EERO TECHNICAL REPORT NO. 7

PREDICTION OF AIRBLAST OVERPRESSURES FROM UNDERGROUND EXPLOSIONS

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Two methods are presented for predicting airblast overpressures from underground chemical explosive and nuclear detonations. The first method utilizes empirical scaling techniques to predict both ground-shock-induced and gas-vent-induced overpressures. Empirical procedures are also provided for predicting airblast from underground row-charge and array detonations and from surface or near-surface bursts. The second method uses peak vertical spall velocities combined with basic physical principles to predict ground-shock-induced overpressures. Between these two methods, it is possible to predict airblast overpressures caused by detonations at scaled depths of burst from zero to 700 $ft/kt^{1/3}$ in a wide variety of media.

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Foreword

The Explosive Excavation Research Office (EERO) is embarked on a program of research in topical areas critical to the overall technology titled "explosive excavation." This work was funded by the Office of the Chief of Engineers (OCE) Appropriation 96X3121, General Investigations. Some of these topical areas involve the prediction of safety-related effects. Effort is being expended in these areas to review all pertinent measured data and all current prediction methods in use, and to make an attempt to advance the state-of-the-art. This report presents prediction methods that integrate and are based on the systems described in detail with supporting data in two previous EERO reports, EERO TR-39, "A Revised Empirical Approach to Airblast Prediction," and EERO TR-40, "Prediction of Ground-Shock-Induced Airblast Overpressures for Subsurface Explosions from Peak Vertical Spall Velocity." Critical review and comment are invited.

Abstract

Two methods are presented for predicting airblast overpressures from underground chemical explosive and nuclear detonations. The first method utilizes empirical scaling techniques to predict both ground-shock-induced and gas-vent-induced overpressures. Empirical procedures are also provided for predicting airblast from underground row-charge and array detonations and from surface or near-surface bursts. The second method uses peak vertical spall velocities combined with basic physical principles to predict ground-shock-induced overpressures. With the use of one or both of these methods, it is possible to predict airblast overpressures caused by detonations at scaled depths of burst from zero to 700 ft/kt$^{1/3}$ in a wide variety of media.

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The Directors of the Explosive Excavation Research Office (formerly the Nuclear Cratering Group) during the time this work was conducted were COL William E. Vandenberg and LTC Robert L. LaFrenz. The Deputy Director (Civil) was Walter Day.

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Nomenclature

c	= Sonic velocity in ambient air (in ft/sec).
c_0	= Sonic velocity in air at standard sea-level conditions (in ft/sec).
DOB	= Depth of burst = distance from shot point (center of charge) to surface ground zero - SGZ (in ft).
dob	= Scaled depth of burst to the center of a charge (in ft/kt$^{1/3}$).
f_{max}	= Maximum transmission factor (may refer to either ground-shock-induced or gas-vent-induced airblast); f_{max} is used in predicting airblast by the empirical method.
h	= Height of an elevated location above the ground surface level (in ft).
M	= Mach number of the induced air shock at SGZ (dimensionless) (calculated from the peak vertical surface velocity, V_0).
m	= Velocity profile constant (for all single-charge detonations in a given medium) (dimensionless). This constant is used to relate the ground surface spall velocity as a function of inverse dimensionless slant range (DOB/S) to the spall velocity at SGZ.
n	= Total number of charges in a row or array of buried charges.
$P_{ambient}$	= Ambient atmospheric pressure at the location of an experiment – as obtained from meteorological or altitude data (in mbar).
ΔP_s	= Standard line overpressure as a function of standard line range (in mbar). Standard line points (Table 1) are used as reference points in predicting airblast by the empirical method. For surface bursts, ΔP_s is also used to represent a standard surface burst overpressure.
ΔP	= Peak airblast overpressure at any location beyond the immediate vicinity of the detonation; may be used to refer to either a ground-shock-induced or a gas-vent-induced overpressure (ΔP may be expressed in psi or mbar).
ΔP_0	= Ground-shock-induced peak local airblast overpressure directly above SGZ (in psi).
ΔP (elevated)	= Peak airblast overpressure at an elevated location – above the ground surface level (may be expressed in psi or mbar).
R_s	= Standard line range (in ft/kt$^{1/3}$). Standard line points (Table 1) are used as reference points in predicting airblast by the empirical method. For surface bursts, R_s is also used to represent a standard surface burst range.
R	= Range from SGZ to any location at or above the ground surface (in ft).
S	= Slant range from the shot point to any location on the ground surface (in ft).
SGZ	= Surface ground zero; the location at the ground surface lying vertically over the shot point.

V = Peak vertical surface spall velocity of the ground surface at any location other than SGZ (in ft/sec).

V_0 = Peak vertical surface spall velocity of the ground surface at SGZ (in ft/sec).

W = Yield of a buried detonation; usually expressed in kilotons (kt).

α = Dimensionless airblast constant (for all single-charge detonations in a given medium); used in the theoretical prediction of ground-shock-induced airblast; dimensionless quantity.

ρ_0 = Density of air at standard sea-level conditions.

$\rho_0 c_0$ = Acoustic impedance of air at standard sea-level conditions (in psi-sec/ft).

θ = Angle between the vertical direction and a vector from SGZ to an elevated location ($\cos \theta = h/R$); (in degrees).

$\perp$ = Ground-level location in a direction perpendicular to the axis of a row of buried charges.

$\parallel$ = Ground-level location in a direction off the end of a row of buried charges (i.e., along the axial direction of the row).

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PREDICTION OF AIRBLAST OVERPRESSURES FROM UNDERGROUND EXPLOSIONS

Introduction

PURPOSE

The use of underground explosions in construction applications is often limited by considerations of damage to nearby man-made structures or to the natural environment. There are three major sources of damage from such underground explosions· material throwout, ground motion, and airblast. The effects of airblast can be a limiting factor at ranges greater than several hundred feet from the detonation site.

Airblast from buried detonations has been under systematic investigation for two decades. Sufficient data are now available to permit the development of a general prediction scheme. Damage due to airblast is very closely correlated with the peak overpressure of the airblast pulse (pressure increase above the local ambient pressure) for almost all cases of interest. Therefore, this is the quantity which must be predicted. This report incorporates prediction procedures, which were developed in Refs. 1 and 2 by considering the data from all previous large-yield chemical and nuclear subsurface detonations, into a general method which predicts peak airblast overpressure as a function of range from the surface ground zero (SGZ) of the detonation site. The prediction method is summarized and complete instructions for performing predictions are given, together with sample problems.

BACKGROUND

Most buried detonations at useful cratering depths give rise to two separate airblast pulses. The first pulse is produced when the shock wave from the detonation reaches the ground-air interface, is reflected as a tension wave, and forces the overlying ground surface to move upwards. The rising ground surface compresses the air above it, producing a distinct airblast pulse. This pulse is referred to as the ground-shock-induced airblast. The peak overpressures for the ground-shock-induced pulse can be predicted by using empirical techniques or by using a theoretical method based on the theory of acoustics (sound) and the predicted peak vertical spall velocity of the ground surface.

After the ground surface above the detonation is shocked, a mound of material rises into the air. The mound grows for a time, then begins to disintegrate. When disintegration occurs, the explosion cavity gases beneath the mound escape or vent to the surrounding atmosphere. If the pressure of these gases at vent time is appreciably greater than the ambient pressure of the surrounding atmosphere, a second pressure pulse will be produced. This pulse is known as the gas-vent-induced airblast. At the present time, its peak overpressures can be predicted only by using empirical techniques.

In addition to the two primary airblast components, additional pulses of lesser amplitude are sometimes observed. These additional pulses are always smaller than the dominant (ground-shock-induced or gas-vent-induced) pulse, and they may be ignored for purposes of safety predictions.

Figure 1 shows a typical measured pressure-vs-time history recorded at a few hundred feet from a chemical explosive detonation occurring near optimum cratering depth in alluvial soil. Note that the ground-shock-induced pulse and the gas-vent-induced pulse are both clearly visible. The gas-vent-induced pulse happens to be "dominant" in this case (producing a larger peak overpressure than the ground-shock-induced pulse).

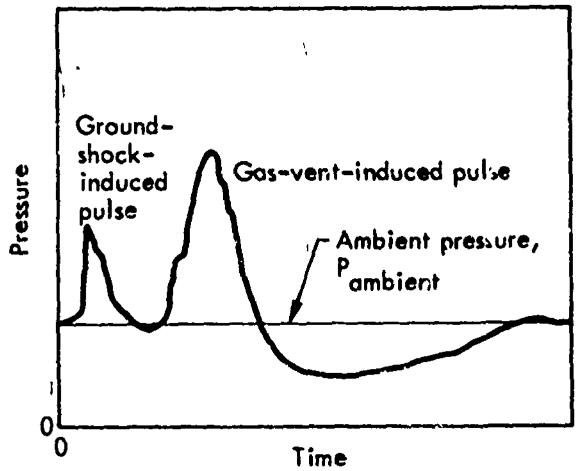


Fig. 1. Typical intermediate-range airblast overpressure tracing (for a TNT detonation in unsaturated alluvium), showing ground-shock-induced pulse and gas-vent-induced pulse.

PREDICTION METHODS

Most detonations buried at cratering depths in unsaturated media give rise to both ground-shock-induced and gas-vent-induced airblast pulses. The larger of these two pulses will determine the maximum peak overpressures and thus the airblast damage limitations for the detonation. Gas-vent-induced airblast is usually dominant for detonations at shallow scaled depths. However, the gas-vent-induced pulse is very rapidly suppressed with increasing depth of burst and also lags further behind the ground-shock-induced pulse in time. At great depths of burst, the ground-shock-induced pulse becomes dominant, and the gas-vent-induced pulse disappears altogether.

Since either of the two pulses may be dominant in a particular case, it is usually necessary to predict both ground-shock-induced and gas-vent-induced airblast. This report presents two prediction methods. The first method is empirical in nature and is based on earlier studies by L. J. Vortman.[3-5] The empirical method predicts both ground-shock-induced and gas-vent-induced air-blast for most detonations in unsaturated media. The second method is based on a theoretical treatment,[6,7] and it predicts ground-shock induced airblast for certain types of detonations in certain media. The theoretical method is often more accurate than other techniques, but it is applicable only to a limited number of cases.

Both methods require the same basic input parameters. First, the yield, W, and the scaled depth of burst, dob, of the charge must be known:

$$\text{dob} = \frac{\text{Depth of burst (in ft)}}{[\text{W (in kt)}]^{1/3}}$$

W = Yield of charge in kilotons.

In addition, it is necessary to specify the type of explosive used, the emplacement medium, and the approximate moisture content of the medium. The theoretical method also requires the peak vertical spall velocity, V_0, of the surface at SGZ.

The empirical and theoretical methods predict peak overpressures as a function of range along the ground surface. All ranges are measured from SGZ, the surface point directly above the detonation. Empirical predictions are valid at or near ground surface level (elevations less than several yards). The theoretical method likewise predicts overpressures at or near ground surface level, but it can also be used to predict elevated overpressures (above the ground surface) if desired.

Airblast can also be predicted for rows or arrays of buried charges which are emplaced close together so as to excavate a continuous crater.[1, 2, 8] The airblast overpressures for an "average" single charge in the row or array are first predicted by means of either the empirical method or the theoretical method. These predicted overpressures are then multiplied by a reinforcement factor which depends on the number of charges in the row or array. This procedure gives the predicted overpressures for the entire row or array. The reinforcement factors are determined by means of an empirical method, but may be applied to either empirical or theoretical single-charge predictions.

The correct choice of which method to use in specific cases is discussed in the following pages. The general rules are summarized as follows: The empirical method may be used to predict ground-shock-induced and gas-vent-induced airblast from nuclear and chemical explosive detonations at cratering depths (dob $\approx$ 15 to 250 or 300 ft/kt$^{1/3}$) in unsaturated media. Gas-vent-induced airblast is always strongly dominant for detonations shallower than dob = 60 ft/kt$^{1/3}$, and ground-shock-induced airblast need not be predicted in these cases. The empirical method is also used to predict reinforcement factors for row-charge and array detonations. The theoretical method may be used to predict ground-shock-induced airblast from nuclear and chemical explosive cratering detonations in most (but not all) unsaturated media. Theoretical predictions of ground-shock-induced airblast are usually somewhat more accurate than empirical predictions when the dob is greater than 60 ft/kt$^{1/3}$. If the theoretical method is used for ground-shock-induced airblast predictions in these cases, the gas-vent-induced airblast must still be predicted by the empirical method. There are also certain types of events for which ground-shock-induced airblast is strongly dominant and gas-vent-induced airblast is negligible. The theoretical method is generally used to predict airblast from these events (although the empirical method can be used in some cases). Ground-shock-induced airblast is strongly dominant for all mounding or contained detonations (700 ft/kt$^{1/3}$ > dob $\gtrsim$ 300 ft/kt$^{1/3}$), for most well-stemmed nuclear detonations of yield less than 5 kt deeper than dob = 125 ft/kt$^{1/3}$ in dry high-strength rock, and for all detonations deeper than dob = 170 ft/kt$^{1/3}$ in saturated media or under water.

SURFACE-BURST AND FREE-AIR-BURST AIRBLAST PREDICTION

Airblast from detonations shallower than dob = 15 ft/kt$^{1/3}$ is very nearly equal to the airblast from a surface burst of the same yield. An approximate method for predicting airblast overpressures from surface and near-surface events is included with the empirical prediction method. A method for predicting airblast from free-air bursts is also given.

