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EERO TECHNICAL REPORT NO. 40

**PREDICTION OF GROUND-SHOCK-INDUCED AIRBLAST
OVERPRESSURES FOR SUBSURFACE EXPLOSIONS FROM
PEAK VERTICAL SPALL VELOCITY**

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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 96 X 3121, General Investigations. Some of these topical areas relate to 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 and a companion report, EERO/TR-39, A Revised Empirical Approach to Airblast Prediction, provide the basis for, and present improved methods of, making airblast overpressure predictions for surface and underground chemical and nuclear detonations. Critical review and comment are invited. An additional report, EERO/TR-7, in preparation, will develop a simplified prediction system that integrates and is based on the systems presented in this report, and its companion report, TR-39.

Abstract

A technique is presented for the prediction of ground-shock-induced airblast overpressures resulting from the subsurface detonation of nuclear and chemical explosives. The technique is based on a theory and physical model, developed by D. N. Montan of the Lawrence Livermore Laboratory, which correlates ground-shock-induced airblast overpressures with the vertical velocity of the rising mound above the detonation point. The derivation of the theory is reviewed in detail and the model's predictions are compared with airblast overpressure values measured during almost a score of large-yield chemical and nuclear detonations. Appendixes provide supplementary information on the correlation between vertical surface velocities and induced overpressures, extend the theory to five- and seven-charge row detonations, and apply the theory to contained and mounding detonations and to detonations in a noncompetent saturated medium overlain with water.

Acknowledgments

The authors wish to express appreciation to D. N. Montan of the Lawrence Livermore Laboratory, who developed and published the techniques on which this prediction method is based; to L. J. Vortman of Sandia Laboratories, who is responsible for a major portion of the published air-blast data on underground detonations and who generously provided additional information; and to Edward J. Leahy for numerous helpful suggestions throughout the preparation of this report.

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 Technical Director was Mr. Walter Day.

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Nomenclature and Conventions

c	$1087 \frac{\text{ft}}{\text{sec}}$ = sonic velocity in air at sea level (STP).
D	Depth of burst (DOB); distance from the shot point to surface ground zero—SGZ (in ft).
dob	$\frac{D \text{ (in ft)}}{(\text{Yield in kt})^{1/3}}$ = scaled depth of burst (in ft/kt ^{1/3}).
M	Mach number of the induced shock at SGZ; calculated from the peak vertical surface velocity (V_0). Note that V_0 is the shock particle velocity at the shock front. M is given by the quadratic equation: $M^2 - \frac{\gamma + 1}{2} \frac{V_0}{c} M - 1 = 0.$
P_{ambient}	Ambient (environmental) pressure for a given experiment, as obtained from meteorological or altitude data.
P_{STP}	1013 mbar = 14.7 psi = standard sea-level ambient pressure, to which all experiments are compared (Montan sometimes refers to this quantity as " P_0 "). Although experimental data are usually compared to a standard sea-level pressure of 1000 mbar, this analysis presumes a standard pressure of 1013 mbar. Always use $P_{\text{STP}} = 1013$ mbar with the methods discussed in this report.
R	Distance or range from SGZ (in ft).
$\frac{R}{D}$	$\frac{\text{Distance from SGZ}}{\text{Depth of burst}}$ = dimensionless range from SGZ; usually expressed as inverse dimensionless range (D/R).
S	True slant range from the shot point to any point on the ground surface (measured in ft).
SGZ	Surface ground zero; the point on the ground surface lying vertically over the shot point.
V	Peak vertical surface velocity at any location other than SGZ (in ft/sec or m/sec).
V_0	SGZ peak vertical surface velocity (in ft/sec or m/sec); generally, the peak early-time spall velocity—that velocity which induces the peak overpressure at SGZ.
$V(\tau)$	Time-dependent vertical velocity (not necessarily peak velocity).
W	Yield of a buried detonation, in kt.

- α Quantity relating dimensionless overpressure to dimensionless range:

$$\frac{\Delta P}{\Delta P_0} = \alpha \frac{D}{R}. \text{ For linear acoustic theory and simple sources,}$$

$$\alpha = \frac{1}{2\pi D} \int_{-\infty}^{+\infty} \frac{V}{V_0} dy. \text{ The "dy" implies integration of the velocity profile}$$
along an axis perpendicular to the line of sight through SGZ.
- $\beta(u,v)$ Euler's integral of the first kind, used to solve the above integral for certain velocity profiles.
- γ 1.4 = ratio of specific heats for an ideal gas.
- ΔP Far-field ground-shock-induced overpressure, far from SGZ (in psi).
This is the measured or predicted quantity. ΔP is the combined overpressure pulse due to the total effect of the entire rising mound. A completely combined pulse is seen only at large distances, outside the range of appreciable vertical ground motion.*
- ΔP_0 $\Delta P_{SGZ} = \frac{P_{\text{ambient}}}{P_{STP}} (\rho c)_{STP} V_0 M = \text{near-field (ground-transmitted) ground-shock-induced overpressure directly above SGZ (corrected to the ambient pressure of the given experiment; cf. } \frac{P_{\text{ambient}}}{P_{STP}} \text{ correction term in the equation).}$
- $\frac{\Delta P}{\Delta P_0}$ $\frac{\text{Far-field overpressure at any dimensionless range } > 1.0}{\text{Near-field overpressure directly above SGZ}} = \text{dimensionless overpressure in Montan's method. Calibrated to the local SGZ overpressure, } \Delta P_0, \text{ which is in turn directly related to the peak vertical velocity, } V_0.$
- $(\rho c)_{STP}$ $0.01841 \frac{\text{psi-sec}}{\text{ft}} = 4.17 \frac{\text{mbar-sec}}{\text{m}} = \text{the acoustic impedance of the ambient air at standard conditions of temperature and pressure.}$

These sketches illustrate the nomenclature and conventions used in this report.

* For purposes of this report, overpressure in the far field is inversely proportional to range R ($\Delta P \propto R^{-1}$, simple acoustic attenuation of overpressure).

Nomenclature for far-field airblast overpressure gage located at ground level and at range R along X -axis from SGZ.

PREDICTION OF GROUND-SHOCK-INDUCED AIRBLAST OVERPRESSURES FOR SUBSURFACE EXPLOSIONS FROM PEAK VERTICAL SPALL VELOCITY

Section I Montan's Theory—Vertical Surface Velocity and Ground-Shock-Induced Overpressure

INTRODUCTION

Airblast overpressures from buried explosive detonations, consisting of a ground-shock-induced component and often a gas-vent-induced component, can cause damage. Workers in the field have long sought a comprehensive theory capable of providing airblast predictions for planned events. D. N. Montan of the Lawrence Livermore Laboratory, Livermore, California, has developed a complete explanation of the ground-shock-induced component of airblast from single-charge events.^{1,2} It is the purpose of this paper to relate Montan's theory to observed experimental data, and to present a method of predicting ground-shock-induced airblast overpressures.

For the reader's convenience, the derivation of Montan's theory is summarized in this section. Section II presents the data measured during numerous high-explosive and nuclear subsurface detonations that are relevant to Montan's theory, develops the input data necessary to employ the theory, and compares theory-predicted ground-shock-induced overpres-

ures for single-charge detonations with values measured in the field. Section III provides a procedure for predicting the ground-shock-induced overpressures from single-charge detonations. Appendixes provide supplementary information about the correlation between vertical surface velocities and induced overpressures, and extend the theory to five- and seven-charge row detonations, contained detonations, and detonations in a noncompetent saturated medium overlain with water. Theory predictions for the row-charge and saturated medium overlain with water events are compared with the few field-measured overpressures available for these detonation conditions.

The ground-shock-induced component of airblast overpressure is dominant for deeply buried TNT and nitromethane detonations ($\text{dob} > 200 \text{ ft/kt}^{1/3}$), for nuclear detonations in strong dry rock ($\text{dob} > 125 \text{ ft/kt}^{1/3}$), and for all detonations underwater or in saturated media ($\text{dob} > 170 \text{ ft/kt}^{1/3}$). The gas-vent-induced component of airblast overpressure is larger in many other cases and will thus determine damage limitations. A

definitive theory of gas-vent overpressures is not yet available; gas-vent-induced air-blast can be predicted using empirical techniques.³

DERIVATION OF MONTAN'S THEORY

Montan's theory predicts ground-shock-induced overpressure from the vertical surface velocity of the mound above the detonation point. The vertical surface velocity of the mound results from the interaction of the detonation's shockwave at the surface-air interface. The basic theory of shockwave propagation adequately describes transmission and reflection of shockwaves at a rock-air (or soil-air) interface. The impedance of air is orders of magnitude lower than that of rock. Therefore, the incident shockwave propagating outward from a detonation below the surface is almost completely reflected as a rarefaction wave. The rock interface spalls upward as a free surface. In moving upward, it compresses the overlying air. This compression of the air causes the ground-shock-induced overpressure pulse. The pulse then propagates outward in all directions like any sound wave in air. The action of the moving ground surface in pulsing the overlying air has been compared to a moving piston. Thus, ground-shock-induced airblast is sometimes called the ground-piston effect.

The increase in overpressure produced by the rising surface can be calculated. For small velocities, the increase in pressure is directly proportional to the vertical velocity. A Mach number correction is necessary for larger velocities. The local overpressure, ΔP_{local} , above a

small section of the rising ground surface is given by

$$\Delta P_{\text{local}} = V \rho c M \quad (1)$$

where

$$M^2 - \frac{\gamma + 1}{2} \frac{V}{c} M - 1 = 0. \quad (2)$$

The V term represents the local surface velocity, c is the ambient sonic velocity, ρc is the acoustic impedance of ambient air, and M is the Mach number of the air shock ($M \approx 1.0$ for small velocities). The ground surface velocity produced by cratering explosions is known to increase from zero to some maximum value over a very short period of time. Since the maximum or peak overpressure caused by the rising surface is of greatest interest, the peak vertical velocity must be used in Eq. (1).

If the entire overpressure pulse were produced by one small section of rising ground, the above analysis would be complete; ΔP_{local} would be the overpressure above that section. This overpressure would then decrease with range away from its point of origin. For small overpressures, $\Delta P \propto \frac{1}{R}$ (acoustic propagation in a homogeneous atmosphere).

Unfortunately, the real situation is not so simple. Buried explosions do not launch one section of ground with a uniform velocity. They give rise instead to a sharply peaked mound. Velocity is always highest in the center of the mound (at surface ground zero-SGZ), and drops off rapidly away from SGZ. Thus, a buried explosion develops a complex field of surface velocities, each giving rise to its own local overpressure, ΔP_{local} . The local overpressure will be highest

at SGZ, dropping off rapidly in all directions away from the center. For explosive excavation safety prediction, the user will want to predict the overpressure at some range well outside the rising mound (outside the range of appreciable ground motion). Roughly speaking, this distant or far-field overpressure will be a "combination" of all the local overpressure pulses created by the entire surface of the rising mound. At long ranges, the far-field overpressure will propagate like any other sound in air—it will decay acoustically ($\Delta P_{\text{far-field}} \propto \frac{1}{R}$). The far-field overpressure will therefore be a combination of the form:

$$P_{\text{far-field}} \propto \frac{1}{R} \sum \Delta P_{\text{local}}$$

summed over the entire surface area of the rising mound.

The following paragraphs describe the development of a general expression for far-field overpressures.

Obviously, large local overpressures will give rise to large overpressures in the far field. It is equally evident that a mound of large surface area will cause greater far-field overpressures than a small mound. In order to obtain an equation applying to all cases, overpressures and distances must be expressed in dimensionless form.

The greatest local overpressure occurs directly above SGZ (highest surface velocity). It is logical to relate all other overpressures to this value. Let $\Delta P_0 = \Delta P_{\text{local}}$ (at SGZ). Then by Eq. (1), $\Delta P_0 = V_0 \rho c M$, where V_0 = SGZ peak vertical velocity. In this way, the overpressure at any range can be expressed as a dimensionless ratio $\left(\frac{\Delta P}{\Delta P_0}\right)$.

If the shape of the rising mound is examined for explosions at various depths, it can be shown that dimensionless overpressure is a function of range alone, and range can also be expressed in a dimensionless form. The peak vertical velocity at SGZ is dependent on depth of burst. Deep explosions give rise to a small surface velocity, while shallow detonations give a much higher V_0 . However, for both deep and shallow detonations, the overall shape of the velocity profile moving away from SGZ remains the same. (The surface velocity profile may change slightly between different media, as will be seen; but it is not a function of depth.) Figure 1 is a schematic diagram of a surface velocity profile. The SGZ vertical velocity is V_0 . At a given range R , the velocity has decreased to a value V_{local} . Because the shape of the profile is constant and depends only on the geometry of the situation, the value of V_{local} that is a given fraction of V_0 (i.e., the given value of V_{local}/V_0) will always occur at the same dimensionless range R/D . The actual linear values of R and D do not matter.

