREE AIR DURATION OF POSITIVE PHASE VS. SLANT RANGE

Figure 2-4 shows the duration of the positive pressure phase as a function of distance in free air for a 1 KT burst in a sea level homogeneous atmosphere.

Scaling. To scale to yields other than 1 KT, use the following scaling:

\[
\frac{t_i^+}{t_i^-} = \frac{W_i^{1/3}}{W_1^{1/3}} = \frac{d_i}{d_1}
\]

where \(t_i^+\) = duration of the positive phase for yield \(W_i\) KT at distance \(d_i\), and \(t_i^-\) = duration of the positive phase for yield \(W_1\) KT at distance \(d_1\).

Example.

Given: A 160 KT detonation in free air.

Find: The positive phase duration at 27,000 feet.

Solution:

\[
d_i = \frac{W_i^{1/3} \times d_i}{W_1^{1/3}} = 1 \times 27,000 = 5,000 \text{ feet}
\]

(corresponding distance for 1 KT).

From figure 2-4, \(t_i\), the duration of the positive phase for 1 KT at 5,000 feet is 0.35 second. For 160 KT the duration is,

\[
t_i = \frac{t_i^+ \times W_i^{1/3}}{W_1^{1/3}} = \frac{0.35 \times (160)^{1/3}}{1} = 1.90 \ (\pm 0.57) \text{ seconds. Answer.}
\]

Reliability. Durations obtained from this curve are considered to be reliable to ±30 percent (0.1 KT to 20 MT).

Related material.

See paragraph 2.1 b(3)(b).

See also figures 2-2, 2-3, 2-5, and 2-11.
FREE AIR DURATION OF POSITIVE PHASE VS SLANT RANGE FOR A 1 KT BURST IN A HOMOGENEOUS SEA LEVEL ATMOSPHERE
FREE AIR PEAK DYNAMIC PRESSURE VS. SLANT RANGE

A curve of free air peak dynamic pressure for a 1 KT burst in a homogeneous sea level atmosphere is presented in figure 2–5.

_Scaling._ To calculate the distance at which a given dynamic pressure extends for a yield other than 1 KT, use the following scaling:

\[
\frac{d_1}{d_2} = \frac{W_1^{1/3}}{W_2^{1/3}}
\]

where \(d_1\) = distance to which a given dynamic pressure extends for yield \(W_1\), and \(d_2\) = distance to which the same dynamic pressure extends for yield \(W_2\).

_Example._

_Given:_ A 100 KT detonation in free air.
_Find:_ The distance to which 10 psi dynamic pressure extends.

_Solution:_ From figure 2–5, one KT produces 10 psi at a distance of 560 feet. Hence,

\[
\frac{560}{d_1} = \frac{1}{(100)^{1/3}}
\]

and

\[
d_2 = 560 \times (100)^{1/3} = 560 \times (4.64) = 2,590 \text{ feet. Answer.}
\]

_Reliability._ Peak dynamic pressures obtained from this curve are considered to be reliable to ±5 percent for pressures greater than 2 psi and to ±10 percent for pressures below 2 psi (0.1 KT to 100 MT).

_Related material._

See paragraph 2.1.b(4).
See also figures 2–2 through 2–4, 2–12, and 2–13.
FREE AIR PEAK DYNAMIC PRESSURE VS SLANT RANGE FOR A 1 KT BURST IN A HOMOGENEOUS SEA LEVEL ATMOSPHERE.
MACH STEM HEIGHT

Figure 2-7 is a plot of ground distance vs. Mach stem height for various heights of burst of a 1 KT detonation in a sea level atmosphere. These curves are for average surface conditions; depending upon the thermal qualities and the roughness of the surface, the triple point rise may be somewhat different from that shown.

Scaling. Distances scale as the cube root of the yield, so that—

\[
\frac{H_1}{h_1} = \frac{d_1}{W_1^{1/3}} = \frac{H_2}{h_2} = \frac{d_2}{W_2^{1/3}}
\]

where \( H_1, h_1 \) and \( d_1 \) are Mach stem height, height of burst and ground distance for yield \( W_1 \), and \( H_2, h_2 \) and \( d_2 \) are the corresponding Mach stem height, height of burst and ground distance for yield \( W_2 \).

Example.

Given: A 60 KT detonation at 1,000 feet height of burst.

Find:

(a) The range at which the Mach stem is 50 feet high.

(b) The minimum ground range for which an aircraft at 5,000 feet altitude is in the Mach reflection region.

Solution:

(a) The corresponding burst height for 1 KT is—

\[
h_1 = \frac{1,000 \times 1}{(60)^{1/3}} = 255 \text{ feet.}
\]

The corresponding Mach stem height for a 1 KT burst is—

\[
H_1 = \frac{50 \times 1}{(60)^{1/3}} = 13 \text{ feet.}
\]

From figure 2-7, a Mach stem height of 13 feet is found at 95 yards for a 1 KT burst at 255 feet HOB. For a 60 KT burst, the range is \( 95 \times (60)^{1/3} = 370 \) yards. \textit{Answer}.

(b) 5,000 feet altitude for a 60 KT burst corresponds to \( \frac{5,000}{(60)^{1/3}} = 1,280 \) feet altitude for a 1 KT burst. Interpolating between the 200 feet and 300 feet burst height curves, the ground range for a Mach stem height of 1,280 feet is 810 yards. The corresponding range for a 60 KT burst is \( 810 \times (60)^{1/3} = 3,200 \) yards. \textit{Answer}. This indicates that for the burst condition and altitude specified, an aircraft at ranges greater than 3,200 yards will experience a single shock.

Reliability. The range at which a given Mach stem height occurs as obtained from figure 2-7 is considered to be reliable to \( \pm 10 \) percent for 1 KT and to \( \pm 25 \) percent for 20 MT. This decrease in reliability with increasing yield is a result of the lack of knowledge concerning the effect of atmospheric inhomogeneity on the triple point trajectory. It is suggested that no correction be made for altitude effects; however, when the basic data are applied to high yield air bursts, the results should be treated with somewhat less confidence.

Related material.

See paragraph 2.1.c(1).

See also figure 2-6.
BLAST WAVE ARRIVAL TIMES AT THE SURFACE

Figures 2-8A and 2-8B show families of curves representing the arrival time of the blast wave on the ground as a function of burst height and ground distance. The curves are drawn for a 1 KT burst in sea level atmospheric conditions. Figure 2-8A is for good surface conditions; figure 2-8B is for average surface conditions.

Scaling. The height of burst, the range, and the arrival times all scale as the cube root of the yield:

\[
\frac{h_1}{h_2} = \frac{W_1^{1/3}}{W_2^{1/3}} = \frac{d_1}{d_2} = t_1^{1/3} = t_2^{1/3},
\]

where \( h_1, d_1, \) and \( t_1 \) are the height of burst, range, and arrival time for \( W_1 \) KT; and \( h_2, d_2, \) and \( t_2 \) are the corresponding height of burst, range, and arrival time for \( W_2 \) KT.

Example.

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

Find: The arrival time at a ground range of 2,000 yards, for good surface conditions.

Solution: The corresponding burst height for 1 KT is:

\[
h_1 = \frac{3,000 \times 1}{(160)^{1/3}} = 550 \text{ feet.}
\]

The corresponding range for 1 KT is:

\[
d_1 = \frac{2,000 \times 1}{(160)^{1/3}} = 370 \text{ yards.}
\]

From figure 2-8A, at a range of 370 yards and a burst height of 550 feet, the arrival time is approximately 0.65 second (for 1 KT). The corresponding arrival time for 160 KT is \( 0.65 \times (160)^{1/3} = 3.5 \) (±0.4) seconds. Answer.

Reliability. Arrival times obtained from these curves are considered to be reliable to ±10 percent for 0.1 KT to 20 KT. In the region of precursor formation, because of thermal effects on shock velocity, the values given are less certain. The curves may be used outside this range of yields with somewhat less confidence.

Related material.

See paragraphs 2.1c(1) and (2).

See also figures 2-2 and 2-9 through 2-13.
PEAK OVERPRESSURES ON THE SURFACE

(Good and Average Surface Conditions)

Figures 2-9 and 2-10 are families of curves representing peak overpressures on the ground as a function of ground range and height of burst for a 1 KT burst under sea level conditions. The solid lines are based upon experimental data established as a result of full-scale nuclear explosions and the dashed portions are based upon theoretical and high explosive experiments. The curves in figures 2-9A and 2-9B are considered representative for "good" target surfaces approaching the ideal, while the curves in figures 2-10A and 2-10B are considered appropriate for all other target conditions ("average"). Surface influences are discussed in paragraphs 2.1c and d(4).

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

\[
\frac{d_1}{d_2} = \frac{h_1}{h_2} = \left(\frac{W_1}{W_2}\right)^{1/3}
\]

where for a given peak overpressure, \(d_1\) and \(h_1\) are ground range and height of burst for \(W_1\) KT, and \(d_2\) and \(h_2\) are the corresponding ground range and height of burst for \(W_2\) KT.

Example.

Given: An 80 KT detonation 2,550 feet above an average surface.

Find: The distance to which 3 psi extends.

