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US Army Corps of Engineers

Waterways Experiment
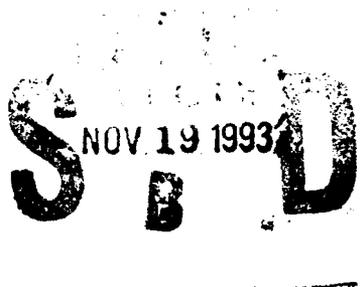Station

Hazards from the Detonation of Buried Explosive Ordnance: Literature Survey

by   John N. Strange, William K. Dornbusch, Allen D. Rooke, Jr.
Science and Technology Corporation

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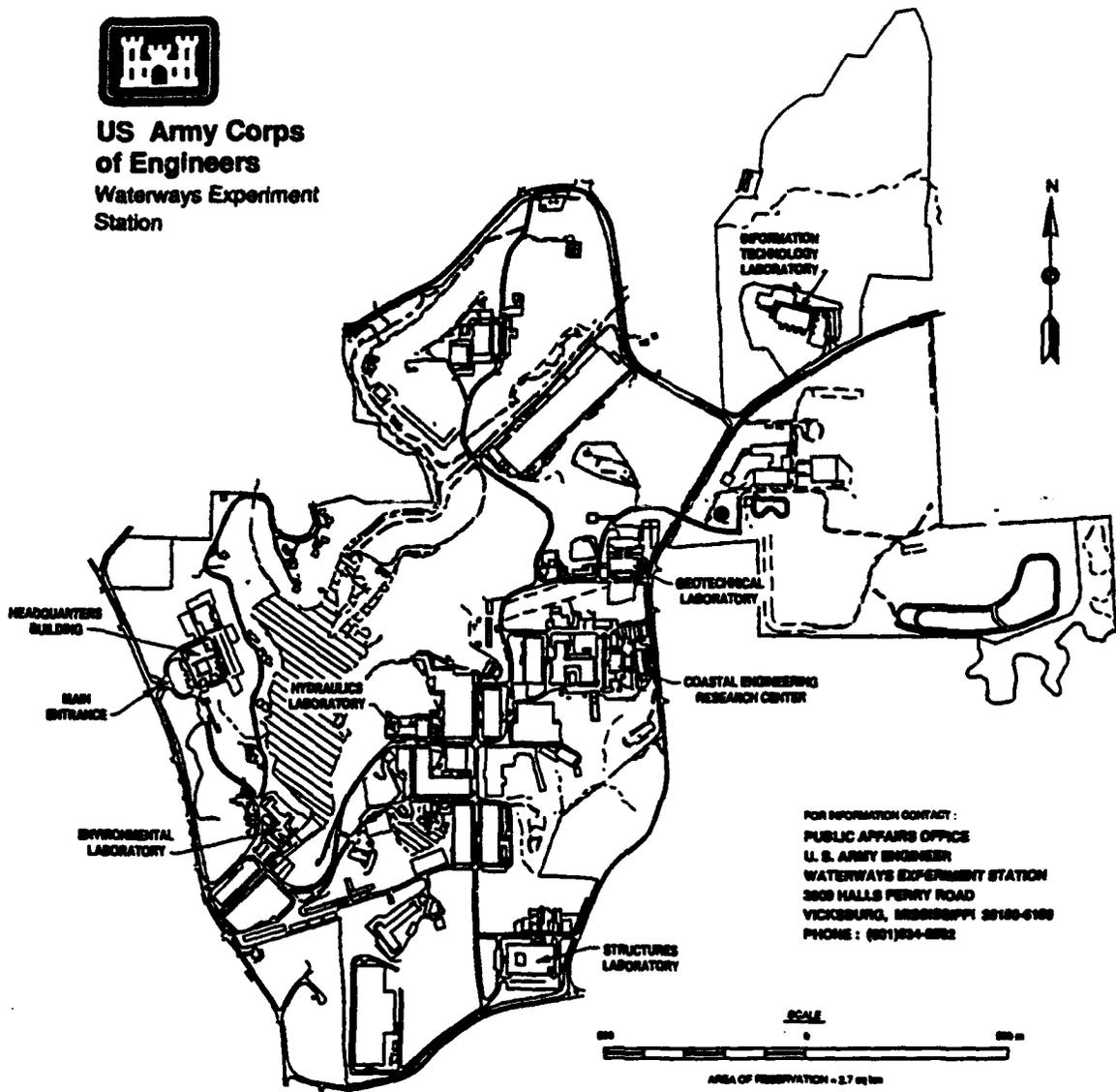P.O. Box 820237
Vicksburg, MS   39182-0237

Final report

US Army Corps of Engineers
Waterways Experiment
Station

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Preface

In July 1992 the Vicksburg, Mississippi, office of Science and Technology Corporation (STC), under contract to the U.S. Army Engineer Waterways Experiment Station (WES), undertook a literature survey to support a research project intended to better define hazards resulting from disposal of buried munitions by detonation. The work was done under Purchase Order No. DACA-39-92-M-5446, with period of performance 8 July through 31 October 1992.

The study was monitored by Mr. Charles E. Joachim, Explosion Effects Division (EED), Structures Laboratory (SL), WES. During this time Mr. Landon K. Davis was Chief, EED; Mr. Bryant Mather was Director, SL.

The literature survey documented in this report was prepared by Messrs. John N. Strange, William K. Dornbusch, and Allen D. Rooke, Jr., all of STC-Vicksburg. Mrs. Frances R. Charles, STC-Vicksburg, prepared the preliminary version of the report, while final preparation was accomplished under the supervision of Ms. Diana McQuestion, STC headquarters in Hampton, VA.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
feet (ft)	0.3048	metres (m)
ft^2	9.290×10^{-2}	m^2
feet per second (ft/sec)	0.3048	m/sec
ft/sec^2	0.3048	m/sec^2
foot-pounds force (ft-lb (f))	1.356818	joules (j)
inches (in.)	25.40	millimetres (mm)
in./sec	25.40	mm/sec
kiltons (kt) (nuclear equiv. of TNT)	4.184×10^{12}	J (nuclear equiv. TNT)
miles	1.609347	kilometres (km)
pounds (force) (lb)	4.448222	newtons (N)
lb/ft^3	1.601846 E + 01	kg/m^3
$lbf/in.^2$ (psi)	6894757×10^3	pascals (Pa)
scaled distance, $ft/lb^{1/3}$	2.399×10^{-3}	$m/J^{1/3}$†
scaled time, millisec/$lb^{1/3}$	7.872×10^{-3}	$msec/J^{1/3}$†
scaled unit (area) impulse, $lb\text{-}msec/in.^2\text{-}lb^{1/3}$	5.427×10^{-5}	$N\text{-}msec/mm^2\text{-}J^{1/3}$†
$ft/lb^{1/3}$	3.967×10^{-1}	$m/kg^{1/3}$††
in./sec	2.54	cm/sec††

* Systeme International d'Unites, published as *Standard Practice for the Use of SI* (E 380-92) by the American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

** Commonly shown in g/cm^3, a measure of <u>mass</u>.

† Conversion of lb or tons TNT equivalent to J is based upon 1080 mean calories/gram heat of detonation (U.S. Army Materiel Command Pamphlet 706-177, January 1971) and upon 453.6 grams (units of <u>mass</u>) = 1 lb (unit of <u>force</u>).

†† Conversions applied to reference data in Part IV.

HAZARDS FROM THE DETONATION OF BURIED EXPLOSIVE ORDNANCE: LITERATURE SURVEY

PART I: INTRODUCTION

Background

1.1   In April 1991 the U.S. Army Engineer Waterways Experiment Station (WES) and the U.S. Naval Surface Warfare Center (NSWC) jointly proposed to the Department of Defense Explosives Safety Board (DDESB) a study of siting requirements for destruction of explosive ordnance by detonation at some predetermined burial depth (dependent upon the quantity and type explosive as well as the local geology) at those Department of Defense (DOD) installations where such a disposal need exists. The proposed study (Appendix A) would examine "Quantity-Distance" (QD) requirements for such detonations, where "Quantity" refers to explosive weight (lbf) and "Distance" is the standoff necessary to reduce all hazards to an acceptable minimum (Assistant Secretary of Defense (Manpower, Installations, and Logistics)). It was assumed that the most serious hazard would usually be that of munition-casing fragments or earth ejecta, but that airblast and ground shock might occasionally govern and must necessarily be considered.

1.2   The thrust of the proposed research was that existing QD standards did not consider the suppressive effects of burial on fragment/ejecta distribution and airblast, and that QD standoff could be significantly reduced and siting requirements simplified by introducing this variation in explosion (shot) geometry. However, quantification of these suppressive effects would be necessary, and would be achieved by development of a predictive model followed by an experimental program to verify and/or finalize the model.

Proposed Literature Survey

1.3   The proposal further specified that development of the predictive model would be preceded by a comprehensive literature survey to "assemble and evaluate all available...information" bearing on the subject, and that this survey should provide a starting point for the model and identify areas where additional research is needed. In May 1992, STC was contracted by WES to perform the literature survey described in the WES/NSWC proposal. This report is the end product of the STC contractual work.

Survey Procedure and Format

1.4   The literature survey is formatted so as to address site geology, ejecta/fragment hazards, and airblast/ground shock in separate parts, citing literature pertaining to each. In selecting reference literature, our approach was toward development of a predictive model, one that is (at least, initially) tabular/graphical in form, from which hazards associated with explosive disposal can readily be identified for given explosion geometries in a given media. We also highlighted areas for which we find no reliable means of prediction.

1.5   In general, the sources that we have pursued are the following:

    a.   The WES Library, which conducted two computer searches for us involving seven databases, including National Technical Information Service and Defense Technical Information Center.

    b.   The EED reference collection, plus loans of references from personal contacts at WES, including the very useful DDESB Explosives Safety Seminar Abstracts (Chemical Propulsion Information Agency), coupled with the DDESB Seminar collection maintained in EED.

    c.   Our own (STC-Vicksburg) office and personal collection of notes and references assembled during our service at WES and the contract work we have subsequently done for WES.

Bibliography for Part I

Assistant Secretary of Defense (Force Management and Personnel); "Ammunition and Explosives Safety Standards," Department of Defense, Army Regulation 385-64, Washington, DC. July 1984.

> This Standard is issued under authority of a Department of Defense (DOD) directive to establish uniform safety standards applicable to ammunition and explosives during their development, manufacturing, testing, transportation, handling, storage, maintenance, demilitarization, and disposal. It applies to all DOD offices, departments, commands, and agencies.

Department of Defense Explosives Safety Board; "Explosives Safety Seminar Abstracts," Chemical Propulsion Information Agency; Johns Hopkins University; Columbia, MD. Nov. 1991.

> A compilation of papers prepared for presentation at the Explosives Safety Seminar (formerly annual, now biannual) covering a broad range of topics of interest in this field. It is indexed to facilitate location by subject matter, and includes a brief description of each paper.

PART II: GEOLOGICAL CONSIDERATIONS

Munition Disposal Site Characteristics

2.1 Site Scenarios

2.1.1. In evaluating munitions disposal sites, three generalized geological scenarios are possible, as discussed below. Definition of a particular scenario will influence the extent of the explosion effects described in Parts III and IV.

2.1.2. The site may contain one or more soils of various textures, densities, and depths. The water table may be apparent (i.e. normal), perched, or artisan, although the latter is usually associated with rock formations. It may, of course, be shallow or deep. A shallow water table is highly significant because it presents a strong reflecting surface to ground shock waves emanating from the explosive source.

2.1.3. The site may consist of shallow soils overlying rock formations. They may be azonal, immature soils having no well-developed profiles, or zonal. In most cases they will be residual, having some characteristics of the underlying rock. Vibrations resulting from the explosion of buried munitions in relatively loose overburden soils (Rayleigh waves) are more intense than in cohesive soils or rocks. Resonant vibrations from explosions in this overburden material could occur in the case of sufficiently prolonged excitation, such as multiple detonations, and would be influenced by the constructive interference of shear (S) waves. The relation of the period of resonant vibration T_r(sec) and soil thickness h (ft) is given by Gupta (1961):

$$T_r = 4 \ h/(2 \ m - 1) \ V_s \qquad (2.1)$$

where V_s = wave velocity in the soil, ft/sec

and   m = a positive integer describing the fundamental frequency and/or multiples thereof.

For the fundamental period m = 1, equation 2.1 becomes

$$T_r = 4 \ h/V_s \qquad\qquad (2.2)$$

Compressional (P) waves create resonant vibrations in a similar fashion (O'Brien, 1957). The destructive effects of such resonant vibrations would depend upon the natural vibrational frequencies of nearby structures.

2.2 Site Characterization.

2.2.1. Unfortunately, physical properties of soils below the surface are difficult to characterize. Soils may exhibit significant vertical changes evident as layers with sharply contrasting elastic properties, or the changes may be gradational, lacking sharply-defined contacts. Horizontally, soils may exhibit facies changes which are also gradational. Thus, soils are rarely a continuous, homogeneous medium. Seismic waves generated by explosions propagate through soils with velocities which represent an average for the media variations they encounter. Without the benefit of detailed soils and geology maps, soil profiles, and borings, there is no way to accurately characterize layering and pertinent, physical properties at specific sites.

2.2.2. There are geologic site parameters which are considered critical to site evaluation. These can be determined from examination of existing literature and data coupled with a limited on-site investigation. These are discussed briefly below:

a. Surface considerations:

(1) Slope. Slope controls, to a degree, surface runoff and thus limits the volume of water which infiltrates the soil.

(2) Drainage. Includes both run-off and downward percolation of rainwater through the underlying formations. Run-off is affected by slope, vegetation, surface roughness, and permeability.

(3) Topographic position. This parameter is related to slope and relief and would control, along with the existing road network, the accessibility of the site.

(4) Soil type. The following soil parameters should be considered:

a. Texture. Generally, fine-textured soils, e.g., clay, silty clays, sandy clays, have higher plasticity indexes than coarse-grained soils and are the most cohesive. The degree of cohesiveness controls the tendency of the soil to remain in large aggregations when ejected from an explosion crater. Also, the presence in the soil of gravel, cobbles, and stones is an important consideration.

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b. Density. Measured in lb/ft³, soil density (or specific weight) affects the size of the resulting crater and thus to a degree determines the distance from the crater that ejecta will be deposited. Density of the in situ material determines the speed of the body waves that propagate through the interior of the cratered medium.

c. Structure. Primary soil structural types are (a) platy, (b) prismatic (c) blocky or polyhedral and (d) spheroidal. Dimensions of these structural types range from 1 mm for very fine platy to greater than 100 mm for very coarse prismatic. Soils may range from structureless or loose to strongly cohesive. Soils may form clods and fragments when ruptured or disturbed or concretions when local concentrations become indurated. Subsurface layers or hard, cemented soils known as hardpans (usually cemented with silica or calcium carbonate), fragipans, and in arid regions, caliche, may occur. All of these hardened soils become cohesive ejecta particles during the cratering process.

d. Moisture content and degree of saturation. Probably the single most important parameter regarding cratering in soil is its moisture content. Soils with high moisture contents will produce larger craters than the same soils with low moisture contents, and will deposit ejecta at greater ranges. Body waves propagate at higher velocities in soils with high moisture contents, at least partly attributable to the replacement of some of the air in the pore spaces with water. Moisture content is a transient phenomenon, the percentage in part related to the time of the last rainfall. Moisture content should not be confused with the degree of saturation; soils with 30 percent moisture contents may be 100 percent saturated.

e. Permeability. Surface soils with high permeabilities become moisture-depleted much sooner than soils with low permeabilities. Completely dry or saturated conditions in surface soils do not persist over extended periods of time except in certain climatic regimes. Generally, the same soils will have an increase in moisture content with depth if permeability remains unchanged.

b. Subsurface considerations: The deeper subsurface conditions are of limited interest here. At some depth(s), ground water and rock will occur; as discussed above, these depths may be determined by on-site investigation or by reference to the available literature.