Fig. 1. Vertical velocity profile of rising mound as seen from side.

Since local overpressure is nearly proportional to vertical velocity, the local overpressures follow the mound velocity profile. Thus, the local overpressure which is a given fraction of ΔP_0 will always occur at the same R/D . The far-field overpressures will also reflect this simple geometrical dependence on the local velocity profile because a given far-field dimensionless overpressure, $\Delta P/\Delta P_0$, is always at the same dimensionless distance R/D from any given point on the mound velocity profile.

From the above discussion and from the assumption of acoustic propagation, the following dimensionless overpressure relationship can be written:

$$\frac{\Delta P_{\text{far-field}}}{\Delta P_0} = \text{constant} \left(\frac{D}{R} \right) = \alpha \left(\frac{D}{R} \right). \quad (3)$$

The constant α will depend only on the surface velocity field. In order to solve for ΔP , α must be determined. It is a crucial quantity in Montan's derivation.

To determine the constant α , consider the local overpressure at some point above a small section of the rising mound. This local overpressure will vary with time as the mound velocity changes. It will also give rise to the far-field overpressure, $\Delta P_{\text{far-field}}$, at range R away from the mound. Call this far-field overpressure ΔP . The local surface velocity of the mound is some function of time, $V(\tau)$. The local overpressure induced by velocity $V(\tau)$ will occur instantaneously at time τ . This overpressure pulse will then propagate outward, reaching the far-field point at time $t = \tau + \frac{R}{c}$ (where c = sonic velocity). Let dA equal the area of this small section of the rising mound. The far-field overpressure induced by the

rising section will depend on its area. More precisely, it can be shown that the far-field overpressure caused by a surface dA rising with velocity function $V(\tau)$ is given by:

$$(\Delta P) \approx \frac{\rho}{2\pi R} V'(\tau) dA, \quad (4a)$$

where

$$V'(\tau) = \frac{dV(\tau)}{d\tau}$$

(for linear acoustic theory, a simple source of sound radiating into a hemisphere—see Ref. 1, or the summary in Appendix D). This equation indicates that the far-field overpressure is proportional to dA , and to the normal acceleration of the surface $V'(\tau)$. Since the overpressure pulse created by $V'(\tau)$ will reach far-field point R at time $t = \tau + \frac{R}{c}$, the overpressure in the far-field is a picture of the surface acceleration at some time $\frac{R}{c}$ earlier.

The total overpressure at long range from a compact mound is made up of pulses from many small rising surface areas. Each pulse will result from the overpressure contributed by a little area, dA , with its own velocity function, $V(\tau)$. It is necessary to sum the pulse contributions for these surfaces. To sum pulses, set up an x-y coordinate system in the plane of the ground surface with the x-axis pointing toward the far-field point at R . This coordinate system is centered on SGZ (see sketches in Nomenclature). The area of each little surface section will be given by $dA = dx dy$:

$$(\Delta P)_{\text{one area}} = \frac{\rho}{2\pi R} V'(\tau) dA.$$

Total ΔP

$$= \iint \frac{\rho}{2\pi R} V'(\tau) dA = \iint \frac{\rho}{2\pi R} V'(\tau) dx dy.$$

In the direction of propagation toward R (along the x-axis),

$$dx = cd\tau.$$

Thus,

$$\Delta P = \frac{\rho}{2\pi R} \iint V'(\tau) cd\tau dy;$$

$$\Delta P = \frac{\rho c}{2\pi R} \int V(\tau) dy.$$

It is possible to calculate ΔP for any time segment of the velocity function $V(\tau)$. Since the peak overpressure is of greatest interest, select τ such that $V(\tau)$ is the peak vertical surface velocity, V . Then,

$$\text{Peak } \Delta P = \frac{\rho c}{2\pi R} \int V dy.$$

Technically, V should be integrated only over the limited range of appreciable surface motion. For real velocity profiles, however, the surface velocity V drops off very rapidly away from SGZ. It soon approaches zero and makes no contribution to the integral. Thus,

$$\Delta P = \frac{\rho c}{2\pi R} \int_{-\infty}^{+\infty} V dy.$$

Substituting $\alpha = \frac{R}{D} \frac{\Delta P}{\Delta P_0}$ —from the dimensionless overpressure⁰ Eq. (3)—this equation becomes:

$$\alpha = \frac{\rho c}{2\pi D} \int_{-\infty}^{+\infty} \frac{V}{\Delta P_0} dy.$$

The local overpressure at SGZ is approximately $\Delta P_0 = V_0 \rho c$ (from Eq. (1)); therefore,

$$\alpha = \frac{1.0}{2\pi D} \int_{-\infty}^{+\infty} \frac{V}{V_0} dy, \quad (4b)$$

where V_0 is the SGZ peak vertical velocity, and the y-axis is perpendicular to a line

of sight through SGZ. Equation (4b) shows that α is proportional to the integral of the velocity field over the y-axis. The expression is perfectly general—if V_0 and the velocity field are known, α can always be found. If necessary, the y-axis velocity field can be plotted on linear graph paper and integrated graphically. However, Montan^{1,2} has developed an analytic solution for certain types of velocity fields.

The surface velocity profiles for single charges are usually quite simple. The shape of the profile depends only on the geometry of the situation; i.e., on R and D . This dependence can be most simply expressed by looking at V as a function of the slant range from the shot point to the surface ($S = \sqrt{R^2 + D^2}$). If a log-log plot of V vs $1/S$ is constructed for a given experiment, the observed velocity points will be found to lie very close to a straight line. In other words, peak surface velocity is logarithmically related to slant range:

$$V = \text{constant} \left(\frac{1}{S} \right)^n.$$

The exponent n is determined by the slope of a line through the points. Observational verification of this velocity law will be presented in Section II.

The above relation may be converted to a simplified dimensionless form that accurately expresses the simple geometrical dependence of the velocity profile. First, all velocities are expressed in terms of the SGZ velocity, V_0 :

$$V = V_0 \text{ when } S = D \text{ (at SGZ)}$$

$$V = \text{constant} \left(\frac{1}{S} \right)^n = V_0 \text{ at } S = D$$

from which we obtain:

$$\text{constant} = V_0 D^n$$

and

$$V = V_0 \left(\frac{D}{S} \right)^n,$$

$$\frac{V}{V_0} = \left(\frac{D}{S} \right)^n. \quad (5)$$

Velocity profiles of this sort can be directly integrated to obtain α :

$$\begin{aligned} \alpha &= \frac{1}{2\pi D} \int_{-\infty}^{+\infty} \frac{V}{V_0} dy \\ &= \frac{1}{2\pi D} \int_{-\infty}^{+\infty} \left(\frac{D}{S} \right)^n dy \\ &= \frac{1}{2\pi} \int_{-\infty}^{+\infty} \left(\frac{D}{S} \right)^n d\left(\frac{y}{D}\right). \end{aligned}$$

The integral in the above equation reduces to Euler's integral of the first kind, giving the simple result:

$$\alpha_n = \frac{1}{2\pi} \beta\left(\frac{1}{2}, \frac{n-1}{2}\right), \quad (6)$$

where

$$\beta\left(\frac{1}{2}, \frac{n-1}{2}\right) = \frac{\Gamma\left(\frac{1}{2}\right) \Gamma\left(\frac{n-1}{2}\right)}{\Gamma\left(\frac{1}{2} + \frac{n-1}{2}\right)}.$$

The Γ function is tabulated in mathematical handbooks (see Table 6, and Refs. 1 and 4). Given the SGZ velocity V_0 , it is possible to calculate ΔP_0 ($\Delta P_0 = V_0 \rho c M$). Thus, the overpressure equation, $\frac{\Delta P}{\Delta P_0} = \alpha \left(\frac{D}{R} \right)$, is uniquely defined.

Certain limitations of the above analysis should be noted. First, Eq. (1) is based on the assumption of small velocities. The essential requirement is that $\frac{V_0}{c}$ be small. If the peak surface velocity reaches an appreciable fraction of the sonic velocity ($V_0/c \gtrsim 1/2$), predictions will no longer be accurate. The accepted acoustic transmission in the far-field— $\Delta P \propto \frac{1}{R}$, Eq. (3)—is also based on the assumption of small overpressures.

CONSIDERATIONS FOR ROW CHARGES

Equations (4a) and (4b) were developed through the application of linear acoustic theory for simple sources. Specifically, they apply to far-field overpressures at large distances from a compact, symmetrical vertical velocity field. These assumptions hold quite well for a single-charge explosion mound. The vertical velocity has a maximum value at SGZ, and drops off rapidly with range. The situation is not so favorable for row or multiple charges. The linear extent of the surface velocity field is much larger and the field itself is more complex. The degree of complexity can be seen by examining the surface velocity profile from a location off the end of a charge row. Instead of a neat symmetrical velocity profile with one peak, a row charge produces a series of velocity peaks (one over each charge). These peaks will produce corresponding maxima in the overpressure pulse. However, the individual pulse maxima will reach the observer at different times (due to the separation of the charges). They may or may not undergo partial combination. Thus, peak overpressures off the end of the row will be quite difficult to predict. The situation perpendicular to a charge row is somewhat better since relative time separation of the peaks is less. More rapid and complete combination of the induced overpressure field occurs. Nonetheless, it is expected that the observed peak overpressures perpendicular to the row will be somewhat smaller than the theoretical predicted overpressures (based on an α integration over the entire velocity field). This effect has now been confirmed. An

observed velocity profile⁵ was integrated along the Buggy I five-charge row. The integration gave a theoretical $\alpha \approx 0.784$, while observed overpressures perpendicular to the row indicated $\alpha \approx 0.54$ (see Appendix B).

The dimensionless overpressures near small-charge rows (total yields of 100 lb or less) are systematically higher than those from large-charge row experiments at the same dimensionless range. Montan's theory explains this effect: the actual linear dimensions of small-charge rows are less ($\approx$ a few feet). Thus, the delay times between arrivals of the successive peaks are shorter, and the peaks combine more efficiently. The small-charge row acts more like a true point source of sound.

Predictions based on the theoretical α should be correct for small-charge rows.

OVERPRESSURES AT ELEVATED LOCATIONS

The equations derived above apply only to far-field overpressures in the plane of the rising ground surface—x-y plane; see derivation Eqs. (4a) and (4b). Equation (4b) can be modified to account for overpressures at gages elevated above the ground surface. Let h be the height of a gage above the x-y plane. Draw a vector from SGZ to this gage. The length of this vector is the range R . Projection of the vector onto the ground surface determines the x-axis. The vector makes an angle θ with a vertical through SGZ:

$$\cos \theta = \frac{h}{R} \quad (\text{see Fig. 2}).$$

From Eq. (4a),

$$\Delta P = \iiint \frac{\rho}{2\pi R} V'(\tau) dx dy,$$

Fig. 2. Overpressure at height h above ground surface.

where:

$V'(\tau)$ = derivative of the vertical velocity for a small ($dx dy$) section of the rising surface.

For overpressure propagation along the x-axis (in the ground surface plane), it was found that $dx = cd\tau$. However, for the direction of propagation toward the elevated gage,

$$\cos (90^\circ - \theta) = \frac{cd\tau}{dx}$$

and

$$dx = \frac{cd\tau}{\cos (90^\circ - \theta)} \quad (\text{see Fig. 2}).$$

At the elevated gage,

$$\Delta P = \frac{\rho}{2\pi R} \iint V'(\tau) \frac{cd\tau}{\cos (90^\circ - \theta)} dy$$

$$\Delta P = \frac{\rho c}{2\pi R} \frac{1}{\cos (90^\circ - \theta)} \int_{-\infty}^{+\infty} V dy,$$

where

V = peak vertical velocity.

However, for ground level gage at R,

$$\Delta P = \frac{\rho c}{2\pi R} \int_{-\infty}^{+\infty} V(\tau) dy.$$

Therefore,

$$\Delta P (\text{elev. gage}) = \frac{1}{\cos (90 - \theta)} \Delta P (\text{ground level gage at same range}).$$

Substituting this result into Eq. (3),

$$\left[\frac{\Delta P (\text{elevated gage})}{\Delta P_0} \right] (\cos 90 - \theta) = \alpha \left(\frac{D}{R} \right). \quad (3\text{-elevated})$$

Equation (3-elevated) gives ΔP for all elevated gages. The only additional piece of information needed is the height of the gage, h , and the value of $\cos \theta = \frac{h}{R}$.

Section II

Application to Experimental Data

The derivation of Montan's theory is now complete. If the theory is sound, it should give predictions that compare favorably with experimental observations of overpressure, at least for single-charge events with "nice" surface velocity profiles. Prior to comparing experimental observations with Montan predictions, vertical surface velocities, SGZ overpressures, and velocity profiles will be discussed and compared with experimental measurements (all of these quantities are basic to Montan's method).