Solution: The corresponding burst height for 1 KT is

\[
h_1 = \frac{W_1^{1/3} \times h_1}{W_1^{1/3}} = 1 \times 2,550 = 600 \text{ ft}.
\]

From figure 2-10B, 3 psi extends to 920 yards for a 600 foot burst height for a 1 KT weapon. The corresponding distance for 80 KT is:

\[
d_2 = \frac{W_2^{1/3} \times d_2}{W_1^{1/3}} = \frac{(80)^{1/3} \times 920}{1} = 3,960 \text{ yards. Answer.}
\]

Reliability. The pressures obtained from figures 2-9 and 2-10 are considered to be reliable to ±20 percent for yields of 1 KT to 20 MT. Outside this range of yields the figures may be used with somewhat less confidence.

Related Material.

See paragraphs 2.1c(3) and d(4).

See also figures 2-3, 2-8, 2-11 through 2-13, and 2-18.
Figure 2-10A

Peak overpressure on the surface as a function of height of burst and ground range. 1 KT at sea level for average surface conditions.
Figures 2-11A and 2-11B are families of curves representing positive phase durations on the ground as functions of ground range and burst height for a 1 KT burst under sea level conditions. Figure 2-11A represents positive phase duration under good surface conditions, while 2-11B represents the same values under average surface conditions.

Scaling: Use:

\[
\frac{h_1}{h_2} = \frac{d_1}{d_2} = \frac{W_1^{1/2}}{W_2^{1/2}} = \frac{t_1}{t_2},
\]

where \( h_1, d_1, \) and \( t_1 \) are the height of burst, range, and duration for \( W_1 \) KT; and \( h_2, d_2, \) and \( t_2 \) are the corresponding height of burst, range, and duration for \( W_2 \) KT.

Example.

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

Find: The positive phase duration at 4,000 yards for average surface conditions.

Solution: The corresponding 1 KT height of burst is:

\[
h_1 = \frac{3,000}{(160)^{1/2}} = 550 \text{ feet};
\]

and the corresponding ground range is:

\[
d_1 = \frac{4,000}{(160)^{1/2}} = 740 \text{ yards}.
\]

From figure 2-11B, the positive phase duration for 1 KT at 740 yards and a burst height of 550 feet is 0.34 second. The corresponding duration for 160 KT is:

\[
t_2 = 0.34 \times (160)^{1/2} = 1.8 (\pm 0.9) \text{ seconds}.
\]

Answer.

Reliability. Durations obtained from these curves are considered to be reliable to \( \pm 50 \) percent for 0.1 KT to 20 MT. The curves may be used outside this range of yields with somewhat less confidence.

Related material.

See paragraphs 2.1.c(1) and (3).

See also figures 2-4 and 2-8 through 2-13.
PEAK DYNAMIC PRESSURE ON THE SURFACE

(Good and Average Surface Conditions)

Figures 2-12 and 2-13 are families of curves representing the horizontal component of peak dynamic pressure on the ground as a function of burst height and ground distance. The curves are drawn for a 1 KT burst in sea level atmospheric conditions. The curves in figure 2-12 are considered representative for "good" target surfaces approaching the ideal, while the curves in figure 2-13 are considered appropriate for all other target conditions ("average"). Surface influences are discussed in paragraphs 2.1c and d(4).

Scaling. The height of burst and range to which a given peak dynamic pressure extends scale as the cube root of the yield:

\[
\frac{h_1}{h_2} = \frac{d_1}{d_2} = \frac{W_1^{1/3}}{W_2^{1/3}}
\]

where for a given peak dynamic pressure, \(h_1\) and \(d_1\) are the height of burst and range for yield \(W_1\); and \(h_2\) and \(d_2\) are the corresponding height of burst and range for yield \(W_2\).

Example.

Given: A 160 KT burst at a height of 3,000 feet, with average surface conditions.

Find: The horizontal component of peak dynamic pressure on the ground at a range of 2,000 yards.

Solution: The corresponding burst height for 1 KT is:

\[
h_1 = \frac{3,000 \times 1}{(160)^{1/3}} = 550 \text{ feet.}
\]

The corresponding range for 1 KT is:

\[
d_1 = \frac{2,000 \times 1}{(160)^{1/3}} = 370 \text{ yards.}
\]

From figure 2-13, at a range of 370 yards and a burst height of 550 feet, the dynamic pressure is approximately 3.7 psi. Answer.

Reliability. Range for peak values of dynamic pressure less than 10 psi are considered to be reliable to ±25 percent. This reliability factor applies from 1 KT to 20 MT. Outside these limits the curves may be used with somewhat less confidence.

Related material.

See paragraphs 2.1c(1), (4) and d(4).

See also figures 2-5, 2-8 through 2-11, and 2-17.
RAIN OR FOG EFFECTS ON PEAK OVERPRESSURE

Figures 2–14A and 2–14B present range correction factors as a function of height of burst and overpressure for a 1 KT detonation in rain or fog. The range to which a given overpressure would extend under normal conditions is multiplied by the correction factor to account for the presence of the rain or fog.

Scaling. Use the relation:

\[ \frac{h_1}{h_2} = \left( \frac{W_1}{W_2} \right)^{1/6} \]

where \( h_1 \) = height of burst for yield \( W_1 \), and \( h_2 \) = the corresponding height of burst for yield \( W_2 \).

Example.

Given: A 30 KT burst at 600 feet in a moderate rain.

Find: The distances to which 8 and 30 psi extend on the ground surface under average surface conditions.

Solution: The corresponding burst height for 1 KT is:

\[ h_1 = \frac{600 \times 1}{(30)^{1/3}} = 190 \text{ feet.} \]

From figure 2–10, the ground range for 8 psi overpressure is 380 yards and for 30 psi overpressure is 164 yards for a 1 KT burst. The corresponding ranges for a 30 KT burst are 1,220 yards (for 8 psi) and 530 yards (for 30 psi). From figure 2–14A (moderate rain), the correction factors for a burst at 190 feet are 0.9 (for 8 psi) and \( \geq 0.99 \) (for 30 psi).

The range to which 8 psi extends in moderate rain is \( 1,220 \times 0.9 = 1,100 \) yards. Answer.

The reduction in range for 30 psi is negligible; it therefore extends to 530 yards. Answer.

Reliability. At a given range obtained in this manner, overpressures are considered to be reliable within ±40 percent.

Related material. See paragraph 2.1.d(2). See also figures 2–9, 2–10, and 2–18.
FIGURE 2-14A
FIGURE 2-14B

RAIN OR FOG EFFECTS ON PEAK OVERPRESSURE
AS A FUNCTION OF HEIGHT OF BURST
FOR 1 KT AT SEA LEVEL
CRITERIA FOR PRECURSOR FORMATION

Figure 2-17 gives conditions of burst height and yield for precursor formation over average surfaces, and may be utilized to predict precursor formation if these conditions are known.

**Example.**

*Given:* A 100 KT burst at 600 feet over an "average" surface.

*Find:* Whether or not a precursor may be expected.

*Solving:* Enter figure 2-17 with a height of burst of 600 feet and a yield of 100 kilotons. The intercept falls within the portion of the figure indicating a precursor will form. *Answer.*

*Reliability.* Based on data obtained from extensive full scale testing over desert surfaces and limited tests over coral.

*Related material.*

See paragraphs 2.1c and 6(4), and appendix I. See also figure 2-16.
FIGURE 2-17

CRITERIA FOR PRECURSOR FORMATION (AVERAGE SURFACE CONDITIONS)

Precursor Will Form

Some Thermal Effects on
Wave Forms May Be Expected

No Precursor

Yield in Kilotons

Height of Burst (feet)
PEAK AIR OVERPRESSURES AT THE SURFACE AS A FUNCTION OF DEPTH OF BURST IN EARTH OR WATER AND HORIZONTAL RANGE

Figure 2-18 is a family of curves representing peak air overpressures on the surface as a function of depth of burst and surface range for a yield of 1 KT.

Scaling. The depth of burst and the range to which a given peak overpressure extends are directly proportional to the cube root of the yield:

\[ \frac{d_1}{d_2} = \frac{h_1}{h_2} = \frac{W_{1}^{1/3}}{W_{2}^{1/3}} \]

where \( h_1 \) = depth of burst for yield \( W_1 \) KT, \( h_2 \) = the corresponding depth of burst for yield \( W_2 \) KT, \( d_1 \) = distance to which given overpressure extends for yield \( W_1 \) KT, \( d_2 \) = the corresponding distance to which given overpressure extends for yield \( W_1 \) KT.

Example.

Given: A 20 KT weapon burst 60 feet underground.

Find: The peak air overpressure 1,300 yards from surface zero.

Solution: Applying the above scaling to scale to 1 KT,

\[ h_1 = \frac{W_{1}^{1/3} \times h_2}{W_{2}^{1/3}} = \frac{1 \times 60}{(20)^{1/3}} = 22 \text{ ft}, \]

and \( d_1 = \frac{W_{1}^{1/3} \times d_2}{W_{2}^{1/3}} = \frac{1 \times 1,300}{(20)^{1/3}} = 480 \text{ yd}. \)

The 22-foot depth line and 480-yard distance line intersect on figure 2-18 at about 4 (±1) psi. Answer.