RANGE OF VALIDITY

Both of the subsurface-burst prediction methods discussed here utilize straight line log-log fits for predicting airblast as a function of range. The straight line approximation is valid at intermediate-to-long ranges. Ground-shock-induced airblast predictions are accurate for scaled ranges* greater than 600 ft/kt$^{1/3}$, out to true ranges of at least several miles or more. Gas-vent-induced airblast predictions are accurate for scaled ranges greater than 3000 ft/kt$^{1/3}$, out to true ranges of at least several miles or more.

*Scaled range

$$(\text{ft/kt}^{1/3}) = \frac{\text{actual range (in ft)}}{[W(\text{in kt})]^{1/3}}.$$

The true ranges at which the predictions are accurate for a typical chemical explosive detonation (yield = 1.0 ton) would be 60 ft to several miles (ground-shock-induced airblast) and 300 ft to several miles (gas-vent-induced airblast). Local meteorological effects may become important at ranges beyond several miles.* These long ranges are usually of no interest for buried chemical explosive detonations smaller than 1.0 kt because the airblast overpressures are not great enough to cause damage.

Within the range intervals specified above, predicted airblast overpressures are normally accurate to about ± 40%. The accuracy may be somewhat lower for media or explosives different from those specified in the prediction methods, for highly inhomogeneous media, for individual charges of very small yield (less than one ton), and for row-charge or array detonations. Predictions are not extremely accurate for very long or complex rows of many charges.

The surface-burst and free-air-burst overpressure predictions are valid at scaled ranges greater than 30 to 100 ft/kt$^{1/3}$, out to true ranges of several miles or more. The predicted overpressures are usually correct within ± 40% for the explosives specified in the prediction method.

*Atmospheric refraction and focusing effects, which become important at very long ranges for large-yield detonations, are discussed in Ref. 9.

Empirical Prediction Method

PREDICTION PROCEDURE FOR SINGLE-CHARGE SUBSURFACE BURSTS

Airblast overpressures from buried single-charge detonations at cratering depths ($15 < dob < 250$ or $300\ ft/kt^{1/3}$) in unsaturated media may be predicted by the method described in this section. The method involves a scaling process whereby "standard line" overpressure-vs-range points are scaled to the yield and ambient atmospheric pressure of the experiment to be predicted. The scaled overpressures are then multiplied by a ground-shock transmission factor, f_{max} (ground-shock), to predict the ground-shock-induced airblast, and by a gas-vent transmission factor, f_{max} (gas-vent), to predict the gas-vent-induced airblast. These transmission factors are empirically determined corrections which convert the scaled overpressures to true predicted overpressures for the detonation in question. The following are the steps of the empirical prediction procedure.

Step 1

Calculate the scaled depth of burst, dob, of the detonation to be predicted:

$$dob = \frac{DOB}{W^{1/3}}, \tag{1}$$

DOB = Depth of burst to center of charge (in ft)

W = Yield of charge (in kt).

Scaled depth of burst, dob, is expressed in units of $ft/kt^{1/3}$.

Step 2

Calculate several overpressure-vs-range points for the detonation to be predicted. First, select several standard line overpressure-vs-range points from Table 1. Then scale the standard line overpressures and ranges according to the following equations:

$$\Delta P = \Delta P_s \left(\frac{P_{ambient}}{1000\ mbar}\right) \tag{2}$$

$$R = R_s \left(\frac{W}{1.0\ kt}\ \frac{1000\ mbar}{P_{ambient}}\right)^{1/3}, \tag{3}$$

where

ΔP = overpressure (in mbar)

R = range (in ft)

ΔP_s = standard line overpressure (in mbar) from Table 1

R_s = standard line range (in $ft/kt^{1/3}$) from Table 1

$P_{ambient}$ = ambient atmospheric pressure at location of experiment (in mbar)

W yield of charge (in kt).

The ambient atmospheric pressure, $P_{ambient}$, at the project location may be estimated either from meteorological data or from the altitude of the location above sea level. Normally, $P_{ambient} \approx 1013$ mbar at sea level, and $P_{ambient} \approx 844$ mbar at 5000 ft above sea level (a 34-mbar decrease for each 1000 ft above sea level).

In order to insure the accuracy of the predictions, it is necessary to scale three or more standard line points (R_s, ΔP_s). These points should be selected at a variety of R_s ranges. The scaling process will then provide a set of points (R, ΔP) which are used in making predictions.

Step 3

Determine the transmission factors f_{max} (ground-shock) and f_{max} (gas-vent).

Table 1. Approximate values of standard line overpressure ΔP_s as a function of range R_s assuming a straight line of slope $R_s^{-1.2}$ through ΔP_s = 25.5 mbar at R_s = 9000 ft/kt$^{1/3}$.

R_s (ft/kt$^{1/3}$)	ΔP_s (mbar)
10	89,500
30	24,000
80	7,400
100	5,650
300	1,510
400	1,070
500	816
600	658
700	546
1,000	357
1,500	219
2,000	155
3,000	95.4
5,000	51.6
6,000	41.5
8,000	29.4
9,000	25.5
10,000	22.5
15,000	13.8
20,000	9.8
50,000	3.26

Figures 2, 3, and 4 are used for this purpose. Enter the appropriate figure at dob on the horizontal axis, go up to the appropriate curve or line, and read f_{max} from the vertical axis. The correct figures to use are summarized below.

Ground-Shock f_{max} Values—(determined only for dob > 60 ft/kt$^{1/3}$; ground-shock-induced airblast is not important for shallower detonations)

a. Well-stemmed nuclear detonations in dry high-strength rock, 60 < dob < 250 to 300 ft/kt$^{1/3}$, 0.05 kt < W < 5 kt. Use the nuclear detonations dry rock line (lower line) in Fig. 2.

b. Nuclear detonations, nitromethane, TNT, and similar chemical explosive detonations, in alluvium or soil, 60 < dob < 250 to 300 ft/kt$^{1/3}$, 0.001 kt < W < 1.0 kt. Use the alluvium curve (center dashed curve) in Fig. 2.

c. Nitromethane, TNT, and similar chemical explosive detonations, in dry high-strength rock, 60 < dob < 250 to 300 ft/kt$^{1/3}$, 0.001 kt < W < 1.0 kt. Use the chemical explosives in basalt or rhyolite line (upper line) in Fig. 2.

d. Nitromethane and similar chemical explosive detonations in saturated clay shale and saturated weak media, at optimum depth (dob = 170 to 200 ft/kt$^{1/3}$), all yields. Use ground-shock f_{max} = 0.06. Gas-vent airblast is negligible for these events. The airblast from detonations in saturated media is more accurately predicted by the theoretical method (discussed in the next section).

e. Aluminized ammonium nitrate slurry and ammonium nitrate fuel oil (ANFO) detonations in sandstone or weak rock, 160 < dob < 300 ft/kt$^{1/3}$, 0.001 < W < 0.1 kt. Use the ground-shock f_{max} line in Fig. 4. Airblast from detonations of this type shallower than dob = 160 ft/kt$^{1/3}$ cannot be accurately predicted due to lack of data, but the gas-vent will be strongly dominant, and the airblast may approach that expected from a surface burst of the same yield.

Gas-Vent f_{max} Values—

a. Nuclear detonations in moist or wet alluvium, moist or wet rock, and all moist or weak media, 15 < dob < 160 ft/kt$^{1/3}$,

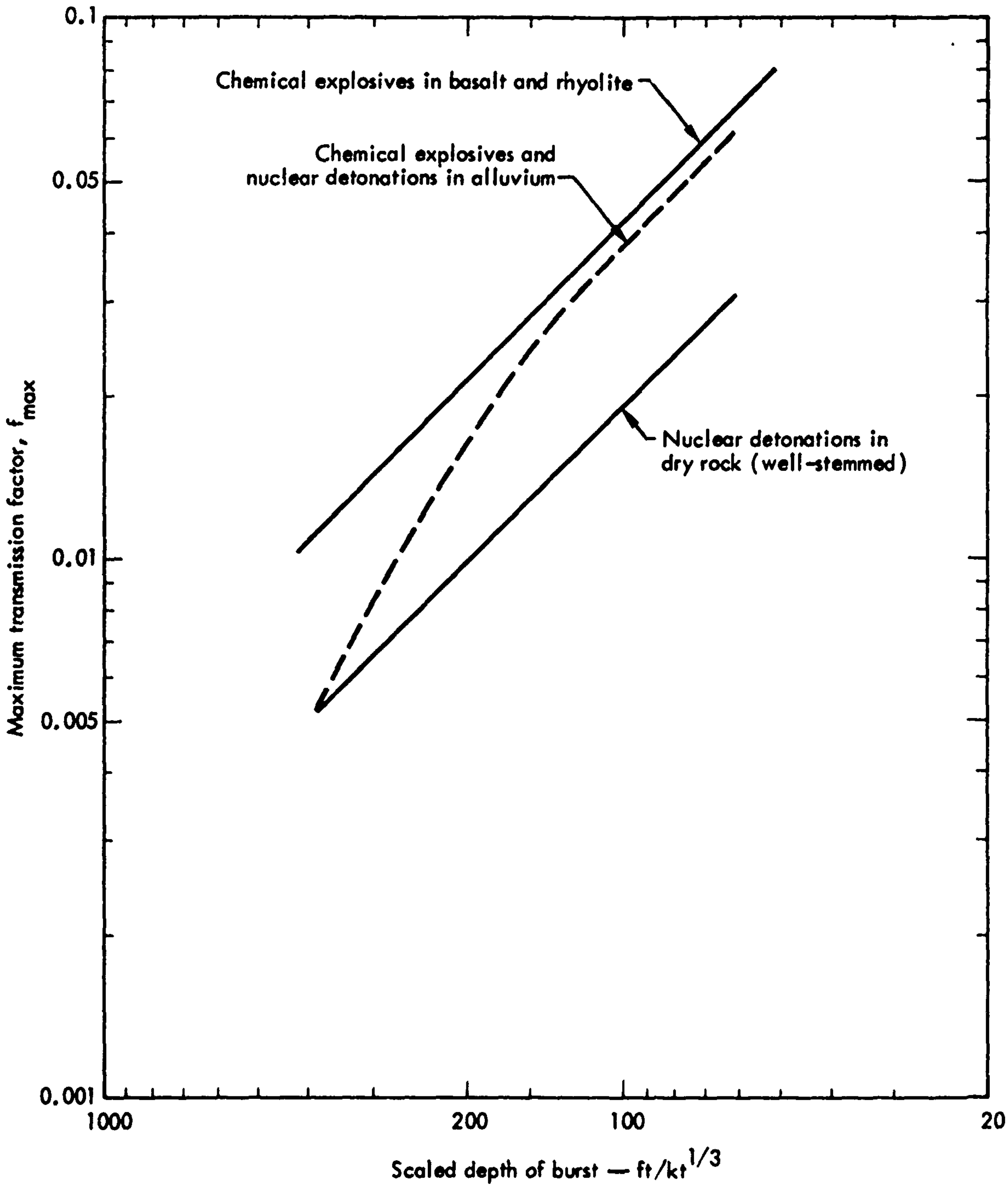


Fig. 2. Ground-shock airblast maximum transmission factor f_{max} for single-charge events as a function of scaled depth of burst (for TNT and similar chemical explosives in basalt and rhyolite, for TNT and similar chemical explosives and nuclear explosives in alluvium, and for nuclear explosives in dry high-strength rock).

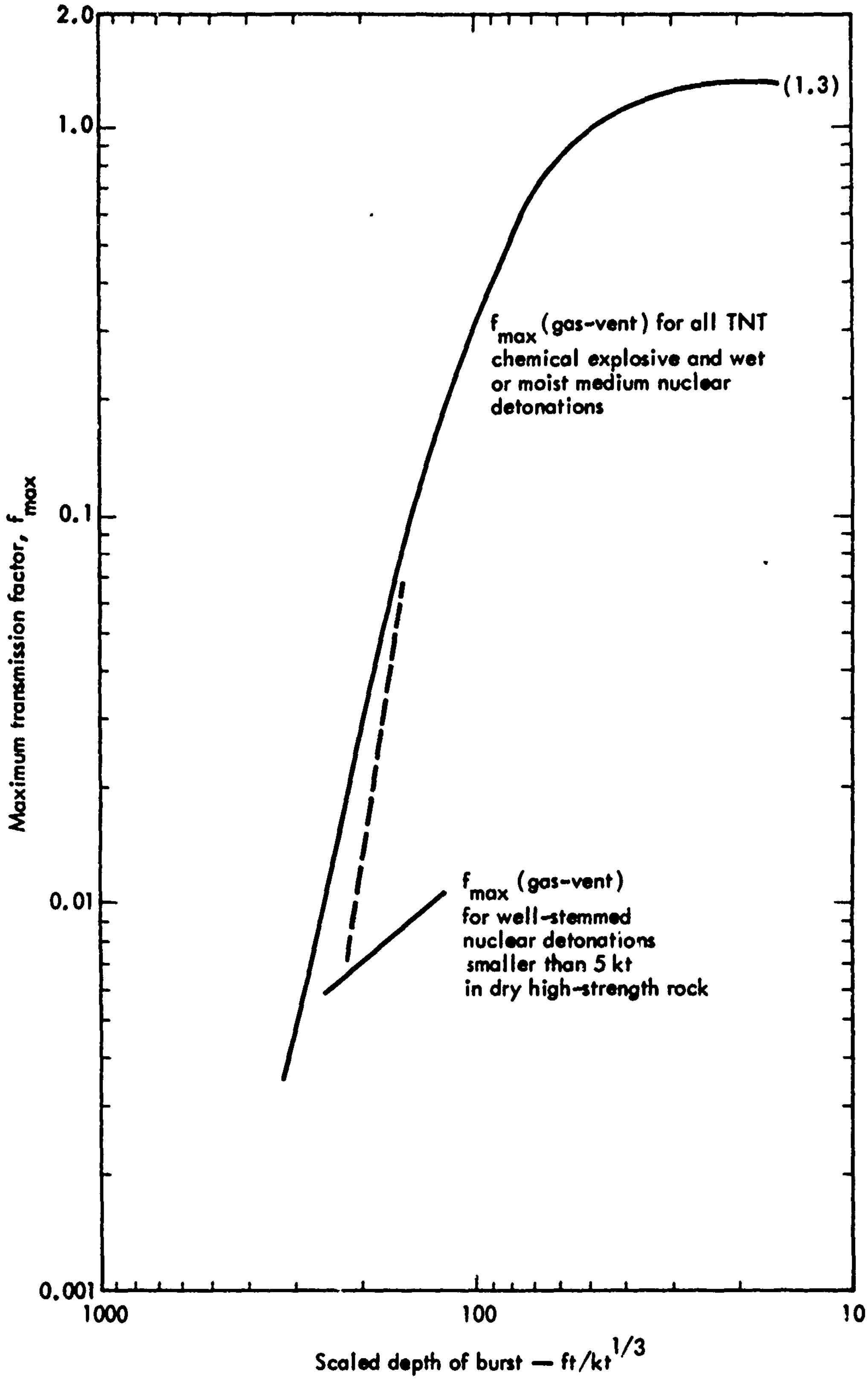


Fig. 3. Gas-vent airblast maximum transmission factor f_{max} for single-charge events as a function of scaled depth of burst (for TNT and similar chemical explosives in all unsaturated media and nuclear explosives in moist media, and for nuclear explosives smaller than 5 kt in dry high-strength media).