VERTICAL SURFACE VELOCITIES

The SGZ peak vertical velocity, V_0 , is a very important quantity in Montan's theory. It is used to calculate the SGZ overpressure, ΔP_0 , which in turn calibrates the overpressure relation. It is important to use the correct V_0 ; i.e., the V_0 which actually induces the true peak overpressure.

A strong, well-defined velocity maximum occurs early in the growth of the mound. This is the peak spall velocity, and it correlates well with the peak ground-shock-induced overpressure. The Cabriolet Event⁶ demonstrates this correlation. Cabriolet had an overpressure gage located at SGZ. The record from this gage clearly showed that peak local overpressure correlated with peak spall velocity (see Appendix A).

In order to verify the theory for past experiments, peak vertical spall velocities are required. Table 1 lists the peak velocities for 23 detonations. This table

gives the event name, medium, depth of burst, D (ft), scaled depth of burst, dob ($ft/kt^{1/3}$), peak vertical spall velocity, V_0 (ft/sec), literature reference, yield (kt or tons), explosive type, and approximate time of peak vertical spall velocity (msec). Note that two or more V_0 's are listed for some experiments. These are independent results which give some idea of the possible scatter in V_0 . Overpressures will be predicted using each listed V_0 .

The peak spall velocities for alluvium, basalt, and rhyolite are plotted in Figs. 3 and 4. A few clay shale points are shown in Fig. 4 for comparison. Fitted lines are drawn through the points for the various media and explosive types. These lines are drawn slightly high, so as to overpredict the overpressures (safe-sided). An additional fitted line for clay shale and saturated media is discussed in Appendix B.*

The fitted lines in Figs. 3 and 4 may be used to predict V_0 for future experiments. To make a prediction, enter Fig. 3 or 4 for the appropriate explosive type and medium at the planned dob ($ft/kt^{1/3}$). Read V_0 from the fitted line. The following list summarizes the figure selection criteria:

1. For high explosives and nuclear experiments in alluvium, and for nuclear experiments in rhyolite, use the fitted line in Fig. 3.
2. For nuclear experiments in basalt, use the lower line in Fig. 4.

* Figure B4 of Appendix B.

Table 1. Peak vertical spall velocity at SGZ, V_0 , for 23 experiments.

Event	Medium	D (ft)	dob (ft/kt ^{1/3})	V_0 (ft/sec)	Refer- ence ^a	Yield W (explosive)	Time of V_0 (msec)
Stagecoach I	Alluvium	80	295	18.5	7	20 tons (TNT)	75
Stagecoach II	Alluvium	17	62.6	580	7	20 tons (TNT)	6
Stagecoach III	Alluvium	34	125	105-121	7	20 tons (TNT)	26-52
Scooter	Alluvium	125	157.5	75-78	8	500 tons (TNT)	200
Sedan	Alluvium	635	136.9	114.5	9	100 kt (Nuclear)	—
Cabriolet	Rhyolite	170.75	129.3	95-103	10 11 12	2.3 kt (Nuc)	75-160
Palanquin	Rhyolite	280	172.2	23.9- 34.6- 37.7	13	4.3 kt (Nuc)	55
Pre-Schooner II	Rhyolite	71	161	129	14	85.5 tons (NM)	27
Buckboard 11	Basalt	25.5	94	470	15	20 tons (TNT)	7
Buckboard 12	Basalt	42.7	157.5	127	15	20 tons (TNT)	21
Buckboard 13	Basalt	58.8	217	85-86	15	20 tons (TNT)	31
Dugout (row)	Basalt	59	217	105-118- 134.5	16 17	5 of 20 tons (NM)	—
Buggy I (row)	Basalt	135	130.5	(105?)- 115-131- 138	5	5 of 1.1 kt (Nuc)	—
Danny Boy	Basalt	110	146	138-147	18 19 10	0.43 kt (Nuc)	— ^b
Schooner	Basalt	355	113	161-181	20	31 kt (Nuc)	200
Sulky	Basalt	90	205	85	20	0.085 kt (Nuc)	—
Pre-Schooner IA	Basalt	58	215	120	21	19.6 tons (NM)	—
Pre-Schooner IB	Basalt	50.2	186	150	21	19.7 tons (NM)	—
Pre-Schooner IC	Basalt	66.1	244	100	21	19.9 tons (NM)	—
Pre-Schooner ID	Basalt	41.8	154	170	21	19.8 tons (NM)	—
Pre-Gondola IC	Clay shale	43	158	180	22	20 tons (NM)	22
Pre-Gondola IB	Clay shale	46	169	155	22	20 tons (NM)	40
Pre-Gondola IA	Clay shale	53	195	150	22	20 tons (NM)	70

^aComplete information on all references is given in the reference list.^b V_0 could be 125 ft/sec; time not given.

Fig. 3. Peak vertical spall velocity as a function of scaled depth of burst for nuclear in alluvium and rhyolite and for HE in alluvium.

3. For high explosive experiments in basalt and rhyolite, use the upper line in Fig. 4. For clay shale and saturated media, $V_0 = 3.8 \times 10^5 \times (D/W^{1/3})^{-1.5}$. This equation has been plotted.*

These fitted lines are well-established for dob's greater than $60 \text{ ft/kt}^{1/3}$ but less than $250 \text{ to } 300 \text{ ft/kt}^{1/3}$. They should not be used outside this range. Appendix C gives a prediction method used for events at dob's greater than $250 \text{ to } 300 \text{ ft/kt}^{1/3}$.

Other workers in this field have used slightly different fitted lines for V_0 . Certain earlier fits are listed in Table 2 along with appropriate comments. Most

of these fits give lower V_0 's than Figs. 3 and 4. A few recent fits give slightly higher velocities for deep HE detonations (about 10 to 15% higher than the fitted V_0 's at great depths). It is believed that the fits shown in Figs. 3 and 4 are the most satisfactory for purposes of overpressure prediction, because they slightly overpredict spall velocities and thus give safe-sided overpressures.

There is some indication that high explosive spall velocities may be lower for rhyolite than for basalt. There are also hints of higher surface velocities for nitromethane experiments than for TNT. Separate fitted lines cannot be drawn for these different cases until more data become available.

* See Appendix B, Fig. B4.

Fig. 4. Peak vertical spall velocity as a function of scaled depth of burst for nuclear in basalt and HE in basalt or rhyolite.

It should be noted that even Montan's prediction method is ultimately based on an empirical dob dependence (Figs. 3 and 4). The Montan method carries predictions one step closer to the original causative mechanism. It does have an advantage over direct empirical methods: with an assumed or predicted V_0 and velocity profile, ground-shock-induced overpressures can always be predicted

(even when no experiment has been performed).

CALCULATION OF ΔP_0 'S USING OBSERVED V_0 'S

Given observed V_0 's for actual experiments, the corresponding ΔP_0 's can be calculated. The observed V_0 's (rather than fitted line values) will be used in

Table 2. Fitted equations used to give peak vertical spall velocity, V_0 , as a function of scaled depth of burst (see Figs. 3 and 4 for fitted lines used in prediction).

<u>Basalt</u>	$V_0 = 6.35 \times 10^6 \left(\frac{D}{W^{1/3}} \right)^{-2.1}$	V_0 = peak velocity, ft/sec D = depth of burst, ft; W = yield, kt	(PNE 603-F, Ref. 16)
	$V_0 = 17 \times 10^6 \left(\frac{D}{W^{1/3}} \right)^{-2.3}$		

Both equations tend to fall at or slightly above (V_0 greater than) the lower Fig. 4 fitted line in the region of interest ($60 < \text{dob} < 250 \text{ ft/kt}^{1/3}$). The first equation is notably higher at shallow depths; the second equation becomes less than the fitted line at deep depths.

<u>Basalt and rhyolite</u>	$V_0 = 6.41 \times 10^6 \left(\frac{D}{W^{1/3}} \right)^{-2.1}$	(PNE 513-F, Ref. 14)

This line is near or slightly above (V_0 greater than) the lower Fig. 4 fitted line in the region of interest.

<u>Alluvium</u>	$V_0 = 8.08 \times 10^6 \left(\frac{D}{W^{1/3}} \right)^{-2.3}$	(PNE 242-F, Ref. 9)
	$V_0 = 7.82 \times 10^6 \left(\frac{D}{W^{1/3}} \right)^{-2.3}$	

Both equations are near or below (V_0 less than) the Fig. 3 fitted line in the region of interest.

Clay shale The Pre-Gondola peak spall velocities are fitted to a line of slope $(D)^{-1.5}$ (Ref. 22). The fitted equation is approximately $V_0 = 3.8 \times 10^5 \times (D/W^{1/3})^{-1.5}$. The fit agrees with all observed peak spall velocities.^{22,23,24,25} This somewhat unusual fit arises because Pre-Gondola velocities refer to a weak saturated medium which transmits shockwaves much as does an incompressible fluid. The shallow $D^{-1.5}$ line is slightly above the Fig. 4 HE fit near optimum depth of burst (in the region of the measured points). It gives smaller velocities at shallow scaled depths and greater velocities for deeper experiments. The equation cited above is believed to be reasonable for events in weak saturated media and will be used as a prediction tool. It is plotted in Appendix B, Fig. B4.

<u>All Media</u>	$V_0 \approx 7.3 \times 10^5 \left(\frac{D}{W^{1/3}} \right)^{-1.71}$	(after J. W. Reed, SC-TM-69-340, Ref. 26)

This line is a general fit for all media. It gives lower velocities than the Fig. 4 lines for dob shallower than $300 \text{ ft/kt}^{1/3}$. It gives higher velocities than the fit for alluvium (Fig. 3). However, the individual alluvium velocities lie far below Reed's fitted line. Alluvium surface velocities are significantly lower than those for other media.

order to obtain the best possible correlation between velocities and overpressures. Equation (1) is used to calculate ΔP_0 's, which must then be corrected for ambient pressure, because some of these experiments were not conducted at sea level.

The equation for true local overpressure at SGZ derived from Eq. (1) is:

$$\Delta P_0 = \frac{P_{\text{ambient}}}{P_{\text{STP}}} (\rho c)_{\text{STP}} V_0 M,$$

where V_0 's are taken from Table 1.

$$P_{STP} = 1013 \text{ mbar}$$

$$(\rho c)_{STP} = 0.01841 \frac{\text{psi-sec}}{\text{ft}}.$$

The ambient pressures for most experiments were measured near SGZ. Mach numbers (M) are calculated from the quadratic equation, Eq. (2):

$$M^2 - \frac{\gamma + 1}{2} \frac{V_0}{c} M - 1 = 0.$$

At sea level, $c \approx 1087 \frac{\text{ft}}{\text{sec}}$, $\gamma \approx 1.4$. This equation is tedious to solve by hand. Therefore, a solution for $\gamma = 1.4$ is plotted in Figs. 5a and 5b. Calculate V_0/c , enter Fig. 5a or 5b, and read off M . Note that $M \approx 1.0$ for small V_0/c . Figure 5b extends up to $V_0/c = 0.5$. The solution may be calculated for larger V_0/c , but predictions are likely to prove inaccurate.

Final calculated ΔP_0 's for each experiment are compiled in Table 3. This table

gives the experiment name, ambient pressure at SGZ (from published meteorological data), peak vertical spall velocity (several listed in some cases), Mach number of the air shock " M ," the calculated ΔP_0 (several listed in some cases, one corresponding to each V_0), and the observed or inferred ΔP_0 for the experiment.

The calculated ΔP_0 is a crucial parameter in Montan's prediction method, and the calculated values should be compared with observed data to verify their accuracy. Although the extant data are limited, there are good local overpressure tracings near SGZ for four experiments: Pre-Schooner II,^{27,3} Palanquin,³ Cabriolet,⁶ and Schooner.³ These results, tabulated in Table 3, are listed and discussed in Table 4. Comparison with the calculated ΔP_0 's shows good agreement in all cases (Palanquin's calculated ΔP_0

Fig. 5. Mach number M as a function of V_0/c .

Table 3. Tabulation of SGZ peak vertical spall velocity, Mach number, and ΔP_0 for all experiments (Ref. 3 lists all sources of airblast data).