Reliability. The reliability of pressures taken from figure 2-18 is estimated to be ±25 percent.

Related material.

See paragraph 2.1e.
See also figures 2-9 and 2-10.
2.2 Ground Shock and Cratering Phenomena.

a. Cratering.

(1) Land.

(a) General. Land craters are pits, depressions or cavities formed in the surface of the earth by vaporizing, throwing, compressing and scouring the soil in an outward direction from a nuclear detonation. Usually they are further characterized as to apparent or true craters. The apparent crater is the visible crater remaining after a detonation, while the true crater is the crater excluding fall-back material. The true crater is bounded by a surface which represents the limiting distance from the explosion at which the original material surrounding the apparent crater was completely disassociated from the underlying material. The ensuing discussion of craters from underground bursts assumes weapons with no air space surrounding them, in locations that have been completely backfilled and tamped, and burst under a horizontal ground surface plane. Figure 2–19 shows schematically the dimensions used in describing a crater.

(b) True and apparent craters. The fall-back zone is the zone between the true and apparent craters as defined above. It contains both disassociated material that has fallen back into the crater and material that, even though disassociated, received insufficient energy to be thrown out of the crater. There is usually insignificant fall-back in craters from air or surface bursts, or bursts at depths less than 25 W/pa feet. Consequently, there is little difference between apparent and true craters from such bursts.

(c) Crater radius and depth. The crater radius is the average crater radius as measured at the original ground surface and scales as the cube root of the yield. The crater depth is the maximum depth of the crater as measured from the original ground surface and scales as the fourth root of the yield. Estimated crater radii and depths are given in figures 2–20 and 2–21 as functions of burst height and depth for 1 KT. Figures 2–22 and 2–23 are derived from figures 2–20 and 2–21, and present expected crater diameters and depths as functions of yield for specific burst conditions. All figures are directly applicable to dry soil or soft rock (rock that crumbles easily). For other types of soil or rock, crater dimensions may be estimated by multiplying the dimensions taken from figures 2–20 through 2–23 by the appropriate factors shown in the facing pages of these figures.

(d) Crater lip. The lip of the crater is formed both by fall-back and by the rupture of the soil surrounding the crater. For a deep underground burst, the resulting crater lip is formed primarily from fall-back. For a shallow underground or surface burst on the other hand, the crater lip is formed primarily by the ground nearest the burst shearing and piling up against the soil farther away from the crater. The approximate relative dimensions of the crater lip resulting from a surface burst are indicated in figure 2–19.

(e) Rupture zone. The rupture zone is characterized by extreme cracking. The zone surrounds the true crater and at the ground surface extends outward approximately 1.5 times the apparent crater. However, for bursts at large scaled depths, the zone at the ground surface extends outward only slightly beyond the true crater. When an explosion occurs in rock, it disturbs the rock in the ruptured zone by causing surface slabbing of local areas, by opening pre-existing cracks, and by developing new fractures tending to be radial from the point of burst. The rupture zone in sand may be difficult to define or may be non-existent.
CRATER PROFILE

- $D_p$: Diameter of Rupture Zone = $1.5 D_A \pm 25\%$
- $D_R$: Diameter of Plastic Zone = $3D_A \pm 50\%$
- $D_L$: Diameter of Lip = $2.0 D_A \pm 25\%$
- $H_L$: Height of Lip = $0.25 H_A \pm 50\%$
- $V_C$: Volume of Apparent Crater = $\frac{\pi D_A^2 H_A}{8}$ (Assumed Paraboloid)

$D_A$: Diameter of Apparent Crater

$H_A$: Depth of Apparent Crater

$D_T$: Diameter of True Crater

$H_T$: Depth of True Crater

Original Ground Surface

Elastic Zone

Rupture Zone

Fall Back =

- True Crater

Fall Back on Lip

Elastic Zone

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Plastic zone. In the plastic zone the soil is permanently displaced but without visible rupture. This zone surrounds the rupture zone and may extend outward at the ground surface approximately three times the apparent crater radius. Even for bursts at large scaled depths, where there is an appreciable difference between the true and apparent crater dimensions, the plastic zone still extends considerably beyond the true crater at the surface. In rock, little or no plastic deformation occurs.

Height and depth of burst. At a height of burst less than about 10 \( W^{1/3} \) feet, the expanding gases from a nuclear detonation form a land crater primarily by vaporizing, throwing and compressing the soil in an outward direction from the detonation. As the height of burst decreases from about 10 \( W^{1/3} \) feet or the depth of burst increases, the crater radius continues to increase appreciably until a depth of burst of about 25 \( W^{1/3} \) feet is reached. Below about 25 \( W^{1/3} \) feet, however, the apparent crater radius increases only slightly with increasing depth of burst, and, below a depth of burst of approximately 70 \( W^{1/3} \) feet, the apparent crater radius then decreases with increasing depth of burst.

As the height of burst is lowered from about 10 \( W^{1/3} \) feet or the depth of burst is increased, the crater depth increases appreciably with increasing depth of burst, until a depth of burst of approximately 60 \( W^{1/3} \) feet is reached. Below about 60 \( W^{1/3} \) feet, the apparent crater depth increases but slightly with increasing depth of burst, until a depth of burst of about 90 \( W^{1/3} \) feet is reached. Below this depth of burst, the fall-back material may form a crater with an apparent depth less than the depth of burst. The true depth of the crater, however, remains greater than the depth of burst by a constant value of approximately 57 \( W^{1/3} \) feet when the depth of burst is below about 60 \( W^{1/3} \) feet.

For bursts at heights greater than about 10 \( W^{1/3} \) feet, the mechanism of cratering is primarily compression and scouring of soil. As indicated in figure 2–20, the crater radius increases for burst heights above 20 \( W^{1/3} \) feet, reaching a maximum at about 60 \( W^{1/3} \) feet. This results in a crossover of the 50, 100, and 300 foot burst height curves of figures 2–22A and 2–22B. However, this increase in radius is not considered significant, since the crater depth decreases very rapidly with increasing height of burst to relatively small values in the range of crossover.

For bursts at heights above about 60 \( W^{1/3} \), the crater may be difficult to detect.

Effect of slope. Crater dimensions are not expected to change materially with ground slope, except for very steep terrain. On very steep slopes, craters will be somewhat elliptical in shape, with the downhill lip considerably wider than the uphill lip. The crater depth with respect to the surface plane of the terrain involved is not expected to be appreciably different from that of a burst under horizontal terrain conditions.

Underwater.

General. An underwater crater is considered to be the crater existing in the bottom material at a time shortly after the burst when conditions are no longer changing rapidly. Subsequent hydraulic wash action by the current, tides, etc. will tend to erode away any crater lip, while making the crater wider and shallower. The degree of this effect depends on the depth of water, type of bottom material, and current, wave, and tidal activity.

Burst geometry. The size of the underwater crater is dependent upon burst depth, water depth, bottom composition and weapon yield. Figures 2–24 through 2–26 give the crater diameter,
depth, and lip height for a burst on the surface and on the bottom in 25, 50, 100, and 200 feet of water. The figures show that the crater dimensions are greater for a bottom burst than for a surface burst. Also for a bottom burst, as the depth of water increases the crater dimensions increase, whereas for a surface burst, as the water depth increases the crater dimensions decrease.

b. Ground Shock.

(1) General. The production of ground shock by nuclear explosions is extremely complex, and, in some respects, not well understood. Basically, ground shock may be produced by two separate mechanisms. One mechanism is the sudden expansion of the bubble of gas from a surface or underground explosion which generates a pulse or oscillation in the ground. This is termed “direct ground shock.” As this direct shock propagates through the ground, it may be modified by reflections and refractions from underlying bedrock or hard strata, or rarefaction from the air-ground interface. The second mechanism is the production of a ground shock by the air blast wave from a nuclear explosion striking and moving parallel to the ground surface. This is termed “air induced ground shock.” For a given burst geometry, except at extremely short ranges, these two forms of ground shock are separated in time. Because the direct ground shock is usually attenuated very rapidly, induced ground shock is more important from the point of view of damage to underground installations, except for extremely close ranges and for deep underground bursts. Figure 2-27A shows in schematic form the relation of these two phenomena in the case of a surface burst. Since sonic velocity is generally higher in ground than in the air, the direct ground shock is indicated as moving faster than the air blast, and consequently faster than the air induced ground shock. Although the direct ground shock and the air blast of a surface or near-surface burst initially propagate approximately together, the velocity of the air blast decreases more rapidly with distance in the higher pressure region than the direct ground shock. Hence, the direct ground shock moves ahead.

Figure 2-27B shows the relation in idealized form of the vertical acceleration caused by the two different forms of ground shock. The direct vertical acceleration is initiated upon arrival of the direct ground shock. The “air blast slap acceleration” is initiated upon the arrival of the air blast which causes a sudden local increase in soil particle acceleration.

The physical mechanisms of major interest in regard to the production of ground shock damage are acceleration, displacement and pressure (or stress). Although extensive measurements have been made, no consistent correlation between these parameters has been found. Each is discussed for both direct ground shock and air induced ground shock in the following paragraphs.

(2) Direct ground shock.