(1) For the small explosive yields involved here, it is difficult to imagine damaging an aquifer. However, since a common complaint accompanying blasting is that of alleged drops in water levels in wells, this aspect of the disposal operation should be carefully considered.

(2) If rock should exist at a shallow depth, vibrational waveforms produced by explosions may travel considerable distances and cause seismic or shock damage to surface structures or the foundations of surface structures. Subsurface structures include water wells, pipelines, buried utility lines, etc. A pipeline would not be buried in rock, but might lie near a rock stratum, and thus undergo enhanced levels of shock/motion. Buried pipes are quite resistant to any of the shock stresses propagating from an explosion, and especially so it filled with fluid. Pipelines may be severely damaged, however, by large soil displacements in or adjacent to craters formed by munition disposal detonations.

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c.   Meteorological considerations. Meteorological parameters such as rainfall amounts and distributions, surface temperature range, and wind velocities, directions, and durations are mentioned here, since all impact upon surface geological conditions or long-range propagation of blast effects.

Seismic Phenomena

2.3 Underground explosions. This section briefly discusses the propagation of seismic motions, or ground shock, produced by an underground explosion. If more details are desired, the reader is referred to the references provided.

2.4 Waveforms. The seismic wave front is composed of component waveforms conveniently classified as body waves and surface waves.

2.4.1. Body waves. The body wave is the more important of the two types; its propagation is through the body of the medium. Body waves consist of compressional waves and shear waves. The two types are significantly dissimilar in regard to their modes of vibration, velocities, frequencies, and wavelengths.

a.   Compressional waves. These waves are also known as primary (P) or longitudinal waves. Particle vibrations result from alternating expansion and compression in a direction parallel to the direction of propagation. Any elastic solid, liquid, or gaseous medium can transmit a compressional wave. In any soil medium, both compressional and shear waves are transmitted.

b.   Shear waves. These wave forms are also known as transverse or secondary (S) waves, due to their lower velocities and later arrival times. Particle vibration and movement is in a direction perpendicular to the direction of propagation. Shear waves vibrate at slower rates than compressional waves and have longer periods and greater amplitudes. Shear waves do not exist in air or water.

2.4.2. Surface waves. The occurrence of boundaries separating layers of dissimilar elastic properties results in the creation of waveforms other than body waves. By far the most significant such contact in nature is the ground-air interface. Two basic surface waveforms are generated at this interface and at any depth where two contacting layers with dramatically dissimilar elastic properties occur. The fundamental types of surface waves are identified as Rayleigh and Love waves.

a.   Rayleigh waves. This is considered the most important type of surface wave. In Rayleigh waves, particle motion describes an ellipse in the vertical plane, moving backward at its peak; it is said to be elliptical and retrograde. As such, it is similar to a surface wave on water. It may be thought of as a combination of P and S waves.

b.   Love waves. The Love wave is a surface manifestation of the shear wave and has horizontal particle motion only. There are two special types of Love waves: the G wave is a long-period Love wave occurring in the earth's upper mantle, usually

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restricted to an oceanic path, while the L_s wave is a short-period Love wave that travels in long paths in the continental crust only. Neither of these two special waveforms should have relevance here.

2.5 Wave velocities. Here two separate velocities must be considered: (a) the velocities of the body and surface waves, and (b) particle velocities of the individual medium (earth) particles when excited by a passing wave front.

2.5.1. Compressional waves have the highest velocities of all wave types, ranging from several hundred ft/sec in loose over-burden materials to in excess of 20,000 ft/sec in dense rock. Thus, P-waves are the first arrivals, followed by S-waves, which generally have velocities about half to two-thirds those of P-waves.

2.5.2. Velocities for surface waves are similar to those for body waves; however, frequencies are much less. Longer period waves have higher velocities than waves with shorter periods. Maximum velocities for surface waves may be 12,000 ft/sec, although smaller values, e.g. 600-800 ft/sec in some clay soils, are most often encountered. Calculated velocities usually represent an average for the wave form passing through the medium. Velocities of body waves in homogenous media can be calculated from:

$$V_P = \sqrt{\frac{k + 4/3\ \mu}{=\ \rho}} \qquad (2.3)$$

where V_P = velocity of the P-wave
K = bulk modulus of medium
μ = modulus of rigidity of the medium
and ρ = medium density,

and

$$V_S = \sqrt{\frac{\mu}{\rho}} \qquad (2.4)$$

where V_S = velocity of the S-wave.
Unfortunately, the parameters needed are difficult to determine in nature.

2.5.3. Particle velocity, several orders of magnitude less than wave velocity, is the most meaningful measure of ground-shock intensity. It is typically measured in in./sec. Part IV discusses the destructive levels of particle velocity.

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2.6 <u>Wave attenuation, reflection, and refraction</u>. The kinetic energy in the P-wave attenuates rapidly as it travels outward in an ever-enlarging spheroidal wave front. When the front intersects two layers with dissimilar elastic properties, the wave is reflected and refracted and new body waves are generated. Obviously, as the wave front enlarges and continues to encounter discontinuities, the overall wave "picture" can and generally does become exceedingly complex.

<u>References/Bibliographies for Part II</u>

This section contains two parts: (a) references/bibliographies that may help in characterizing the geology of munitions disposal sites, and (b) a listing of references used as background for the discussion of seismic phenomena, with specifically cited references denoted by (*).

a.   <u>Site Geology References</u>:

Soil Survey Staff, Bureau of Plant Industry, Soils, and Agricultural Engineering, <u>Soil Survey Manual</u>, U.S. Department of Agriculture (USDA), Washington, DC. 1951.

<u>Soil Survey County Reports</u>, Listed by states, USDA, Soil Conservation Service (SCS), Washington, D.C.

> Describes the various soil series which occur in the area of study (usually counties). A typical profile is included for each series to maximum depths of 80 in. Profiles include texture, structure, thickness, color, and consistency of each discrete layer. Descriptions of hardpans or fragipan are included if present in the profile. Accompanying tables contain engineering, physical, and chemical parameters of each series. Soil is identified by texture and classified in both USCS and USDA systems. Types of data included in the tables for each series include sieve analysis, liquid limits, plasticity indexes, permeability, available water capacity, flooding periods and duration, depth to perched or apparent water tables, and depth to bedrock.

> Unfortunately, the USDA does not ordinarily prepare survey reports for military reservations. Reports may have been prepared for a period prior to the existence of the reservation or may have been prepared in response to a special request from the DOD. If the reservation has not been mapped, survey reports for counties contiguous to the reservation may permit characterization of site soils by analogy.

<u>Geology and Mineral Resource County Bulletins</u>. Prepared by State Geological or Departments of Natural Resources.

> Typical survey reports include stratigraphic sequences and descriptions, areal geology, lithology, and structural geology. Some reports include sections on ground water resources. These county reports do not include portions of neighboring military reservations. However, bulletin data may be useful in developing general geological site characterizations.

<u>Military Reservation Terrain Analysis Studies</u>. These may be known by a variety of titles and are prepared by numerous governmental agencies, most frequently the Corps of Engineers (CE), e.g., "Terrain Study of Hunter Liggett Military Reservation," prepared by Army Map Service, Corps of Engineers (AMS, CE).

Reports contain maps and descriptions of geology, soil, vegetation, ground water, surface water, surface configuration, climate, lines of communica-tion, cantonment areas and non-urban cultural features. Copies of these reports should be available at the Directorate of Facilities Engineering.

<u>U.S. Geological Survey (USGS) Water Supply Papers</u>. Prepared for various locations and regions of the U.S.

Annotated bibliographies of these papers are published periodically.

<u>State Geological Survey Reports on water supplies for various counties or regions</u>. May be prepared jointly with Ground Division, USGS, who maintains offices in most states.

<u>Universities and Colleges, Departments of Geology, Ground Water, and Hydrogeology</u>.

Varies graduate studies and theses often contain useful geological and ground water information. Also, departments may receive grants for the conduct of specific geology and ground water studies in selected areas.

<u>USGS, Ground Water Division, and State Geological Surveys</u>.

Water well records and logs.

<u>Directorate of Facilities Engineering</u>.

Logs of foundation studies, aggregate pits and quarries, disposal site borings, water supply well logs.

<u>Department of Commerce, Weather Bureau, Washington, D.C.</u>

Local climatological summaries and comparative data.

<u>Defense Mapping Agency (DMA), U.S. military reservation special topographic maps</u>.

Consists of composite of 1:50,000 maps covering military reservations. In addition to the usual topographic, hydrographic, vegetative, and LOC information, these maps delineate cantonment, training, and impact areas as well as locations of numerous military structures, e.g. POL facilities, towers, ammunition bunkers, etc.

<u>U.S. Geologic Survey: Topographic Quadrangles</u>.

Cover most of U.S. at scales of 1:24,000, 1:63,360, and 1:31,180. Usually include military reservations and may complement 1:50,000 DMA map coverage.

Military Reservation Master Plan Reports.

Defines future mission of reservation and optimum utilization of resources. A plethora of useful information that may relate to selected detonation sites. For instance, the location of buried gas pipelines. Directorate of Facilities Engineering. Prepared by various CE agencies and contractors.

U.S. Military Reservations, Environmental Impact Statements.

These may provide general guidance for site selection as well as possible adverse effects on the environment resulting from detonations. Directorate of Facilities Engineering.

USGS, SCS.

General soils maps of counties and special study areas. Scale 1:253,440. Depict general distribution of major soil series associations.

USGS Circulars.

USDA Miscellaneous Publications.

Geological Society of America Bulletins.

USGS Professional Papers.

American Association of Petroleum Geologists.

All of the five publications listed above appear in periodic indexes which are listed by states or geographic regions. The publications, in addition to the libraries of the individual organizations, are available in government agency research libraries. All articles in these publications are devoted to some aspect of geology or natural resources and where available in the general area of a disposal site could provide valuable information. Unfortunately, the time required to borrow the publication or reprints from the various libraries may prove excessive.

b.   Seismic Wave Propagation References:

Bollinger, G. A.; "Blast Vibration Analysis," Southern Illinois University Press, Carbondale and Edwardsville, IL. Feffer and Simons, Inc. London and Amsterdam. 1971.

Coulson, C. A.; "Waves," Oliver and Byrd. 7th Ed. Edinburgh. 1961

EM 110-2-3800; "Systematic Drilling and Blasting for Source Excavations," U.S. Department of the Army, CE, OCE. 1972.

Dowding, C. H.; "Blast Vibration Monitoring and Control," Prentice-Hall International Series in Civil Engineering and Engineering Mechanics; Prentice Hall, Inc. Englewood Cliffs, NJ.

EM 1110-1-1801; "Geological Investigations."

EM 1110-2-1803; "Subsurface Investigations."

Engineering Research Associates, Inc., Armour Research Foundation, Rensselaer Polytechnic Institute, Explosion Test Program, Vol. I Soil; St. Paul, MN, Arlington, VA. 1952.

Grant, F. S. and West, G. F.; "Interpretation Theory of Applied Geophysics," McGraw Hill, New York, NY. 1965.

*Gupta, I. N.; "Resonant Oscillations of the Overburden Excited By Seismic Waves," Earthquake Notes, Vol. 32; pp. 5-11. 1961.

Gupta, I. and Kisslinger; "Radiation of Body Waves from Near-Surface Explosive Sources," Geoph., Vol. 31, No. 6. 1966.

Heiland, C. A.; "Geophysical Exploration," Prentice Hall, New York, NY. 1940.

Imai, T. and Yoshimura; "Elastic Wave Velocity and Mechanical Characteristics of Soft Ground," Soils and Foundations. Vol. 18 No. 1. 1970.

Nettleton, L. L.; "Geophysical Prospecting for Oil," Prentice Hall, New York, NY. 1940.

*O'Brien, P. N. S.; "Multiple Reflected Refractions in a Shallow Layer," Geophysical Prospecting, Vol. 5, pp. 371-380. 1957.

White, J. E. and Sengbush, R. L.; "Velocity Measurements in Near-Surface Formations," Geoph. 1953.

White, J. E. and Sengbush, R. L.; "Shear Waves from Explosive Sources," Geoph. 1963.

West S. S.; "Dependence of Seismic Velocity Upon Depth and Lithology," Geoph. 1950.

Wyllie, M. R., Geogory, A. R. and Gardner, L. W.; "Elastic Wave Velocities in Heterogeneous and Porous Media," Geoph. 1956.

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*Cited in Text.

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Abbreviations Used in Part II

Text

G-wave	long-period Love wave in earth's upper mantle
L_g-wave	short-period Love wave in continental crust
P-wave	primary (compressional) wave
S-wave	secondary (shear) wave

References/Bibliographies

AMS	Army Map Service
CE	U.S. Army Corps of Engineers
DMA	Defense Mapping Agency
DOD	Department of Defense
EM	Engineer Manual
LOC	line(s) of communication
OCE	Office, Chief of Engineers
POL	petroleums, oils, lubricants (U.S. Army Supply System)
SCS	Soil Conservation Service
USCS	Unified Soil Classification System
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

Note: Notations are defined where used in text.

PART III: HAZARDS FROM CRATER-EJECTA
AND MUNITION FRAGMENTS

General Approach

3.1 In assessing ejecta and fragment[1] hazards from the detonation of ordnance, we would prefer to work from a database of past experience. Unfortunately, this is quite limited for the unique problem at hand, so it is necessary to approach the problem indirectly in order to develop a prediction model for safe distances (see Appendix A). The general approach to this part of the literature survey is outlined in the following steps:

a. Conduct a general review of literature on cratering and ejecta distribution from various charges in various geometries and in various soils, with emphasis on the following:

(1) Cratering by exploding munitions, especially buried munitions. Here we find no references that define distribution of discrete ejecta particles, and it becomes necessary to rely on uncased, or "bare" charges from which to obtain this information

(2) Studies of in-flight (dynamic) ejecta, from which to obtain data on natural earth "missile" sizes, trajectories, impact parameters, etc. Here the most complete research has been confined to near-surface explosions, and it is necessary to include surveys of as-found (static) ejecta fields, wherein impact breakage has occurred, to assess the effects of depth of burial (DOB).

b. Select those experiments which best depict, from static-ejecta observations, ejecta size distributions from buried explosions, beginning with cohesive soils (probably a "worst case" for soil ejecta), to include varying soils and DOB's. List the references which best describe and analyze these data, including step-by-step conceptual approaches to construction of the prediction models described in Appendix A.

c. Include the cratering experiments in which data have been obtained on metal fragments mixed with natural ejecta, as in missile launch-cell explosion tests, in order to estimate behavior of secondary fragments ejected during disposal.

d. Obtain and review available literature on fragment hazards from the detonation of single and multiple munitions with varying depths of earth cover, beginning with no cover.

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[1] As used here, "ejecta" means earth material ejected from the explosion crater. The term "fragment" refers to a piece of a munition casing; "primary fragments" are those formed upon detonation of the munition during disposal, and "secondary fragments" are those from previous detonations, as in an impact area, embedded in the soil and also ejected during disposal.

e. Expand (in concept) the prediction models to include variations of soil types, citing whatever references can be found for this purpose. It will be assumed that munitions disposal will not be conducted in dense rock. However, variations that include granular soils, gravelly soils and dry clays, in addition to cohesive soils, may be helpful.