Experiment	P_{ambient} (psi)	V_0 (ft/sec)	M	Calculated ΔP_0 at SGZ (psi)	Observed (or inferred) ^a ΔP_0 near SGZ ^b (psi)
Stagecoach I	12.69	18.5	1.0107	0.2977	—
Stagecoach II	12.64	580	1.37	12.60	—
Stagecoach III	12.56	105-121 (125?)	1.0593- 1.068	1.75- 2.034	—
Buckboard 11	12.16	470 (7 msec)	1.292	9.25	—
Buckboard 12	12.06	127 (21.5 msec)	1.073	2.06	2.9 psi at slant range $S = 50$ ft (based on $S-3$ extrapolation from one observed point).
Buckboard 13	12.16	85-86 (at 31 msec) use 85.5	1.0482	1.365	1.4 at $S = 65$ ft (based on $S-2.82$ fit to 4 points).
Scooter	12.58	75-78	1.0427, 1.0443	1.232, 1.284	4.05 ^c (Vortman's unpublished value, 2.3 ft above SGZ).
Pre-Schooner II	12.17	129 (at 27 msec)	1.074	2.112	2.034 (at 41 msec).
Sulky	12.06	85	1.0482	1.347	1.75 at $S = 100$ ft (based on $S-4.09$ fit to 2 points).
Palanquin	12.32	23.9- 34.6- 37.7	1.0133 1.0192 1.0211	0.373 0.544 0.595	0.62 psi (at 43 msec) to 0.74 psi later.
Danny Boy	12.06	138- 147	1.080 1.085	2.253 2.41	2.73 at $S = 120$ ft (based on $S-3.58$ fit to 2 points).
Cabriolet	11.63?	95- 103	1.0538 1.0584	1.457 1.585	1.45 (at 65 msec).
Schooner	12.32	161- 181	1.093 1.105	2.72 3.085	3.18 psi.
Dugout	12.32	(118) (not used) 105- 134.5	1.0595 1.077	1.715 2.24	1.65 at $S = 70$ ft to 2.76 at $S = 59$ ft (based on $S-3$ ex- trapolation from one observed point, the closest station).
Buggy	12.26	115 131 138 (105) ^d (not used)	1.066 1.076 1.080	1.884 2.165 2.288	—

^aThe extrapolated ΔP_0 's are for distances a few feet from SGZ; closer extrapolation to peak velocity is not valid; vertical velocities tend to level off a few feet from SGZ.

^bSee Table 4.

^cThis value is quoted by Vortman (Dugout, Ref. 17) as an unpublished measurement 2.3 ft above SGZ; it may not refer to ground-transmitted overpressure.

^dThis value was obtained from bowling ball (falling mass) experiment; accelerometer results indicate $V_0 = 130$ ft/sec.

Table 4. Observed and inferred ΔP_0 's at SGZ (for comparison with calculated values).

Scooter:

Vortman¹⁷ quotes an unpublished $\Delta P_0 = 4.05$ psi. This value may not be a ground-shock-transmitted peak overpressure and should be treated with caution. It is the only case that significantly disagrees with the calculated ΔP_0 .

Pre-Schooner II:

Observed $\Delta P_0 = 2.034$ psi; peak at 41 msec (initial arrival at 13 msec).

Palanquin:

Observed $\Delta P_0 = 0.62$ psi at 43.1 msec, 21 ft from SGZ. The ΔP_0 rose to about 0.74 psi slightly later. These ΔP_0 's appear to correspond to actual ground-transmitted, ground-shock-induced pulses. The arrival time is correct for ground transmission. A later overpressure pulse, which rose to 5.52 psi, arrived at the gage in 46 to 49 msec. This pulse corresponded to an anomalous local gas vent through a pipe.

There is one additional observation of a ground-transmitted ΔP_0 : at ground range = 328 ft, $\Delta P_0 = 0.185$ psi. A ground range of 328 ft corresponds to slant range $S = 431$ ft (from shot point). Comparing this observation to the SGZ observation above, we find that ground-shock-transmitted ΔP_0 varies with slant range (S)-2.8. This exponent is quite reasonable for the variation of peak vertical spall velocity (and thus of peak ground-transmitted overpressure). It is concluded that both values probably refer to genuine ground-shock-transmitted pulses.

Cabriolet:

The SGZ gage (3 ft above and 3.35 ft from SGZ) recorded an initial arrival at 33 msec, climbing to a peak $\Delta P_0 = 1.45$ psi at 65 msec. The time of arrival is reasonable for a ground-transmitted pulse. The gage record does not show a steep rise to peak overpressure, but rather shows a gradual climb to a maximum. This fact provides a crucial piece of evidence that the peak ground-transmitted overpressure does indeed correspond to the peak vertical spall velocity—not to some earlier highly accelerated phase of ground motion. Pressure immediately above the rising mound increases gradually to a peak, in conjunction with the increasing spall velocity (see Appendix A). The records of gages farther out from SGZ did not show a clearly defined separation of the ground-transmitted and air-transmitted peak overpressures. However, on the basis of arrival times and inferred transmission velocities, Vortman determined that the transition between ground and air transmission occurred at a range of 375 ft from SGZ ($R/D = 2.2$).

Schooner:

Observed $\Delta P_0 = 3.18$ psi 21 ft from SGZ.

Buckboard 12:

$D = 42.7$ ft

Station	Distance from SGZ (ft)	Slant range, S (ft)	$\Delta P_{\text{local}} = \Delta P$ (ground-transmitted) (psi)
12A	110	118	0.22

On the basis of this one ground-transmitted overpressure, using an S-3 attenuation law for peak vertical spall velocity (and thus for overpressure), calculated $\Delta P_0 = 2.9$ psi at $S = 50$ ft (near SGZ). (The inferred ΔP_0 's will not be extrapolated quite all the way back to SGZ because observed vertical velocities are known to "level off" a few feet from the actual SGZ location.)

Buckboard 13:

$D = 58.8$ ft

Station	Distance from SGZ (ft)	Slant range, S (ft)	$\Delta P_{\text{local}} = \Delta P$ (ground-transmitted) (psi)
2A	79.5	99	0.465
4A	159.75	170	0.095
5	214.75	222	0.0295
6	298.5	304	0.0150

Fitting these four points gives a $\Delta P_0 = 1.4$ psi at $S = 65$ ft. The attenuation law is about S-2.82, a reasonable result, comparable to the value used above for the other Buckboard experiment.

Sulky:

$D = 90$ ft

Station	Distance from SGZ (ft)	Slant range, S (ft)	$\Delta P_{\text{local}} = \Delta P$ (ground-transmitted) (psi)
(Not numbered)	165	188	0.1332
	361	372	0.0081

A straight line fit through these two ground-transmitted overpressures gives an attenuation law $S^{-4.09}$. Extrapolating back toward SGZ at this attenuation rate, calculated $\Delta P_0 = 1.75$ psi at $S = 100$ ft. (The above may not be true ground-transmitted pulses, but the arrival times of 30 and 71 msec are consistent with ground transmission.)

Danny Boy:

$D = 110$ ft

Station	Distance from SGZ (ft)	Slant range, S (ft)	$\Delta P_{\text{local}} = \Delta P$ (ground-transmitted) (psi)
1	200	228	0.276
3	350	367	0.050

Fitting to the above two points gives an attenuation law of S-3.58. The inferred $\Delta P_0 = 2.73$ psi at $S = 120$ ft.

Dugout:

$D = 59$ ft

This is a row-charge experiment, and thus somewhat difficult to interpret. In the analysis, all overpressures have been empirically reduced to approximate single-charge values. A true ΔP_0 at SGZ (corresponding to actual observed SGZ spall velocities) is desired. Presumably, even the ground-transmitted pulses will be least reinforced off the end of the row (although it is not known exactly how these overpressures will behave for a row-charge experiment—the entire spall velocity field would have to be known in detail). Therefore, the closest approximation to single-charge behavior will be obtained by looking at the ground-transmitted pulse off the end of the row. Only one station showed the ground-transmitted pulse:

Distance from SGZ (ft)	Slant range, S (ft)	$\Delta P_{\text{local}} = \Delta P$ (ground-transmitted)
170	180	6.76 mbar = 0.098 psi

The arrival time for this one observation at the 170-ft (closest) station was 28.5 msec—quite consistent with a ground-transmitted pulse. Using an R⁻³ attenuation law,

$\Delta P_0 = 114$ mbar = 1.65 psi at $S = 70$ ft, or

$\Delta P_0 = 190$ mbar = 2.76 psi at $S = 59$ ft.

Attenuation rates, as listed above, vary from S-2.8 to S-4.09. These attenuation rates should be comparable to the attenuation rates of peak vertical spall velocity in the various media. In reality, some of the overpressures used for the above derivations may not be true ground-transmitted near-field overpressures. It is probable that part of the data refers to Rayleigh wave transmitted pulses or other effects. Therefore, the inferred SGZ overpressures and ground-transmitted attenuation rates should be viewed as rough estimates. The observed SGZ overpressures, on the other hand, are quite accurate (Pre-Schooner II, Palanquin, Cabriolet, Schooner).

is a little low). This agreement provides strong support for Montan's theory.

There are no other experiments with observed SGZ ΔP_0 's. The literature does contain a few local overpressures measured at locations other than SGZ (these are usually referred to as ground-transmitted ground-shock-induced overpressures). Some of these local overpressures can be extrapolated back to

SGZ, giving ΔP_0 . There are two possible methods of extrapolation: (1) if several local overpressures at different ranges are known, one can plot them as a function of slant range from shot point "S"; a straight-line log-log fit to the points extrapolates back to the S at SGZ, giving ΔP_0 ; and (2) given a single local overpressure, one can extrapolate back to SGZ on the basis of an assumed

attenuation rate S^{-n} . This attenuation rate should be approximately equal to the observed attenuation of vertical velocity (since peak vertical velocity induces the local overpressure).

The above extrapolation procedure and the observed local overpressures have been used to estimate ΔP_0 for five experiments: Buckboard 12, Buckboard 13, Sulky, Danny Boy, and Dugout. These results are unreliable for two reasons. The local (ground-transmitted) overpressures are poorly established and may not be true local overpressures; in addition, the extrapolation procedure is very crude. Nonetheless, extrapolated (inferred) ΔP_0 's are discussed in Table 4. The inferred ΔP_0 's are also listed in the last column of Table 3. Compare them with the calculated ΔP_0 's. Again, agreement is excellent, except for Buckboard 12 (calculated ΔP_0 too low). This agreement gives further verification of Montan's theory. Figure 6 shows a graphical comparison

Fig. 6. Comparison of calculated ΔP_0 's (based on V_0 's) with actual observed or inferred ΔP_0 's.

of calculated ΔP_0 's with observed and inferred ΔP_0 's.

VELOCITY PROFILES

The next step is to determine α . As mentioned in Section I, α may be calculated for velocity profiles of the form $V/V_0 = (D/S)^n$. It will be shown that the observed vertical surface velocity profiles are consistent with this law.

Table 5 lists observed peak surface velocities for six experiments. The SGZ velocity V_0 is listed in all cases, as well as velocities at various other ranges. The calculated value D/S for each range is listed in the table. Also, $(D/S)^2$ is given—this quantity is used for convenience in constructing the log-log plots because it expands the scale of the graphs. Results from Table 5, plotted in Figs. 7 through 12, show that surface velocities follow a $(1/S)^n$ relationship. The observed peak velocities for Scooter (in alluvium) lie very close to a $(D/S)^3$ line. The points for Cabriolet and Pre-Schooner II (rhyolite) also fit a $(D/S)^3$ law. The observations for Sulky (basalt) follow a $(D/S)^6$ line. The velocity profiles for Pre-Gondola I agree with a $(D/S)^{2.5}$ law (observed points are not plotted in Fig. 12—see Ref. 22 for detailed Pre-Gondola results). Only the Buggy I surface velocities (Fig. 11) fail to follow a simple $(1/S)^n$ relation. Figure 11 gives some idea of the complexity of row-charge velocity profiles.

It is concluded that the following peak surface velocity profiles accurately describe single-charge experiments:

$$\frac{V}{V_0} = \left(\frac{D}{S}\right)^3 \text{ alluvium and rhyolite,}$$

Table 5. Surface velocity profiles.