(a) Propagation. The direct ground shock wave produced by a surface or underground burst propagates radially outward from the burst point. For a 1 KT surface or shallow underground burst, in Nevada type soil, propagation velocities on the ground surface are 4,600 feet per second approximately 300 feet from surface zero, and decrease to a more constant 3,500 feet per second approximately 2,500 feet from surface zero. The propagation velocity of ground shock at the surface may increase with distance from the burst due to refraction and reflection from underlying higher velocity strata; and, as the shock reduces to an acoustic wave, the velocity will approach the normal acoustic velocity of the medium near the surface. In sound rock and outside the zone of rupture, the propagation of shock obeys elastic formulae.
DIRECT AND AIR INDUCED GROUND SHOCK

GROUND ACCELERATION WAVE FORM WITH "SLAP"

\[ t_d = \text{Arrival Time Direct Acceleration} \]
\[ t_s = \text{Arrival Time, Slap} \]
\[ \frac{1}{2T} = \text{Slap Frequency} \]
\[ A_d = \text{Max. Downward Slap Acceleration} \]
\[ A_u = \text{Max. Upward Slap Acceleration} \]
In such a homogeneous medium (not generally characteristic of surface conditions), there is little attenuation due to internal friction or plastic deformation. Ground shock (compression type wave) in rock is reflected from an air-rock interface as a tensile wave. The intensity of this tensile wave is dependent on shock strength, wave shape, and angle of incidence of the direct shock with the free surface.

(b) Pressure (stress). At any given point air blast or water shock overpressures resulting from a nuclear detonation are equal in all directions, but ground pressures are not. The shear and cohesive strength of the soil change the ground pressure into directional components which differ in magnitude depending upon the direction in which measured. These directional pressure components are termed stress. Under the dynamic loading from a nuclear explosion, the direct ground stresses rise most abruptly in the ground nearest the explosion, whereas at greater distances the peak stresses at any specific point are reduced and the rise times are increased. Stress pulses appear as various combinations of direct ground and air induced shock stresses, depending on arrival time and the range, depth and direction of the measurement. Direct and air induced ground shock stress pulses may coincide at close-in ranges outside the crater, as indicated in (1) above, but will gradually separate with increasing distance along the ground surface until two separate pulses may be detected a few feet beneath the ground surface. The peak stresses from direct ground shock usually attenuate rapidly with distance; however, in highly saturated soils the attenuation of these stresses is less, approaching the attenuation in water (approximately inversely as the range). The stress pulse from the direct ground shock is composed of vibrations of high and low frequencies, the period of which may vary from a few tenths of a second to several seconds. Two hundred feet from a 1 KT underground burst in Nevada type soil, the horizontal earth stress at a depth of 10 feet may be 125 psi; at 250 feet it may be 40 psi; while at 600 feet it may be only 3 psi. A rough comparison of peak stress intensities for various yields at the same distances may be made on the basis of relative crater size.

(c) Acceleration of soil particles. Acceleration of soil particles may be caused as a direct result of the explosion (direct acceleration), as a result of any shock reflection or refraction from underlying bedrock (indirect acceleration), or as a result of air blast (induced acceleration). Direct and indirect accelerations are generally indistinguishable and together are termed direct or fundamental acceleration. For acceleration values of 1 g or greater measured beyond a range of two crater radii from ground zero the frequency in soil will usually be less than 80 cycles per second for all yields, and for 1 KT the predominant frequencies will be from 3 to 15 cycles per second. In rock, the amplitude of accelerations may be considerably greater and the period may be less than in average soil.

(d) Displacement of soil particles. Displacement of soil particles is largely permanent within the plastic zone of a crater and transient beyond the plastic zone. For a small, near-surface burst, and at a range of three crater radii, the permanent displacement along the ground surface will probably be less than 0.0003 of a crater radius and the transient displacement will probably be less than 0.001 of a crater radius. A short distance beneath the ground surface, soil particle displacement is usually less than the displacement along the ground surface. Displacements are
appreciably affected by soil types. In wet soils, for example, they may be of the order of ten times greater than the preceding values.

(3) Air induced ground shock.

(a) Propagation. Air induced ground shock propagates outward from the burst with the air blast. The air blast loading may be considered as a moving, non-uniform load that generates a ground shock. The air induced shock in soil quickly attains a velocity that may exceed the air blast velocity; however, the magnitude of any outrunning shock is small and its effects may be ignored. Consequently, as the air blast wave proceeds, the air induced ground shock propagates with a rather complex underground time-of-arrival contour depending on underground shock velocities; but, in general, the ground shock front slopes backward from the air blast shock front as shown in figure 2-27A. Air induced ground shock usually arrives with or after the direct ground shock.

(b) Pressure (stress). Air induced ground stress (pressure) is closely related to direct ground stress (pressure) discussed in (2)(b) above. Just below the surface, the air induced shock stresses and durations are approximately equal to the changing positive air blast pressure and duration. These induced ground stresses attenuate gradually with depth and the rise time of the stress pulse increases. The pulse of the air induced ground stress is composed of vibrations of high and low frequencies, the periods of which may vary from a few tens of a second to several seconds. In general, air induced ground stress is larger than direct ground stress at distances greater than two crater radii for average soils, and for all heights and depths of burst down to about 75 feet for 1 KT.

(c) Acceleration of soil particles. Air blast induced acceleration maintains its identity in the acceleration pattern and can be separated from the direct shock acceleration. When interactions with other accelerations from reflection and refraction occur, the magnitude is affected markedly and separation is difficult. Upon its arrival, the air blast will cause a sudden local increase in soil particle acceleration termed "air blast slap acceleration" (see fig. 2-27B). For acceleration values of 1 g or greater measured away from ground zero, the predominant frequencies in soil of air blast induced acceleration are 20 to 120 cycles per second. Peak vertical accelerations are larger than peak horizontal (radial) accelerations by an amount approximating 50 percent. Peak accelerations attenuate with depth and are directly proportional to the overpressure and indirectly proportional to the rise time of the pressure pulse in the soil. See figure 2-28 for the relationship of peak accelerations to peak air blast overpressures at a depth of 10 feet.

(d) Displacement of soil particles. Air induced ground shock causes little permanent horizontal displacement of ground particles beyond two crater radii. When the shock is reflected from vertical soil-air interfaces, local displacement (spalling) of ground particles may occur. Air induced ground shock may cause a vertical displacement of soil particles. Dry Nevada type soil subjected to a peak overpressure of 250 psi has sustained a permanent downward displacement of approximately 2 inches and a transient downward displacement of approximately 8 inches.

c. Column and Base Surge. A general discussion of the column and base surge resulting from an underground burst has been given in paragraph 1.4e(4). The maximum column diameter is generally 2 to 3 times the apparent crater diameter and the maximum column height is roughly equal to 400 \( W^{1/3} \). The characteristics of the base surge depend upon the depth and yield of burst. The shallowest burst depth at which an earth base
surge has been observed is 16 \( W^{1/4} \) feet. As the burst depth is increased, the extent of the base surge is expected to increase until a burst depth of about 125 \( W^{1/4} \) feet is attained. No further increase in base surge extent is expected below this depth of burst. Figure 2–29 shows the rate of growth of the base surge and maximum radii for various scaled depths of burst.

2.3 Water Shock and Surface Phenomena


(1) General. The underwater detonation of a nuclear weapon at a distance from either the water surface or the bottom boundaries produces a shock wave early in the formation of the bubble. This shock wave propagates spherically at the rate of roughly 5,000 feet per second, and is characterized by an instantaneous rise in pressure followed by an exponential decay. In addition to this initial primary shock wave, several subsequent pressure pulses are produced within the water (see par. 1.4(f) and (3)).

(2) Burst geometry.

(a) Deep burst in deep water. When the pressure wave is reflected from the water surface it is reflected as a rarefaction or tensile wave. This reflected rarefaction wave cuts off the tail of the primary compressional shock wave, thereby decreasing the duration of its positive phase. Figure 2–30 shows qualitatively the effect of the reflection wave upon the pressure-time history. The effect of this "cut-off" decreases rapidly with depth of the target in the water; that is, the deeper a target, the less the effect of cut-off for the same depth of detonation. Likewise, the greater the depth of detonation, the less the effect of cut-off for the same target location. The reflection of pressures from the bottom surface is similar to the reflection of pressures from the ground surface for an airburst. A crude approximation of the magnitude and shape of this
Non-linear Surface Reflection Effects

Reflected water shock wave can be obtained by assuming that this wave is identical to an imaginary direct wave which has traveled a distance equal to the path distance of the reflected wave, i.e., that perfect reflection occurred. Estimated peak overpressure vs. slant range for various yields are shown in Figure 2-31, where the order of magnitude of these pressures may be noted. However, the durations of these pressures are short, being measured in tens of milliseconds. They may even be shorter at points near the water surface, where the surface reflected wave arrives at the point before the complete passage of the primary compressional wave.