3.2 The literature search accompanying the foregoing approach is simplified by reference to several studies which are in themselves compilations and analyses of a large body of test literature. Full use has been made of these studies, which are referenced herein. Also, in the course of the conceptual model developments, gaps in the desired database are noted.

Cratering by Exploding Munitions

Artillery and Mortar Projectiles

3.3 Field tests involving cratering by artillery and mortar projectiles are contained in numerous reports, two of which deserve special mention here.

a. Joachim and Davis (1983) documents a very comprehensive experiment and analysis on this subject, detailing crater and other data, but not ejecta distribution.

b. Strange and Rooke (1988), which incorporates most of the data of the preceding reference, reviews and analyzes munitions and simulated munitions crater data, mostly near-surface charge geometries, and further calculates actual or inferred ejecta data (but not particle-size distribution). This study arrived at two conclusions that have application.

(1) Volume-wise, there is little difference in craters resulting from cased (munition) or uncased charges. Crater-scaling exponents long in use were re-verified.

(2) Near-surface bare charges loft more ejecta than do near-surface munitions, but this difference becomes less pronounced as DOB increases.

Bomb Craters

3.4 Studies in World War II established crater dimensions for bombs that had penetrated to (or had been deliberately emplaced at) various depths in various soils. These studies were incorporated by Strange, Denzel and McLane (1961) and that work concluded that the resulting crater dimensions conformed to the widely-used cube-root scaling "law", wherein a linear dimension is normalized by $W^{1/3}$, W being charge explosive yield in terms of TNT equivalent, thus permitting comparison of craters from different charge sizes. This very comprehensive analysis also developed nomographs permitting estimates of crater sizes for a wide range of DOB's in a variety of soils.

3.5 More recently, in Joachim and Davis (1983), the cratering potential of modern bombs was assessed, and this time trends distinguishing munitions and bare-charge craters were displayed in normalized form. Neither of the above references addresses ejecta per se, but the findings are useful in that ejecta quantity and distribution can be inferred from crater size.

Use of Bare-Charge Data to Predict Munition Craters

3.6 As explained above, we are forced to rely on bare-charge data to predict ejecta distribution associated with munitions craters. In examining these data, it should be kept in mind that --

a. The real interest, for hazard predictions, is the peripheral area of the ejecta field, where we require:

(1) A critical missile strike density, defined by the Department of Defense Explosives Safety Board (DDESB, from Assistant Secretary of Defense (1984)) as one strike per 600 ft^2 by hazardous missiles, measured in the trajectory-normal plane, and

(2) A definition, by size and impact speed, of what constitutes a hazardous missile, established by DDESB as 58 ft-lb.[2]

b. Insofar as possible, we should rely on pre-impact ("dynamic") ejecta data, such as that obtained by photography, in preference to post-impact ("static") data, obtained by sampling the as-found ejecta field, after ejecta particles have struck the ground, broken up, and bounced and rolled to new locations.

Dynamic-Ejecta Observations

3.7 The landmark study of dynamic ejecta was that which accompanied the MIDDLE GUST (MG) test series in a layered, cohesive soil (Air Force Weapons Laboratory 1980). This series involved near-surface charge geometries only, and is therefore of limited use here; nevertheless, it is possible to draw some important information from it. The study employed photography to track individual natural missiles, correcting for differences in the trajectory planes and the planes of photography, and using computer routines to calculate the various ejecta parameters, including size, velocity, and impact energy.

3.8 Of those parameters measured, the most important may be impact velocity. The considerable body of data presented in the report deserves more careful study than is possible here; it

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[2] We here employ English units of measure, since this predominates in our references. For conversion of English to metric, see the Conversion Table on Page 4.

would seem, however, that small, long-range natural missiles from surface explosions would impact at velocities similar to those of small long-range missiles from buried explosions, both near terminal velocities. Thus, it should be possible to glean impact velocity, v_i, for ejecta near the periphery of the ejecta field from the MG study, verifying it with studies such as Basler (1981) and others to be cited later.

"Allowable" Ejecta-Particle Size

3.9   Once v_i is known, we can solve for impact kinetic energy thusly:

$$E_k = 1/2 \ m \ v_i^2 \qquad (3.1)$$

where E_k = kinetic energy of impact, ft-lb
  and m   = particle mass = $\frac{w_p}{g}$, lb-sec^2/ft
where w_p = particle weight, lb
  and g   = constant of gravitational acceleration, ft/sec^2.

Particle weight, w_p, depends, of course, upon the soil specific weight, ρ_s(lb/ft^3) (in situ or as backfill). If we assume a generally spherically shape, then:

$$w_p = (4/3 \ \pi \ r_p^3) \ \rho_s \qquad (3.2)$$

sphere r_p = particle radius (ft).

If the allowable impact energy, $E_{k \ allow}$ = 58 ft-lb, then w_p will be small, probably on the order of 1/4 to 1/2 lb.

Ejecta Fields from Underground Explosions: Cohesive Soils

3.10   There is a large body of research on underground (buried) explosions, and many of these were accompanied by ejecta studies. Rooke (1976) tabulates most of these up to the time of publication; those occurring later and having application here will be discussed in succeeding paragraphs. Very few ejecta studies, however, completely define distributions by particle sizes, which is a necessary parameter if we are to define the range to DDESB-allowable hazard levels.

3.11 For cohesive soils, a comprehensive study that helps approach the problem is that of the ESSEX Test Program. ESSEX occupies a series of technical reports, but the two that will be most useful here are Dishon (1975 and Strange, et al (1975). ESSEX tested three distinct DOB's in a layered, sandy clay, with various stemming (i.e., charge-emplacement backfill) options -- unstemmed, partially stemmed, fully stemmed, etc. The series contained several innovative experiments, including photography, to define the dynamics of the peripheral ejecta.

3.12 Both of the cited ESSEX references contain multivariate fits of three variables with DOB-dependent exponents. The expression in Strange, et al (1978), page 102, is (in our notation):

$$\delta_m = 10^{C1} R_e^{C2} \, W^{C3} \qquad (3.3)$$

where δ_m = areal density of missiles $\geq$ 1 lb in size
  R_e = ejecta impact range, or distance from ground zero (GZ), ft
  W = charge weight, tons

and C1, C2, C3 are obtained graphically from Figure 6.4, page 111, of the reference. Unfortunately, data-gathering on the project did not discriminate further regarding particle-size distribution.

3.13 For cohesive soils, an ejecta-field study wherein natural missiles resulting from an underground explosion were located by survey and sized comes from a seemingly unlikely experiment: the SPRINT missile event, a test involving the detonation of the high explosive (HE) components (e.g., propellant) of a full-scale SPRINT (air defense) missile in its underground launch cell (Rooke and Chew 1966). Despite the unusual shot geometry, the resulting crater and ejecta field were similar in many ways to those of a four-ton TNT charge at a scaled DOB of ~ 1.0 ft/lb$^{1/3}$. The ejecta study which accompanied this experiment, despite certain limitations (particle sizing was by estimation) and the fact that it is confined to postimpact observations, is nevertheless helpful in describing the distribution of natural ejecta missiles from a buried explosion in an unusually homogeneous, cohesive clay--practically a worst case (excluding rock) from the standpoint of generation of discrete missiles.

Hazardous Particle Range and Areal Density

3.14 As a first step in establishing a relation describing particle weight versus impact distance in cohesive soils, the data describing the "outer" portion of the SPRINT ejecta field, found in Tables 3.4 and 3.5, pp 38-39, and Figure 3.11, p 53 of the reference can be reduced to graphical/equation form for further analysis, using whatever form provides the best data fit. What constitutes "outer" must be

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a judgmental decision; obviously, there must be enough data points spanning a sufficient distance to ensure adequate representation of the peripheral ejecta field. Figure 3.1 illustrates this concept in rectangular-coordinate form.
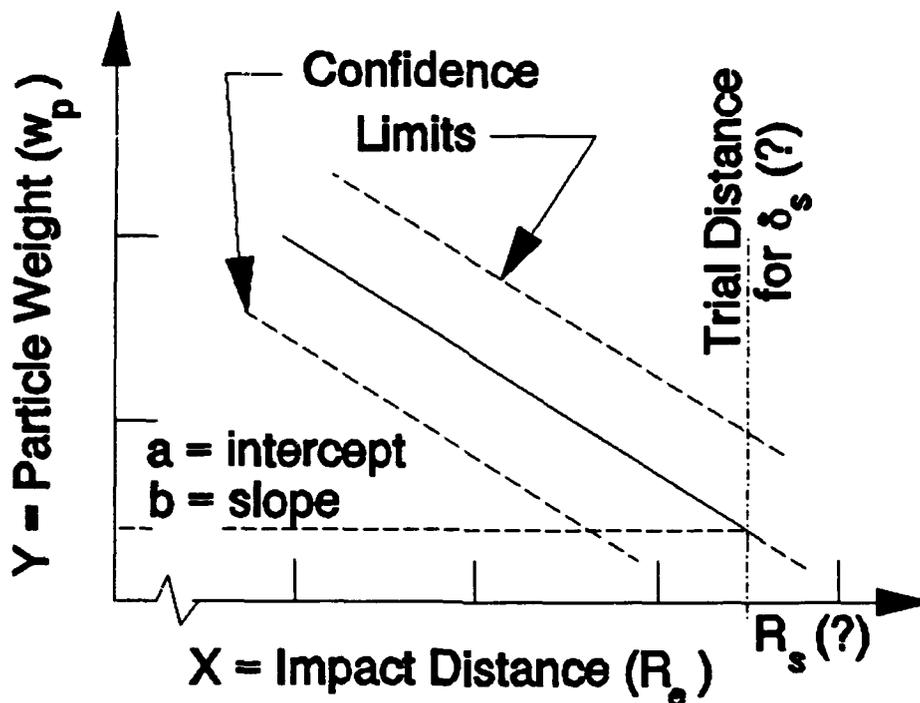
Figure 3.1. Conceptual graph of ejecta particle size versus impact distance, establishing a trail range, $R_s(?)$, for trial safe areal density, $\delta_s(?)$.

3.15 Note that Figure 3.1 introduces a trial "safe" distance, δ_s, at which the critical impact density for an allowable ejecta particle weight, w_p, occurs. Since the SPRINT study did not record ejecta particles judged to be less than 10 lb in weight, the resulting graph will provide conservative estimates of range for w_p. Using this trail range, we need to find the areal density δ_s associated with w_p. It would be possible to solve this problem graphically, constructing an areal density-versus-range graph in a form similar to that of Figure 3.1, using the same source of data discussed in paragraph 3.14. The result would, however, be definitely nonconservative, since the (probably) many particles < 10 lb would not be included. An alternative approach is to solve Equation 3.3, by substituting $R_s(?)$ for R_e. This is still a rough estimate, since we will be solving for missile sizes $\geq$ 1 lb, while we expect w_p < 1 lb. Also we are effectively applying data from one test site to another. Within these recognized shortcomings, however, a reasonable estimate should be obtainable.

The solution will show δ_m at this range to be either less than or greater than the allowable hazardous missile density of 1 strike/600 ft^2, or 1.67×10^3 ft^{-2}. This allowable density can be bracketed by adding or subtracting range as necessary and continuing to solve Equation 3.3. Once a bracket is obtained, δ_a may be found by linear interpolation.

3.16 Before moving to the next step, we will briefly consider a possible modification -- and improvement -- to the SPRINT ejecta data. Rooke (1980), a study of ejecta-hazard predictions on the MGI event, included a comparison of static-versus-dynamic ejecta counts that revealed significant differences between the two in the mid-range of sizes. Such differences had been long suspected, but this study may be the only attempt to quantify such differences. On this test, the number of static ejecta pieces counted was some 40 percent higher (by number) for sizes < 10 lb, than counted as dynamic ejecta by photography, and while completely failing to record the largest particles observed photographically in flight. The largest dynamic size class was three times the weight of the largest static class. If we use Rooke (1980) as a guide (pages 55-61 and 189-194), it may be possible to improve static counts such as SPRINT by decreasing numbers in the midrange and adding size classes in the high range. Any such modification, however, must be based on relative rather than actual size classes (e.g., classes established as fractions of maximum size for each event), since we would be comparing entirely different events. The expected effect would be to steepen the slope of Figure 3.1.

3.17 At this point, the analyst constructing a prediction model has established, at least roughly, the distance from GZ at which an allowable areal density of an allowable ejecta-particle size can be expected for the SPRINT conditions, after borrowing Equation 3.3 from ESSEX. Similar calculations can be made for varying DOB's in this medium, again using Equation 3.3. A conceptualized graph of the result is a Figure 3.2, normalized so as to make it applicable to a range of charge yields. Note that one means of normalization is by apparent crater radius r_a.

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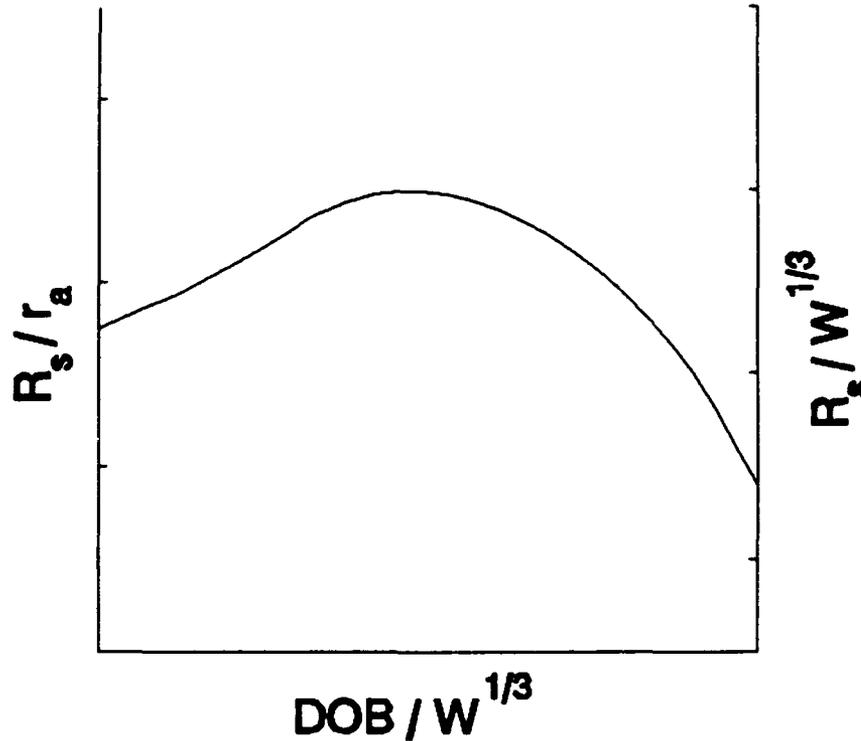
Figure 3.2. Conceptual graph of safe distance for buried charge W in a single medium.

Dry Clay and Shale

3.18 It would be desirable to extend the foregoing to dry clays and perhaps to shale, which are also cohesive. Rooke (1976) lists the documented experiments in these media, which include crater and limited ejecta measurements over a range of charge yields. Air Force Weapons Laboratory (1980) includes dynamic ejecta observations on five such events. The main problem is the lack of particle size-versus-impact range data for buried charges. This vital relation (see Figure 3.1) must be inferred by comparing such parameters as ejecta areal density, total ejecta weight deposited at any distance, and maximum particle size with those of the SPRINT event. Rooke (1976) (pages 29-31)

may be helpful in this regard[3]. To build a predictive model for this condition, judgmental decisions must be made while weighing these data; this is an area in which the proposed experimental program can be very helpful in filling gaps in the data.