Target	Peak velocity (m/sec)	Range (ft)	D/S	(D/S) ²		
A. Scooter, D = 125 ft (alluvium)						
Unnumbered	23.8	0	1.0	1		
Unnumbered	23.2	30	0.972	0.945		
Unnumbered	17.7	60	0.903	0.815		
Unnumbered	7.0	120	0.722	0.521		
B. Cabriolet, D = 170.75 ft (dry rhyolite)						
6	30 ^a	7	1.0	1.0		
5,7	28 ^a	15	0.994	0.987		
4,8	26 ^a	45	0.964	0.929		
3,9	21 ^a	90	0.884	0.780		
2,10	15 ^a	135	0.783	0.613		
1,11	10.5 ^a	180	0.688	0.473		
12	6 ^a	225	0.603	0.364		
C. Pre-Schooner II, D = 71 ft (dry rhyolite)						
Mass	39.4	7	1.0	1.0		
1	33.6	20	0.96	0.920		
2	22.6	40	0.871	0.759		
3	15.84	60	0.764	0.583		
4	11.28	80	0.663	0.439		
5	7.93	100	0.577	0.333		
6	3.96	140	0.449	0.202		
7	2.44	180	0.366	0.134		
D. Sulky, D = 90 ft = 27.4 m (basalt)						
1,11 ^b	5.64	75	0.767	0.588		
2,10 ^b	8.47	60	0.833	0.694		
3,9 ^b	12.17	45	0.895	0.800		
4,8 ^b	15.89	30	0.949	0.900		
5,7 ^b	21.35	15	0.986	0.971		
6 ^b	26.09	0	1.0	1.0		
E. Pre-Gondola I, Bravo, D = 46 ft ^c						
Unnumbered	47.3 ^d	46 ^e	1.0	1.0		
Unnumbered	4.57 ^d	117.4 ^e	0.392	0.1537		
F. Buggy, D = 135 ft = 41.1 m; charge separation = 150 ft (basalt). Some velocities are average values.						
Target	Time (msec)	Peak velocity (m/sec)	Range (m)	D/S	(D/S) ²	Remarks
4 (E)	(130)	19.1	0	1.0	1.0	1 to row, directly beside a charge (A,B,C, D, or E)
8 (D)	(150)	29 ^f	0	1.0	1.0	
Mass (C)	(100)	32 ^f	0	1.0	1.0	
19 (C)	(130)	19.8	15.3	0.937	0.877	
18 (C)	(150)	11.3	30.4	0.805	0.648	1 to row, halfway between charges C and D
17 (C)	(150)	7.4	45.5	0.671	0.450	
13 (B)	(140)	32.8 ^f	0	1.0	1.0	
Mass (A)	(80)	24 ^f	0	1.0	1.0	
20 (C-D)	(150)	24.8	15.3	0.937	0.877	Off ends of row
21 (C-D)	(150)	14.2	30.4	0.805	0.648	
22 (C-D)	(150)	10.4	45.5	0.671	0.450	
23 (C-D)	(180)	8.4	60.8	0.561	0.314	
3 & 15	(130)	18.5	15.3	0.937	0.877	Along row, between charges
2 & 16	(150)	10.5	30.4	0.805	0.648	
1	(270)	6.8	45.5	0.671	0.450	
5,7,9,10, 11	(150)	25-28.5	11.4	0.964	0.929	
6,12	(150)	24.5-25	22.9	0.873	0.761	

^aEarly time: <200 msec. Some velocities are average values.^bFlare targets. Some velocities are average values.^cFitted line²² to Pre-Gondola Bravo points (other Pre-Gondola detonations give almost exactly the same slope; therefore, only this case will be plotted).^dFitted line values, in m/sec.^eSlant range, S (ft).^fAccelerometer results are somewhat more scattered and not suitable for determining the slope of the $V = V_0(D/S)^n$ line. However, they do indicate a higher SGZ peak velocity—on the order of 40+ m/sec.

Fig. 7. Attenuation of peak vertical spall velocity as a function of slant range for Scooter.

Fig. 8. Attenuation of peak vertical spall velocity as a function of slant range for Cabriolet.

Fig. 9. Attenuation of peak vertical spall velocity as a function of slant range for Pre-Schooner II.

Table 17. Airblast peak overpressures, Buckboard 11 (see Fig. 20).

$\Delta P_0 = 9.25$ psi; $D = 25.5$ ft

R/D	ΔP (psi)	$\Delta P/\Delta P_0$
4.24	0.406	0.0439
5.08	0.329	0.0356
6.40	0.285	0.0308
8.14	0.242	0.0262
10.35	0.174	0.0188
13.68	0.125	0.0135
18.70	0.084	0.00908

Table 18. Airblast peak overpressures, Buckboard 12 (see Fig. 20).

$\Delta P_0 = 2.06$ psi; $D = 42.7$ ft

R/D	ΔP (psi)	$\Delta P/\Delta P_0$
2.580	0.24	0.116
3.045	0.192	0.0932
3.865	0.155	0.0752
4.92	0.109	0.0529
6.21	0.108	0.0524
8.20	0.065	0.0316
11.25	0.051	0.0248

Table 19. Airblast peak overpressures, Buckboard 13 (see Fig. 20).

$\Delta P_0 = 1.365$ psi; $D = 58.8$ ft

R/D	ΔP (psi)	$\Delta P/\Delta P_0$
1.015	0.504 (??)	0.369
1.35	0.465 (??)	0.341
2.72	0.097	0.0711
3.66	0.079	0.0579
5.08	0.068	0.0498
7.31	0.037	0.0271

indicate an $\alpha \approx 0.35$. Perhaps the true surface velocity profile for Schooner's medium was closer to $(D/S)^3$ than to $(D/S)^6$. This hypothesis would explain

Table 20. Airblast peak overpressures, Stagecoach I (see Fig. 21).

$\Delta P_0 = 0.2977$ psi; $D = 80$ ft

R/D	ΔP (psi)	$\Delta P/\Delta P_0$
1.0	0.092	0.309
1.375	0.0565	0.190
2.0	0.0265	0.089
3.38	0.0280	0.094
5.38	0.0145	0.0487

Table 21. Airblast peak overpressures, Stagecoach II (see Fig. 21).

$\Delta P_0 = 12.60$ psi; $D = 17$ ft

R/D	ΔP (psi)	$\Delta P/\Delta P_0$
6.47	0.68 ^a	0.0540
9.41	0.42 ^a	0.0333
15.9	2.58 ^b	0.205 ^b

^aUse as an approximation only.

^bProbably not a ground-shock-induced overpressure.

Table 22. Airblast peak overpressures, Stagecoach III (see Fig. 21).

$\Delta P_0 = 1.75$ and 2.034 psi;
 $D = 34$ ft

R/D	ΔP (psi)	$\Delta P/\Delta P_0$
3.24	0.29	0.166-0.143
4.70	0.19	0.109-0.0934
7.94	0.08	0.0457-0.0393
12.65	0.06	0.0343-0.0295
22.05	0.04	0.0229-0.0197
32.4	0.02	0.0114-0.00983
47.0	0.015	0.00857-0.00737

most of the difference between the observed points and the plotted $\alpha = 0.188$ line.

Observed V_0 's for the Buckboard 12 experiment and for Schooner both fall

Fig. 13. $\Delta P/\Delta P_0$ as a function of R/D for Sulky and Danny Boy nuclear detonations in basalt.

Fig. 15. $\Delta P/\Delta P_0$ as a function of R/D for Dugout high explosive detonation in basalt.

Fig. 14. $\Delta P/\Delta P_0$ as a function of R/D for Palanquin and Cabriolet nuclear detonations in rhyolite.

Fig. 16. $\Delta P/\Delta P_0$ as a function of R/D for Buggy nuclear detonation in basalt.

appreciably below the fitted V_0 lines (Fig. 4). If fitted rather than observed V_0 's had been used, both these experiments would have been better predicted. (Larger V_0 gives larger ΔP_0 , which

brings the observed $\Delta P/\Delta P_0$ points down to the theoretical line.) The fitted V_0 lines will safely predict all experiments in Figs. 13 through 21. The observed V_0 's for Dugout fall at or above the fitted

Fig. 17. $\Delta P/\Delta P_0$ as a function of R/D for Schooner nuclear detonation in moist rock-tuff.

Fig. 19. $\Delta P/\Delta P_0$ as a function of R/D for Pre-Schooner II high explosive detonation in rhyolite.

Fig. 18. $\Delta P/\Delta P_0$ as a function of R/D for Scooter high explosive detonation in alluvium.

Fig. 20. $\Delta P/\Delta P_0$ as a function of R/D for Buckboard 11, Buckboard 12, and Buckboard 13 high explosive detonations in basalt.

line $[(V_0 - \text{fitted}) \approx 105 \text{ ft/sec in Fig. 4}]$, but the fitted V_0 will still safely predict Dugout.

The observed points in Figs. 13 through 21 typically scatter about the

theoretical lines by 20 or 30%. Uncertainties in V_0 and the velocity field account for part of this scatter. Deviations from acoustic $R^{-1.0}$ attenuation also account for part of the scatter in some

Fig. 21. $\Delta P/\Delta P_0$ as a function of R/D for Stagecoach I, Stagecoach II, and Stagecoach III high explosive detonations in alluvium.

cases (Sulky and Cabriolet are two good examples). However, deviations in the

attenuation rate are never large enough to have a serious ill effect on the fits at close to intermediate ranges.

The Pre-Schooner II elevated gage data points are also in reasonable agreement with the theoretical line (see Fig. 19). These data were reduced using Eq. (3-elevated). Thus, Montan's derivation correctly predicts elevated overpressures, at least for close-in ranges and for $(90^\circ - \theta) < 75^\circ$.

The above results give a very favorable picture of the Montan prediction technique. It is capable of reproducing observed ground-shock overpressures to the limit of accuracy with which V_0 is known. Therefore, the method may safely be adopted as a general technique for predicting ground-shock-induced airblast from cratering detonations.

Section III

Prediction Method for Single-Charge Events

MONTAN PREDICTION METHOD

This section is a summary of the procedure for predicting ground-shock-induced overpressures from single-charge detonations:

Necessary Information:

- (1) Medium.
- (2) Yield W of the explosive (in kt).
- (3) Depth of burst, D (in ft).
- (4) Ambient pressure, P_{ambient} (in mbar). Obtained from meteorological data or altitude of the proposed experiment.
 $P_{\text{ambient}} \approx 1013$ mbar at sea level;
 $P_{\text{ambient}} \approx 844$ mbar at 5000-ft altitude above sea level.

- (5) Location of any elevated point for which predictions are desired.

Calculations:

- (1) Determine n and α for the medium of the experiment (Table 6).
- (2) Calculate scaled depth of burst:

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

- (3) Determine V_0 . For soil or rock, enter Figs. 3 or 4 at the calculated dob and read V_0 from the appropriate (medium and type of explosive) fitted line. For peak velocities in clay shale and saturated weak media, see Appendix B, Fig. B4. If $\text{dob} > 250 \text{ ft/kt}^{1/3}$, the explosion will probably be semi-contained, and Figs. 3 and 4 are not valid. To predict airblast from mounding or moderately deep contained bursts, see Appendix C. To predict airblast from underwater detonations, see Appendix E. Ground-shock-induced air-

blast is always dominant for all contained bursts and for all experiments deeper than $\text{dob} = 170 \text{ ft/kt}^{1/3}$ in water or saturated weak media.

- (4) Constants of interest:

$$P_{\text{STP}} = 1013 \text{ mbar}$$

$$(\rho c)_{\text{STP}} = 0.01841 \text{ psi-sec/ft}$$

$$c \approx 1087 \text{ ft/sec.}$$

- (5) Using $c \approx 1087 \text{ ft/sec}$, calculate the ratio (V_0/c) .*

- (6) Enter Fig. 5a or 5b at (V_0/c) ; read off the Mach number M .

- (7) Calculate

$$\begin{aligned} \Delta P_0 &= \frac{P_{\text{ambient}}}{P_{\text{STP}}} (\rho c)_{\text{STP}} M V_0 \\ &= \frac{P_{\text{ambient}}}{1013 \text{ mbar}} 0.01841 M V_0. \end{aligned}$$

- (8) Predict $\Delta P = \Delta P_0 \alpha \left(\frac{D}{R} \right)$.

Calculate the $\Delta P_0 \alpha D$ term; then calculate predicted ΔP for any desired R . Calculate several points, and plot a log-log graph of ΔP vs R ; it will be a straight line of slope R^{-1} .

Do not extend predictions from the Montan method inside $R/D = 1.0$ (inner limit for far-field ΔP 's).

- (9) If desired, predict elevated overpressures above the ground surface. Using an elevated point at height h above the ground and true range R from SGZ, find:

$$\cos \theta = \frac{h}{R}$$

Determine θ .

Determine $90^\circ - \theta$.

* It is permissible to use the true local sonic velocity, c_{ambient} , rather than 1087 ft/sec, if c_{ambient} is known. However, the sonic velocity for most cases differs from the sea level value by only a few percent.

Predicted overpressure ΔP (elevated) is given by Eq. (3-elevated):

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

where α is the standard ground level value of α for the detonation in question ($\alpha = 0.188$ for basalt, $\alpha = 0.318$ for alluvium and rhyolite, etc.).

If the ambient pressure at the elevated position is different from the ground level ambient pressure, another correction factor is necessary. Multiply the predicted overpressure, ΔP (elevated), by the correction factor:

$$\frac{P_{\text{ambient}} \text{ (at elevated point)}}{P_{\text{ambient}} \text{ (ground level)}}.$$

Normally, this correction is not necessary unless the elevated point is at much greater altitude than SGZ (several thousand feet higher).