(b) Shallow burst in deep water. If the weapon is fired at shallow depths in deep water, the peak overpressure estimates of Figure 2-31 overestimate actual overpressures for most regions of interest. For example, a 10 KT weapon fired at a depth of 200 feet in deep water would develop a peak overpressure of approximately 350 psi at a point which is at a range of 2,000 yards and at a depth of 50 feet, instead of the 550 psi predicted by the figure. This reduction is the result of the initial shock wave striking the water surface at a high obliquity and reflecting in an anomalous manner. The sharp cut-off from the reflected pressure does not occur; rather, the reflected tensile wave modifies the pressure-time history at early times and forms a nearly triangular pulse (see fig. 2-32). The region wherein this anomalous reflection affects the pressure history is termed the "non-linear" region. This non-linear region is in the form of a wedge, increasing in depth as the range from the burst point increases. At the shallower depths in this region, the anomalous behavior is sufficient to reduce the magnitude of the initial peak overpressure. At deeper depths the effect shades off, until only at the later times of the pressure history is there any reduction of overpressure. As the depth of burst is raised or the yield increased, the non-linear zone increases in scope and magnitude. Finally, for a surface burst, all points beneath the water surface (except those directly under the weapon) are in the non-linear region. Because the peak pressure in the non-linear region is a sensitive function of burst and
target geometry, pressure-distance curves are not presented to account specifically for this effect. In the damage curves of part two, however, the non-linear effect is incorporated in the damage estimates for targets and bursts at shallow depths.

(c) Shallow water burst. When a nuclear weapon is detonated in shallow water, both the reflecting boundaries of the water surface and the bottom alter the peak pressure and duration of the primary underwater shock wave. In addition to the multiple reflections that occur, the shock wave is transmitted across these boundaries (i.e., propagated through the air and the bottom and then coupled back into the water). Hence, at a point distant from the source, there will be a direct water shock, water shocks induced by ground and air shocks, and water shocks reflected from the surface and the bottom. The order of arrival will be: first, the ground induced shock; then, the direct shock with the reflections; and finally, the air induced shocks (see fig. 2-33). At most scaled depths, the direct water shock is the greatest. As the direct shock travels outward, the rate of attenuation with distance is primarily determined by the depth of water and the relative position of the weapon within that depth. The shallower the depth of water and/or the closer the weapon to the water surface, the greater the rate of attenuation. This difference in attenuation can be attributed to the non-linear surface reflection and to the interference of multiple reflection waves with the direct shock wave. These effects far outweigh any apparent yield increase as a result of the weapon being detonated on the bottom, as occurs in the case of the land surface burst. Insufficient data exist for the preparation of water overpressure versus distance curves for detonations in shallow water, as is possible for deep water detonations. In the case of a 20 KT detonation at mid-depth in 180 feet of water, the peak overpressures at moderate ranges have been observed to be on the order of one-half those indicated for deep water. Pressures even less than these are expected for a mid-depth burst in more typical harbor conditions because of the shallower depths of water and bottom irregularities. On the other hand, a burst on the bottom will result in slightly higher peak overpressures than one at mid-depth in shallow water.

(3) Cavitation collapse. Since water has no tensile strength, the rarefaction resulting from a reflection at the water-air interface causes the water surface to cavitate. Thus, a "spray dome" is formed. When this collapses, an additional shock is induced in the water by an effect similar to water hammer. Little is known about the magnitude of the shock from this source; however, it is believed that it can generally be neglected.

(4) Refraction. The propagation of the underwater shock waves is distorted on passing through regions of sharp temperature changes within the water, with the result that the pressure wave form is affected. If the weapon is fired in close proximity to a region of temperature change, there is a shadow zone formed, wherein predictions based upon free water conditions overestimate the effectiveness of the shock wave. When the weapon is fired well above or below this temperature region, pressure histories at the normal ranges of interest are changed very little.

b. Waves.

(1) General. Surface waves generated by underwater explosions are the result of the emergence and collapse of the bubble. The first wave is generally a well defined breaking wave. (In the case of a deep burst in deep water, this wave was first observed at roughly 2,000 feet horizontal range.) The first wave is followed by a
WAVE FRONT PROPAGATION IN SHALLOW WATER

Air Blast From Venting

Water Surface

Air Induced Water Shock

Detonation Position

Bottom Reflection

Direct Water Shock

Surface Reflection

Bottom Induced Water Shock

Bottom Shock

Pressure History at Points Along Line A-A

Pressure

Time

a - Bottom Induced Water Shock
b - Direct Water Shock
c - Surface Reflection
d - Bottom Reflection
e - Later Pulses
train of more stable oscillatory waves. As the disturbance moves outward, the number of waves in the wave train increases. At first, the initial wave of the group is the highest, but as the wave train progresses farther from the origin, the maximum wave height appears in successively later waves. It has been observed for a shallow water burst that by the time the wave train had progressed out to 22,000 feet the ninth wave was the highest of the group; while for a deep water burst at 10,000 feet the seventh wave was observed to have the largest amplitude. For the shallow water burst, the maximum wave height one mile from the detonation was about 20 feet; for the deep burst it was about 40 feet at the same distance, reflecting the greater depth of water and burst depth in the latter case. Figure 2–34 gives maximum wave heights as a function of range, under a number of stated conditions for a 1 KT underwater burst. These predictions are based upon the maximum wave passing the point of interest without regard to its position in the train. Thus, the maximum crest-to-trough amplitude decreases linearly as the reciprocal of distance, while the amplitude change with distance for any individual wave varies in a more complex manner. In a given depth of water, a wave no higher than about 0.7 times the water depth can propagate as a stable phenomenon. Higher waves are unstable and decrease in height until stability is attained.

(2) Burst geometry.
(a) Shallow water burst. The formation, propagation and magnitude of surface waves generated by an underwater burst in shallow water vary rapidly with the scaled depth of water and the configuration of the bottom. For prediction purposes in water shallower than 80 W^1/4 feet, the burst position has little effect on the wave generation.
(b) Deep water burst. For the underwater burst in deep water, the size of the surface waves generated is dependent upon the position of the weapon relative to the surface. For practical purposes, as the depth of burst is lowered from the surface to a depth of 180 W^1/4 feet, the maximum wave height can be considered to increase constantly. The scaled depth of 180 feet (two-thirds of the maximum bubble radius of a 1 KT burst) represents an optimum depth. With further increases in depth, the maximum height again drops off, approaching the scaled magnitude of waves observed from a burst at deep depth (scaled depth of burst of 850 W^1/4 feet).

(3) Terminal waves. Waves moving from deep into shallow water, or from open water into narrows, may be considerably increased in magnitude, but this increase is unpredictable unless the exact geometry of the bottom is known. Waves "break" on arriving at water depths about equal to the wave height, momentarily increasing in height by approximately 30 percent, then rapidly decreasing.

c. Column and Base Surge.
(1) Shallow burst. For depths of detonation less than 10 W^1/4 feet, the formation of a significant base surge is unlikely. When the detonation is at a greater depth, but one shallow enough that the gaseous explosion bubble vents the surface while it is still expanding to its first maximum radius, an extensive column of water is thrown into the air. The collapse of this column forms the base surge. An example of such a shallow shot is illustrated in figure 1–5. In this shot, a conical spray dome began to form about four milliseconds after the explosion. Its initial rate of rise was greater than 2,500 feet per second. A few milliseconds later, a hollow column began to form, rapidly overtaking the spray dome. The maximum height attained by the column of water was probably some 8,000 feet, and the greatest diameter was about 2,000 feet. The maximum thickness of the walls of the column was about 300 feet. Approxi-
mately 1,000,000 tons of water were thrown into the air. As the column fell back into the water, there developed on the surface, at the base of the column, a large doughnut-shaped cloud of dense mist. This cloud, called the base surge, formed about 10 seconds after detonation and traveled rapidly outward at an initial velocity greater than 100 feet per second, maintaining an ever-expanding doughnut-shaped form. In the first 100 seconds, the average velocity was 63 feet per second. In 180 seconds, the surge traveled 8,100 feet.

(2) Deep burst. If the detonation is at a depth such that the bubble goes through several oscillations prior to venting, a bushy, ragged plume-like mass of water is thrown into the air by the emerging bubble (see fig. 1–6). The collapse of these plumes generates the base surge. For this deep burst, the first visible surface phenomenon was a very flat spray dome some 7,000 feet in radius and 170 feet in height. Three seconds later a second spray dome emerged out of the first, sending spikes to a height of 900 feet. At 10 seconds the plumes appeared, reaching a height of 1,450 feet and a diameter of 3,100 feet. As the plumes collapsed, a base surge spread out laterally to a cross wind radius of 4,600 feet at 90 seconds and approximately 7,000 feet at 15 minutes.

(3) Intermediate depths. At intermediate depths of burst, such that the bubble vents after the first expansion is completed but before several oscillations are completed, the magnitude of the base surge varies in a manner dependent upon the phase of the bubble at venting, together with the motion of the water surrounding the bubble at venting. When the bubble vents in an expanding phase the surge phenomenon is similar to that described for a shallow burst. When the bubble vents in a contracting stage, a tall spire of water is jetted into the air. The base surge resulting therefrom is less dense and of a smaller final radius. However, lack of knowledge of bubble behavior permits only a coarse prediction of the maximum size of base surge.