Ejecta Fields in Noncohesive Soils

3.19 Noncohesive soils would be expected to present a reduced missile hazard insofar as natural crater-ejecta is concerned. Desert alluvium in its "pure" form should be no hazard at all. However, dry, sandy soils may contain gravel or cobbles, and these inclusions may indeed be hazardous, especially to personnel. An opportunity to evaluate this potential hazard, using an approach much the same as that developed above, is afforded by yet another missile silo study -- the PEACEKEEPER Quantity-Distance Tests (QDT), Jones et al (September 1984) and Jones et al (December 1984). These were large-scale model tests of the PEACEKEEPER launch silo conducted at White Sands Missile Range to evaluate the hazards of an accidental in-cell explosion, similar to the SPRINT study. Test QDT-3 contained a detailed survey of ejecta (from a sand-and-gravel backfill) and silo fragmentation, including dynamic ejecta photography. This excellent study can be exploited to provide a particle size-versus-distance relation for the QDT DOB, for comparison with the SPRINT event. It remains to be seen whether or not this relation will be in the form of Figure 3.1, but appears certain that a useful relation can be obtained from which to estimate allowable particle-size density versus range, and thus an estimate of safe distance R_s as shown in Figure 3.2.

Hazards from In Situ Fragments and Debris

3.20 During disposal, munition-casing fragments or other debris may originate from detonation of a munition or from "secondary" fragments previously deposited in the surrounding soil, as may

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[3] In reviewing this reference, an error was discovered on page 30. The equation for calculation of range wherein a given percentage of total ejecta weight is deposited should read:

$$R_p = \left[\frac{(Ew_p)(m+2)}{2 \pi C_e} - \frac{(r_e)^{m+2}}{m+2} \right]^{1/m+2}$$

Notation is explained in the reference. Note that the constant of integration, "a," has been dropped, and "m" will be negative.

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occur when disposal sites are in an old impact area.[4] These fragments may exit the crater with velocities approximating those of natural ejecta, but experience indicates that they will travel farther than natural ejecta because of better ballistic characteristics. The "experience" is that of the SPRINT and QDT-3 events (Rooke and Chew, 1966; Jones et al, September 1984; and Jones et al, December 1984). Although these silo shots were of unusual geometry, both ejected a mixture of earth and metal particles from decoupled charges in two distinctly different media.

3.21 The SPRINT event ejected about one-third (by weight) of its launch cell, depositing a wide variety of metal shapes and sizes out to a scaled distance of 77.3 ft/lb$^{1/3}$ (39.5 R/r$_a$), exceeding R$_{e \, max}$ by a factor of 1.83. A similar analysis of QDT-3 would be helpful; cursory examination of Jones et al (September 1984) shows that excluding the extreme long-range metal debris that may not be representative of embedded material, scaled R$_{max}$ for metal debris was approximately 71.6 ft/lb$^{1/3}$ (40.9 R/r$_a$), but exceeded earth ejecta R$_{e \, max}$ by a factor of only 1.24. At this point, we will assume that the difference lies in the backfill media of the two events. Note that use of apparent crater radii for scaling provides a very close and probably more reliable comparison. Further analysis should be made of the data on this very important and well-documented experiment. In particular, ejecta and metal debris densities and impact kinetic energies should be examined (Jones et al, September 1984, documents impact velocities). Combining data from the two events may permit an estimate of a safe distance for this hazard and answer the question as to whether or not metal debris is likely to extend R$_a$ beyond the range of natural ejecta. In any event, the SPRINT and QDT-3 experiences will provide only current evidence of the secondary fragment/debris hazard.

<u>Hazards from Primary Fragmentation</u>

3.22 Casing fragments originating from a detonation of one or more munitions constitute the third hazard considered here. When such detonations occur in the open, as at ground surface, they have high initial velocities and extensive ranges, typically 2,000 to 3,000 ft. DDESB-acceptable safety standards are the same here as discussed earlier: E$_k$ $\geq$ 58 ft-lb defines a hazardous fragment, for which δ_a $\leq$ 1.67 $\times$ 10^{-3} ft^{-2}.

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[4] Foreign material from many sources may be in the disposal site soil, some of which may warrant special consideration. Concrete particles, for instance, have been ejected to long distances in silo tests (Jones et al, September 1984).

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3.23 To better understand the origin and properties of fragments, let us briefly consider a single munition detonating in the open, at ground surface. Technical Manual 5-855-1 (1986) (pages 6-1 through 6-11) describes fragment origin. Recently a considerable amount of work has been done, largely through computer programs, to quantify fragment properties, trajectories, and distributions, and this has been reported in succinct form in DDESB seminars; Jones (1967) and Ahlers (1969) are recommended in this regard. The latter reference also addresses multiple munitions.

3.24 A natural assumption might be that fragmentation from more than a single munition of a given type would result in increased areal density of fragments, δ_f, in multiplicative fashion, without increase in range. This is largely true, except that only exposed munitions effectively contribute to the fragment field in any particular direction (i.e., munitions masked by other munitions contribute little or nothing). Also, it has been shown that munitions "stack" configurations may result in interaction zones wherein fragment velocity and density are both enhanced (Feinstein and Nagaoka, 1970).

3.25 Finally, from the standpoint of detonations in the open, a very recent study (Swisdak) undertakes to reconcile existing data and testing techniques to the DDESB requirement for a "trajectory-normal" interpretation of the area for which the 1 strike/600 ft² safety standard is set. This interpretation visualizes an area at the terminus of the trajectory rotated so as to be at right angles to the trajectory, rather than in the ground plane. To accomplish this, the study proposes a procedure by which sampling-sector densities are calculated as equal to the number of fragments at a given range in a given sampling sector plus all fragments found beyond that range. The assumption behind this procedure appears to be that all effective fragments will have a relatively flat trajectory. While this procedure is open to question, for our purposes, as long as we are dealing with the outer limits of the fragment field, it appears acceptable.

3.26 Swisdak presents normalized graphs which illustrate this concept for four different single-round munitions. Ranges corresponding to acceptable fragment density can be readily calculated using these graphs and Table 1; a conservative answer will result. We are, however, left with the problem of extending our answer to multiple munitions. This can be accomplished, at least approximately, with McClesky (1984), wherein increases in fragment hazard distances are calculated as a function of the number of projectiles contributing to the fragment field; this is attributable to increases in δ_f for fragments equal to or greater than the hazardous size.

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Effect of Earth Cover On Fragment Distance/Density

3.27 The foregoing discussion leads to the crux of the problem: the suppressive effects of earth cover on primary munitions fragments. To assist us we have the igloo models of Fugelso and Rathmann (1973) and a single Australian field experiment (Goold, 1990) dealing with maximum "throw distances" only.

3.28 Fugelso and Rathmann (1973) propose three computer models of an accidental explosion in a storage igloo containing M117 750-lb bombs, and select a model (No. 3) that essentially ignores the thin earth cover. We agree with this selection for the igloo problem and its very large charge of stored munitions, but we feel that Model No. 2, which considers interac..n n between earth clods and fragments, is more suited to the disposal problem. Figure 7 in the above reference (page 1159 in the proceedings) compares Model 2 with the unconfined case for a single munition, indicating that areal density δ_f will never be more than 10^{-3} ft^{-2}. We assume that, in this case, $\delta_f \sim$ the density of hazardous fragments, since the model is concerned chiefly with those fragments that reach the outer limits of the fragment field, and for this reason confines itself to fragments whose weight is greater than the mean.

3.29 The model of Fugelso and Rathmann (1973) can be helpful, even though the data generated will be ultra-conservative for this problem. Graphs similar to Figure 7 are badly needed for other munitions, such as artillery shells; hopefully, such graphs can be obtained in the course of the analysis that follows this literature survey. We would like to compare these graphs with those of Swisdak, and perhaps adapt the accompanying equation on page 5 of the same reference to our use for a closed-form solution for safe range from hazardous fragments for a single, buried munition R_{s1}. But to do this we need more information on the construction of the equation.

3.30 Assuming that R_{s1} can be satisfactorily determined, McCleskey (1984) can estimate the increase in R_{s1} due to the detonation of more than one warhead. The appropriate number of warheads to consider depends on the manner in which the weapons are stacked for disposal; only those not masked by other munitions need be considered, but this may be judgmental. In the illustration of Figure 3 in Appendix A, for example, the appropriate number should be six. The model given in McCleskey (1984) arrives at a hazardous-distance multiplier to be applied to R_{s1} to obtain hazardous range R_h for the number of munitions being detonated. In the example given in Table 3 of the reference (page 1069 of the proceedings), the multiplier corresponding to the 90th percentile, as specified by DDESB, would be 5.33, obtained by interpolation. This multiplier is based upon a

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prediction of fragment impacts in the ground plane, and may require modification to meet DDESB standards. Here again, more details are needed for different types of warheads.

3.31 The above approach probably gives an overly conservative estimate of fragment density for a buried munition, since the igloo and its earth cover in the model represent a relatively thin covering. Even considering the strength of the igloo arch, it seems unlikely that the effective scaled DOB exceeds 0.1 ft/$W^{1/3}$. In the disposal process, DOB's more on the order of 0.5 to 1.0 ft/$W^{1/3}$ are expected, or even deeper. The proposed experimentation should be designed to bridge the gap between the igloo model and disposal DOB. For now, it seems pointless to attempt to refine the rough estimate of the igloo model by applying the trends toward increased or decreased densities or ranges as observed in the "open-stack" data discussed in paragraphs 3.24 and 3.25 above.

3.32 We know of only a single field test involving disposal of buried munitions -- one conducted by the Australian Army (Goold, 1990). It consisted of 14 trails in which antitank mines were detonated in augered holes and trenches at three different DOB's. The explosive weights involved and the scaled DOB's were quite similar to those envisioned for this problem. A number of parameters were measured, including maximum "fragment" range, $R_{f\,max}$, or throw distance (fragments were represented by 37-mm projectiles taped to the charges). Fragment density was not measured, however.

3.33 While the data are limited, the test served to demonstrate a rather dramatic effect of earth cover on $R_{f\,max}$. An oft-quoted "rule-of-thumb" is that $R_{f\,max}$ for fragments from a cased munition detonated in the open is given by

$$R_{f\,max} \sim 600 \; W^{1/3} \qquad\qquad (3.4)$$

Where R_{max} is in ft and W is in lb TNT equivalent (Richmond and Fletcher, 1971)[5]. Based on this "rule," the maximum observed fragment range (at the shallowest DOB) was 15 percent of the calculated safe distance (3.4). For both hole- and trench-geometries, throw distances at DOB = 1.13 ft/lb$^{1/3}$ were only about 30 percent of those at DOB = 0.56 ft/lb$^{1/3}$. And it is interesting to note that the augered hole enjoyed an average suppressive advantage over the trench that increased with

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[5] The rule-of-thumb actually addresses safe distance from fragments, but as it is presented it is synonymous with $R_{f\,max}$.

increasing DOB. The investigators had some difficulty identifying natural ejecta, but thought that $R_{e\,max}$ had exceeded $R_{f\,max}$.

Combining Ejecta and Fragment Deposition Parameters

3.34 Obviously, the total problem here is that of crater ejecta plus munitions fragments, the latter originating either from the soil matrix, (as in an old impact area, or from the residual fragments (from previous tests) in the soil) or from the munitions undergoing disposal. From one or more of numerous cratering references (say, Strange, Denzel and McLane, 1961; Rooke, 1976; Strange et al, 1978; and Rooke, Carnes, and Davis, 1974), we can obtain satisfactory estimates of crater size for a number of media and, with less accuracy, ejecta deposition distances and densities. Relying mainly on experiments in clay, it appears possible to construct a general predictive model along the lines of Rooke (1980; see page 195).

3.35 What is the effect of foreign inclusions, such as old fragments, in the soil? The experiences of SPRINT and QDT-3 indicate that secondary fragments will exceed $R_{e\,max}$ in range, but further experimentation and analysis are needed to determine whether or not the areal density is such as to increase the hazard distance R_h. It seems doubtful that this would be the case, but if it is, how could such a prediction be made? Clearly, this is possible only if there is previous experience at the disposal site or if some sort of soil sampling is done.

3.36 Lastly, will primary fragmentation extend R_h? This may well be the most difficult part of the problem, since it is so dependent upon the disposal shot geometry, i.e., type, number and orientation of warheads, DOB, type and condition of backfill, and method of initiation. The igloo model of Fugelso and Rathmann (1973), which we have already recognized as overly conservative, indicates that, at ranges common to the outer portion of one of our typical disposal-shot ejecta fields, we can expect single-warhead fragment densities δ_f below a value that could possibly be hazardous. Multiple warheads, however, may bring about the condition $\delta_f \leq 1.67 \times 10^{-3}$ ft^{-2}, and make it necessary that we ask ourselves whether or not this poses a hazard under the DDESB standards. The model of Swisdak can probably answer this question (again conservatively), given proper input from the proposed experiment.

3.37 While we are not yet ready to make any meaningful estimates of the hazards involved here, the overall impression gained from review of the references cited is that hazardous distances are rather small. Earth-ejecta hazards will probably not exceed 300 to 400 ft for explosive weights and

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burial depths addressed in Appendix A, i.e. up to 100 kg and at depths of burial $= 1.0 \text{ W}^{1/3}$. Throw distances for secondary fragments and other debris will be greater than this, but it is unlikely that hazardous densities will occur at these greater ranges. As to primary fragments, hazardous distances again appear to be on the order of 400 ft, so either ejecta or fragmentation could govern safe distance, depending upon details of shot geometry.

3.38 As a final observation on this phase of the literature survey, we note that the DDESB definitions of hazards are definitely nonconservative both from the standpoint of allowable impact energy and strike density. It seems likely that severe injuries will be incurred at energy levels well under 58 ft-lb, while allowable strike density suggests casualties approaching 1 percent. The point has been made in some of the referenced literature. We suggest that, in addition to observing safe distances, some protective precautions for personnel would be in order. In this regard, portable frontal and overhead shelters or even the protection provided by vehicles would make the disposal operation much safer.

Bibliography for Part III

Ahlers, E. B.; "Fragment Behavior Discussions for Storage of Ammunition and Explosives," Paper presented at Eleventh Explosives Safety Seminar, IIT Research Institute, Chicago, IL. Sep. 1969.

> Results of a parametric study of fragment trajectories are discussed in this paper. It was demonstrated that maximum terminal distances for high-speed fragments from surface detonations corresponded to an initial trajectory angle of about 20 degrees from the horizontal. Maximum trajectory heights for low-angle, high-speed fragments occurred at about 65-75 percent of terminal distance. Correlations are shown between maximum fragment distance and equivalent weight of explosives for a large number of explosions.

Air Force Weapons Laboratory, "Dynamic Ejecta Measurements for Selected Middle Gust and Pace Cratering Events," AFWL-TR-79-214; Air Force Systems Command; Kirtland Air Force Base, NM. Mar. 1980.

> This is the premier study of crater-ejecta photography. It reports a very carefully planned and executed experiment in which discrete ejecta from near-surface bursts in clay and coral are captured on film as they emerge from the explosion cloud and are tracked throughout their trajectories. In a detailed analysis that corrects for differences in trajectory and photography planes, the important ejecta parameters are calculated, tabulated, and displayed graphically.

Assistant Secretary of Defense (Force Management and Personnel); "Ammunition and Explosives Safety Standards;" Department of Defense, Army Regulation 385-64, Washington DC. July 1984.

> This Standard is issued under authority of a Department of Defense (DOD) directive to establish uniform safety standards applicable to ammunition and explosives during their development, manufacturing, testing, transportation, handling, storage, maintenance, demilitarization, and disposal. It applies to all DOD offices, departments, commands, and agencies.