Note that the $1/\cos(90 - \theta)$ term in the above equation increases without limit if $(90 - \theta)$ is close to 90° . This occurs because of the nature of the simple physical model employed. Montan's method cannot be used to predict elevated ΔP 's for $(90 - \theta) > 75^\circ$ (i.e., almost directly above SGZ).

SAMPLE PROBLEMS

Sample Problem No. 1 (Optimum Depth of Burst):

Take Stagecoach III as an example. This was a 20-ton high explosive experiment, at a depth of burst = 34 ft in alluvium. Predict the ground-shock-induced airblast using Montan's method:

Yield $W = 20$ -ton high explosive
 $= 0.02$ kt

Depth of burst, $D = 34$ ft

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

$\alpha = 0.318$ [for alluvium, $(D/S)^n$, $n = 3$; Table 6].

Scaled depth of burst dob

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

Going to Fig. 3 (for alluvium) at dob = $125 \text{ ft/kt}^{1/3}$, the predicted peak vertical spall velocity, V_0 , is 138 ft/sec. The sonic velocity, $c \approx 1087$ ft/sec. Therefore, $V_0/c = 0.127$. Enter Fig. 5b and read the Mach number M : $M = 1.079$.

$P_{\text{STP}} = 1013$ mbar.

$(\rho c)_{\text{STP}} = 0.0184$ psi-sec/ft.

Now it is possible to calculate the SGZ near-field overpressure:

$$\Delta P_0 = \frac{P_{\text{ambient}}}{P_{\text{STP}}} (\rho c)_{\text{STP}} M V_0 = 2.347 \text{ psi}$$

$$\Delta P = \Delta P_0 \alpha \left(\frac{D}{R} \right) = (2.347)(0.318)(34)/R \\ = 25.4/R$$

The following are sample predicted overpressures, from this equation:

Distance from SGZ, R (in ft)	ΔP (psi)
25	1.02
50	0.51
100	0.25
300	0.08
1000	0.03

Figure 22 shows the predicted line drawn through these sample points. Its slope is R^{-1} . True observed overpressures from the Stagecoach III experiment are included in the diagram for comparison. The

Fig. 22. Comparison of actual (observed) ground-shock-induced overpressures with Montan's prediction method for experiment Stagecoach III (20-ton HE, 34 ft deep, in alluvium)

predicted line agrees well with the observed points. Do not extend predictions inside $R/D = 1$.

Montan's method also predicts high-angle elevated overpressures. There were no elevated gages in the Stagecoach experiment, but an imaginary problem has been constructed. Predict one overpressure at an elevated gage 100 ft high, at true range $R = 300$ ft from SGZ:

$$h = 100 \text{ ft}$$

Therefore, the angle θ from the vertical to the gage direction is:

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

$$\theta = 70.5^\circ$$

$$90 - \theta = 19.5^\circ$$

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

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

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

$$\Delta P (\text{elevated}) = 0.09 \text{ psi at elevated gage.}$$

Sample Problem No. 2 (Shallow Depth of Burst):

Two shallow experiments in alluvium have measured ground-shock overpressures, but no observed surface velocities. These experiments are Teapot ESS (nuclear) and Jangle HE-3 (TNT).³ The Montan method can be tested by performing overpressure predictions for these two events.

Both detonations were at dob
 $= 63 \text{ ft/kt}^{1/3}$. From Fig. 3, the predicted peak surface velocity $V_0 \approx 580 \text{ ft/sec}$; $V_0/c \approx 0.534$. Thus, the predicted surface

Fig. 23. Observed and predicted ground-shock overpressures, using Montan's method; no vertical spall velocities were measured for these two experiments— $V_0 = 580 \text{ ft/sec}$ was assumed in making the predictions (see Fig. 3, alluvium).

velocity is more than half as large as the sonic velocity. Predictions at this large velocity may not be extremely accurate.

The method is identical to the sample problem above. Results are shown in Fig. 23. The predicted line for Teapot ESS is slightly higher than the measured overpressure points, while the prediction for Jangle HE-3 is a bit low. In view of the shallow burial depth and high surface velocities, these results should be con-

sidered quite satisfactory. Comparison of the observed and predicted overpressures does indicate that the true V_0 may have been slightly greater than 580 ft/sec for Jangle (high explosive) and somewhat less than 580 ft/sec for Teapot ESS (nuclear).*

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*Note that these two very shallow events produced dominant gas-vent airblast pulses. Thus, the accurate prediction of ground-shock airblast, although a severe test of the theory, is not a matter of great importance.

Section IV

Summary

A technique, based on theory and a physical model, has been presented to correlates ground-shock-induced airblast overpressures with the vertical velocity of the rising mound above single-charge subsurface detonations. Verification of the technique has been accomplished by comparing predictions with measured data from almost a score of large-yield high explosive and nuclear detonations. The field data employed in the comparison are tabulated for each event.

The prediction technique is usable in preparing airblast-overpressure damage predictions for deeply buried cratering explosions. For this emplacement con-

dition the ground-shock-induced overpressure is the dominant airblast damage mechanism. Specifically, the ground-shock-induced overpressures are dominant for TNT and nitromethane detonations where $\text{dob} > 200 \text{ ft/kt}^{1/3}$; nuclear detonations in strong dry rock where $\text{dob} > 125 \text{ ft/kt}^{1/3}$; and for all detonations underwater or in saturated media where $\text{dob} > 170 \text{ ft/kt}^{1/3}$.

The appendixes extend the prediction technique to five- and seven-charge row detonations and to detonations in a non-competent medium overlain with water. The paucity of field-measured data prohibits complete verification of this extension.

Appendix A

Justification for Correlating ΔP_0 With Peak Vertical Spall Velocity

The local overpressure, ΔP_0 , at SGZ is directly related to the peak surface velocity, V_0 , by Eq. (1):

$$\Delta P_0 = M\rho c V_0.$$

The reliability of all calculated ΔP_0 's depends directly on the accuracy and consistency with which V_0 's are determined.

In most cases, the time-dependent SGZ surface velocity curves show two velocity peaks. The initial peak corresponds to spall-wave-induced motion. It is followed by a second velocity peak corresponding to the gas-acceleration-induced phase of motion. The initial peak (spall velocity) was used to calculate ΔP_0 's in this study. It is necessary to show that this peak does indeed correlate with ΔP_0 .

Surface velocities for any event can be determined by four methods. Velocity gages give a direct measure of the SGZ surface velocity. Falling mass experiments, accelerometers, and surface tar-

get motion photography give data from which the SGZ surface velocity can be obtained. Velocities from the different methods usually agree quite well when independent results from two or more methods are available for the same experiment.

SGZ surface velocities for the Cabriolet experiment⁶ were determined by two different methods. The local overpressure pulse was also measured by a gage 3 ft above the 3.35 ft away from SGZ. Therefore, Cabriolet will be used to correlate ΔP_0 and the velocity curves. Measured Cabriolet velocities are given in Table A1. Velocity curves for Cabriolet are shown in Figs. A1 and A2. Compare the SGZ velocity curves, Figs. A1 and A2, to the SGZ local overpressure tracing, Fig. A3. It is immediately apparent that the overpressure is indeed closely related to the spall velocity. The first motion at SGZ (30 msec) compares quite favorably with

Table A1. Peak spall velocities for Cabriolet.

	Velocity gages	Accelerometers	Falling mass experiment	Surface target photography
Shock-induced				
Velocity (ft/sec)	103	95	92	92
Time (msec)	75	— ^a	75	80
Gas pressure-induced				
Velocity (ft/sec)	157	— ^b	— ^a	197
Time (msec)	840 ^b	— ^a	— ^a	770

^aData not available.

^bTime velocity gage failed.

Fig. A1. Surface velocity as indicated by velocity gage compared with SGZ flare data (Ref. 12).

Fig. A2. Vertical velocity of surface motion Target 6 as a function of time (Target 6 was 7 ft from SGZ—from Ref. 11).

the first observed overpressure arrival (32 msec). The peak vertical spall velocity at SGZ (75 msec) compares well with the time of peak local overpressure ΔP_0

Fig. A3. Pressure-time record at SGZ for Project Cabriolet (from Ref. 6).

(65 msec). These measured values seem to indicate that the ground-transmitted ground-shock-induced overpressure is directly coupled to the spall-wave-induced surface motion. (The late-time peak and fluctuations in the Fig. A3 overpressure gage tracing represent violent physical acceleration and final failure of the gage.)

The connection between peak vertical spall velocity and peak overpressure can also be verified by examining the pressure pulse arrival times in the far-field. Peak pressure arrival at any distant gage should correspond to the time of peak spall velocity plus transit time to the gage. The selected gage location should be far enough from SGZ to insure reasonably complete combination of the overpressure pulses from various parts of the mound.

The Cabriolet experiment (in rhyolite)^{6,10,11,12} reached peak vertical spall velocity at 0.075 sec (see above). The pulse transit time to a gage 800 ft from SGZ is approximately 0.726 sec.

Peak arrival at 800 ft would thus be expected at 0.80 sec. Peak ground-shock-induced far-field overpressure at the 800-ft gage actually occurred near 0.711 sec, with a peak width ≈ 0.12 sec.

The Sulky test (in basalt)^{20,28,29} achieved peak vertical spall velocity around 0.104 sec. The transit time to a range of 820 ft is about 0.745 sec. The predicted peak arrival time at the 820 ft gage is 0.85 sec, comparable to the recorded peak at 0.757 sec with a width ≈ 0.075 sec.

The Stagecoach III event (in alluvium)⁷ gave peak spall velocity at 0.026 sec. The expected transit time to a 1600-ft gage is roughly 1.45 sec, giving a predicted peak

arrival at 1.48 sec. The true peak occurred near 1.42 sec, with a width ≈ 0.03 sec (timing not extremely precise).

It is evident that peak ground-shock-induced overpressures cannot correspond to a phase of the surface motion history later than the peak spall velocity. The somewhat early apparent arrival of most of the far-field peak overpressures discussed above is due to local pressure pulses from parts of the rising mound nearer than SGZ, and to a finite amplitude effect which causes sinusoidal or slowly increasing compression waves in air to advance and "shock up" to a sharper peak pressure front.

Appendix B

Preliminary Application of Montan's Method to Row Events in Strong Rock and Saturated Clay Shale

Velocity profiles for row charges are quite complex and not amenable to analytic integration. However, α can be obtained for an observed row-charge profile by graphically integrating Eq. (4b):

$$\alpha = \frac{1}{2\pi D V_0} \int_{-\infty}^{+\infty} V dy.$$

The Buggy five-charge event (in basalt) has an excellent observed velocity profile along the row.⁵ This profile will be integrated in order to predict overpressures perpendicular to the row.

Figure B1 shows the observed Buggy velocity profile along the row. Assume that $V = V_0 (D/S)^6$ off either end of the row (where S is the slant range from the last charge in the row). There was not suffi-

cient room to plot these velocity "wings" off the ends of the row in Fig. B1. Therefore, the wings are plotted together in the center of the figure. This wing profile is just equivalent to a $(D/S)^6$ profile for a single charge. Integration was performed along the row and under the wings by using a planimeter. Then α is the sum of the two integrals:

For Buggy, $V_0 \approx 105$ ft/sec (used in Fig. B1), and $D = 135$ ft.

$$\begin{aligned} \alpha(\text{wings}) &= \frac{1}{2\pi D V_0} \int_{\text{over wing profile}} V dy \\ &= \frac{1}{2\pi (135 \text{ ft})(105 \text{ ft/sec})} \\ &\quad \times (16,700 \text{ ft}^2/\text{sec}) \\ &= 0.188. \end{aligned}$$

Fig. B1. Graphical integration of velocity profile along Buggy row (to determine " α " for a 5-charge row in basalt with optimum spacing).

Table B1. Airblast peak overpressures, Buggy—theoretical predictions (see Fig. B2).

$\Delta P_0 = 1.884, 2.165, \text{ and } 2.288 \text{ psi}$; $D = 135 \text{ ft}$; $n = 5 \text{ charges in row}$; overpressures perpendicular ($\perp$) to row

R/D	$\Delta P \text{ (psi)}^a$		$(\Delta P/\Delta P_0)^a$	
3.79	0.206	0.109	0.0952	0.0900
7.42	0.161	0.0854	0.0744	0.0704
18.2	0.0493	0.0262	0.0228	0.0216
30.2	0.0389	0.0206	0.0180	0.0170
44.2	0.0229	0.0122	0.0106	0.0100
48.9	0.0152	0.00806	0.00702	0.00664
57.5	0.0145	0.00770	0.00670	0.00634

^aNot corrected to single-charge values.

$$\alpha(\text{along row}) = \frac{1}{2\pi DV_0} \int_{\text{along row}} V \, dy.$$

$$\alpha(\text{along row}) = \frac{1}{2\pi(135)(105)} (53,100) \\ = 0.596$$

$$\alpha_{\text{total}} = 0.596 + 0.188 = 0.784.$$

Note that the α under the wing profile above agrees with α (single charge) = 0.188 for $n = 6$ (Table 6), as it should. In other words, graphical integration of the velocity profile gives the same result as the analytic procedure. Note also that α_{total} for the entire row is 4.17 times larger than α_6 (for a single charge in basalt).