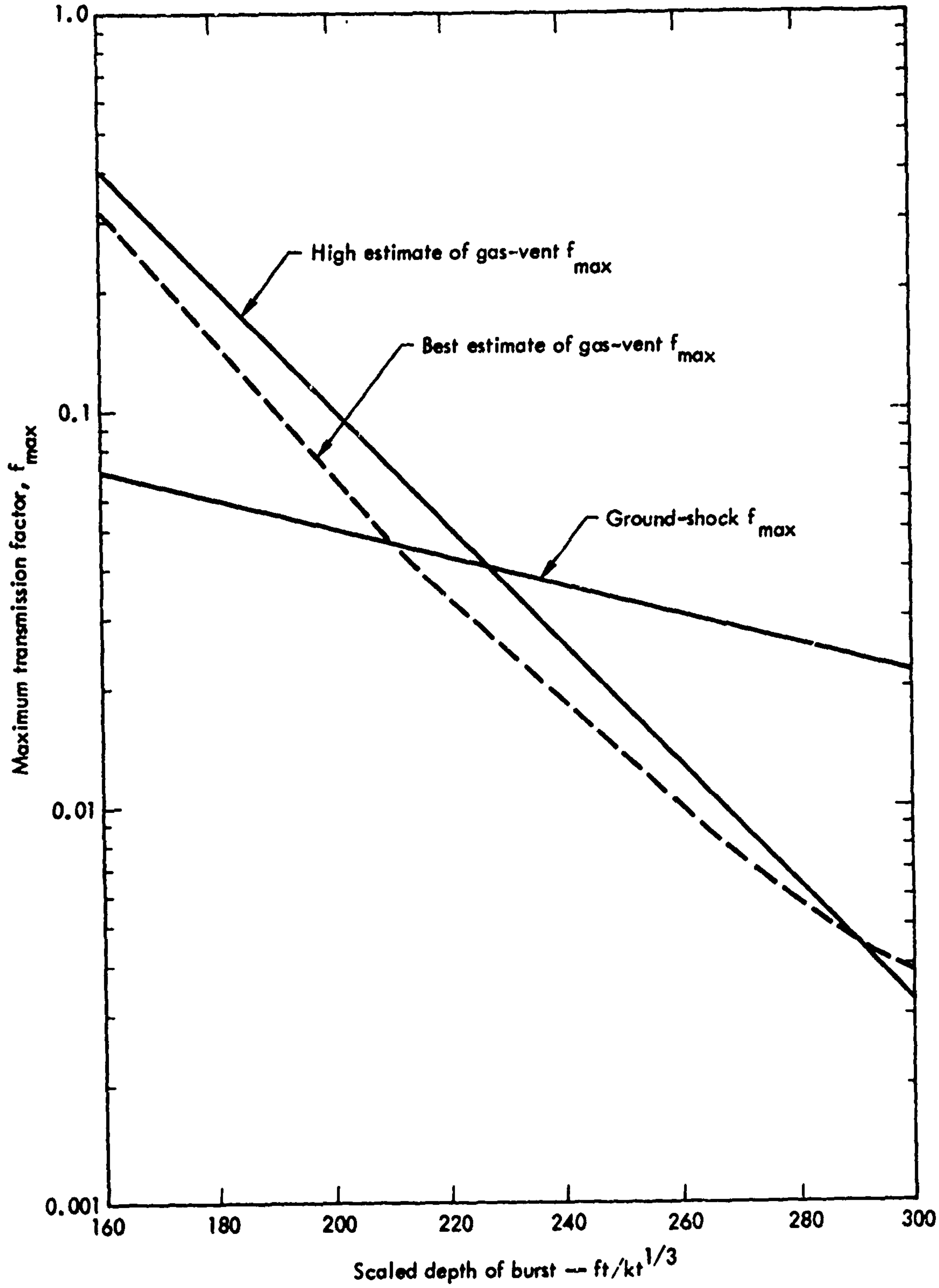


Fig. 4. Ground-shock and gas-vent maximum transmission factors f_{max} for stemmed single-charge events as a function of scaled depth of burst (for aluminized ammonium nitrate slurry explosive in weak rock).

$0.1 < W < 100$ kt. Use the solid upper curve in Fig. 3.

b. Nitromethane, TNT, and similar chemical explosive detonations in alluvium, soil, and high- or intermediate-strength rock, $15 < dob < 250$ to $300\ ft/kt^{1/3}$, $0.001\ kt < W < 1.0$ kt. Use the solid upper curve in Fig. 3. For slightly more optimistic (lower) estimates of f_{max} at dob > 160 ft/$kt^{1/3}$, use the dashed line in Fig. 3.

c. Well-stemmed nuclear detonations in dry* high-strength rock, $125 < dob < 250\ ft/kt^{1/3}$, $0.05\ kt < W < 5$ kt. Use the straight line labeled "f_{max} (gas-vent) for well-stemmed nuclear detonations smaller than 5 kt in dry high-strength rock" shown in Fig. 3. This line lies well below the curve (Cases a and b, above), and gas-vent airblast is usually quite small for these events. Ground-shock-induced airblast is generally dominant.

d. Aluminized ammonium nitrate slurry and ANFO detonations in sandstone or weak rock, $160 < dob < 300\ ft/kt^{1/3}$, $0.001 < W < 0.1$ kt. Use either of the two suggested gas-vent f_{max} curves (solid or dashed) in Fig. 4. The upper (solid) curve will give a somewhat more pessimistic (higher) estimate of the gas-vent overpressures. Airblast from detonations of this type shallower than dob = $160\ ft/kt^{1/3}$ cannot be accurately predicted due to lack of data, but gas-vent overpressure will be strongly dominant, and the airblast may approach that expected from a surface burst of the same yield.

The f_{max} Values for Unstemmed Detonations—Buried detonations which are unstemmed produce greater airblast overpressures than do normally stemmed events at the same dob. Unstemmed events are predicted using the normal f_{max} method and the f_{max} values given below. No distinction is drawn between ground-shock and gas-vent airblast for most of these predictions, and the f_{max} values given here predict the greatest expected airblast overpressures. (Note that all f_{max} values discussed in this paragraph are based on experiments with 1-ton aluminized ammonium nitrate slurry charges in weak rock; these values may not produce accurate predictions for widely differing yields, explosive types, or media.) To predict for an unstemmed chemical explosive detonation at $40 < dob < 360\ ft/kt^{1/3}$, with a cylindrical open shaft to the surface $30\ ft/kt^{1/3}$ in diameter, use $f_{max} \cong 0.99$. To predict for an unstemmed chemical explosive detonation at dob > $200\ ft/kt^{1/3}$, with a cylindrical open shaft to the surface $12\ ft/kt^{1/3}$ in diameter, use $f_{max} \cong 0.27$. To predict for an unstemmed chemical explosive detonation at dob > $200\ ft/kt^{1/3}$, with an open shaft to the surface much less than $12\ ft/kt^{1/3}$ in diameter: because the narrow shaft will collapse and seal itself at early time, the event will simulate a stemmed detonation; therefore, predict the normal ground-shock-induced and gas-vent airblast for a stemmed detonation at the same dob.

Step 4

After obtaining the ground-shock f_{max} and the gas-vent f_{max} values, make the airblast predictions and plot them on a sheet of log-log graph paper.

*Moisture content less than or equal to 1.0% by weight.

First, predict the ground-shock-induced airblast (detonations deeper than dob = 60 ft/kt$^{1/3}$ only) as follows: In Step 2, several overpressure points (R, ΔP) were calculated for the detonation. Multiply each overpressure ΔP by the ground-shock transmission factor, f_{max} (ground-shock). This calculation gives the predicted ground-shock-induced overpressure points: (R, ΔP (ground-shock)).

Next, predict the gas-vent-induced airblast: again, use the overpressure points (R, ΔP) calculated in Step 2. Multiply each overpressure ΔP by the gas-vent transmission factor, f_{max} (gas-vent). This calculation gives the predicted gas-vent-induced overpressure points: (R, ΔP (gas-vent)).

The overpressures listed in Table 1 are in millibars (mbar). Therefore, the predicted overpressures will also be in mbar. If desired, convert all predicted overpressures to psi by dividing them by 69.0:

$$\Delta P \text{ (in psi)} = \Delta P \text{ (in mbar)}/69.0.$$

Step 5

Plot the predicted overpressures on log-log graph paper (predicted overpressures as a function of range, R, from SGZ). First, plot the ground-shock-induced overpressures: (R, ΔP (ground-shock)). All of these points should lie on a straight line (of slope $R^{-1.2}$). Draw a straight line through them. Next, plot the gas-vent-induced overpressures: (R, ΔP (gas-vent)). All of these points should lie on another straight line (also of slope $R^{-1.2}$). Draw a straight line through them. The higher of the two straight lines determines the peak or dominant airblast overpressure pulse as a function of range. The peak overpressure at any range of interest may be easily predicted by means of the higher line.

Note that the empirical method gives overpressures at ground-level only. ΔP is predicted as a function of R, range along the ground surface from SGZ. Note also that the predictions are not valid at very close ranges.[1,2] The overpressures may be somewhat overpredicted at all ranges such that the original R_s (from Table 1, before scaling) is $R_s < 3000$ ft/kt$^{1/3}$ (gas-vent-induced airblast) or $R_s < 600$ ft/kt$^{1/3}$ (ground-shock-induced airblast). In other words, the true overpressures very close to SGZ will be less than the predicted values. A more thorough review of close-range airblast will be found in Ref. 1.

PREDICTION PROCEDURE FOR ROWS AND ARRAYS OF CHARGES

Airblast overpressures from rows or arrays of buried charges may be approximately predicted by means of the methods discussed in the following paragraphs. The basic procedure is to predict ground-shock-induced airblast and gas-vent-induced airblast from an "average" single charge in the row or array (using either the empirical or the theoretical prediction method). The predicted overpressures are then multiplied by appropriate reinforcement factors. A few important differences between single-charge and multiple-charge predictions should be mentioned. First, all multiple-charge events are assumed to be detonated simultaneously unless otherwise stated. They are also assumed to be emplaced at or near optimum intercharge spacing* 'for excavation of a continuous crater of maximum volume) unless otherwise stated. The range from a row or array is measured horizontally along the ground surface as usual, but SGZ is considered to lie at the geometric center of the row or array. Finally, all overpressures from row charges are predicted in two different directions: perpendicular to the row axis (⊥) and off the end of the row (‖). The reinforcement factors are always different for these two directions, and the predicted overpressure at a given range is always higher perpendicular to the row than off the end. The overpressures at directions between the ⊥ direction and the ‖ direction will lie between the predicted overpressures for the two directions.

The procedure for determining the reinforcement factors and predicting airblast from a row-charge or array is summarized below:

Step 1

Calculate the dob of each charge in the row or array:

$$dob = \frac{DOB}{W^{1/3}} \quad (\text{in ft/kt}^{1/3})$$

DOB = Depth of burst to center of charge (in ft)

W = Yield of charge (in kt)

Take the average of the scaled depths of all the charges. This average is considered to be the mean dob for the entire row or array.

*Optimum spacing of charges is approximately equal to the crater radius for a single charge having the weight of one row-charge member.

Step 2

Calculate the average yield of the charges in the row or array. Sum the yields of all the charges, and divide the sum by the total number of charges, n. This average is considered to be the mean yield per charge or the individual charge yield for the entire row or array.

Step 3

Perform a normal single-charge airblast prediction for the "average" charge in the row or array. Use the mean dob calculated above for dob, and the mean yield per charge for W. Predictions may be performed by the Prediction Procedure for Single-Charge Subsurface Bursts, or by the Theoretical Prediction Procedure, as appropriate for the particular case in question. Begin with Step 2 of either procedure.