Basler, Ernst; "Effects of Debris and Fragments on Protected and Unprotected Persons;" First Results of a Literature Review; TM ttt.2-67a/TM 364-21. Ernst Basler and Partner; Zurich, Switzerland. Sept. 1981.

> This is a literature review on the stated subject, gathering and presenting excerpts from a wide variety of sources. The text is in German, and needs translation in order to make full use of the study. However, many of the figures and tables are in English, and can be used in their present form. The study is important to any complete consideration of the effects of explosion-generated fragments and debris.

Department of the Army; "Protective Design, Fundamentals of Protective Design (Non-nuclear)" TM 5-855-1; Headquarters, Department of the Army. Nov. 1986.

> A U.S. Army Technical Manual devoted to assembly and correlation of the mass of data that became available during World War II on the destructive effects of a wide variety of weapons and, conversely, the structural design requirements for protection against them. Thus it can be

used for both attack and defense. It contains in both tabular and graphical forms the essential characteristics of weapons, explosives, projectiles, gases an ' incendiaries and their terminal effects on structures and fortifications.

Dishon, John F.; "Essex-Diamond Ore Research Program: "Ejecta Measurements Report, Essex I, Phase 2,: TR SL-79-9; U.S. Army Engineer Waterways Experiment Station; Vicksburg, MS. Oct. 1979.

This is one of two volumes documenting a major research effort sponsored by Defense Nuclear Agency and entitled "Effects of Subsurface Explosions (ESSEX)," intended to better define the effects of low-yield nuclear weapons in a wet, layered clay. Large chemical (high-explosive) charges were used as the energy source. All major explosion effects were measured and reported. This volume describes a portion of the crater-ejecta study.

Feinstein, D. I. and Nagaoka, H. H.; "Fragment Hazards from Munition Stacks," Paper presented at Twelfth Explosives Safety Seminar; Aug. 1970.

An investigation of fragment hazards from multiple munitions in open stores. The objective of the study was to estimate fragment hazards as functions of type and quantity of munitions, configuration of the store, and location of detonation origin. A series of small- and full-scale tests on a variety of stack configurations was conducted to develop an analytical model for simulation of a munition stack.

Fugelso, L. E. and Rathmann, C. E.; "Effect of Earth Cover on Far-Field Fragment Distributions," Paper presented at Fifteenth Explosives Safety Seminar; Aug. 1973.

The effect of earth cover on the far-field fragment distribution from the accidental detonation of igloo-stored munitions was estimated by preparing three models of fragment-cover interaction. A model was chosen which best represented the igloo, but a second model best represents the munitions-disposal problem. Numbers of munitions effectively contributing fragments are examined, as are effects of altered mass distribution and fragment shape and behavior on quantity-distance relations.

Goold, J. J.; Australian Ordnance Council, Canberra, "Safety Distances for the Underground Demolition of Explosive Ordnance," Paper presented at the Twenty-Fourth Explosives Safety Seminar, Aug. 1990.

This paper describes the development of the Australian Department of Defense safety criteria for underground demolition of explosive ordnance. Safe distances from all overt explosion effects were developed by literature searches and field trials. Regarding fragmentation effects, maximum throw distance was the governing criterion.

Joachim, Charles E. and Davis, Landon K.; "Munitions/Bare Charge Equivalence (MBCE) in Soil," TR SL-83-5. U.S. Army Engineer Waterways Experiment Station; Vicksburg, MS. Sep. 1983.

Documentation of what may well be the most comprehensive field experiment ever conducted regarding blast and shock characteristics of exploding munitions, including artillery and mortar

projectiles and bombs, mostly in near-surface geometries. The test was conducted in three phases at three separate test sites. Measurements obtained were crater profiles, soil stress, ground motion and surface overpressures. Analysis included recommendations for bare-charge simulation of munitions.

Jones, D. H.; "The Properties and Performance of Fragments," Paper was presented at Ninth Explosives Safety Seminar; Naval Weapons Lab, Dahlgren, VA. Aug. 1967.

The calculation of fragment trajectories as performed at the Naval Weapons Laboratory, Dahlgren, Virginia is discussed in this paper. This computation has been performed to determine minimum safe release attitudes for low-altitude dive bombing such that the delivery aircraft is not endangered by fragments projected from a delivered weapon. Data needed for the calculation of trajectories and how the data are derived are presented. Fragment motion during flight, drag coefficient, reciprocal ballistic coefficient, initial velocity, elevation angle, equations of motion, and trajectory variation are the trajectory data described.

Jones, Patricia S., et al.; "Peacekeeper Quantity-Distance Verification Program; Quantity-Distance Tests (QDT), Main Text and Appendices A Through F," TR SL-84-15; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Sep. 1984.

The Peacekeeper ballistic missile was designed for launch from a Minuteman (ballistic missile) silo, and three model tests were devised to assess damage from an accidental in-silo, and three model tests were devised to assess damage from an accidental in-silo explosion of high-explosive components. These tests were known as (explosive) Quantity-Distance (from explosion) tests (QDT), and were numbered QDT-1 through -3. This report details the fabrication and emplacement of the models, the test plan, and results. Of particular interest here is the ejecta/debris study of the QDT-3 crater and its associated field of backfill ejecta (to include artificial inclusions) and silo debris.

Jones, Patricia S., et al.; "Peacekeeper Quantity-Distance Verification Program; Quantity-Distance Test (QDT), Appendix G," TR SL-84-15; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Dec. 1984.

Although published separately, this reference merely supplements the previous reference, containing detailed tabulations of crater-ejecta/debris locations and descriptions.

McCleskey, F. R.; "Fragmentation Hazard Computer Model," Paper presented at the Twenty-First Explosives Safety Seminar; Aug. 1984.

This paper presents a computer model for establishing the fragment hazard produced by the mass-detonation of ammunition stacks stored in the open. The model uses fragmentation characteristics from small-scale arena tests as input and calculates the trajectory for each fragment recovered. It calculates the incremental increase in hazard distance resulting from increases in the number of munitions detonating and thus increasing fragment areal densities.

Richmond, D. R. and Fletcher, E. R.; "Blast Criteria for Personnel in Relation to Quantity-Distance," Paper was presented at the Thirteenth Explosives Safety Seminar, Armed Services Explosives Safety Board, Washington, DC. 1971.

A paper that discusses safety considerations for protection of personnel from the effects of explosions. Effects considered were airblast, blast displacement of the individual, casing fragments and debris, crater ejecta, and explosion heat. Safe distances were developed for all such effects.

Rooke, Jr., Allen D.; "Graphic Portrayal of Discrete Explosion-Produced Crater-Ejecta Characteristics," MP N-76-7; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. June 1976.

This reference is intended to be a compendium of crater-ejecta experiments and analyses. It employs graphical approaches to provide approximate solutions to a number of practical problems regarding ejecta characteristics and deposition parameters, especially discrete ejecta. It also lays the groundwork for definition of strike probabilities — and thus hazards — posed by ejecta particles, based upon the Poisson probability distribution.

Rooke, Jr., Allen D.; "Crater-Ejecta Hazard Predictions in Cohesive Soils: The Middle Gust I Event," Thesis submitted to Mississippi State University, Mississippi State, MS. Aug. 1980.

This thesis has as its purpose the calculation of ejecta strike hazards for the MIDDLE GUST I (MGI) explosion event in layered clay/shale. In order to achieve this, another explosion test (ESSEX 6 MPS) was examined to establish ejecta size-weight relations. Using the inferred particle weights and the "as-found" (static) MGI ejecta distribution, comparisons were made with ejecta photographic analysis, and modifications were made to the static distribution. A predictive model for ejecta distribution by size class was developed and translated into an automated model, and graphs of strike probabilities by size class were presented, scaled upward into the low-yield nuclear regime.

Rooke, Jr., A. D., Carnes, B. L., and Davis, L. K.; "Cratering by Explosions: A Compendium and an Analysis," TR N-74-1; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Jan. 1974.

This report is intended to extend and update "Cratering from High Explosive Charges: Analysis of Crater Data," referenced separately. As such, it considers only charges of one lb or more, but includes nuclear events. It contains tables of cratering events in virtually all media, automated plots of crater parameters, and composite graphs for comparison.

Rooke, Jr., A. D. and Chew, T. D.; "Crater and Ejecta Measurements for a Full-Scale Missile Detonation in an Underground Cell," MP 1-853, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Nov. 1966.

This reference documents measurements of the crater and ejecta field resulting from a full-scale detonation of the high-explosive (HE) components of an air-defense SPRINT missile in its launch cell, the purpose being to assess the total damage from such an accident. Since the HE components included propellant whose TNT equivalence had not been established, this study approached the question of charge yield through the size of the crater. Despite the unusual shot geometry, the crater was similar to that of a four-ton TNT charge at a depth of burial approaching optimum. The ejecta field was characterized by discrete clay particles mixed with metal components of the cell. Insofar as was feasible, locations and estimated clod sizes were recorded.

Strange, J. N., Denzel, SP-4 C. W., and McLane, III, SP-4; "Cratering from High Explosive Charges: Analysis of Crater Data," TR 2-547, Report 2; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. June 1961.

This is a classic study of cratering phenomenology. It builds a data base of over 1700 HE shots ranging in yield from less than 1 to 320,000 lb in virtually all conceivable media. The accompanying analysis includes scaling factors and nomographs generalizing crater dimensions for a broad spectrum of soil/rock conditions, and also includes discussion of major factors contributing to crater size and shape.

Strange, John N. and Rooke, Jr., Allen D.; "Battlefield Dust from Exploding Munitions: Contribution by Cratering from Artillery and Mortar Projectiles," Final Report; TR EL-88-16; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Nov. 1988.

This study assembled a data base of over 550 explosion tests of artillery and mortar projectiles, mostly near-surface, and bare charges intended to simulate these projectiles. Analysis of the data base re-verified scaling procedures long in use. Determination of crater "shape factors" permitted volume computations and thus estimates of crater-ejecta and dust. Simulation of munitions by bare charges was analyzed regarding ejecta/dust production.

Strange, John N., et al.; "ESSEX-Diamond Ore Research Program, Summary Report of the ESSEX Program, Vol. I: Phenomenology and Effects," TR N-78-5; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Dec. 1978.

This is one of two volumes reviewing and summarizing the major research effort sponsored by Defense Nuclear Agency and entitled, "Effects of Subsurface Explosions" (ESSEX); it was intended to better define (by use of high-explosive charges) the effects of low-yield nuclear weapons as they might be employed in a wet, layered clay. All phenomenology experiments, including crater-ejecta measurements, are summarized in this volume.

Swisdak, Jr., Michael M.; "Procedures for the Analysis of the Debris Produced by Explosion Events," Abstract. Department of Defense Explosives Safety Board.

This paper describes and recommends a procedure for collection of munition casing fragments from planned tests and debris from accidents, and accompanying analytical procedures. For fragments, an experimental procedure is described which gives results approaching computer simulation of the "trajectory-normal" requirement by Department of Defense Explosives Safety Board for definition of allowable areal density of hazardous fragments.

Abbreviations Used in Part III

DDESB	Department of Defense Explosions Safety Board
DOB	Depth of burial
ESSEX	Effects of Subsurface Explosions
GZ	Ground Zero
HE	High Explosive
MG, MGI	MIDDLE GUST, Event I
QDT, QDT-3	Quantity-Distance Test, Test No. 3
SPRINT	SPRINT Air-defense missile

Notations Used in Part III

C1, C2, C3	Constants (used as exponents) in Equation 3.3
E_k, $E_{k\ allow}$	Kinetic energy, "allowable" kinetic energy
g	Constant of gravitational acceleration ~ 32.2 ft/sec^2
m	Mass
R_{max}	Maximum range
R_e, $R_{e\ max}$	Ejecta range, maximum ejecta range
R_f	Fragment range
R_h	Hazardous range
R_s, $R_s(?)$, R_{s1}	Safe range, trial safe range, safe range for one munition
r_a	Apparent crater radius
v_i	Initial velocity
W	Charge weight
W_e	Weight of ejecta
w_p	Ejecta particle weight
δ_e, δ_f, δ_h, δ_m	Areal densities of ejecta, fragments, hazardous fragments, missiles ≥ 1 lb, respectively
δ_s, $\delta_s(?)$	Safe areal density, trail safe density
π	pi, ~ 3.142
ρ_s	Soil specific weight

PART IV: AIRBLAST, NOISE AND GROUND SHOCK

Airblast and Noise

4.1 Introduction

4.1.1. For several centuries, explosion effects on man and man-made structures have been observed and/or studied, especially in conjunction with mining, quarrying, and construction projects. The studies were done with varying degrees of sophistication as far as instrumentation and gaging techniques were concerned. Since the advent of nuclear and thermonuclear weapons, much research has been done to document and assess the phenomenology and effects of these weapons. The urgency to define these effects brought about a major improvement in gaging techniques and the instrumentation needed in order to record transient phenomena.

4.1.2. During the decades of the 50's and 60's, airblast instrumentation channels were at a premium; thus gages were most often sampling overpressure levels in the range of a few pounds per square inch (psi) up to 50 psi. In subsequent decades, particularly from 1975 on, more sophisticated gaging and instrumentation techniques were available, along with a marked increase in the number of channels. Concurrently, emphasis on higher overpressure levels ( ) 100 psi) developed because of a necessity to define the force-loading signatures and critical standoff distances for threshold failure levels for various defensive installations, e.g., missile silos.

4.1.3. With all the emphasis on the high overpressure end of the spectrum, there is comparatively little data in the fractional psi range from any source. The Bureau of Mines and the blasting manuals of Corps of Engineers do contain data in the fractional psi range, but the major portion of their data are derived from blasting operations involving multiple charges and sequenced time delays in order to maximize the volume of earth disassociated and at the same time to control airblast and throw-out. In subsequent research by various groups, where a single energy source was involved, many of the long-range measurements (where pressures in the fractional psi levels prevail) were reported to be either anomalous or inconsistent. In some cases, either the data were of poor quality (gages overstressed, instrumentation noise masking the desired signal, etc.) or anomalies were caused at various ranges from the explosion's epicenter (GZ) by wave refraction due to variations in the sound velocities as a function of altitude in the near-surface atmosphere.

4.1.4. Airblast from underground explosions involving energy yields in the range of a few hundred pounds of explosives is affected mainly by the depth of burial (degree of confinement), the charge weight (equivalent weight in pounds of TNT), the type explosive, and to varying degrees, the medium in which the explosion occurs. Temperature/density variations in the near-surface atmosphere may be naturally structured at any given time so as to cause refraction of the airblast wave, thus causing anomalously high (caustics) or low overpressures at a given range from GZ. Refraction effects can markedly alter overpressure levels at intermediate and far-out ranges, especially where large explosions are involved and blast effects reach the altitudes where gradual or marked changes (inversions) in temperature can affect sonic velocity. For the study of interest herein, where explosion yields are on the order of a few hundred pounds, the atmospheric effects are thought to be relatively small, especially where their is no severe temperature/density gradient with altitude. Some refraction will occur, but it should not produce severe caustics in the ranges of interest (likely less than 1/2 mile), especially if the sonic velocities decrease with an increase in altitude above ground and especially if the charges are buried.

4.1.5. While there are in existence highly complex computer codes to predict the airblast levels for a variety of input conditions, their complexity and cost to run make them impractical for addressing the variety of munition disposal conditions of concern. The development of graphic solutions (empirical models), based on an acceptable data base, should be more appropriate for this problem area.