It is useful to compare the derived $\alpha = 0.784$ with the observed overpressures perpendicular to the Buggy row. In addition, a comparison with the Dugout row is included (five charges, also in basalt). A theoretical value of $\alpha = 0.784$ is assumed for Dugout, as for Buggy. Overpressures for Buggy and Dugout are listed in Tables B1 and B2 (ΔP not corrected to single-charge values). $\Delta P/\Delta P_0$'s are plotted in Figs. B2 (Buggy) and B3 (Dugout). It is evident that the observed overpressures fall below the predicted

$\alpha = 0.784$ line. They are more consistent with an $\alpha \approx 0.54$. This is the effect expected from the discussion in Section I (inefficient and incomplete reinforcement between signals from a large, complex velocity field). Montan's method can now be used to predict airblast from large-yield five-charge rows near optimum inter-charge spacing in basalt. An $\alpha = 0.54$ is recommended.

Surface velocities and airblast have also been observed for nitromethane single-charge and row experiments in

Table B2. Airblast peak overpressures, Dugout—theoretical predictions (see Fig. B3).

$\Delta P_0 = 1.715 \text{ and } 2.24 \text{ psi}$;
 $D = 59 \text{ ft}$; $n = 5 \text{ charges in row}$;
overpressures perpendicular
($\perp$) to row

R/D	$\Delta P \text{ (psi)}^a$		$(\Delta P/\Delta P_0)^a$
2.90	0.406	0.237	0.181
5.95	0.141	0.0822	0.0630
14.4	0.0833	0.0486	0.0372
39.0	0.0206	0.0120	0.0092
84.8	0.00754	0.0044	0.00337

^aNot corrected to single-charge values.

Fig. B2. $\Delta P/\Delta P_0$ as a function of R/D for Buggy nuclear detonation in basalt (perpendicular to row, not corrected to single charge).

Fig. B3. $\Delta P/\Delta P_0$ as a function of R/D for Dugout high explosive detonation in basalt (perpendicular to row, not corrected to single charge).

saturated clay shale. SGZ peak vertical spall velocities for both row and single-charge events are shown in Fig. B4. Unfortunately, good airblast measurements

are available only for two row-charge events (both of which also have measured surface velocity profiles along the row). The velocity profiles are very irregular but can be integrated graphically. Integration using data from Refs. 23 and 24 gives the following α values:

Pre-Gondola II²³ (five-charge row; mean yield = 28 tons; $V_0 \approx 160$ ft/sec, $D = 52.6$ ft):

$$\int_{\text{along row and under wings}} V dy = 68,250 \text{ ft}^2/\text{sec.}$$

$$\alpha = \frac{1}{2\pi D V_0} \int V dy = \frac{68,250}{2\pi (52.6)(160)} = 1.29.$$

Pre-Gondola III, Phase I²⁴ (two widely separated rows of seven 1-ton charges, $V_0 \approx 120.3$ ft/sec, $D = 19.5$ ft; the peak airblast pulse perpendicular to the rows was induced by the closer of the two rows;

Fig. B4. Peak vertical spall velocity as a function of scaled depth (saturated clay shale and saturated weak media).

the measured velocity profile was extrapolated off both ends of the row as $S^{-2.5}$ for purposes of integration):

$$\int_{\text{along row and under wings}} V dy = 24,140 \text{ ft}^2/\text{sec}$$

$$\alpha = \frac{24,140}{2\pi(19.5)(120.3)} = 1.64.$$

These theoretical α 's can be compared with the observed overpressures perpendicular to the rows. Overpressures for Pre-Gondola II and III, Phase I, are listed in Tables B3 and B4, respectively. The

Table B3. Airblast peak overpressures, Pre-Gondola II.

$\Delta P_0 = 2.957$ psi (for $V_0 \approx 160$ ft/sec; $P_{\text{ambient}} \approx 930$ mbar = 13.47 psi); two devices of 40 tons and three of 20; $D = 52.6$ ft; overpressures perpendicular ($\perp$) to row

R/D	ΔP (psi) ^a	$(\Delta P/\Delta P_0)^a$
4.28	0.593	0.2006
12.36	0.230	0.0778
34.2	0.101	0.0342

^aNot corrected to single-charge values.

$\Delta P/\Delta P_0$'s for both experiments are plotted in Fig. B5. The theoretical lines for $\alpha = 1.29$ and $\alpha = 1.64$ are also shown. Observed points for Pre-Gondola III, Phase I fall somewhat above the $\alpha = 1.64$ line. An $\alpha = 1.9$ line would give a better fit. The reason for this disagreement is not known. The predictions could be slightly improved by using a determined sonic velocity of $c \approx 1128$ ft/sec (Ref. 24) instead of 1087 ft/sec.

Table B4. Airblast peak overpressures, Pre-Gondola III, Phase I.

$\Delta P_0 = 2.171$ psi (for $V_0 = 120.3$ ft/sec; $P_{\text{ambient}} \approx 13.47$ psi); seven^a devices of 1 ton; $D = 19.5$ ft; overpressures perpendicular ($\perp$) to row

R/D	ΔP (psi) ^b	$(\Delta P/\Delta P_0)^b$
4.77	0.969	0.446
4.77	0.986	0.454
16.15	0.328	0.151
16.15	0.229	0.106

^aThere were two widely separated rows of seven devices each; the separation was sufficiently great so that no airblast reinforcement occurred between the signals from the two rows. Therefore, peak airblast overpressures are assumed to originate from the closer of the two rows.

^bNot corrected to single-charge values.

Fig. B5. $\Delta P/\Delta P_0$ as a function of R/D for Pre-Gondola II and Pre-Gondola III, Phase I nitromethane experiments in saturated clay shale.

These results demonstrate that row events in saturated clay shale give rise to larger α 's than comparable detonations in basalt, and also that airblast reinforcement perpendicular to the row is more efficient (the observed points do not fall below the integrated α lines). The reason for these differences lies in the broader velocity profiles of the clay shale experiments ($S^{-2.5}$, as compared to S^{-6} for basalt). Efficient reinforcement and large α 's may be expected for all row-charge detonations in media with broad velocity profiles ($n = 2$ to 3), including contained events, underwater and saturated medium events.

The following α 's are provisionally recommended for predicting row-charge airblast in clay shale and saturated weak media (optimum spacing between charges):

Five-charge row: $\alpha \approx 1.29$

Seven-charge row: $\alpha \approx 1.64$ to 1.9

Having verified that the Montan technique produces acceptable results for the above row-charge experiments, it is possible to state with confidence that the technique will work for single-charge events as well. Figure B4 shows the SGZ peak vertical spall velocity for experiments in clay shale (these V_0 's apply to both row- and single-charge detonations). The previous discussion of single-charge events (Section II, 1. to 3.) showed that $n = 2.5$ and $\alpha \approx 0.3815$ for clay shale. These values are used to predict single-charge airblast for saturated clay shale and other saturated weak media. Ground-shock-induced airblast is dominant for saturated medium detonations deeper than $\text{dob} \approx 170 \text{ ft/kt}^{1/3}$.

Appendix C

Prediction of Airblast from Intermediate-Depth Contained Detonations

If an explosive detonation is set off deeper than $\text{dob} \approx 250 \text{ to } 300 \text{ ft/kt}^{1/3}$, it will be totally or partially contained. No crater will be formed, although there may be a mound; explosion gases will not vent strongly to the atmosphere. Ground-shock-induced airblast is always dominant for contained and mounding events.

The shock wave from a contained detonation begins to behave in a rather different fashion as it approaches the ground surface. Very little damage is done to the surrounding medium and the wave propagates almost as a perfect (non-dissipative) elastic wave. The radial particle velocity associated with such a wave varies inversely as slant range from shot point, $V_{\text{radial}} \propto 1/S$.

The radial velocity at SGZ is V_0 , which is entirely a vertical velocity (no horizontal component). The radial velocity at any other slant range S on the surface is given by $V_{\text{radial}} = V_0(D/S)$. D = depth of burst. Let θ_v be the angle between the vertical and the radial velocity vector at this point. The vertical velocity component (ignoring shear effects) is then*:

$$V_{\text{vertical}} = V_0 \left(\frac{D}{S} \right) \cos \theta_v = V_0 \left(\frac{D}{S} \right)^2.$$

* This is the vertical velocity associated with the stress wave in the cratering medium. The spall launch velocity of a free surface is proportional to this vertical velocity (actually, twice the vertical velocity). All velocities discussed subsequently in this section are true spall launch velocities, and may be directly used in all predictions.

The velocity law $V = V_0 (D/S)^2$ corresponds to a spall velocity profile of $n = 2$ (see Table 6).† The α value for $n = 2$ is already calculated: $\alpha = 0.5$. Therefore, it is possible to predict far-field overpressures from a contained or mounding detonation at depth D :

$$\text{Predicted } \Delta P = \Delta P_0 \alpha \frac{D}{R} = \Delta P_0 (0.5) \left(\frac{D}{R} \right)$$

$$\Delta P_0 = V_0^2 \rho_c M \frac{P_{\text{ambient}}}{P_{\text{STP}}}$$

$$P_{\text{STP}} = 1013 \text{ mbar.}$$

In order to use the prediction equations, it is necessary to know V_0 . Figures 3 and 4 do not give the correct V_0 's for contained detonations. Instead, a rather poorly established empirical equation based on previous contained experiments must be used. The following is such an equation currently in use:

$$V_0 = 1.24 \times 10^6 \left(\frac{D}{W^{1/3}} \right)^{-1.713}$$

$$\text{for } 1500 > \frac{D}{W^{1/3}} > 250 \text{ ft/kt}^{1/3} \text{ (Ref. 26)}$$

where:

D = Depth of burst (in ft)

W = Nominal yield of explosion
(in kt)

V_0 (in ft/sec).

† Note that shear effects in the cratering medium may increase the vertical velocities appreciably at large horizontal ranges from SGZ for very deep contained detonations. Thus, n could become somewhat smaller than 2 in these cases, causing α to become greater than 0.5. These effects are normally unimportant for mounding or contained detonations at intermediate depths.

Calculate V_0 from the above equation. Use this value of V_0 to determine ΔP_0 . From ΔP_0 , predict the true overpressure at any desired range R :

$$\Delta P = \Delta P_0 (0.5) \left(\frac{D}{R} \right).$$

This method is used for all detonations* with $1500 > \text{dob} > 250$ to $300 \text{ ft/kt}^{1/3}$. The rest of the procedure is the same as Section III.

It should be noted that the velocity profiles for $n = 2.0$ are much broader than profiles for $n \geq 3.0$. The range of mound motion is considerably larger. Therefore, predicted far-field overpressures, ΔP , do not apply at close ranges. The above prediction technique is approximately valid only for $(R/D) > 2.0$. At dimensionless ranges, R/D , less than 2.0, one is still inside the range of appreciable mound motion. For this vicinity, ΔP_0 gives a safesided estimate of the peak overpressure. The local overpressure,

$$\Delta P_{\text{local}} = (\rho c)_{\text{STP}} V_{\text{local}} M \frac{P_{\text{ambient}}}{P_{\text{STP}}},$$

may provide an even better estimate of the overpressure inside the mound.[†] However, an acoustic phenomenon known as crossfeed, caused by variations in the pressure between various parts of the shock front, sometimes produces overpressure reinforcement inside the mound

* Except those in water and water-covered media; see Appendix E.

[†] $V_{\text{local}} = V_0(D/S)^2$; see previous page. Also, in this equation, the Mach number, M , of the shock, is a function of the local velocity ratio, V_{local}/c .

radius. This effect is particularly serious for a broad shock region ($n = 2$ as above), and cannot be predicted exactly.^{26,30} To summarize the results,

$$\Delta P = \Delta P_0 (0.5) \left(\frac{D}{R} \right) \text{ for } \left(\frac{R}{D} \right) > 2.0.$$

$$\text{Peak overpressure} \leq \Delta P_0 \text{ for } \left(\frac{R}{D} \right) < 2.0.$$

The above prediction method is most accurate for relatively small-scale events. The physical picture of an acoustic simple source and a combined peak overpressure pulse from the entire mound breaks down when the linear dimensions of the shock front become extremely large. Thus, Montan's theory of far-field and elevated overpressures is no longer valid. If the range of appreciable mound motion, R ($R/D \approx 2$) becomes large relative to the wavelength of the emitted pressure pulses, then the time lag between various pressure peak arrivals and interference between pulses from various parts of the mound become extremely important. In cases of this sort, the simple source analysis may overpredict far-field and elevated overpressures (because it includes no allowance for time lag or destructive interference from negative overpressure excursions). The wavelength for deeply buried experiments is typically $\approx 800 \text{ ft/kt}^{1/3}$. Therefore, if the range of appreciable surface motion far exceeds $800 \text{ ft/kt}^{1/3}$, problems may arise. This situation occurs for contained detonations at great scaled depths. Airblast predictions and elevated airblast predictions for deep contained detonations are discussed in Refs. 30 and 31.