Step 4

After completing the single-charge predictions, multiply the predicted overpressures at all ranges by the appropriate reinforcement factors, n^B, where n is the number of charges in the row or array. Since row-charge reinforcement factors for the ⊥ direction are always different from the factors for the ‖ direction, separate predictions must be made for these two directions. Also, the reinforcement factors are sometimes different for ground-shock-induced overpressures and gas-vent-induced overpressures. Be sure to use the proper reinforcement factor in each case. The following is a summary of the reinforcement factors.

For well-stemmed nuclear or chemical explosive row-charge cratering detonations of large individual charge yield ($W \gtrsim 0.01$ kt) in high- or intermediate-strength rock:

ΔP (⊥ to row) = $n^{0.7}$ ΔP (single charge at same range, for ground-shock and gas-vent overpressures)

ΔP (‖ to row) = $n^{0.25}$ ΔP (single charge at same range, for ground-shock overpressures)

ΔP (‖ to row) = $n^{0.6}$ ΔP (single charge at same range, for gas-vent overpressures).

For nuclear or chemical explosive row-charge cratering detonations of moderate to large individual charge yield ($W \gtrapprox 0.001$ kt) at or below optimum depth in saturated weak media such as clay shale:

ΔP (⊥ to row) = $n^{0.7}$ ΔP (single charge at same range, for ground-shock overpressures)

ΔP (‖ to row) = $n^{0.41}$ ΔP (single charge at same range, for ground-shock overpressures).

Ground-shock-induced airblast is strongly dominant for both row- and single-charge detonations at or below optimum depth in saturated weak media.

For chemical explosive row-charge cratering detonations of small individual charge yield ($W \ll 0.001$ kt):

ΔP (⊥ to row) = $n^{0.9}$ ΔP (single charge at same range, for both ground-shock and gas-vent overpressures)

ΔP (‖ to row) = $n^{0.4}$ ΔP (single charge at same range, for ground-shock overpressures)

ΔP (‖ to row) = $n^{0.7}$ ΔP (single charge at same range, for gas-vent overpressures).

For all square array detonations, where n is the total number of charges in the array (n = 4 or 5):

ΔP (for array) = $n^{0.65}$ to $n^{0.8}$ ΔP (single charge at same range, for ground-shock overpressures)

ΔP (for array) = $n^{0.6}$ to $n^{0.7}$ ΔP (single charge at same range, for gas-vent overpressures).

The above relations apply in all directions from the geometric center of the array.

For chemical explosive row-charge cratering detonations of moderate individual charge yield ($W \approx 0.001$ to 0.01 kt) in weak or moist unsaturated media (such as sandstone, weak rock, or soil), intercharge spacing $\approx$ 160 to 350 ft/kt$^{1/3}$:

ΔP (⊥ to row) = $n^{0.75}$ ΔP (single charge at same range, for ground-shock overpressures)

ΔP (‖ to row) = $n^{0.5}$ ΔP (single charge at same range, for ground-shock overpressures)

ΔP (⊥ to row) = $n^{0.6}$ ΔP (single charge at same range, for gas-vent overpressures)

ΔP (‖ to row) = $n^{0.45}$ ΔP (single charge at same range, for gas-vent overpressures).

Recent data obtained from chemical explosive detonations of moderate individual charge yield in weak media make it possible to predict reinforcement factors and airblast from single-row detonations with delays between charges, and from simultaneous and delayed double-row detonations. The prediction procedures are as follows:

Ground-Shock-Induced Overpressures for Intercharge Delays (single rows)—Perpendicular to the row, intercharge delays greater than 0.25 $sec/kt^{1/3}$ (delays greater than 0.025 sec for one-ton charges):

ΔP ($\perp$ to row) = ΔP (single charge at same range)—no reinforcement occurs.

Off the starting or initiated end of the row (end at which the detonation sequence is begun), delays greater than 0.25 $sec/kt^{1/3}$:

ΔP ($\parallel$ to row) = ΔP (single charge at same range).

Off the final or concluding end of the row:

$$\text{Delay} = 0.25 \frac{\text{sec}}{\text{kt}^{1/3}} : \Delta P\ (\parallel \text{ to row}) = n^{0.5}\ \Delta P \text{ (single charge at same range).}$$

$$\text{Delay greater than } 0.5 \frac{\text{sec}}{\text{kt}^{1/3}} :$$

ΔP ($\parallel$ to row) = ΔP (single charge at same range).

Gas-Vent-Induced Overpressures for Intercharge Delays (single rows)— Perpendicular to the row, delays greater than 0.25 $sec/kt^{1/3}$:

ΔP ($\perp$ to row) = $n^{0.45}$ to $n^{0.55}$ ΔP (single charge at same range)—estimate only.

Off both ends of the row, all delays:

ΔP ($\parallel$ to row) = $n^{0.45}$ ΔP (single charge at same range).

These results should apply most reliably to events near optimum depth (dob $\approx$ 200 $ft/kt^{1/3}$) in weak media, with a intercharge spacing $\approx$ 250 $ft/kt^{1/3}$.

Double Row Events—For optimum interrow separation ($\approx$350 $ft/kt^{1/3}$), reinforcement factors and airblast are approximately the same as for a single row containing the same number of charges as both of the double rows (n = total number of charges in both rows). The SGZ is considered to lie at the geometric center of both rows, and predictions are made as discussed above. At wide interrow separations (greater than 1100 $ft/kt^{1/3}$) or long-interrow delay times for optimum separation (delay time between rows greater than 1.2 $sec/kt^{1/3}$), the airblast pulses from the two rows will not normally combine or reinforce. Thus, airblast may be predicted for each row separately, as though that row were being detonated alone. The respective SGZ's of the two rows are considered to lie at the geometric center of each row. Predictions are made as discussed above, for each of the two rows separately. This prediction technique may prove incorrect for a direction in which the distances or delay times between any of the various pulses from the two rows is insufficient to prevent overlap of the pulses,* or for very long rows with spatially extended overpressure pulses (total row length $\gtrsim$ unscaled delay time $\times$ local sonic velocity). There is currently no good method for

*For example, pulses tend to overlap along the exact center line direction off the end of a simultaneously detonated double row; overlap may also occur perpendicular to a delayed double row, in the perpendicular direction closer to the later-detonated of the two rows.

predicting airblast from very long double rows consisting of many charges.

Airblast from Row Charges on Sloping Ground—For row-charge events on moderate hillside slopes, there is no significant difference between peak overpressures in the uphill and downhill directions from the row (the uphill results appear to be very slightly higher in some cases). Predictions are performed as usual (for an event on level ground), except that ranges are measured along the sloping ground surface from the geometric center of the row.

Step 5

After multiplying the overpressures by the appropriate reinforcement factors, plot the reinforced overpressures as a function of range on log-log graph paper. Plot both the ground-shock-induced and gas-vent-induced overpressures. Each set of overpressures will define a straight line. The higher of the two lines at a given ange will determine the dominant airblast pulse and peak overpressures. In the case of row-charge events, separate airblast predictions are made for the ⊥ and ∥ directions. Both the ground-shock-induced and the gas-vent-induced overpressures should be plotted for each direction. Predictions for the two directions should be plotted separately. The higher of the two lines at a given range for a given direction will determine the dominant airblast pulse and the peak overpressures in that direction.

PREDICTION PROCEDURE FOR SURFACE BURSTS AND FREE-AIR BURSTS

The airblast overpressures from near-surface bursts, buried detonations at scaled depths shallower than 15 $ft/kt^{1/3}$, and free-air bursts are also predicted by a scaling procedure. However, the standard line points listed in Table 1 cannot be used because a straight line fit is inadequate for these events. Instead Figs. 5 and 6 are used. These figures are based on the best available data from recent experimental chemical explosive tests, and on theoretical shock calculations.[1]

To predict airblast from near-surface bursts, buried detonations at dob < 15 $ft/kt^{1/3}$, or free-air bursts, read the overpressures, ΔP_s, at several ranges, R_s, from the appropriate curve or set of points (in Fig. 5 or Fig. 6). Scale these overpressures and ranges to the yield, W, and ambient pressure, $P_{ambient}$, of the detonation to be predicted, using Eqs. (2) and (3)—see the section: Prediction Procedure for Single-Charge Subsurface Bursts. The calculated points (R, ΔP) give the predicted airblast for the detonation. These points may be plotted on log-log graph paper, and a smooth curve may be drawn through them. The points will not lie on a straight line in this case. Several points at various ranges should be calculated and plotted in order to define the curve properly.

The following is a discussion of the correct curves to use for predicting various cases. For TNT and similar chemical explosive detonations near the surface and at dob's shallower than 15 $ft/kt^{1/3}$, $0.001 < W < 1.0$ kt, use the upper curve in Fig. 5 or the set of points just below the upper curve in Fig. 5. The points provide a slightly lower (less pessimistic) estimate of the predicted overpressures.

For ANFO detonations near the surface and at dob's shallower than 15 $ft/kt^{1/3}$,

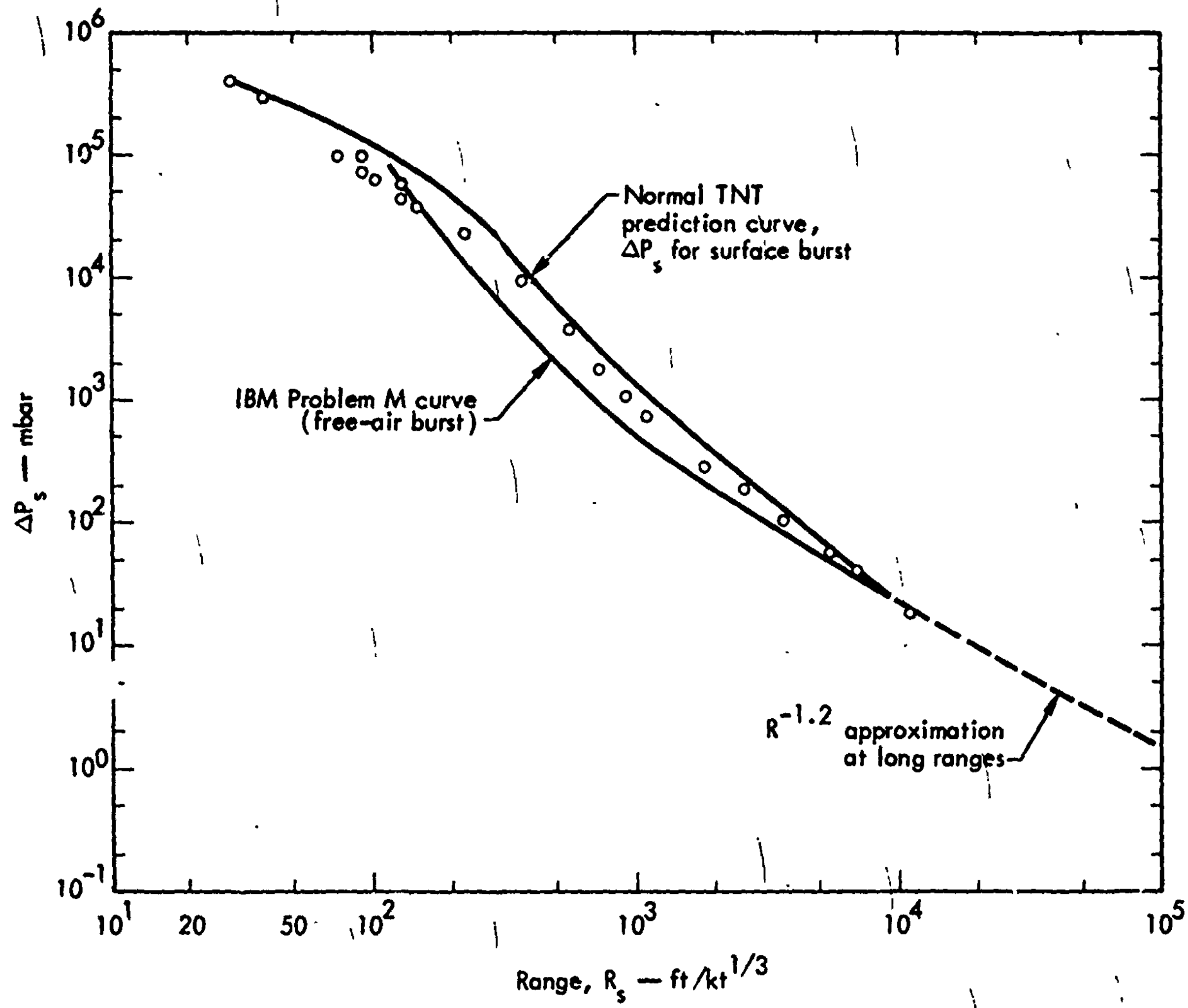


Fig. 5. Overpressure as a function of range for nuclear and TNT chemical explosive surface-burst events (yield = 1.0 kt, ambient pressure = 1000 mbar, and for all free-air burst events (yield = 1.0 kt, ambient pressure = 1000 mbar). Circles represent minimum observed data points for multi-ton TNT surface bursts.

$0.001 < W < 1.0$ kt, use the plotted points (squares and stars only) in Fig. 6. Beyond the range of the plotted points, use the dashed curve in Fig. 6.

For aluminized ammonium nitrate slurry detonations near the surface and at dob's shallower than 15 ft/kt$^{1/3}$, $0.001 < W < 1.0$ kt, use the solid and dashed curve in Fig. 6.

For free-air-burst detonations (events in a homogeneous atmosphere with no nearby ground surface) of all types and yields, use the lower solid curve in Fig. 5. If the event is chemical explosive multiply the true yield, W (in kt), by a factor of 2.0 before substituting it into Eq. (3); if the event is nuclear explosive, use the true yield, W. The free-air-burst curve shown in Fig. 5 is based on a theoretical calculation for nuclear free-air bursts, known as the IBM Problem M.