(4) Growth. Figure 2–35A gives the radius of the base surge as a function of time for a 1 KT yield at various depths of burst. Figure 2–35B gives the maximum radius of base surge as a function of yield for several specific depths of burst. Winds cause the surge to travel faster in the direction in which the wind is blowing. Although relative humidity does not affect the initial formation of the base surge, it does influence its subsequent growth and duration. When the relative humidity is significantly less than 70 percent, the extent and duration of the base surge are apt to be less than predicted. A significant increase in extent and duration of the base surge is expected when the relative humidity is appreciably greater than 70 percent.
CRATER RADIUS VS. BURST POSITION IN DRY SOIL OR SOFT ROCK

Figure 2-20 gives the estimated apparent and true crater radius as a function of burst position for 1 KT bursts in dry soil or soft rock. For other soils, multiplication factors should be used as follows:

Relative crater radius factors

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard rock (granite and sandstone)</td>
<td>0.8</td>
</tr>
<tr>
<td>Saturated soil (water slowly fills crater)</td>
<td>1.5</td>
</tr>
<tr>
<td>Saturated soil (water rapidly fills crater)*</td>
<td>2.0</td>
</tr>
</tbody>
</table>

*Only for apparent craters with sloping or washing action on the crater sides.

Scaling. The following relation can be used to estimate corresponding crater radii for a given burst yield and depth:

\[
d = W^{1/3}h
\]

where \(d\) = crater radius produced by a yield \(W\) at burst height or depth \(h\), and \(d\) = crater radius produced by a yield \(W\) at burst height or depth \(h\).

Example.

Given: An 80 KT burst at a depth of 50 feet in dry sand.

Find: The apparent crater radius.

Solution: The burst depth for 1 KT is:

\[
h = \frac{50 \times 1}{(80)^{1/3}} = 12 \text{ feet.}
\]

From figure 2-20 the apparent crater radius (and also the true crater radius) for 1 KT is 93 feet. Hence, the crater radius for 80 KT is:

\[
d = \frac{93 \times (80)^{1/3}}{1} = 400 (\pm 120) \text{ feet. Answer.}
\]

Reliability. The reliability of crater radii values obtained from figure 2-20 is estimated to be \(\pm 30\) percent for burst heights of 5 \(W^{1/3}\) feet to burst depths of 65 \(W^{1/3}\) feet for all yields above 1 KT. For other burst conditions the reliability is estimated to be \(\pm 40\) percent.

Related material.

See paragraphs 1.4d(4), e(6) and 2.2a(1).

See also figures 2-19 and 2-21 through 2-26.
Figure 2-21 gives the estimated apparent and true crater depth as a function of burst position in dry soil or soft rock. Multiplication factors for other soils are as follows:

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard rock (granite and sandstone)</td>
<td>0.8</td>
</tr>
<tr>
<td>Saturated soil (water slowly fills crater)</td>
<td>1.5</td>
</tr>
<tr>
<td>Saturated soil (water rapidly fills crater)*</td>
<td>0.7</td>
</tr>
</tbody>
</table>

*Only for apparent craters with sloughing or washing action on the crater sides.

Scaling. For yields other than 1 KT, the following relations can be used to estimate corresponding crater depths for a given burst yield and depth:

\[
\frac{h_1}{h_2} = \frac{W_1^{1/3}}{W_2^{1/3}} \quad \text{and} \quad \frac{d_1}{d_2} = \frac{W_1^{1/4}}{W_2^{1/4}}
\]

where \(d_1\) = crater depth produced by a yield \(W_1\) at burst height or depth \(h_1\), and \(d_2\) = crater depth produced by a yield \(W_2\) at burst height or depth \(h_2\).

Example.

Given: An 80 KT burst at a depth of 50 feet in wet sand of an ocean beach where water will rapidly fill the crater.

Find: Apparent crater depth.

Solution: Corresponding burst depth for 1 KT is:

\[
h_1 = \frac{50 \times 1}{(80)^{1/3}} = 12 \text{ feet.}
\]

From figure 2-21 the crater depth for 1 KT at 12 feet = 37 feet.

Crater depth (\(d_1\)) for 80 KT at 50 feet = \(\frac{37 \times (80)^{1/4}}{1} = 111 \text{ feet.}\)

From the soil type table above, the factor for relative crater depth in saturated soil (where water rapidly fills crater) is 0.7. The crater depth is therefore \(0.7 \times 111 = 78 \pm 39\) feet.

Answer.

Reliability. The reliability of crater depths taken from figure 2-21 is estimated to be ±50 percent for all yields and burst positions.

Related material.

See paragraphs 1.4d(4), e(6) and 2.2a(1).

See also figures 2-19, 2-20, and 2-22 through 2-26.
Figures 2–22A and 2–22B give values of apparent crater diameter vs. yield for various depths and heights of burst, derived by scaling from figure 2–20. No interpolation of depth or height of burst should be made for this figure. For values other than those given, use figure 2–20. Since there is little difference between true and apparent crater diameters from bursts at depths less than 25 \( W^{1/3} \) feet or from above-ground bursts, these figures may be used also for true craters in that range. The assumed soil type is dry soil or soft rock (rock that will crumble or fall apart easily). For other soils, the diameter obtained from figure 2–22A or 2–22B should be multiplied by the relative crater dimension factor as follows:

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard rock (granite and sandstone)</td>
<td>0.8</td>
</tr>
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<td>Saturated soil (water slowly fills crater)</td>
<td>1.5</td>
</tr>
<tr>
<td>Saturated soil (water rapidly fills crater)*</td>
<td>2.0</td>
</tr>
</tbody>
</table>

*Only for apparent craters with sloughing or washing action on the crater sides.

**Example.**

*Given:* A 30 KT burst at a depth of 100 feet in dry clay.

*Find:* The apparent crater diameter.

*Solution:* The apparent diameter, taken directly from the 100 foot depth of burst curve of figure 2–22A for 30 KT is 750 \((\pm 223)\) feet. *Answer.*

**Reliability.** The reliability of crater diameters obtained from figures 2–22A and 2–22B for various yields is estimated to be \( \pm 30 \) percent for burst heights of \( 5 \ W^{1/3} \) feet to burst depths of \( 65 \ W^{1/3} \) feet for all yields above 1 KT. For other burst conditions, the reliability is estimated to be \( \pm 40 \) percent.

**Related material.**

See paragraphs \( 1.4d(4), \) \( e(6) \) and \( 2.2a(1) \).

See also figures 2–19 through 2–21 and 2–23 through 2–26.
FIGURE 2-22A

APPROXIMATE CRATER DIAMETER VS YIELD FOR VARIOUS DEPTHS AND HEIGHTS OF BURST IN DRY SOIL OR SOFT ROCK

Yield (kilotons)

Apparent Crater Diameter (feet)

0.1 0.2 0.3 0.4 0.5 0.6 0.8 1.0 2.0 3.0 4.0 6.0 8.0 10.0

10,000 8,000 6,000 4,000 3,000 2,000 1,000 800 600 400 300 200 100 80 60 40 30 20 10

25' Depth

50' Height

200 Depth

Contact Surface

100' Height

100' Depth

CONFIDENTIAL
APPARENT CRATER DIAMETER VS YIELD FOR VARIOUS DEPTHS AND HEIGHTS OF BURST IN DRY SOIL OR SOFT ROCK
APPARENT CRATER DEPTH VS. YIELD IN DRY SOIL OR SOFT ROCK

Figures 2-23A and 2-23B give values for apparent crater depth vs. yield for various depths and heights of burst, derived from figure 2-21 by scaling. No interpolation of depth or height of burst should be made from this figure. For values other than those given, use figure 2-21. Since there is little difference between true and apparent crater depths from bursts above ground or bursts at depths less than 10 $W^{1/3}$ feet, these figures may be used also for true craters in that range. The assumed soil type is dry soil or soft rock (rock that will crumble or pull apart easily). For other types of soil and rock, the depth obtained from figures 2-23A and 2-23B should be multiplied by the appropriate relative crater depth factor below:

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Factor</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>Saturated soil (water rapidly fills crater)*</td>
<td>0.7</td>
</tr>
</tbody>
</table>

*Only for apparent craters with a sloughing or washing action on the crater sides.

Example.

**Given:** An 80 KT burst at a depth of 100 feet in saturated clay containing water that will slowly fill the crater.

**Find:** The apparent crater depth.

**Solution:** From figure 2-23A the crater depth in dry soil is 158 feet. From the soil type table above, the factor for relative crater depth in saturated soil (water slowly fills crater) is 1.5. The crater depth is therefore $1.5 \times 158 = 237$ (±119) feet. **Answer.**

**Reliability.** The reliability of crater depths obtained from figures 2-23A and 2-23B for all yields and burst positions is estimated to be ±50 percent.

**Related material.**

See paragraphs 1.4d(4), e(6) and 2.2a(1).