Appendix D

Acoustic Simple Sources³²

This appendix summarizes the acoustic theory for a simple source of sound radiating an overpressure pulse into a sphere or hemisphere.

Suppose that a sphere of radius a is expanding or contracting. The radial velocity of its surface is everywhere $V(\tau)$. Air will move away from or toward the sphere's moving surface symmetrically in three dimensions. The induced rate of flow of air at time τ is:

$$4\pi a^2 V(\tau).$$

The pressure increase p (overpressure) radiated from the sphere is then given by Newton's equation:

$$\rho \left(\frac{\partial V_{\text{radial}}}{\partial \tau} \right) = - \left(\frac{\partial p}{\partial R} \right).$$

Let p be an arbitrary outgoing overpressure wave of the form:

$$p = P_s (R - c\tau)/R,$$

where P_s is the pressure at the sphere's surface. For R at the surface of the sphere ($R = a$), Newton's equation requires:

$$\frac{1}{R} \frac{\partial P_s}{\partial R} - \frac{P_s}{R^2} = - \frac{\rho}{4\pi a^2} \frac{\partial [4\pi a^2 V(\tau)]}{\partial \tau}.$$

If the vibrating sphere is small ($a \ll$ the wavelength of radiated sound, " a " sufficiently small so that the sphere acts as a point source radiator of energy), it is called a simple source. In this case, $P_s/R \gg dP_s/dR$ at $R = a$. Thus,

$$P_s \approx \frac{\rho}{4\pi} \frac{d[4\pi a^2 V(\tau)]}{d\tau} \text{ at } R = a.$$

The pressure wave at some arbitrary distance R from the center of the simple source at time t is then:

$$P_s \text{ (at } t) \approx \frac{\rho}{4\pi R} \frac{d[4\pi a^2 V(\tau)]}{d\tau} \text{ (assuming } R^{-1.0} \text{ attenuation),}$$

$$\text{where } t = \tau + \frac{R}{c},$$

in which c = sonic velocity of sound wave traveling to range R .

The function $4\pi a^2 V$ gives an instantaneous measure of the total flow of air away from the center of the source at time τ . This pressure pulse will reach range R at a time $t = \tau + R/c$ later. Thus, in the far-field ($R \gg$ source size " a "), pressure will depend on the normal acceleration of the active surface producing the pressure pulse at a time $\tau = t - R/c$ earlier. A steady outward flow velocity [$V(\tau) = \text{constant}$] produces no sound. Only a change in flow can be heard.

Next, modify the above treatment to account for the pressure at range R due to a small moving surface area dA , which has normal velocity function $V(\tau)$. In this case, the area can be thought of as a small square piston moving upward rather than an expanding sphere. The pressure pulse is assumed to propagate into a hemisphere, rather than a sphere. Pressure at R is given by:

$$P_s \approx \frac{\rho}{2\pi R} \frac{dV(\tau)}{d\tau} dA.$$

Again, the pressure pulse will reach R at time $t = \tau + R/c$. Pressure depends on the normal acceleration of the surface producing the pulse at a time R/c earlier.

Consider a radiating surface which consists of many small areas, dA . Each area has its own velocity function, $V(\tau)$. Assume that all areas lie in a plane at time τ ; call it the x-y plane. The instantaneous velocity functions $V(\tau)$ are normal to the plane, and the areas radiate into a hemisphere above the plane. Combined total pressure in the far-field ($R \gg$ combined size of all the areas) is then

$$\text{Total } P_s \approx \frac{\rho}{2\pi R} \int_{\text{over all areas}} \frac{dV(\tau)}{d\tau} dA$$

$$\text{Total } P_s \approx \frac{\rho}{2\pi R} \iint \frac{dV(\tau)}{d\tau} dx dy.$$

This equation is valid as long as the simple source criterion holds (linear size of the entire moving surface is small compared to the wavelength of the sound radiated). The derivation of Eq. (4b) follows.

Appendix E

Airblast from Single-Charge Underwater Detonations, Project Tugboat³³

An underwater detonation throws up a spall dome similar to that caused by an underground explosion. The dome surface induces an overpressure pulse analogous to ground-shock-induced airblast, but, in this case, the phenomenon is somewhat more complex. The time history of the spalled surface motion is affected by an underlying low density region of cavitating water. However, the peak early-time surface velocity and peak overpressures can still be determined using Montan's method.

Naval Ordnance Laboratory researchers have performed careful experiments to measure the peak shock front pressure and particle velocity near underwater explosions. For a typical case (TNT), the peak radial particle velocity varies as $(1/S)^{1.13}$ (Ref. 34). This law holds accurately at intermediate ranges, and is reasonably close to the behavior of a perfect elastic wave. It can be used to determine the peak vertical spall velocity component at the water surface. From the considerations of Appendix C, vertical velocity is given by:

$$V = V_0 \left(\frac{D}{S} \right)^{2.13}.$$

Thus, the vertical velocity field has an exponent $n = 2.13$. Using this value for n and solving for β and α (see Table 6 and Ref. 4), it is found that $\beta = 2.907$ and $\alpha = 0.462$. To close approximation, $\alpha = 0.46$ can be used to predict underwater detonations.

One additional quantity is needed for airblast predictions, the peak SGZ vertical velocity. The peak SGZ vertical velocity above an explosion in water and saturated coral^{*} is given by:

$$V_0 \approx 7.92 \times 10^4 \left(\frac{1}{\text{dob}} \right)^{1.13}$$

V_0 = peak SGZ vertical velocity (ft/sec)

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

dob in ft/kt^{1/3}.

This approximation is valid only for events in water plus a thin layer of coral or similar noncompetent saturated media.

Velocities are lower above strong rock media, and higher for detonations in water only. Also, the approximation is not valid at very shallow scaled depths.

Using V_0 ,

$$\Delta P_0 = \frac{P_{\text{ambient}}}{1013 \text{ mbar}} (\rho c)_{\text{STP}} M V_0$$

and

$$\frac{\Delta P}{\Delta P_0} = \alpha \left(\frac{D}{R} \right) = 0.46 \left(\frac{D}{R} \right).$$

These equations are applicable to water-shock-induced airblast from high explosive detonations. Shallow underwater tests also give rise to a dominant plume or gas bubble blowout pulse, analogous to the gas-vent airblast from underground events. However, the gas blowout is

^{*} The peak SGZ vertical spall velocity above detonations in seawater alone (no cratering medium) is $V_0 \approx 15 \times 10^4 (1/\text{dob})^{1.13}$.

rapidly suppressed with increasing depth of burst. Water-shock-induced airblast becomes strongly dominant by a scaled depth of $170 \text{ ft/kt}^{1/3}$. The Montan method can be used to predict peak overpressures from events deeper than $170 \text{ ft/kt}^{1/3}$.

Montan's method was applied to five underwater detonations of the Project Tugboat series.³³ These were all single-charge events at depths greater than $170 \text{ ft/kt}^{1/3}$; the medium was seawater and

saturated coral. Average sonic velocities in coral are almost the same as for seawater; therefore, this medium variation does not greatly affect shock wave propagation. It tends to decrease the airblast slightly below that observed for detonations at the same depth in free water.

There are no measured surface velocities for the Tugboat experiments. The approximate equation $V_0 = 7.92 \times 10^4 (1.0/\text{dob})^{1.13}$ must be used. After obtaining V_0 , ΔP_0 is calculated as usual. The

Table E1. Airblast peak overpressures, Tugboat.

R/D	ΔP (psi)	$\Delta P/\Delta P_0$	R/D	ΔP (psi)	$\Delta P/\Delta P_0$
A. Tugboat Ia, 1 ton; $\Delta P_0 = 4.87$ psi; D = 17.3 ft (see Fig. E1).			110	0.0078	0.00210
23.2	0.098	0.0202	155	0.0056	0.00151
40	0.042	0.0086	190	0.0040 (?)	0.00108
102	0.0155	0.00318	298	0.003	0.00081
132	0.0096	0.00197	340	0.0028	0.000755
198	0.0078	0.00160	384	0.0036	0.000970
234	0.0040	0.00082	D. Tugboat Id, 1 ton; $\Delta P_0 = 2.95$ psi; D = 25.8 ft (see Fig. E2).		
371	0.0032	0.000657	10.0	0.104	0.0352
423	0.0027	0.000555	21.0	0.038	0.0129
479	0.0018	0.000370	62.5	0.0112	0.0038
B. Tugboat Ib, 1 ton; $\Delta P_0 = 4.64$ psi; D = 17.9 ft (see Fig. E1).			94	0.0067	0.00227
17.3	0.127	0.0274	127	0.0042	0.00142
33.8	0.041	0.0088	163	0.0029	0.000984
93.4	0.014	0.00302	255	0.0026	0.000881
130	0.0137	0.00295	E. Tugboat Ie, 10 tons; $\Delta P_0 = 4.11$ psi; D = 42.9 ft (see Fig. E3).		
187	0.0082	0.00177	6.5	0.259	0.0630
230	0.0064	0.00138	65.5	0.0225	0.00547
364	0.0038	0.000819	73.9	0.0185	0.00450
467	0.004 (?)	0.000861	103	0.0128	0.00311
C. Tugboat Ic, 1 ton; $\Delta P_0 = 3.71$ psi; D = 21.7 ft (see Fig. E2).			157	0.0088	0.00214
16.4	0.083	0.0224	178	0.0085	0.00207
29.4	0.040	0.0108	201	0.0041	0.00100
78.5	0.0143	0.00386			

calculated ΔP_0 's and observed overpressures for five Tugboat detonations are summarized in Table E1. The last column lists $\Delta P/\Delta P_0$ for each observed overpressure. These results are plotted in Figs. E1 through E3. The Montan theoretical line for $\alpha = 0.46$ is also shown. In every case, the observed $\Delta P/\Delta P_0$'s lie near the theoretical line at close ranges

Fig. E1. $\Delta P/\Delta P_0$ as a function of R/D for Tugboat underwater detonations Ia and Ib (1 ton each).

Fig. E2. $\Delta P/\Delta P_0$ as a function of R/D for Tugboat underwater detonations Ic and Id (1 ton each).

Fig. E3. $\Delta P/\Delta P_0$ as a function of R/D for Tugboat underwater detonation Ie (10-ton).

($R/D \approx 10$), but fall below it farther out. Obviously, the attenuation rate is somewhat faster than acoustic $R^{-1.0}$. The agreement at close-in ranges is encouraging.

It is concluded that Montan's method safely predicts water-shock-induced air-blast from underwater high explosive detonations using an $\alpha \approx 0.46$. The predictions may be somewhat high at long ranges ($R/D \geq 50$).

Underwater detonations create a very broad velocity field, similar to the ground motion above contained underground explosions ($n \approx 2.13$ as compared to $n \approx 2.0$). Recall that the Montan technique cannot be used very close to a broad velocity field within the range of appreciable surface motion (see Appendix C). Once more, ΔP_0 or ΔP_{local} provides an estimate of the true peak overpressure inside $R/D = 2.0$.

Note that the above method applies only to events in free water overlying a layer of saturated material very similar to free

water. It is not valid for an explosion in a medium of one acoustic impedance (basalt, for example), which pulses an overlying layer of greatly different acoustic impedance (water), which in turn pulses the air. This problem is more complex because the interface between the two

media cannot be treated as a point source.³⁰ Allowance must be made for the nature of pressure signal transmission in the cratering medium and for transmission and refraction at the interface. A new method³⁵ may be used to predict for such events.

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13. ABSTRACT A technique is presented for the prediction of ground-shock-induced airblast overpressures resulting from the subsurface detonation of nuclear and chemical explosives. The technique is based on a theory and physical model, developed by D. N. Montan of the Lawrence Livermore Laboratory, which correlates ground-shock-induced airblast overpressures with the vertical velocity of the rising mound above the detonation point. The derivation of the theory is reviewed in detail and the model's predictions are compared with airblast overpressure values measured during almost a score of large-yield chemical and nuclear detonations. Appendices provide supplementary information on the correlation between vertical surface velocities and induced overpressures, extend the theory to five- and seven-charge row detonations, and apply the theory to contained and mounding detonations and to detonations in a noncompetent saturated medium overlain with water.		

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