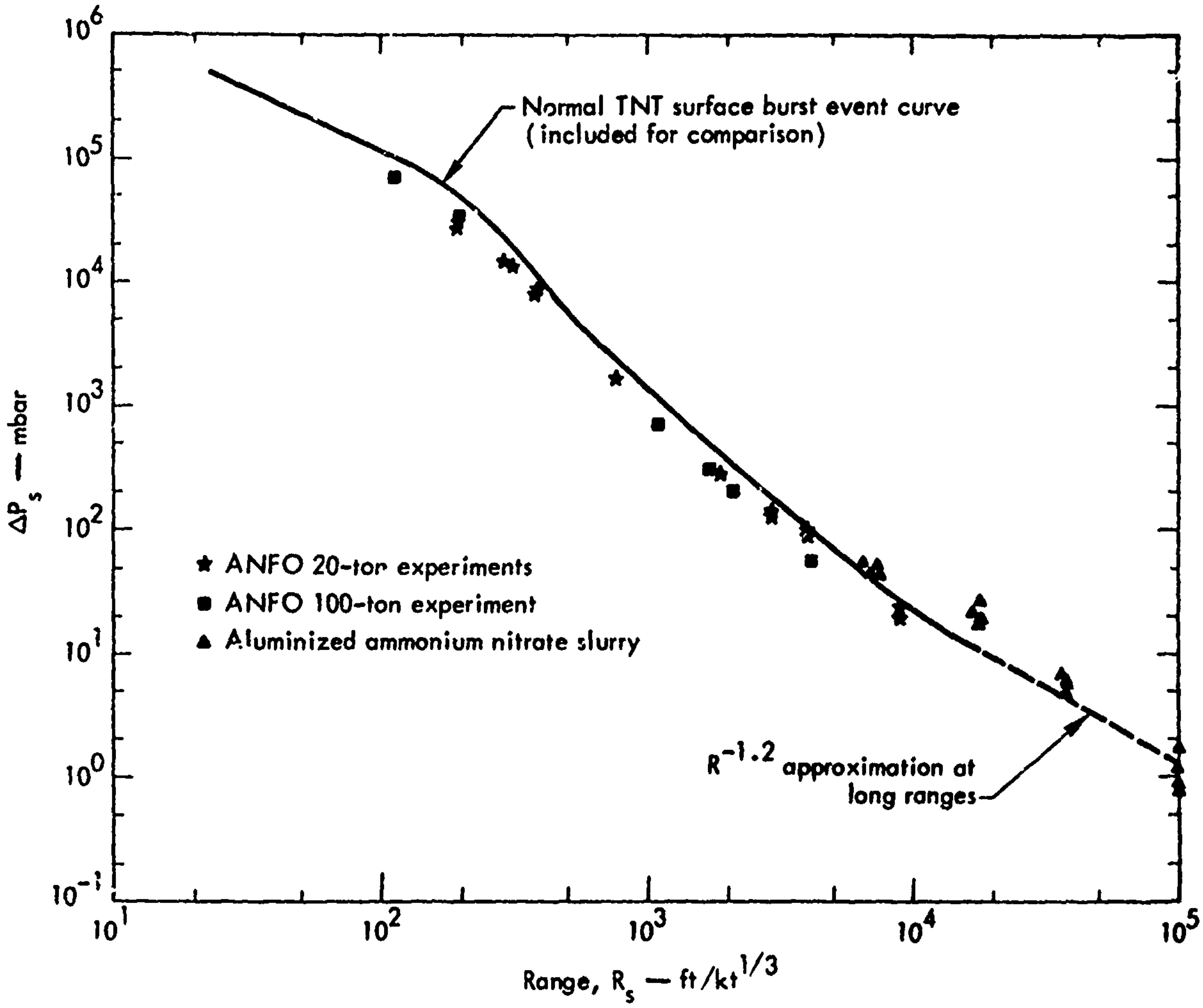


Fig. 6. Overpressure as a function of range for typical ammonium nitrate fuel oil and aluminized ammonium nitrate slurry surface-burst events (yield = 1.0 kt, ambient pressure = 1000 mbar). TNT surface-burst event curve is included for comparison.

SAMPLE PROBLEM FOR SINGLE-CHARGE SUBSURFACE BURST

Predict the ground-shock-induced and gas-vent-induced airblast overpressures for a 20-ton (0.02 kt) TNT detonation at a DOB of 34 ft in alluvium. The ambient pressure at the project location is $P_{ambient}$ = 868 mbar. First, find the scaled depth of burst, dob:

$$dob = \frac{DOB}{W^{1/3}} = \frac{34 \text{ ft}}{(0.02)^{1/3}} = 125 \text{ ft/kt}^{1/3}.$$

Go to Table 1 and select a few appropriate points at ranges of interest:

R_s (ft)	ΔP_s (mbar)
500	816
1000	357
3000	95.4

Scale these points back to a 20-ton experiment at $P_{ambient}$ = 868 mbar:

$$\Delta P = \Delta P_s \left(\frac{868}{1000}\right) = 0.868\ \Delta P_s$$

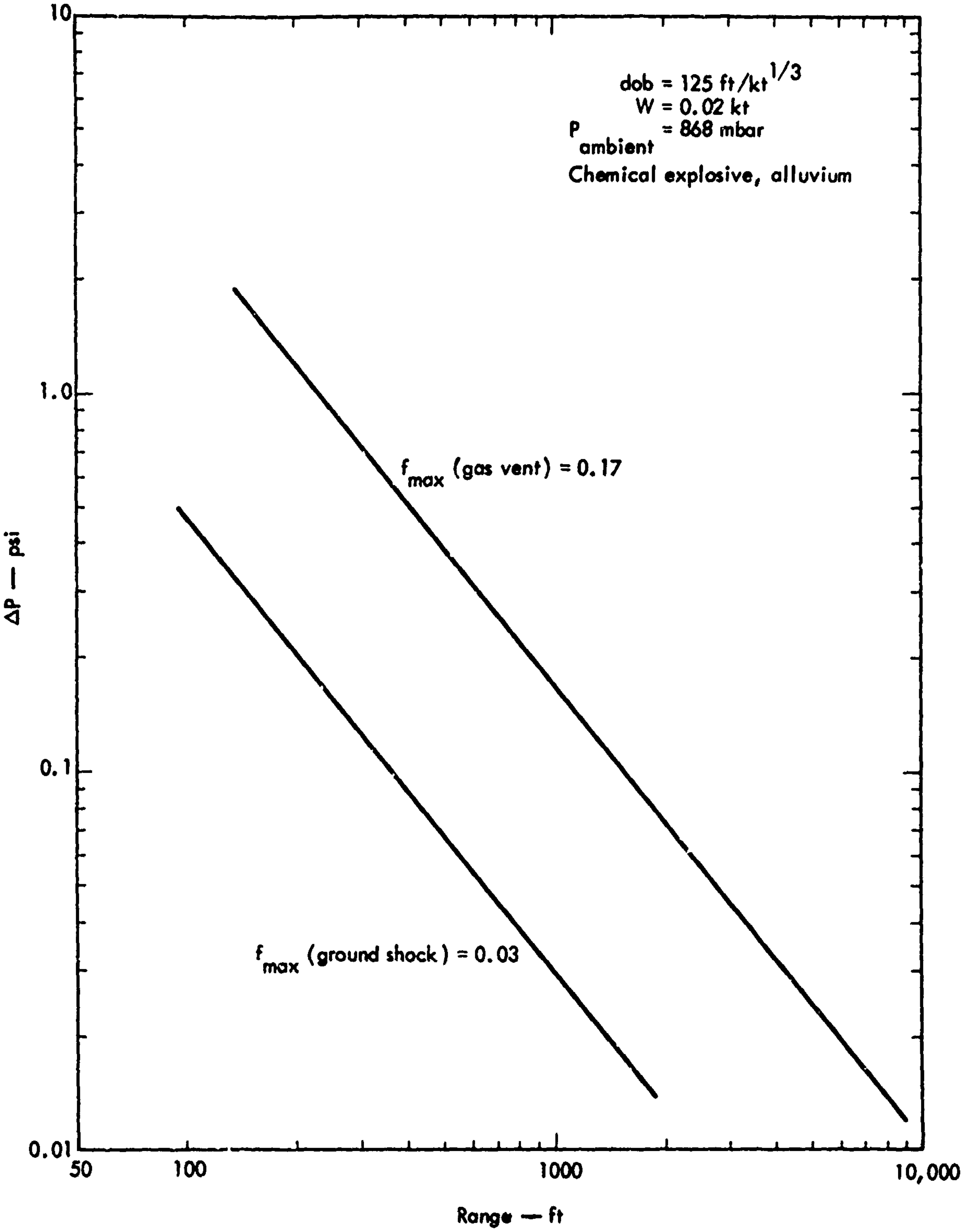


Fig. 7. Sample problem: ground-shock-induced airblast prediction and gas-vent-induced airblast prediction, using empirical method.

$$R = R_s \left(\frac{0.02}{1.0}\ \frac{1000}{868}\right)^{1/3} = 0.285\ R_s.$$

Tabulate the values of R and ΔP:

R (ft)	ΔP (mbar)	
142	709	= 10.28 psi*
285	310	= 4.49 psi
855	82.8	= 1.20 psi

The experiment is in alluvium. Use the dashed (alluvium) curve in Fig. 2. Entering the figure at dob = 125 $ft/kt^{1/3}$, find f_{max} (ground-shock) = 0.03. Using the upper curve in Fig. 3 and entering the figure at dob = 125 $ft/kt^{1/3}$, find f_{max} (gas-vent) = 0.17.

For ground-shock overpressure predictions, multiply the overpressures (either in psi or mbar, as desired) by f_{max} (ground-shock) = 0.03 and tabulate:

R (ft)	ΔP ground-shock (psi)
142	0.308
285	0.135
855	0.036

For gas-vent overpressure predictions, multiply the overpressures (either in psi or mbar, as desired) by f_{max} (gas-vent) = 0.17 and tabulate:

R (ft)	ΔP gas-vent (psi)
142	1.75
285	0.764
855	0.204

These gas-vent and ground-shock predictions are plotted in Fig. 7. They define two straight lines, which are the predicted gas-vent and ground-shock overpressures Gas-vent-induced airblast overpressures are dominant in this case.

*To convert to psi, divide by 69.

Theoretical Prediction Method (for Ground-Shock-Induced Airblast)

THEORETICAL PREDICTION PROCEDURE

The theoretical method predicts ground-shock-induced airblast overpressures from most types of buried single-charge detonations at 60 < dob < 700 $ft/kt^{1/3}$. It does not predict for row-charge events, but it can be used to perform the ground-shock-induced single-charge predictions which are then multiplied by the ground-shock reinforcement factors to predict ground-shock-induced airblast from row-charge events (see the previous section under Prediction Procedure for Rows and Arrays of Charges).

The theoretical method does not utilize scaling relations. Instead, a peak local overpressure, ΔP_0, directly above SGZ is calculated from the peak vertical spalls velocity at SGZ, V_0. This local overpressure is used in predicting overpressures at all other ranges. ΔP_0 is determined from the equation:

$$\Delta P_0 = \frac{P_{ambient}}{1013\ mbar} (\rho_0 c_0)\ MV_0, \qquad (4)$$

where

ΔP_0 = ground-shock-induced peak local overpressure directly above SGZ (in psi)

$P_{ambient}$ = ambient atmospheric pressure at location of experiment (in mbar)

$\rho_0 c_0$ = acoustic impedance of air at standard sea-level conditions $= 0.01841\ \frac{psi\text{-}sec}{ft}$

c_0 = sonic velocity in air at sea level
$\cong$ 1087 ft/sec

V_0 = peak vertical spall velocity of ground surface at SGZ (in ft/sec)

M = Mach number of air shock at SGZ ($M \approx 1.0$ for low velocities, V_0; see below).

The quantities appearing in Eq. (4) are discussed in detail in the following paragraphs. If ΔP_0 is known, the surface level overpressure, ΔP, at any range, R, from SGZ can be calculated from the equation:

$$\Delta P = \Delta P_0 \, \alpha \left(\frac{DOB}{R}\right), \qquad (5)$$

where

ΔP = peak ground-shock-induced overpressure (in psi)

DOB = depth of burst to center of charge (in ft)

R = range along ground surface from SGZ

α = a constant for all detonations in a given medium (dimensionless).

The theoretical method is also capable of predicting ground-shock-induced air-blast at elevated locations (above ground surface level). Assume that an elevated point is located at height h above the ground surface plane, and at range R from SGZ (this is a true range or slant range, not the range along the ground surface). The overpressure ΔP (elevated) in psi at this point is given by:

$$\Delta P \text{ (elevated)} = \Delta P_0 \, \alpha \left(\frac{DOB}{R}\right) \times \left[\frac{1}{\cos(90^\circ - \theta)}\right], \qquad (6)$$

where: R = slant range from SGZ to the elevated point (in ft), and θ is determined from:

$$\cos \theta = \frac{h}{R}. \qquad (7)$$

Equation (6) is not valid if $(90^\circ - \theta) > 75^\circ$ (i.e., for elevated points located almost directly above SGZ).