See also figures 2-19 through 2-22 and 2-24 through 2-26.
APPARENT CRATER DEPTH VS. YIELD
FOR VARIOUS DEPTHS AND HEIGHTS OF BURST
IN DRY SOIL OR SOFT ROCK

Yield (kilotons)

Apparent Crater Depth (Feet)

0.1  0.2  0.3  0.4  0.6  0.8  1.0
2    3    4    6    8    10
20   30   40   60   80   100
1,000 800  600  400  300  200
100  80  60  40  30  20
10   8   6   4   3   2
1 0.1  0.2  0.3  0.4  0.6  0.8  1.0
2    3    4    6    8    10
20   30   40   60   80   100
1,000 800  600  400  300  200
100  80  60  40  30  20
10   8   6   4   3   2
1

2-72
APPARENT CRATER DEPTH VS YIELD FOR VARIOUS DEPTHS AND HEIGHTS OF BURST IN DRY SOIL OR SOFT ROCK
UNDERWATER CRATERING

Figures 2-24 through 2-26 give underwater crater dimensions as a function of yield. These figures are given for both a surface and a bottom burst in 25, 50, 100, and 200 feet of water with bottom material of sand, sand and gravel, or soft rock. For burst positions between the surface and the bottom, linear interpolation may be used for approximate values. Figures 2-24A and 2-24B are for crater diameter; figures 2-25A and 2-25B are for crater depth; and figures 2-26A and 2-26B are for crater lip height.

For other bottom materials, the dimensions can be estimated by multiplying the values from figures 2-24 through 2-26 by the following:

Relative crater dimension factors

<table>
<thead>
<tr>
<th>Bottom Type</th>
<th>Crater Diameter</th>
<th>Crater Depth</th>
<th>Crater Lip Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose (fine grain soil)</td>
<td>0.5 / 0.7 / 0.6</td>
<td>0.7 / 0.8 / 0.8</td>
<td>0.7 / 0.8 / 0.8</td>
</tr>
<tr>
<td>Clay</td>
<td>1.0 / 2.3 / 2.3</td>
<td>1.0 / 2.3 / 2.3</td>
<td>1.0 / 2.3 / 2.3</td>
</tr>
<tr>
<td>Hard rock</td>
<td>0.70 / 0.50 / 0.40</td>
<td>0.40 / 0.40 / 0.40</td>
<td>0.40 / 0.40 / 0.40</td>
</tr>
<tr>
<td>Mud or mud</td>
<td>1.4 / 0.4 / 0.4</td>
<td>0.4 / 0.4 / 0.4</td>
<td>0.4 / 0.4 / 0.4</td>
</tr>
</tbody>
</table>

Example:

Given: A 70 KT burst on the bottom in 50 feet of water. The bottom is predominantly clay.

Find: The crater dimensions.

Solution: The dimensions from figures 2-24A, 2-25A, and 2-26A for a 70 KT burst at the bottom in 50 feet of water are:
- Diameter, 1,500 feet;
- Depth, 99 feet; and
- Lip height, 12 feet.

The dimensions for a clay bottom are then:
- Diameter = 1,500 \times 1.0 = 1,500 (±600) feet;
- Depth = 99 \times 2.3 = 226 (±90) feet; and
- Lip height = 12 \times 2.3 = 28 (±11) feet.

Answers.

Reliability. Dimensions obtained from these curves are considered reliable within ±40 percent.

Related material.
See paragraph 2.2a(2).
See also figures 2-19 through 2-23.
CRATER DIAMETER VS. YIELD FOR UNDERWATER CRATERING FOR VARIOUS WATER DEPTHS WITH SAND, SAND AND GRAVEL OR SOFT ROCK BOTTOMS.
FIGURE 2-24B

CRATER DIAMETER VS. YIELD FOR UNDERWATER CRATERING FOR VARIOUS WATER DEPTHS WITH SAND, SAND AND GRAVEL OR SOFT ROCK BOTTOMS
CRATER DEPTH VS. YIELD FOR UNDERWATER CRATERING FOR VARIOUS WATER DEPTHS WITH SAND, SAND AND GRAVEL OR SOFT ROCK BOTTOMS.

- Surface Burst
- Bottom Burst

- 200' Water Depth
- 100' Water Depth
- 50' Water Depth
- 25' Water Depth

Yield (kilotons)
CRATER DEPTH VS. YIELD FOR UNDERWATER CRATERING FOR VARIOUS WATER DEPTHS WITH SAND, SAND AND GRAVEL OR SOFT ROCK BOTTOMS.
CRATER LIP HEIGHT VS. YIELD FOR UNDERWATER CRATERING FOR VARIOUS WATER DEPTHS WITH SAND, SAND AND GRAVEL OR SOFT ROCK BOTTOMS.
CRATER LIP HEIGHT VS. YIELD FOR UNDERWATER CRATERING FOR VARIOUS WATER DEPTHS WITH SAND, SAND AND GRAVEL OR SOFT ROCK BOTTOMS.
PEAK AIR BLAST INDUCED GROUND ACCELERATION (VERTICAL COMPONENT) VS. PEAK OVERPRESSURE

Figure 2–28 represents the relationship between overpressure and air blast induced ground acceleration. The acceleration shown is the maximum vertical acceleration (upward or downward) measured at a depth of approximately ten feet below the horizontal ground surface in Nevada type soil. Horizontal acceleration can be assumed to be approximately equal to 70 percent of the vertical acceleration. Accelerations measured at a depth of 5 feet may be roughly 150 percent of those indicated and accelerations measured at a depth of twenty feet may be roughly 50 percent of those indicated. Mediums denser than Nevada type soil may experience higher acceleration values and less dense mediums may experience less acceleration. The accelerations shown are applicable only to regions beyond the plastic zone of any crater produced.

Procedure. To determine the acceleration at any range, determine the peak overpressure at that range from figure 2–9 or figure 2–10, whichever is applicable, and read the acceleration directly from the curve.

Example.

Given: An 80 KT detonation at a height of burst of 2,580 feet over an "average" surface.

Find: The vertical ground acceleration at a range of 4,000 yards, 10 feet below the ground surface.

From figure 2–10B the overpressure from an 80 KT burst at 4,000 yards is 3 psi. Reading directly from figure 2–28, the acceleration is 0.2 g. Answer.

Reliability. The curve is based on full scale field tests in Nevada type soil. Accelerations obtained from the curve may be high by a factor of two or low by a factor of three even in Nevada type soil. When applied to other soils, the reliability of the curve is reduced.

Related material.

See paragraph 2.2b.
PEAK AIR BLAST INDUCED GROUND ACCELERATION
VERTICAL COMPONENT VS. PEAK OVERPRESSURE

Peak Overpressure (Psi)

Peak Acceleration (g)
BASE SURGE FOR UNDERGROUND BURSTS

Figure 2–29A gives the expected rate of radial growth of the earth base surge from a 1 KT underground burst; figure 2–29B gives the expected maximum base surge radius vs. yield. Figure 2–29B is based on extrapolation from the maximum base surge radii of the curves in figure 2–29A. Radii obtained from the figures assume no wind, or are crosswind radii. To compute upwind or downwind base surge radii at a specific time after detonation, add the distance traversed by the wind up to this time to the base surge radius obtained from the figures to obtain the downwind base surge radius, or subtract to obtain the upwind base surge radius.

Scaling. Depth of burst and the maximum radius of the base surge scale as the cube root of yield between scaled depths of burst of 16 $W_{16}^{1/3}$ and 125 $W_{125}^{1/3}$ feet, or:

\[ \frac{h_1}{h_2} = \frac{r_1}{r_2} = \frac{W_{16}^{1/3}}{W_{125}^{1/3}} \]

where $h_1$ and $r_1$ are depth of burst and base surge radius for yield $W_1$, and $h_2$ and $r_2$ are the corresponding depth of burst and base surge radius for yield $W_2$.

Time to complete a given percentage of total radial growth of base surge scales as the one-sixth power of the yield for the same scaled depth of burst, or:

\[ \frac{t_1}{t_2} = \frac{W_{16}^{1/6}}{W_{125}^{1/6}} \]

where $t_1$ = time to complete a given percentage of total radial growth for yield $W_1$, and $t_2$ = corresponding time to complete the same percentage of total radial growth for yield $W_2$.

Example.

Given: A 64 KT detonation 65 feet underground.

Find:

(a) The maximum base surge radius.
(b) The time at which the maximum radius occurs.

Solution: The corresponding depth of burst for 1 KT is:

\[ h_1 = \frac{W_{16}^{1/3} \times h_2}{W_{125}^{1/3}} = \frac{1 \times 65}{(64)^{1/3}} = 16 \text{ ft.} \]

From figure 2–29A the maximum radius for 1 KT at a 16 foot depth of burst is 2,010 feet and occurs at 180 seconds.

The corresponding radius for 64 KT is:

\[ r_2 = \frac{r_1 \times W_{125}^{1/3}}{W_{16}^{1/3}} = \frac{2,010 \times (64)^{1/3}}{1} = 8,040 \text{ ft. Answer.} \]

This may also be read directly from figure 2–29B.

The time at which this maximum radius occurs is:

\[ t_2 = \frac{W_{16}^{1/6} \times t_1}{W_{125}^{1/6}} = \frac{(64)^{1/6} \times 180}{1} = 360 \text{ sec. Answer.} \]

Reliability. The data presented in the figure are based on limited full scale testing and extensive HE reduced scale testing.

Related material.

See paragraphs 1.4(4) and 2.2c.
BASE SURGE RADIUS vs. TIME
FOR 1 KT UNDERGROUND BURSTS AT VARIOUS DEPTHS
Figure 2-31 gives the expected values for peak water overpressure versus slant range for various yields burst deep in deep water, where the effects of a reflecting surface are absent.