4.1.6. Using this philosophy, we have compiled a list of references that are particularly suited to the development of graphic predictive methods for inferring airblast overpressure on the order of 10^2 psi on the low side. Since the main emphasis is to determine ranges (distances from GZ) at which the overpressure levels will be low enough so as not to cause damage to structures (especially windows) or damage to exposed personnel, the low pressure levels are emphasized; these will occur generally at scaled distances (λ, ft/lb$^{1/3}$) greater than 100 for charges buried at scaled depths $\lambda_c \sim -0.5$ ft/lb$^{1/3}$ (the minus sign denotes below ground; it does not infer a negative 0.5).

4.1.7. Among all the reports and papers examined, including the Safety Standards of Army Regulation 385-64, those referred to in the text that follows have the potential of providing more reliable and more direct input to the problem at hand, and will permit reasonable intervals of extrapolation that may be necessary, in some cases, to define the domain of the low pressure levels of interest.

4.2 Weather Effects on Airblast and Noise

4.2.1. While weather effects on airblast (as well as noise) levels are expected to be relatively small, they must be considered for the explosion yields of interest to this study. Therefore, it seems appropriate to discuss and illustrate the problem, especially should explosion yields be upgraded to levels significantly greater than a few hundred pounds. Experience has shown that the number of complaints from operations involving the use of explosives is directly related to the sudden and often frightening noise, as opposed to actual overpressure levels or actual vibrations coupled into the ground by the explosion. Experience has also shown that noise level, as well as airblast, at a given point is not dependent on distance alone, but rather on sound/blast caustics produced by wave refraction. Weather conditions are the main cause of sound/overpressure intensification at a given location; weather conditions determine the velocity of sound in different directions and at different altitudes. The principal variables that influence sound velocity are wind velocity and direction and air temperature (density) quantities as a function of altitude. Altitudes greater than a thousand feet or so would usually not be significant in determining severe refraction problems when explosion yields are less than several hundred pounds and when the charges are detonated at respectable depths of burial $(\lambda_c \geq -0.5)$.

4.2.2. The manner in which wave refraction develops due to sound velocity variation with altitude is schematically illustrated in Figure 4.1.
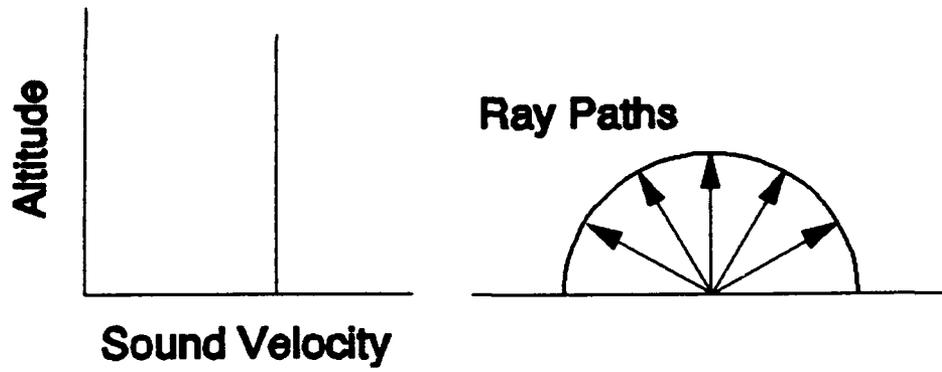
a. Isothermal condition (sound velocity does not change with altitude).
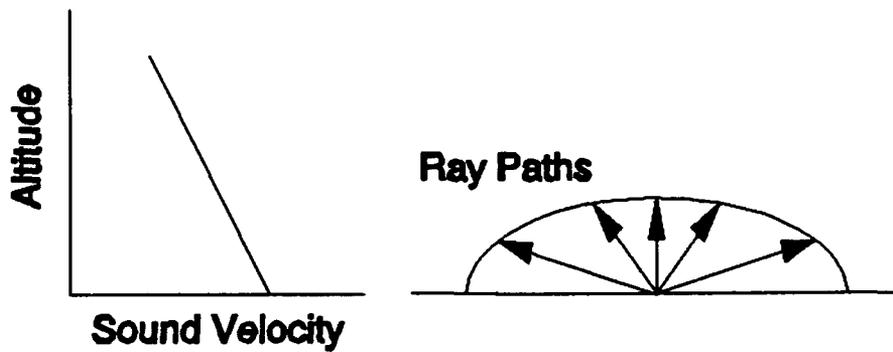
b. Negative thermal gradient (sound velocity decreases with increased altitude).
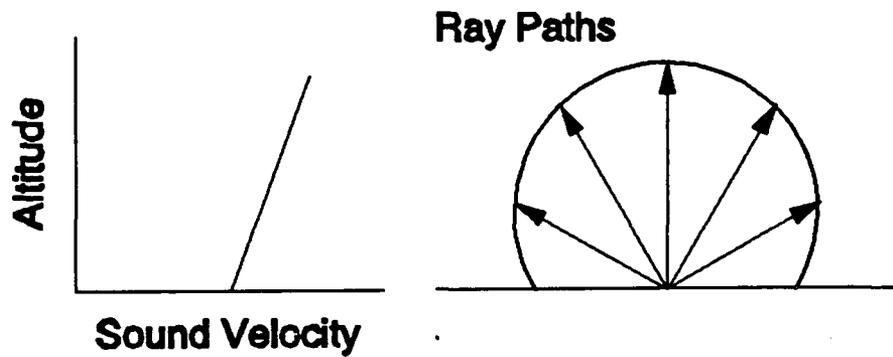
c. Positive thermal gradient (sound velocity increases with increase in altitude).

Figure 4.1. Frontal ray paths associated with sonic velocity change with altitude.

More complex structures within the lower atmosphere, as when the sound velocity decreases with altitude, then increases, then decreases again, are conductive to the formation of caustics, as illustrated in Figure 4.2.

Figure 4.2. Complex alternation of frotal ray paths due to multiple sonic velocity trends.

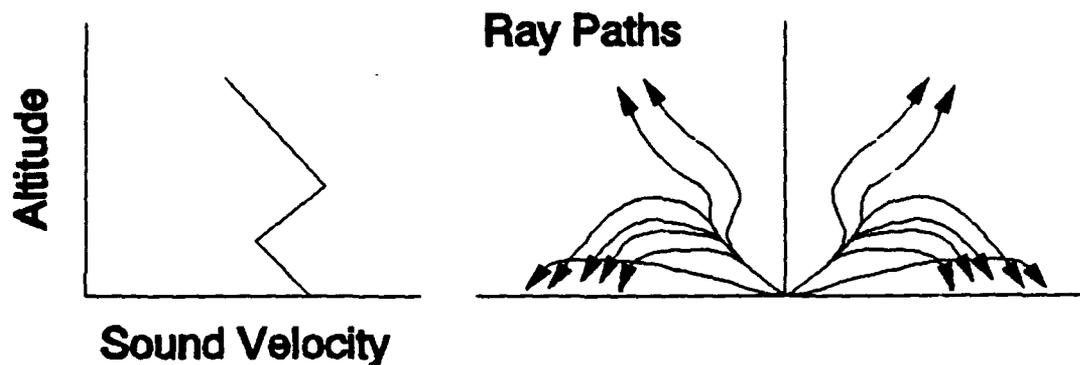4.2.3. Reasonably strong wind patterns, where the wind velocity increases or decreases with an increase in altitude, can also significantly alter wave frontal rays, producing caustics on the downwind side and lesser noise and blast levels on the upwind side. Perkins and Jackson (1964) and Dowding provide a detailed discussion of the effects of weather on the prediction of noise abatement and intensification due to temperature (density) changes with altitude in the lower atmosphere. Their presentation is similar to that illustrated in the preceding sketches.

4.2.4. In any case, when explosions are planned, it is essential that weather conditions be considered in an effort to avoid noise/blast caustics. This is best accomplished by selecting a time when sonic velocity decreases with altitude (preferable) and avoiding times when there is a decrease/increase/decrease structure in the lower atmosphere. A favorable atmospheric structure is most likely to exist in the afternoon hours and when cloud cover and wind are minimal.

4.3 Noise and Its Relation to Overpressure

4.3.1. Public objections to operations involving explosions are generally related directly to the noise levels generated, especially since the noise may be rather intense and may occur unexpectedly. Complaints against such operations may be due to suspected structural damage, according to the rule: "If the house shakes to the point that movement is perceptible, damage has occurred." The threshold of the structural damage by airblast is almost universally tied to window

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breakage. For explosions that are buried at depths such that $\lambda_c > 1$, ground motions from the coupled energy can produce structural damage, especially where structural components such as foundations already exhibit cracks or other evidence of incipient failure. Specific problems associated with ground motion are discussed in Section 4.6.

4.3.2. The Engineer Technical Letter 1110-1-142 (1989) defines noise levels as a function of peak overpressure in graphic form (their Figure 15, p. 40). The graphic presentation is described by the equation:

$$db = 20 \ Log \ P + 170 \qquad (4.1)$$

where db is the noise level in decibels and P is the overpressure in psi.

Obviously, the equation is restricted such that P must be positive (P > 0).

4.3.3. The threshold for ear pain occurs at about 140 db (0.03 psi). Ordinary street traffic registers ~90 db (1×10^{-4} psi), whereas 50 db (3.2×10^{-7} psi) describes the background noise level in the average home. With this scale, zero is the threshold of being able to detect sound.

4.4 Blast Effects -- Phenomenology

4.4.1. In the report by Perkins and Jackson (1964, previously referred to in paragraph 4.2.3, their Figure A3 presents the suppression of airblast peak overpressure by various charge depths of burial, including estimates of peak overpressure in the far-out region. In this figure, it appears that decay rates determined from observations in the domain $\lambda < 50$ were simply extrapolated to the far-out region without any change. The curves are presented for scaled depths of burst (λ_c) of 0, -0.5, -1, and -1.5. Overpressures that are read directly from these curves would doubtlessly form a lower bound for expected values since, in reality, the absolute value of the decay rates decreases with increased values of λ. This would give a decay rate of approximately -1 at $\lambda \sim 1000$, while these curves have slopes ranging from -1.1 to -1.5 for $\lambda_c = -1.5$ and 0, respectively. The scatter about these curves could be expected to be $\pm$ 75 percent of the value of P, as read from the curves.

4.4.2. Joachim (1964) presents both measured and calculated peak overpressures (P) as a function of reduced distance (λ, ft/lb$^{1/3}$). Joachim's computed curve was obtained from:

$$P = \frac{7}{6} \; P_o \left[\left(\frac{u}{c} \right)^2 - 1 \right] \qquad\qquad (4.2)$$

where P is the peak airblast overpressure (psi), P_o is the atmospheric pressure (psi), u is the shock velocity (ft/sec), and c is the velocity of sound in air (ft/sec) at the prevailing temperature. In the computations, the value of c was determined from:

$$c = 49.1 \; (T + 459.6)^{1/2} \qquad\qquad (4.3)$$

Where T is the air temperature in degrees Fahrenheit.

4.4.3. Joachim's computed curve shows excellent agreement with experimental data obtained from 32-, 256-, 2,230-, and 5,000-lb charges that were fired at the surface of the Greenland Ice Cap (a crusted ice/snow surface). Many similar experiments, where surface bursts were fired over various types of soils, have shown consistently that the over-pressure ranges from about 7.8 to 10 psi at λ = 10. Joachim's average curve, presented in Figure 4.3, indicates a well-defined pressure-distance relation between $4 < \lambda < 40$. Extrapolation of this trend to $\lambda = 100$ and 1,000 gives overpressures of about 0.25 psi and 0.02 psi, respectively. Over this domain, the overpressure varies inversely as the scaled distance (λ) to the -1.2 power, or:

$$P \; \alpha \; \frac{k}{(\lambda)^{1.2}} \qquad\qquad (4.4)$$

where k = a constant. It is recognized that extrapolation over these far-out ranges is uncertain and speculative; however, relatively few measurements have been found for λ)70, hence the necessity to resort to extrapolation.

4.4.4. Jackson (1975) reports the airblast and impulse produced by a hypothetical 10-ton surface-tangent burst. These results (averaged) are shown in Figure 4.4. Jackson also links the BRL close-in airblast measurements with the far-out measurements made by Sandia Laboratories; this comparison is shown in Figure 4.5. From Strange, et al (1978), the average true crater radius for the 10-ton surface-tangent burst was 82 ft (~ 25 m); thus, most of the BRL gages were placed at ranges less than one true crater radius. It is likely that these gages measured the shock front of the vented gases and were thrown vertically by the expanding dome and plume. A linear falloff in pressure

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begins at a range equivalent to one true crater radius. At this point (λ = 3.25, referring to Figure 4.5), the peak overpressure level is less than 10 psi even for ESSEX 6MU (6-m unstemmed event -- an 8-ton TNT-equivalent nitromethane charge 6 m below ground with the access hole left open).