In order to apply Eqs. (5) and (6), it is necessary to know the value of the constant α. The value of α is controlled by the shape of the vertical velocity field above a detonation (in other words, by the vertical velocity profile at locations away from SGZ). The shape of the vertical velocity field is the same for all single-charge experiments at all dob's in a given medium.[2] The shape does vary somewhat for different media. More precisely, the peak vertical spall velocities above single-charge detonations at locations other than SGZ are accurately fitted by an equation of the form[2]:

$$V = V_0 \left(\frac{DOB}{S}\right)^m$$

V = peak vertical spall velocity of ground surface at slant range S from shot point

V_0 = peak vertical spall velocity at SGZ

DOB = depth of burst of charge (in ft)

S = slant range from the shot point to the ground surface location (in ft)

m = a velocity profile constant for all single-charge detonations in a given medium

It can be shown that, for single-charge velocity fields of this type, the constant α in Eqs. (5) and (6) is a function only of m. If the velocity field constant m for a particular medium is known, the value of

α can be determined by a straightforward analytic solution. The details of this analysis are discussed in Ref. 2. The analysis has been carried out for typical values of m, and the resultant α's are listed in Table 2. The first column of the table lists the value of m. The second column gives the corresponding value of α. The final column lists the medium to which this value of α applies. The α's listed in Table 2 will be used in making theoretical airblast predictions.

Given the value of α for a particular medium, it is possible to predict ground-shock-induced airblast. The required input data for the prediction include:

(1) Medium and approximate moisture content

(2) Yield W of the explosive charge (in kt)

(3) Depth of burst to center of charge "DOB" (in ft)

(4) The ambient atmospheric pressure at the location of the project, $P_{ambient}$ (in mbar). The ambient pressure may be estimated from meteorological data or from the altitude of the project location above sea level: ($P_{ambient} \approx 1013$ mbar at sea level, $P_{ambient} \approx 844$ mbar at 5000 ft above sea level).

(5) The value of α (from Table 2).

The steps in the prediction procedure may be summarized as follows:

Step 1. Calculate the scaled depth of burst dob for the detonation:

$$\text{dob} = \frac{\text{DOB}}{W^{1/3}} \quad (\text{dob in ft/kt}^{1/3})$$

Step 2. Determine α for the medium of the project (Table 2).

Step 3. Determine the peak vertical spall velocity at SGZ, V_0 (in ft/sec). Peak vertical spall velocities are plotted as a function of dob in Figs. 8 through 12. Enter the appropriate figure at dob on the vertical axis, go across to the appropriate line, and read V_0 (in ft/sec) from the horizontal axis. The following is a summary of the correct figures to use:

For all detonations in alluvium and soil, $60 < \text{dob} < 300$ ft/kt$^{1/3}$, use Fig. 8.

For nuclear detonations in dry rhyolite, $60 < \text{dob} < 300$ ft/kt$^{1/3}$, use Fig. 8.

For chemical explosive detonations in dry high-strength rock (basalt, rhyolite, etc.), $60 < \text{dob} < 300$ ft/kt$^{1/3}$, use the upper line in Fig. 9.

Table 2. Values of "α" for several media of interest.

Velocity profile constant, m	α	Medium
2.0	0.50	Maximum value for contained detonations in any medium
2.13	0.46	Underwater detonations and underwater detonations in saturated weak media, such as coral
2.5	0.3815	Saturated clay shale and other saturated weak media
3	0.318	Alluvium, soil, and rhyolite rock
4	0.250	
5	0.212	(Basalt rock ?)
6	0.188	Basalt rock

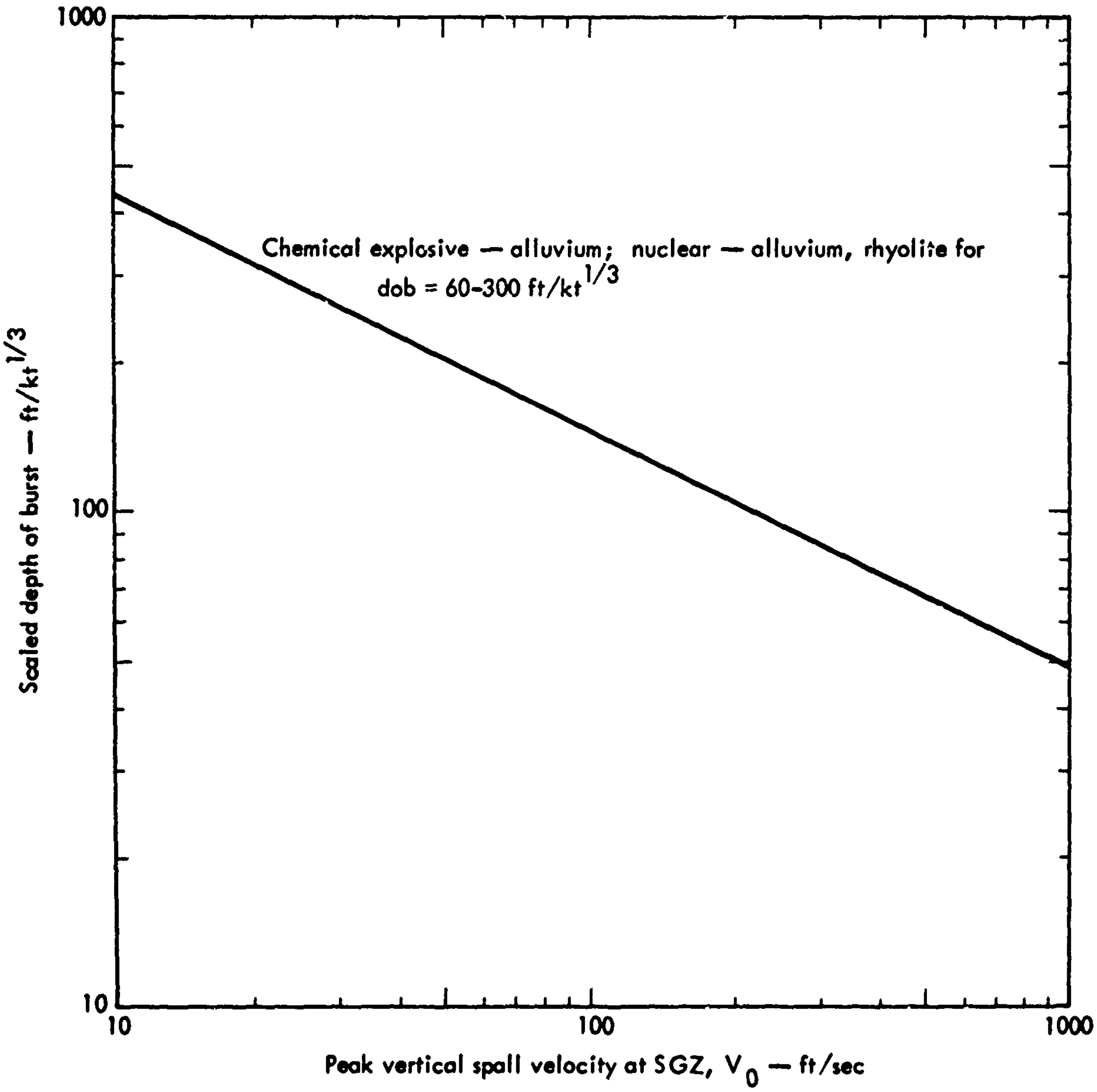


Fig. 8. Peak vertical spall velicity as a function of scaled depth of burst for all events in alluvium and for nuclear events in unsaturated rhyolite.

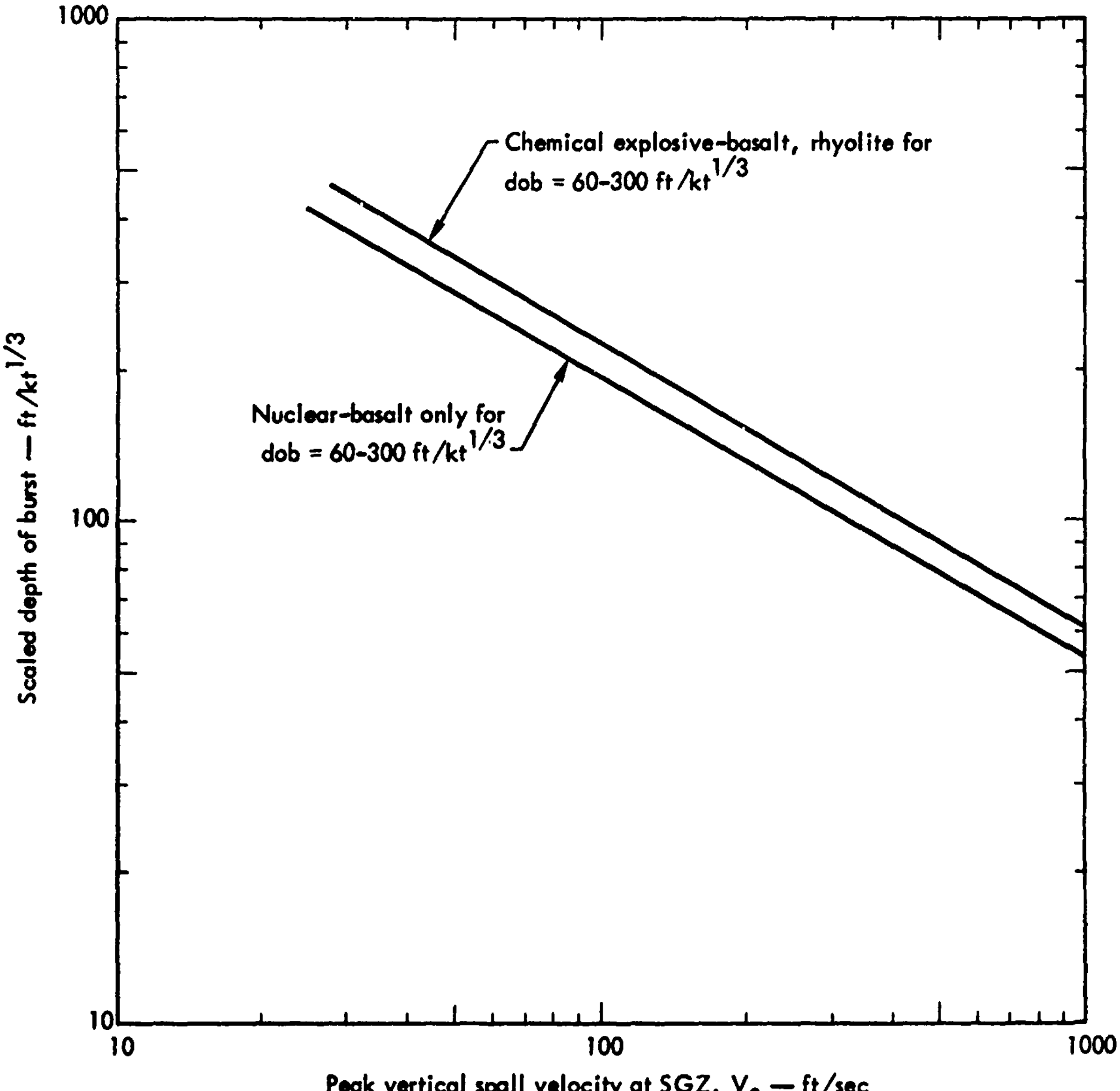


Fig. 9. Peak vertical spall velocity as a function of scaled depth of burst for chemical explosive events in basalt and rhyolite, and for nuclear events in basalt.

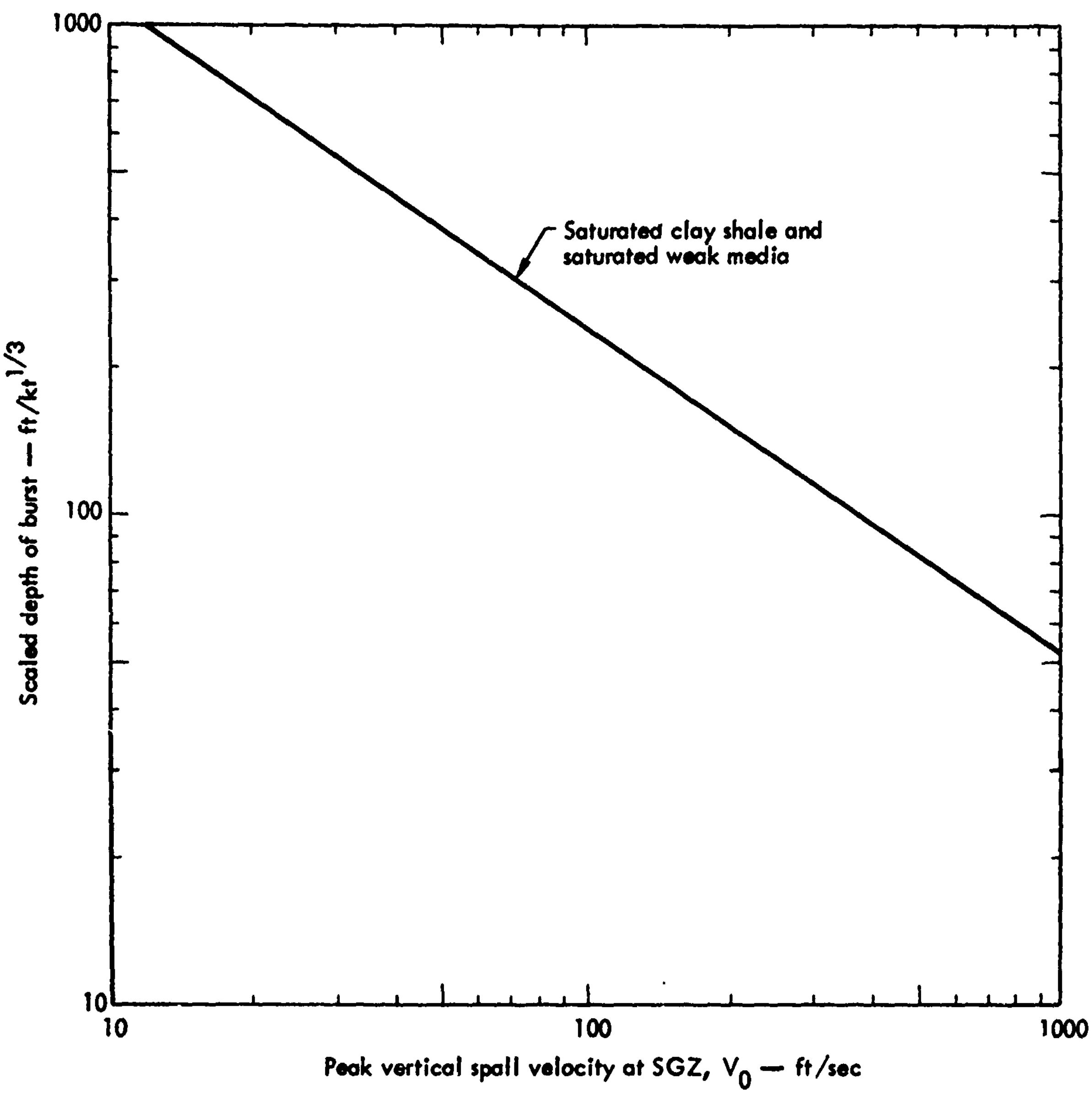


Fig. 10. Peak vertical spall velocity as a function of scaled depth of burst for all events in weak saturated rock, such as saturated clay shale.