Scaling. Scaling for yields other than those shown may be done by linear interpolation between appropriate curves.

Example.

Given: A 40 KT weapon is burst at a depth of 1,000 feet in deep water.

Find: The peak water overpressure at a 1,000 foot depth 4,000 yards from the burst.

Solution: From figure 2-31, the peak water overpressure at a slant range of 4,000 yards for a 40 KT weapon can be read directly as 440 psi. Answer.

Reliability. Slant ranges obtained from figure 2-31 are estimated to be reliable within ±20 percent for the yield range shown.

Related material.
See paragraph 2.3a(2).
FIGURE 2-34

MAXIMUM WAVE HEIGHT FOR WATER BURSTS

Figure 2-34 gives the approximate maximum crest-to-trough wave heights vs. horizontal distance to be expected from surface and underwater bursts of 1 KT weapons. These may be scaled to other yields as explained below. For burst depths greater than 180 \( W^{1/4} \) feet but less than 850 \( W^{1/4} \) feet, a linear interpolation between the values from the above limiting cases will provide a satisfactory prediction. Below 850 \( W^{1/4} \) feet, the wave height is expected to decrease almost inversely with increasing depth.

Scaling. Use the following relations:

\[
\begin{align*}
(a) \quad \frac{W_{1}^{1/4}}{W_{2}^{1/4}} &= \frac{h_{1}}{h_{2}} \\
(b) \quad \frac{d_{1}}{d_{2}} &= \frac{W_{1}^{1/4}}{W_{2}^{1/4}} = \frac{d_{1}'}{d_{2}'}
\end{align*}
\]

where yield \( W_{1} \) will give a wave height of \( h_{1} \), and yield \( W_{2} \) will give a corresponding wave height \( h_{2} \) at the same scaled depth of burst.

Find: The expected maximum wave height at 10,000 yards from surface zero.

Solution: The corresponding burst depth for 1 KT is, from (b) above:

\[
d_{1} = \frac{450}{(40)^{1/4}} \times \frac{450}{2.5} = 180 \text{ feet.}
\]

The corresponding water depth for 1 KT is:

\[
d_{1}' = \frac{1,500}{(40)^{1/4}} \times \frac{1,500}{2.5} = 600 \text{ feet.}
\]

The curve of figure 2-34 for burst depth of 180 feet and water depths of 450 feet or greater is used. From this curve, the maximum wave height at 10,000 yards for a 1 KT burst is 2.2 feet. Therefore, for a 40 KT burst, the wave height at 10,000 yards is, from (a) above:

\[
h_{2} = (2.2) \times (40)^{1/4} = (2.2) \times (6.3) = 14 \text{ (±4) feet. Answer.}
\]

Example. A 40 KT detonation at 450 feet in 1,500 feet of water.

Related material. The wave heights obtained from figure 2-34 are estimated to be reliable within ±30 percent.

See paragraph 2.36.
MAXIMUM WAVE HEIGHT VS. HORIZONTAL DISTANCE FROM SURFACE ZERO FOR WATER BURSTS

SCALE TO 1 KT

- Burst at 800 Foot in Water (Depth less than 200 Feet)
- Burst 100 Foot in Water (Depth less than 400 Feet)
- Burst Any Depth in 85 Feet of Water
- Burst Any Depth in 60 Feet of Water
- Burst Any Depth in 30 Feet of Water
- Burst Any Depth in 15 Feet of Water

Horizontal Distance from Surface Zero (thousands of yards)

Maximum Wave Height, Crest to Trough (feet)
Figure 2-35A gives the expected radial growth of the base surge as a function of time after detonation for a 1 KT weapon at various depths of burst. Figure 2-35B gives the expected maximum base surge radius as a function of yield for several specific depth of burst conditions. The maximum base surge is developed from a weapon detonated at approximately the venting depth (250 $W^{1/4}$ ft.). For very shallow depths of burst, less than 10 $W^{1/4}$ feet, the occurrence of a base surge is improbable. Proximity of the bottom to the point of detonation has little effect upon the production of the base surge. For depths of burst between the limits 10 $W^{1/4}$ and 250 $W^{1/4}$ feet, the diameter of the water column producing the base surge is approximately one fourth of the resultant surge radius. With depths of burst below the venting depth of 250 $W^{1/4}$ feet, no such simple relation of the column or plume to the resultant surge exists. Little data or theory is available for base surge predictions at deep depths. A prediction can be made, however, by linear interpolation between the base surge radius of a burst at venting depth and one at a deep scaled depth (650 $W^{1/2}$ feet). A prediction thus made represents the maximum base-surge which could be expected.

Radii obtained from figures 2-35A and 2-35B assume “no wind” conditions. To compute upwind or downwind base surge radii for a specific time after detonation, add the distance traveled by the wind up to this time to the “no wind” base surge radius to obtain the downwind base surge radius, or subtract to obtain the upwind base surge radius.

Scaling. Depth of burst and the accompanying maximum radius of the base surge scale as the cube root of yield for depths of burst between 25 $W^{1/2}$ and 250 $W^{1/4}$, or:

$$
\frac{h_1}{h_2} = \left(\frac{r_1}{r_2}\right)^{1/3}
$$

where $h_1$ and $r_1$ are depth of burst and base surge radius for yield $W_1$, and $h_2$ and $r_2$ are the corresponding depth of burst and base surge radius for yield $W_2$.

Time to complete a given percentage of total radial growth of the base surge scales as the one-sixth power of the yield for the same scaled depth of burst, or:

$$
\frac{t_1}{t_2} = \left(\frac{W_1}{W_2}\right)^{1/6}
$$

where $t_1$ = time to complete a given percentage of total radial growth for yield $W_1$ and $t_2$ = the corresponding time to complete the same percentage of total radial growth for yield $W_2$.

Time to reach the maximum base surge radius from a detonation at venting depth or less may also be computed by:

$$
t_{\text{max}} = 2.25 r^{1/2}
$$

where $t_{\text{max}}$ = time to the maximum base surge radius in seconds, and $r$ = maximum base surge radius in feet.

**Examples.**

1. Given: A 10 KT detonation at a depth of 150 feet below the water surface.

**Find:**

(a) The maximum base surge radius.
(b) Time to maximum base surge radius.
(c) The expected base surge radius 1 minute after detonation.

**Solution:**

(a) The maximum base surge radius is read directly from figure 2-35B as 7,200 feet. 

(b) The venting depth is 250 $W^{1/4} = 440$ feet. Since the depth of burst is less than venting, the simplified formula for time to maximum may be used. The time of maximum base surge radius is $t_{\text{max}} = 2.25 (7,200)^{1/2} = 190$ seconds.

(c) A 10 KT detonation of 150 feet depth will complete the same percentage of its total radial growth in 60 seconds as a 1 KT detonation will complete at a corresponding scaled time and depth. Using the scaling above, the corresponding depth of burst for 1 KT is:

$$
h_1 = \left(\frac{10^{1/2}}{1}\right)^{1/3} = 1 \times 150 = 70 \text{ ft.}
$$
The time that a 1 KT weapon burst at a depth of 70 feet will have completed the same percentage of its growth that a 10 KT burst will have completed in 60 seconds is:

\[ t_1 = t_2 \times \frac{W_1^{1/8}}{W_2^{1/8}} = \frac{60 \times 1}{10^{1/8}} = 41 \text{ seconds.} \]

From figure 2-35A the maximum surge for a 1 KT at 70 feet is 3,400 feet and at 41 seconds the surge has a radius of 2,000 feet. Thus it has completed 60 percent of its growth. A 10 KT detonation at a depth of 150 feet will then complete in one minute 60 percent of its maximum radial growth or:

\[ 0.60 \times 7,200 = 4,300 \text{ feet.} \]

**Answer.**

(2) **Given:** A 30 KT detonation at a depth of 1,000 feet below the water surface.

**Find:** The maximum base surge radius.

**Solution:** The venting depth for a 30 KT detonation is approximately 250 \( W^{1/4} \) or 600 feet. Little data is available upon which to predict the maximum base surge radius at depths exceeding this. Hence, a prediction must be made by linear interpolation between the venting depth, 600 feet, and a depth of 650 \( W^{1/4} \) or 2,000 feet.

From figure 2-35B the maximum base surge radius at venting depth is 12,000 feet. At 650 \( W^{1/4} \) the maximum base surge radius is 7,000 feet. By interpolation the maximum base surge radius for a 30 KT detonation at 1,000 feet is:

\[ 12,000 \left( \frac{400}{1,400} \times 5,000 \right) = 10,600 \text{ ft.} \]

**Answer.**

**Reliability.** Figures 2-35A and 2-35B are based upon limited full scale and extensive reduced scale testing.

**Related material.**

See paragraph 2.3c.
FIGURE 2-35A

BASE SURGE RADIUS Vs. TIME
FOR 1 KT UNDERWATER BURSTS AT VARIOUS DEPTHS

Time After Detonation (seconds)

Base Surge Radius (feet)

- 250' Depth of Burst
- 100' Depth of Burst
- 50' Depth of Burst
- 25' Depth of Burst