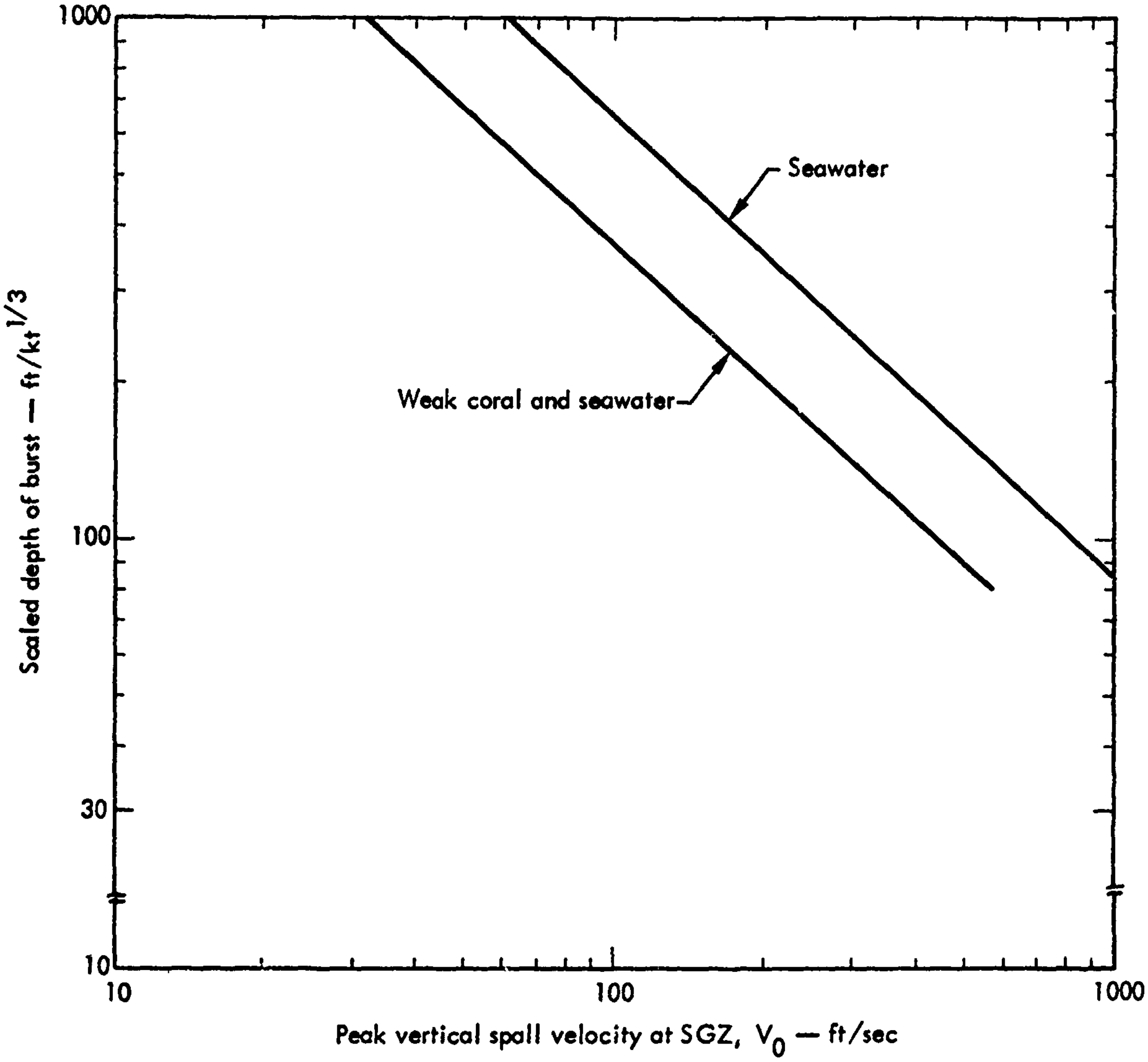


Fig. 11. Peak vertical spall velocity as a function of scaled depth of burst for events in seawater and for events in a very weak saturated medium such as weak coral overlain by seawater.

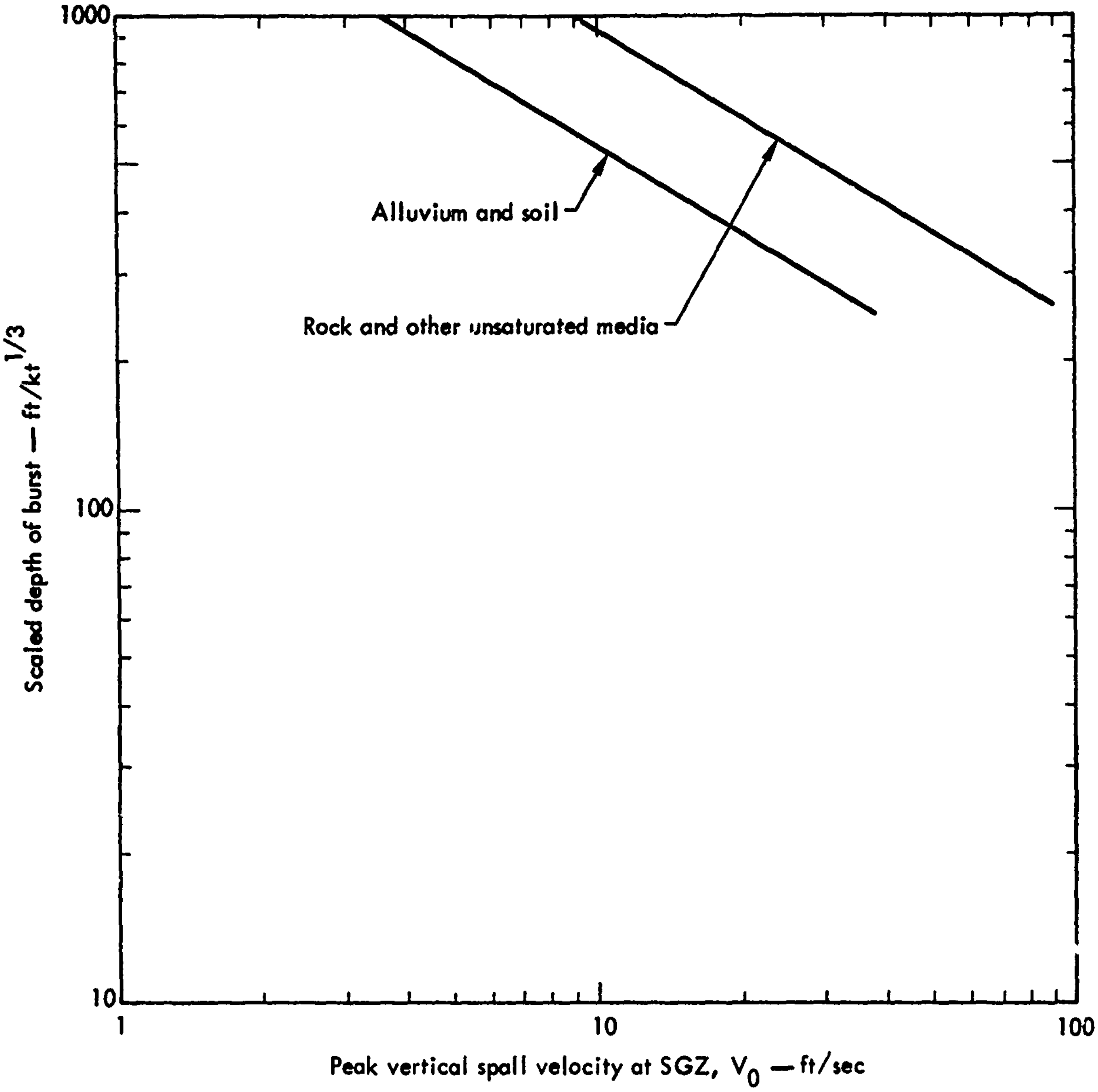


Fig. 12. Peak vertical spall velocity as a function of scaled depth of burst for all contained and mounding events (scaled depths of burst greater than 300 ft/kt$^{1/3}$.

For nuclear detonations in dry basalt, $60 < dob < 300\ ft/kt^{1/3}$, use the lower line in Fig. 9.

For all detonations in weak saturated media (such as saturated clay shale), $60 < dob < 300\ ft/kt^{1/3}$, use Fig. 10. Ground-shock-induced airblast is strongly dominant for all such events deeper than $dob = 170\ ft/kt^{1/3}$.

For all detonations in water, $80 < dob < 700\ ft/kt^{1/3}$, use the upper line in Fig. 11. Ground-shock-induced airblast (more correctly, water-shock-induced airblast) is strongly dominant for all such events deeper than $dob = 170\ ft/kt^{1/3}$.

For all detonations in very weak saturated media overlain by water (such as very weak saturated submerged coral), $80 < dob < 70\ ft/kt^{1/3}$, use the lower line in Fig. 11. Ground-shock-induced airblast (more correctly, water-shock-induced airblast) is strongly dominant for all such events deeper than $dob = 170\ ft/kt^{1/3}$.

For all contained and mounding detonations (normally, events at $700 > dob \gtrsim 300\ ft/kt^{1/3}$), use Fig. 12 (lower line for events in alluvium and soil; upper line for all other media). Ground-shock-induced airblast is dominant for all contained or mounding detonations.

Step 4. Calculate (V_0/c), where c = local sonic velocity in air. ($c \approx 1087$ ft/sec for standard sea-level conditions, and deviates from this value by only a few percent for most cases of interest.)

Step 5. Determine the Mach number, M, of the shock (Ref. 2) using Fig. 13a (for small values of V_0/c) or Fig. 13b (large values of V_0/c). Enter the figure at the calculated value of (V_0/c) on the vertical axis, go across to the curve, and read the Mach number, M, from the horizontal axis.

Step 6. Using the above-determined values of $P_{ambient}$, V_0, and M in Eq. 4, calculate the SGZ local overpressure, ΔP_0 (in psi).

Note: $\rho_0 c_0 = 0.01841\ \frac{psi\text{-}sec}{ft}$

Step 7. Substitute the predicted value of ΔP_0 into Eq. (5), and calculate the overpressures, ΔP (in psi), at several ranges of interest, R.

Step 8. Plot the predicted overpressures, ΔP, as a function of R on log-log graph paper. The plotted points will define a straight line of slope $R^{-1.0}$. Draw a line through the predicted points. This line may be used to predict the ground-shock-induced overpressures as a function of range. The predictions are not valid for (R/DOB) < 1.0 (most cratering detonations in unsaturated media) or for (R/DOB) < 2.0 (detonations in saturated media, detonations under water and in media overlain by water, and contained or mounding detonations). At these very close ranges, ΔP_0 provides an approximate estimate of the peak ground-shock-induced overpressure near the ground surface.

Step 9. If desired, predict the ground-shock-induced overpressures ΔP (elevated) at any elevated locations of interest, using Eqs. (6) and (7). Elevated overpressure predictions are not valid if $(90° - \theta) > 75°$.

SAMPLE PROBLEM

Predict the ground-shock-induced airblast overpressures from a 20-ton (0.02-kt) single-charge TNT detonation at DOB

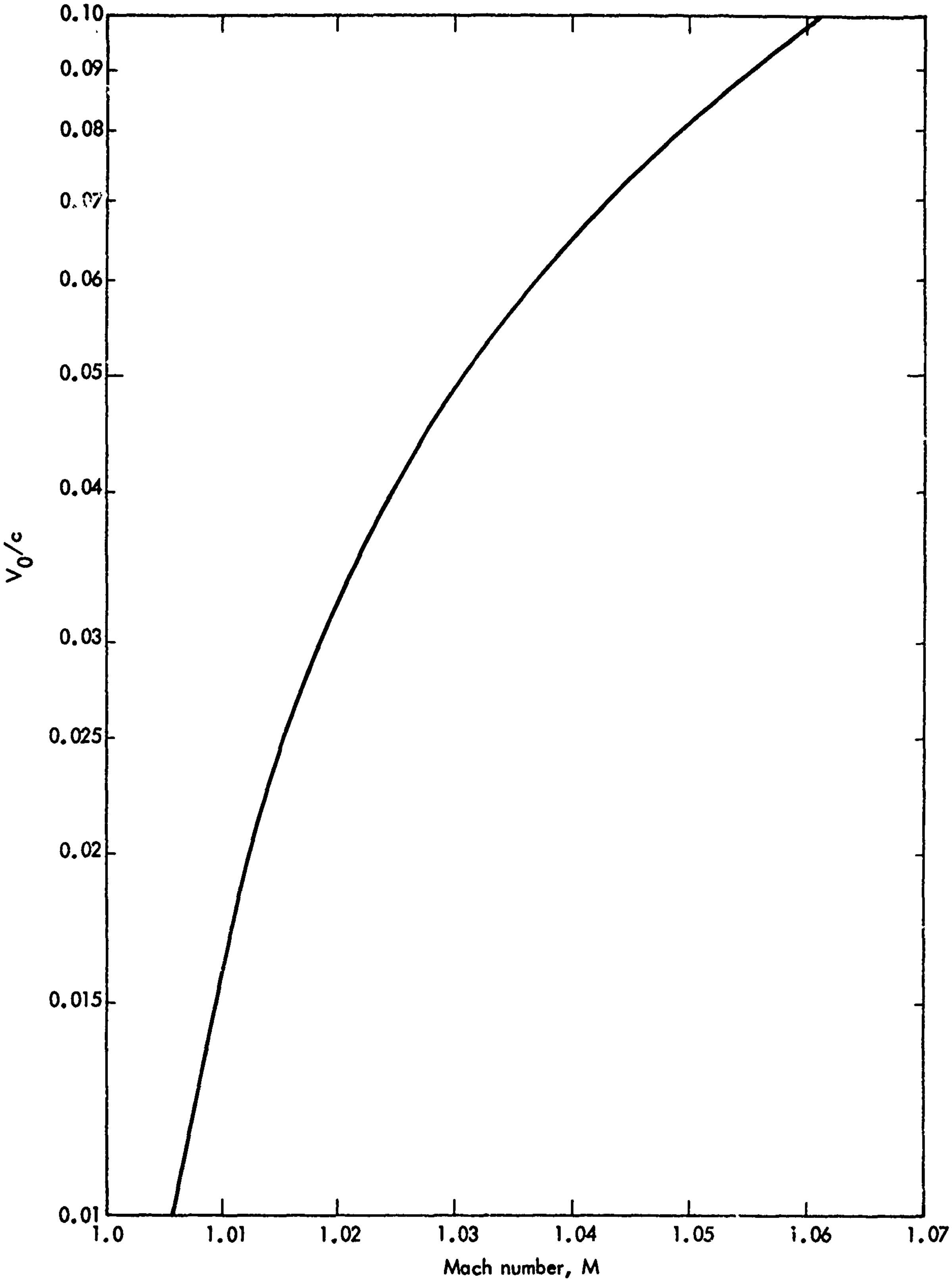


Fig. 13a. Mach Number M as a function of V_0/c (for small V_0/c).

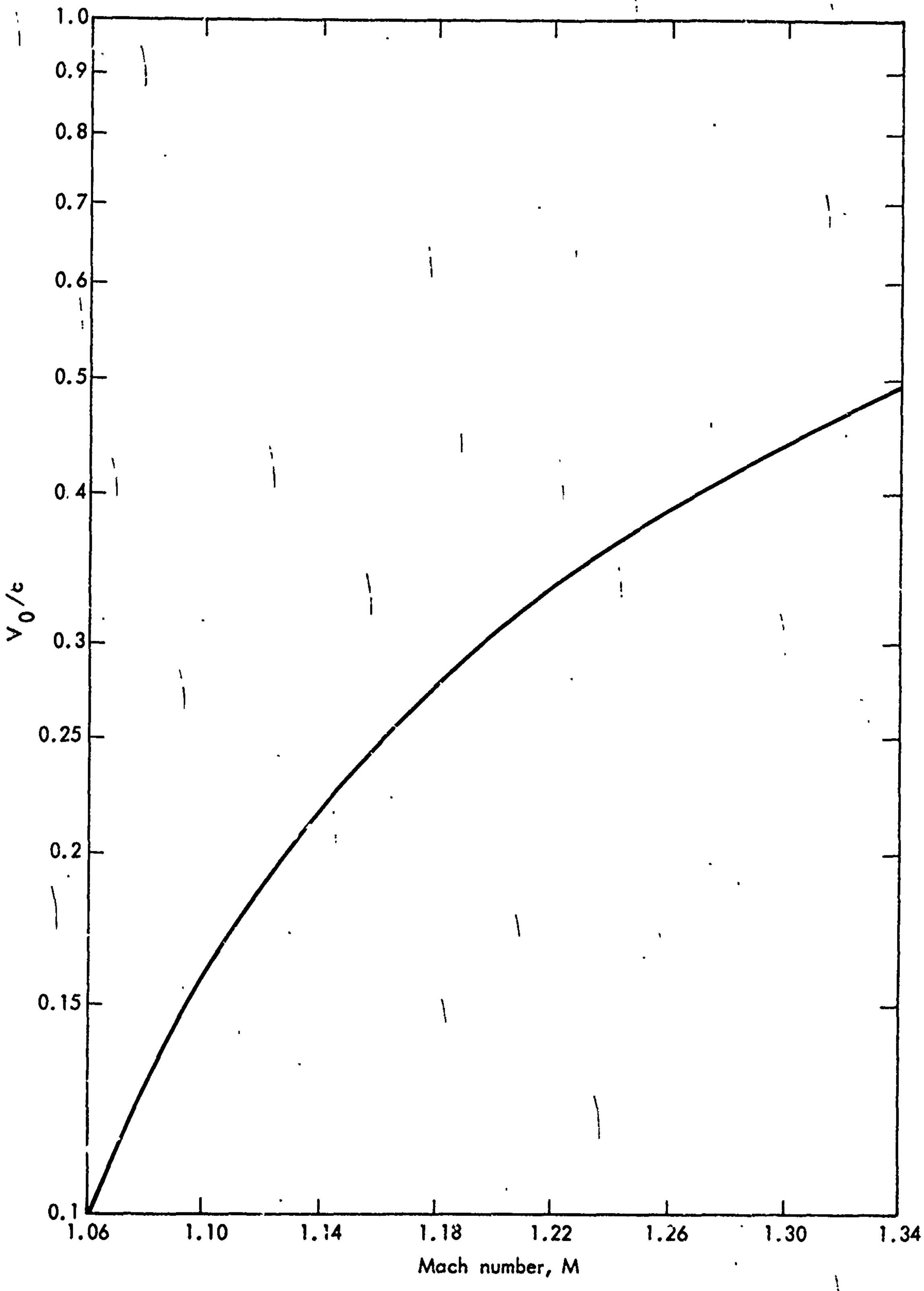


Fig. 13b. Mach Number M as a function of V_0/c (for large V_0/c).

= 34 ft in alluvium. The ambient atmospheric pressure at the experiment location is $P_{ambient}$ = 867 mbar.

Yield W = 20-ton chemical explosive = 0.02 kt

Depth of burst, DOB = 34 ft

$P_{ambient}$ = 867 mbar (known from meteorological data or altitude)

Scaled depth of burst, dob

$$= \frac{\text{DOB (in ft)}}{[\text{W (in kt)}]^{1/3}} = \frac{34}{(0.02)^{1/3}} = 125 \text{ ft/kt}^{1/3}$$

α = 0.318 (for alluvium, Table 2)

Referring to Fig. 8 (for alluvium) at dob = 125 ft/kt$^{1/3}$, the predicted SGZ peak vertical spall velocity, V_0, is 138 ft/sec. The local sonic velocity c ≅ 1087 ft/sec. Therefore, $\frac{V_0}{c}$ = 0.127. Entering Fig. 13b with this value, the Mach number M is found to be M = 1.079. Now it is possible to calculate the local SGZ overpressure, ΔP_0, from Eq. (4):

$$\Delta P_0 = \frac{P_{ambient}}{1013 \text{ mbar}} (\rho_0 c_0) MV_0 = 2.347 \text{ psi}.$$

Substituting this value into Eq. (5),

$$\Delta P = \Delta P_0 \, \alpha \left(\frac{\text{DOB}}{R}\right)$$

$$= (2.347)(0.318)(34)/R = 25.4/R.$$

Sample predicted overpressures from this equation are tabulated below:

Distance from SGZ, R (in ft)	ΔP (psi)
25	1.02
50	0.51
100	0.25
300	0.085
1000	0.025

Figure 14 shows the predicted line drawn through these sample points. Its slope is R^{-1}. Do not extend predictions inside R/DOB = 1.0. At ranges (R/DOB) less than 1.0, ΔP_0 provides an estimate of the ground-shock-induced peak overpressure (ΔP_0 = 2.347 psi).

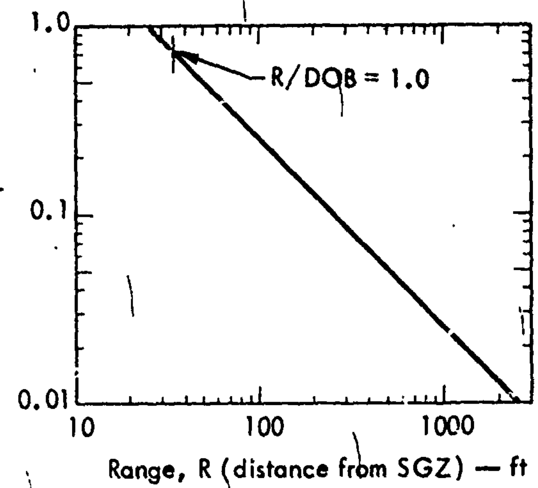
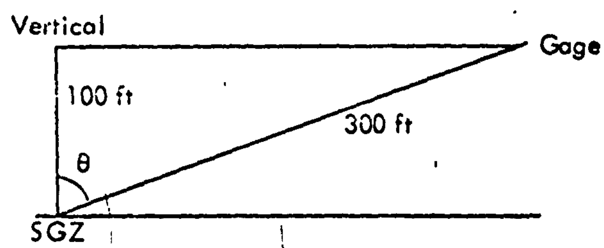


Fig. 14. Sample problem: ground-shock-induced airblast prediction, using theoretical method.

The theoretical method also predicts elevated overpressures. An imaginary problem has been constructed to demonstrate this application. Predict the ground-shock-induced peak overpressure at an elevated gage 100 ft high, at true range R = 300 ft from SGZ:

h 100 ft.

Therefore, the angle θ from the vertical to the gage direction (see sketch) is



$$\cos\theta = h/R$$

$$\cos\theta = \frac{100}{300}$$

$$\theta = 70.5°$$

$$90 - \theta = 19.5°$$

$$\cos(90 - \theta) = 0.943$$

$$\Delta P \text{ (elevated)} = \Delta P_0\, \alpha \left(\frac{DOB}{R}\right)\left[\frac{1}{\cos(90 - \theta)}\right]$$

$$\Delta P \text{ (elevated)} = (2.347)(0.318)\left(\frac{34}{300}\right)(1.06)$$

ΔP (elevated) = 0.09 psi at elevated gage.

This concludes the theoretical prediction of ground-shock-induced airblast. Gas-vent airblast must still be predicted by the empirical method, as discussed in the previous section.

Summary

An empirical method is presented for predicting both ground-shock-induced and gas-vent-induced airblast overpressures from buried single- and row-charge cratering detonations in a variety of media. A semitheoretical technique for predicting ground-shock-induced airblast from single-charge events is also discussed. The range of applicability and limitations of the two methods are reviewed, and suggestions for applying the methods in practice are set forth. Sample problems are included to clarify the prediction procedures. This report summarizes state-of-the-art airblast prediction techniques for typical underground detonations, but does not provide detailed supporting data or discussions.

References

1. C. M. Snell, and D. L. Oltmans, A Revised Empirical Approach to Airblast Prediction, U. S. Army Engineer Explosive Excavation Research Office, Livermore, Calif., Rept. EERO TR-39 (in publication).
2. C. M. Snell, and D. L. Oltmans, Prediction of Ground-Shock-Induced Airblast Overpressures for Subsurface Explosions from Peak Vertical Spall Velocity, U. S. Army Engineer Explosive Excavation Research Office, Livermore, Calif., Rept. EERO TR-40 (1972).
3. L. J. Vortman, Project CABRIOLET: Close-in Airblast from the CABRIOLET Event, Sandia Laboratories, Albuquerque, N. Mex., Rept. PNE-951 (1968).
4. L. J. Vortman, "Close-in Airblast from Underground Explosions," in proceedings: Engineering with Nuclear Explosives, U. S. Atomic Energy Commission, Las Vegas, Nev., Rept. Conf-700101, Vol. 2 (1970), pp. 1508-1543.
5. L. J. Vortman, Airblast from Project TRINIDAD Detonations, Sandia Laboratories, Albuquerque, N. Mex., Rept. SC-RR-710056 (1971).
6. D. N. Montan, Source of Airblast from an Underground Explosion, Lawrence Livermore Laboratory, Livermore, Calif., Rept. UCRL-71202 (1968).
7. D. N. Montan, "Source of Airblast from the Underground Explosion," Trans. Amer. Nucl. Soc. 2, 541 (1968).
8. L. J. Vortman, Airblast and Craters from Rows of Two to Twenty-five Buried Charges, Sandia Laboratories, Albuquerque, N. Mex., Rept. SC-RR-68-655 (1969).
9. J. W. Reed, Acoustic Wave Effects Project: Airblast Prediction Techniques, Sandia Laboratories, Albuquerque, N. Mex., Rept. SC-M-68-740 (1969).