4.4.5. While the data presented by Sauer and Stubbs (1977) considers only surface-tangent spheres (spheres resting on the ground surface) as the explosive source, their work does provide definitive airblast and impulse data for this particular shot geometry as derived from an impressive data base. Figures 1 and 2 of their report (pp 12 and 13) define peak overpressure versus distance and impulse versus overpressure for large-scale explosions. The authors calculated that 380 tons of high explosive was the airblast equivalent of a one kiloton nuclear detonation; thus it is possible to transpose the peak over-pressure-versus-distance curve to a scaled-distance curve by dividing the abscissa scale by 91.3, which is the cube root (in lb) of 380 tons, TNT equivalent. Figure 4.6 shows this transposed curve. Similarly, Figure 4.7 shows the transposed impulse curve (Sauer and Stubbs, 1977; impulse values were divided by 91.3), making the ordinate scale have dimensions of (lb-msec)/(in.^{2}lb$^{1/3}$).
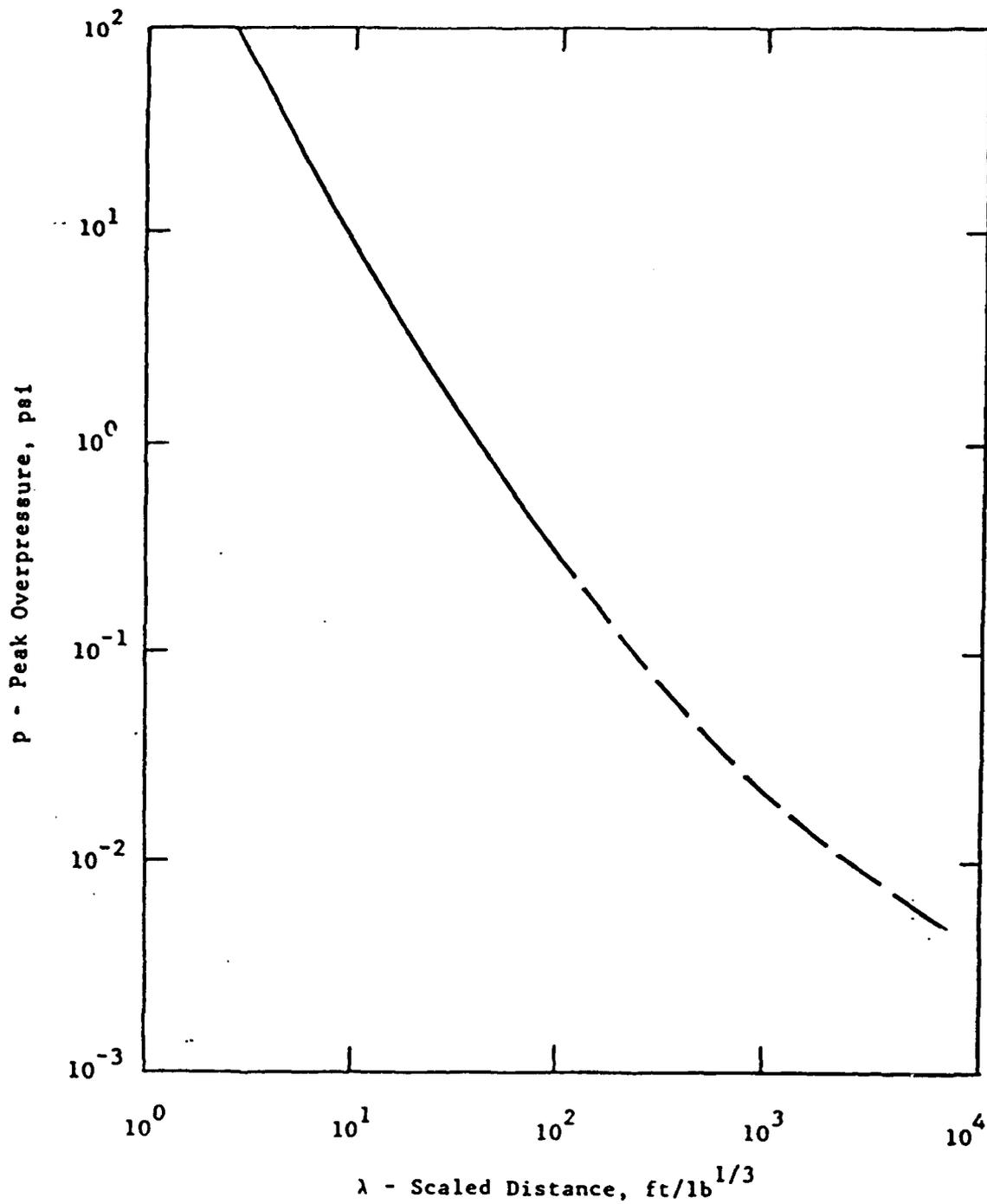
Figure 4.3 Peak overpressure versus scaled distance from bursts at or very near the surface. Curve presented is an average curve as adapted from Joachim (1964).
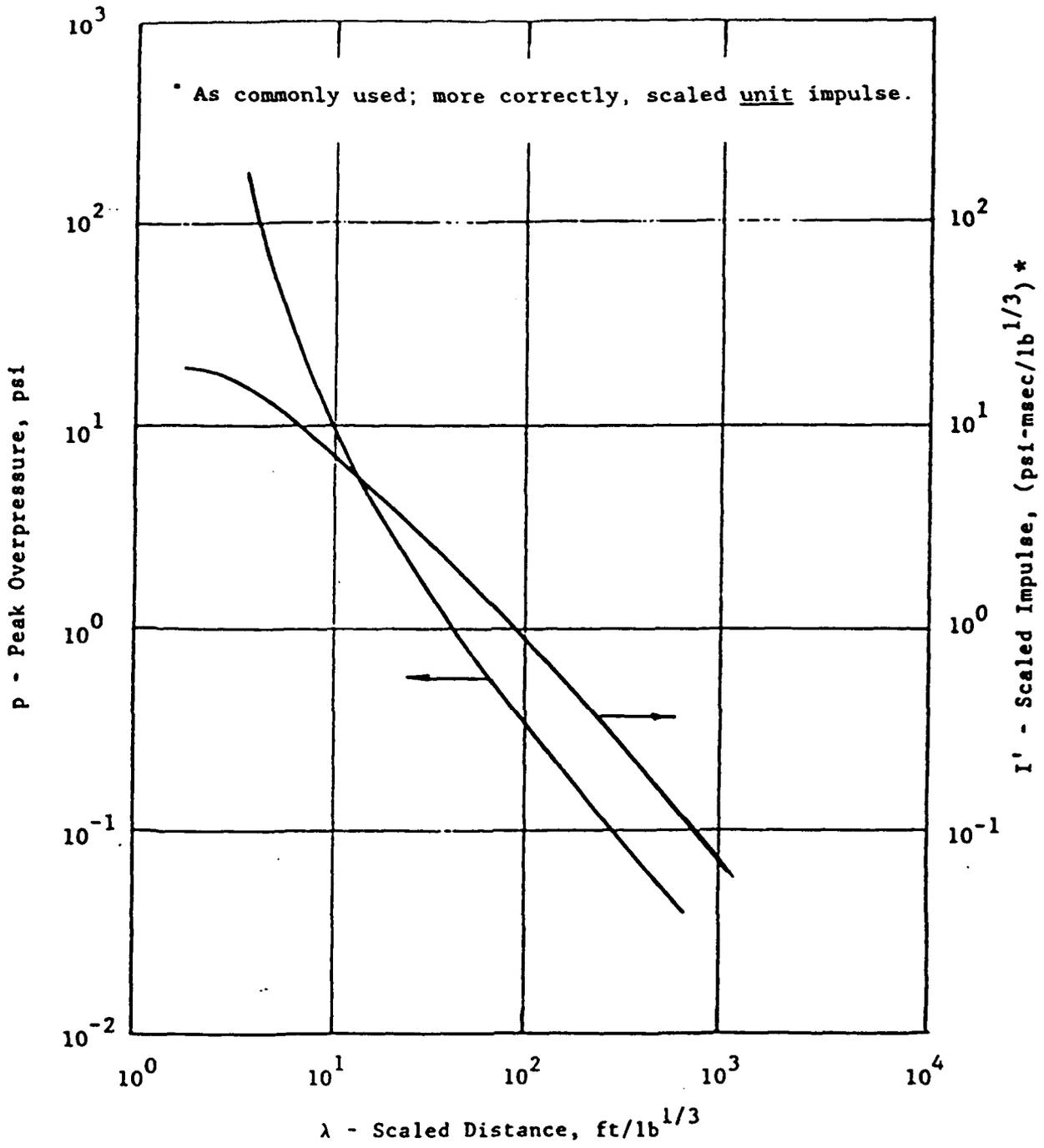
Figure 4.4   Peak overpressure and scaled impulse as a function of scaled
             distance from surface and surface-tangent bursts
             (averaged) from Jackson, (1975).

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Figure 4.5 Peak overpressure versus scaled distance showing close-in and far-out measurements; ESSEX Program Phase I.

Figure 4.6 Peak overpressure versus scaled distance from surface bursts (adapted from Sauer and Stubbs, 1977).

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Figure 4.7 Variation of scaled impulse with peak overpressure from surface
bursts (adapted from Sauer and Stubbs, 1977).

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4.4.6. The combination of these two transposed curves permits the calculation of peak overpressure and impulse for various charge weights for surface-tangent spherical charges. The curves for the pure surface burst (a sphere half-buried) would likely fall within the scatter band of the surface-tangent results.

4.4.7. As a further aid, we note that Figure 7-1 (p 7-3) of Engineer Manual 1110-2-3800 (1972) could serve as a basis for develo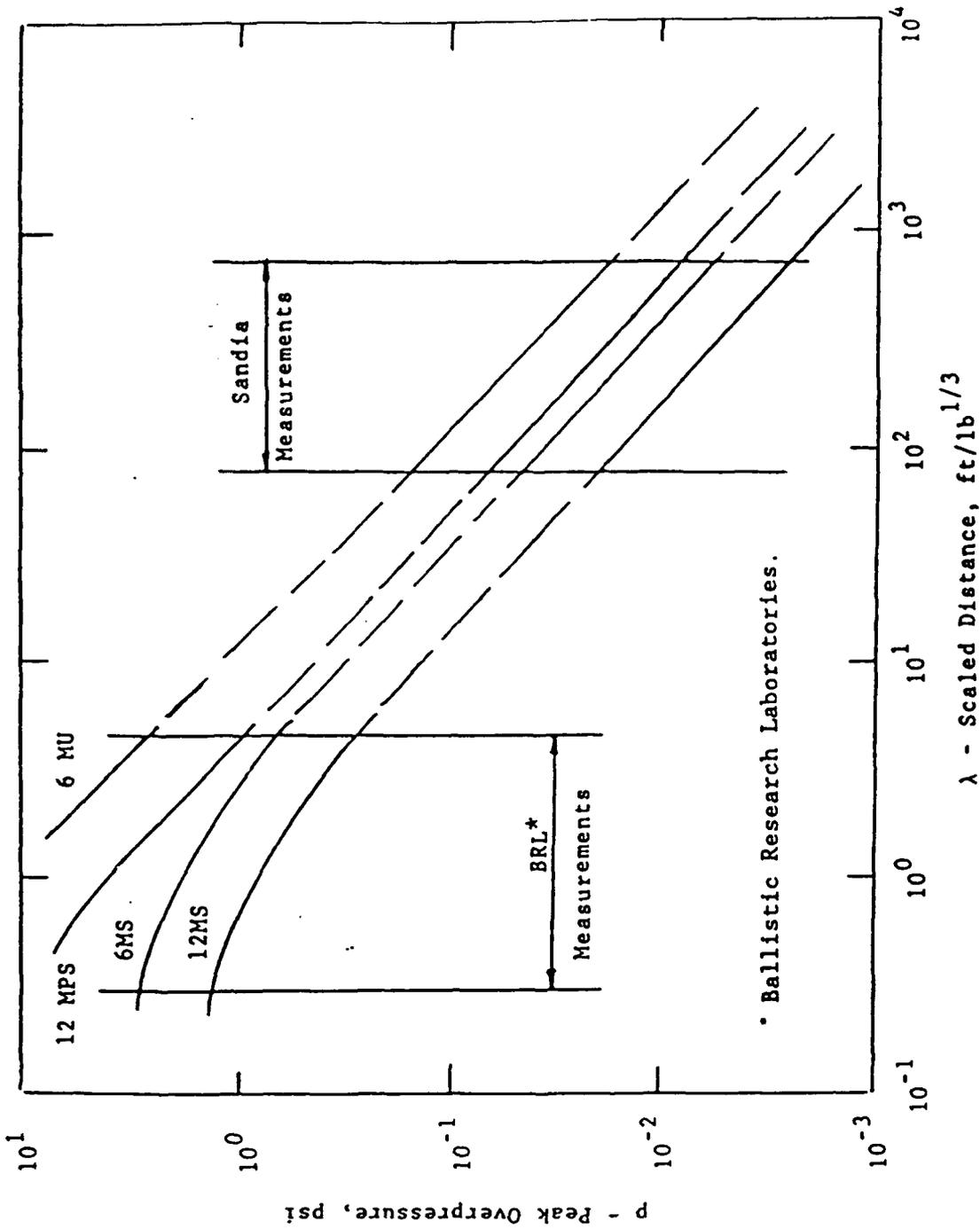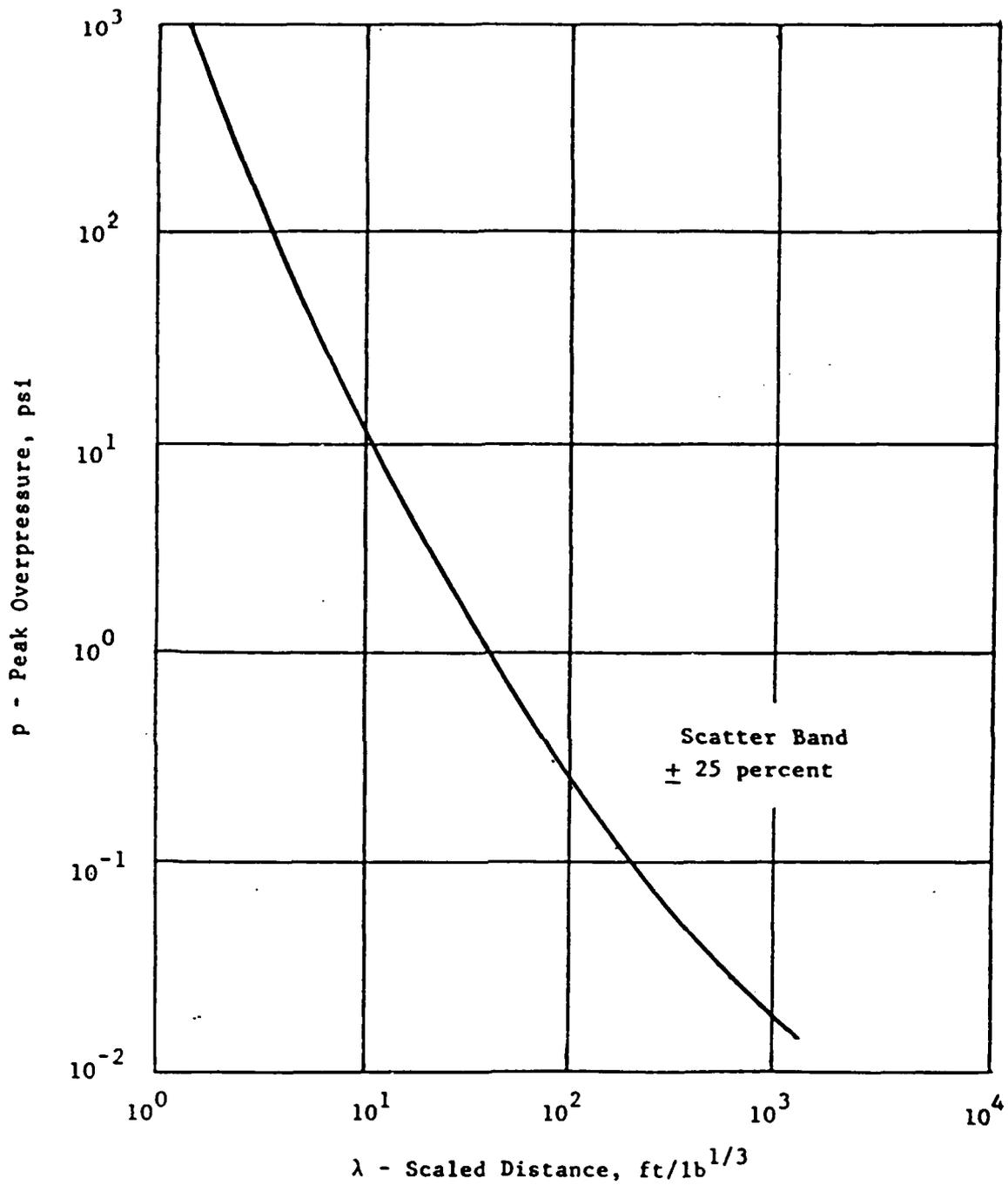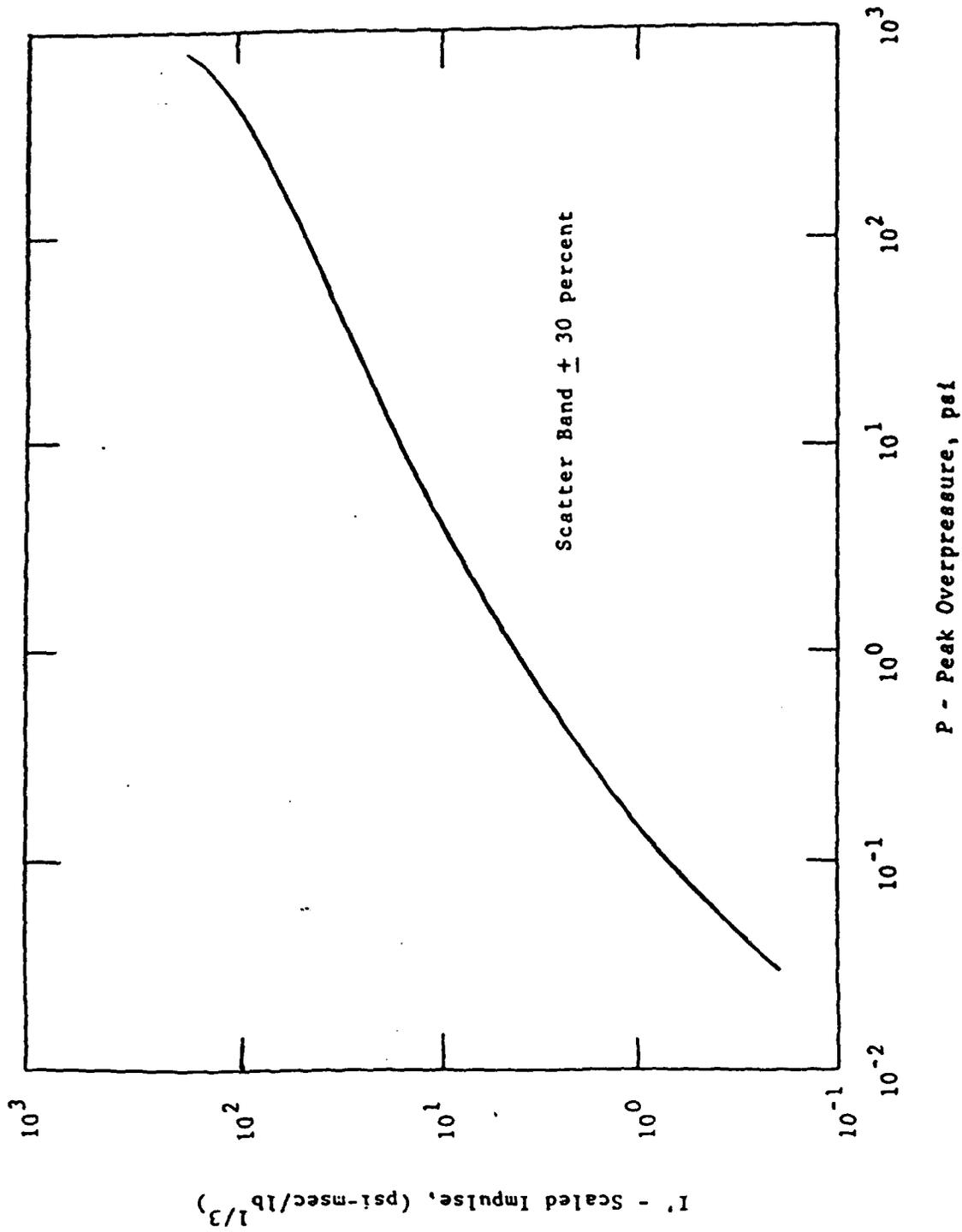ping peak overpressure versus scaled distance equations for various depths of burst. The general form of equation would be:

$$\rho = K(\lambda)^{n} \qquad\qquad (4.5)$$

where both K and n are functions of the scaled depth of burst (λ_c). Since P is always inversely proportional to λ, n will always be negative. Values K and n as functions of λ_c can most likely be graphically determined, resulting in a simple means of estimating peak overpressure versus scaled distance for a variety of charge depths of burial.

4.4.8. From the results of the ESSEX Program (Strange, et al 1978), we have determined that it might well be possible to combine the close-in and far-out airblast results by averaging, and to use the results of Perkins and Jackson (1964) in combination with Figures 4.3 through 4.6 to construct a family of curves that predict overpressures versus scaled range (λ) for $\lambda_c = 0$ (surface burst) to a value of $\lambda_c = -1.5$ for the burial depths envisioned in munitions disposal. While some speculative interpolation would be necessary as regards the ESSEX data, where only the stemmed (backfilled) events would be used, the results should prove to be reasonable and to allow estimates to be made of those distances where critical airblast overpressures might be expected from the detonation of buried munitions.

4.4.9. Day and Joachim describe the airblast associated with the detonation of single bombs that were emplaced in augered holes whose diameters were slightly larger than the bomb diameter; the augered holes were left unstemmed. These results may have relevance in defining K and n values as a function of scaled depth of burst where charges are unstemmed or only partially stemmed.

4.4.10. Raspet and Bobak (1988) describe a three-step graphical procedure for estimating the immediate noise impacts of demolition and explosive opertations. The procedure first requires determination of the pressure level produced by a 1-lb TNT surface burst. Corrections for charge weight and depth of burial are then applied to obtain an estimated peak overpressure level with

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distance from the surface ground zero. Four prediction curves are generated; negative gradient, base, probable focus, and maximum overpressure curves. The graphical routine has been computerized in an interactive program named "PEAKEST."

4.4.11. Swisdak (Chapter 15, 1975) has developed a graphical procedure for predicting far-field noise levels from near-surface detonations (surface and below). The procedure takes into account the soil density in addition to charge weight, depth of burial and distance from the surface ground zero. This technique produces a single prediction curve without the influence of atmospheric conditions. A computer program (EARTHEST) prepared by the U.S. Army Corps of Engineers, Huntsville Division implements both methods (Swisdak and PEAKEST) and includes significant improvements to the program PEAKEST. The DOD Explosive Safety Board recommends EARTHEX for calculation of separation distances from ranges used for demilitarization operations.

4.5 Blast Effects -- Damage

4.5.1. From the results of several large-scale experiments (many tons of TNT-equivalent yields) and from data gathered from the Henderson, NV incident, Reed (1988) has developed a graphic model to establish window breakage probabilities versus airblast overpressure. These results were obtained with blast waves having relatively long durations and thus elevated impulse levels. Window breakage is not a function of peak pressure alone. It is rather a function of peak pressure and a minimum impulse level associated with a particular pressure level. An effort needs to be undertaken to establish the cross relationship between overpressure and impulse as relates to specific damage types.

4.5.2. The onset of damage to structures from airblast is usually tied directly to those overpressure levels that will produce window breakage. Because windows vary widely as to size (overall glass area or pane area), type and thickness of glass, glazing conditions, and orientation of the window with respect to the blast's epicenter, it is impossible to determine a single damage threshold for all windows.

4.5.3. Reed (1980) considers 0.06 psi as the threshold overpressure level to cause breakage of large windows where the blast wave duration is long as from large explosions, e.g., nuclear explosions at the Nevada Test Site). Where overpressure levels persist for short durations, the U.S. Bureau of Mines states that 0.5 psi is acceptable for ordinary residential windows. The

probability of damage at this level is 0.06, i.e., 6 windows out of 100 would likely be broken by a 0.5-psi overpressure level.

4.5.4. Reed's (1980) graph, on p 10 of his report, indicates that from the Medina, TX experience, a pressure of 0.08 psi has a probability of 1 in 5,000 (0.0002) of producing window breakage. Reed's threshold pressure of 0.06 psi seems overly conservative, especially for small residential type windows. Therefore, it seems acceptable to use 0.1 psi as the threshold overpressure for residential type windows, especially since for this study, where explosion yields are to be on the order of a few hundred pounds or less and will be buried to some depth.

4.6 Blast Effects – Shock Coalescence

4.6.1. Based on sequential detonation experiments involving charges ranging in weight from 1/4 to 5,000 lb, Zaker (1967) points out that shock coalescence does not occur when the scaled time (msec/lb$^{1/3}$) delay between charge initiation exceeds 4 msec/lb$^{1/3}$. For munitions that are properly initiated in disposal operations, detonations will almost always occur sympathetically, so no delays of this order seem likely.

4.6.2. Kaplan (1967) has reported that when charges made up from shells, bombs, or various kinds of munitions are placed in a single pile or bunched (bound somehow) together, the shock wave in air will be sharp fronted, smooth, and will possess a single pulse rise. Initially, at scaled distances less than 1 or 2 ($\lambda < 1$ or 2), multiple pulses may be observed, but by the time the shock has travelled several multiples of λ, the individual pulses will have coalesced to form a single sharp-fronted shock.

4.6.3. Kaplan (196?) further found that delays between individual detonations of bunched charges can be as much as 30 to 50 msec and still form a single shock pulse when $\lambda > 4$ or 5. When delay times are short (a few msec), the single pulse as noted by Kaplan (1967) was identical to that which would have been expected from simultaneous detonation of the same charges.

4.7 Injuries from Airblast

4.7.1. Zheng (1990) describes an extensive series of tests in China exposing various animals to various levels of shock from widely varying explosion yields. He also describes the results of two accidental explosions with yields of 2,300 tons of ammonium nitrate and approximately 2 tons of TNT.

4.7.2. The author compares the Chinese results with similar results from the U.S. and the former U.S.S.R. The overall results are summarized below:

Data Source	Pressure Level, psi				
	Ruptured Ear Drum	Light Injury	Medium Injury	Heavy (Severe) Injury	Death
U.S.	4.98	2.27	3.41	7.82	>27
U.S.S.R	4.98	2.84-5.69	–	5.69-14.2	>34
China[1]	1.99	1.56-3.98	3.98-7.11	7.11-18.5	>18.5
China[2]	2.84	1.42-2.84	2.84-5.69	5.69-8.53	> 8.5
This Paper	1.99	1.99	4.27	7.11	>18.5

[1] Accidental Explosions.
[2] Animal Experiments.

4.7.3. Richmond and Fletcher (1971) report that (a) 1 percent of human beings will experience eardrum rupture at a pressure level as low as 3.4 psi when the pulse duration exceeds one msec or so; (b) 50 percent eardrum rupture can be expected when the pressure level is 15 or 16 psi; at this level, some persons would experience severe injury; (c) threshold lung damage occurs at about 10 psi when the blast duration is 50 msec or more – smaller durations, like 3 msec or less would require 20 to 30 psi to produce the same level of injury; and (d) 1 percent mortality will occur at a pressure level in the neighborhood of 25 to 30 psi when the duration is in the range of 50 msec. For durations of a few msec, much higher pressures would be needed to produce the same 1 percent mortality – in the range of 60 to 70 psi.

4.7.4. Richmond and Fletcher (1971) also report human displacement statistics: at 1.25 psi-msec or less, personnel would not be blown down; at 8.3 psi-msec, 50 percent of personnel would be blown down (peak horizontal velocity ~ 2 ft/sec); and 54 psi-msec, serious injury is likely (peak horizontal velocity ~ 13 ft/sec) to occur.

Ground Shock

4.8 General Considerations

4.8.1. The intensity of ground shock, and thus the level of particle motion (both as to velocity and the displacement-time history), is highly dependent upon various parameters. Among the more significant are: the type of soil, its porosity, degree of saturation, gradual changes or marked

discontinuities in density and/or compressibility (causes shock refraction and/or reflections), the proximity of an underlying water table, spatial sound-velocity variations, etc. The ESSEX Program (Strange, et al., 1978) showed the degree of saturation to be especially significant in determining ground motion. The 6 MPS Event (a nominal yield of 10 tons emplaced 6 m below ground and partially stemmed), had a significantly lower degree of saturation than other sites. As a result, the ground motions (stress levels also) were more than an order of magnitude lower than the levels from the other events where the degree of saturation was higher.

4.8.2. Interest in particle motion magnitudes are mainly to determine those levels which produce damage, and to relate, damage levels to particle velocity/motion. For the study of interest, it is most desirable to identify the threshold particle motions that are just capable of causing damage to structures, especially as relates to above-ground structures and, in particular, residential structures. In this study below-ground installations are not considered to be a problem unless they happen to be quite close to GZ. A number of references were examined, and those best suited to furnish significant input to the munition-disposal problem were chosen and studied more closely.

4.8.3. Part II of this report discusses the manner in which geology affects shock propagation, including vibratory motion (waves) produced within the ground mass as well as along the ground surface. Dowding describes the relative velocities of the principal shock waves generated by an explosion. A compressive wave in a typical soil will normally travel faster than the shear wave by a factor approaching 1.5, and faster than the Rayleigh wave by a factor of approximately 2. Rayleigh waves can be approximated mathematically as a combination of compressive and shear waves. While Rayleigh waves are surface waves, they do penetrate into the ground to a depth equivalent to 1 or 2 wavelengths. Thus, compared with body waves, which are the compressive and shear waves within the mass of the soil, the Rayleigh wave effects below ground level are of little consequence.

4.9 Quantification of Particle Motion

4.9.1. Kuzmina, et al. provided a rather massive data base for describing peak particle velocity versus reduced distance, for charge yields of 22, 176, and 2,205 lb in loess/loam type soils. Scaled depths of burst λ_c ranged from -1.0 to -1.8 for all but two of the shots fired; two shots were fired at -3.8. Kuzmina's plots of the data (his Figures 16 and 17) show a linear relation for the radial component of motion for those shots where λ_c ranges between -1.0 and -1.8. The equation fitting the data (method of selected points) is:

$$V_p^x = 625 \ (\lambda)^{-2} \pm a \ factor \ of \ 2 \qquad\qquad (4.6.1)$$

where V_p^x is the radial component of the peak particle velocity (in./sec) and λ is the scaled distance. The equation for the vertical component of motion (shear) as derived by averaging Kuzmina's Figure 17 as a linear plot over the domain $5 < \lambda < 150$ is:

$$V_p^z = 64.4 \ (\lambda)^{-1} \pm a \ factor \ of \ 2 \qquad\qquad (4.6.2)$$

4.9.2. Ingram (1977) describes the ground motions associated with nine explosions (300-lb charges) that ranged from charge positions 10.8 ft aboveground to 10.8 ft below ground. The emphasis was on quantifying particle motions near the ground surface for the various shots. In the general equation for peak particle motion

$$V_p = K \ (\lambda)^n \ , \qquad\qquad (4.6.3)$$

K and n are regression coefficients, λ is the scaled distance and V_p is the peak particle velocity (in./sec). For the above-surface shots when λ ranges from 0.54 to 1.51, the value of n is about -1.3 for $2 < \lambda < 6$. For the shots at and below the surface, n = -3 when $2 < \lambda < 6$. At $\lambda > 6$, the particle velocity is strongly influenced by the reflected shock off the underlying water table and from the free surface, both of which serve to complicate the waveform at the near-surface gage array. Within these scaled distances, the decay rates are typical for the shot geometries involved.

4.9.3. Threshold levels as defined by the U.S. Bureau of Mines and by the Corps of Engineers for human perception (below which human beings will likely not notice the disturbance) are 0.04 in./sec; the minor damage (to structures) threshold is 2 in./sec and the major damage threshold appears to be at about 7 in./sec.

4.9.4. Murrell and Skinner (1991), in a letter report, describe the results of munition-disposal operations which were very similar to those anticipated for the project at hand, with the exception that explosion yields are likely to be greater by a factor of from 10 to 20. Even so, the results are believed to be extrapolatable over an order of magnitude.

4.9.5. Seismic measurements were taken by Murrell and Skinner (1991) at ranges from GZ of 1,000, 1,500, 1,200, 2,500, and 4,000 ft. These distances correspond to scaled distances (λ) of

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385, 578, 770, and 1,541, respectively, assuming the total explosion yield for each series was 17.5 lb, TNT equivalent. Murrell and Skinner's (1991) results are shown in Figure 4.8. Note that over the range of the experimental results, the shear wave dominates the longitudinal (P) wave. Extrapolation of these results indicates that the critical particle-velocity level of 2 in./sec occurs between $30 < \lambda < 40$.

4.9.6. Figure 4.9, adapted from an extensive data base of the Bureau of Mines (RI 8507) presents the envelopes of major, minor, and threshold damage for critical particle velocity levels as a function of frequency as reported by Siskind, et al. (1990). All data points were above the threshold line, 99 percent of the minor-damage points were above the major-damage line.

4.9.7. Siskind, et al. (1990) defines human tolerance to whole-body vibrations of 1 minute duration as follows:

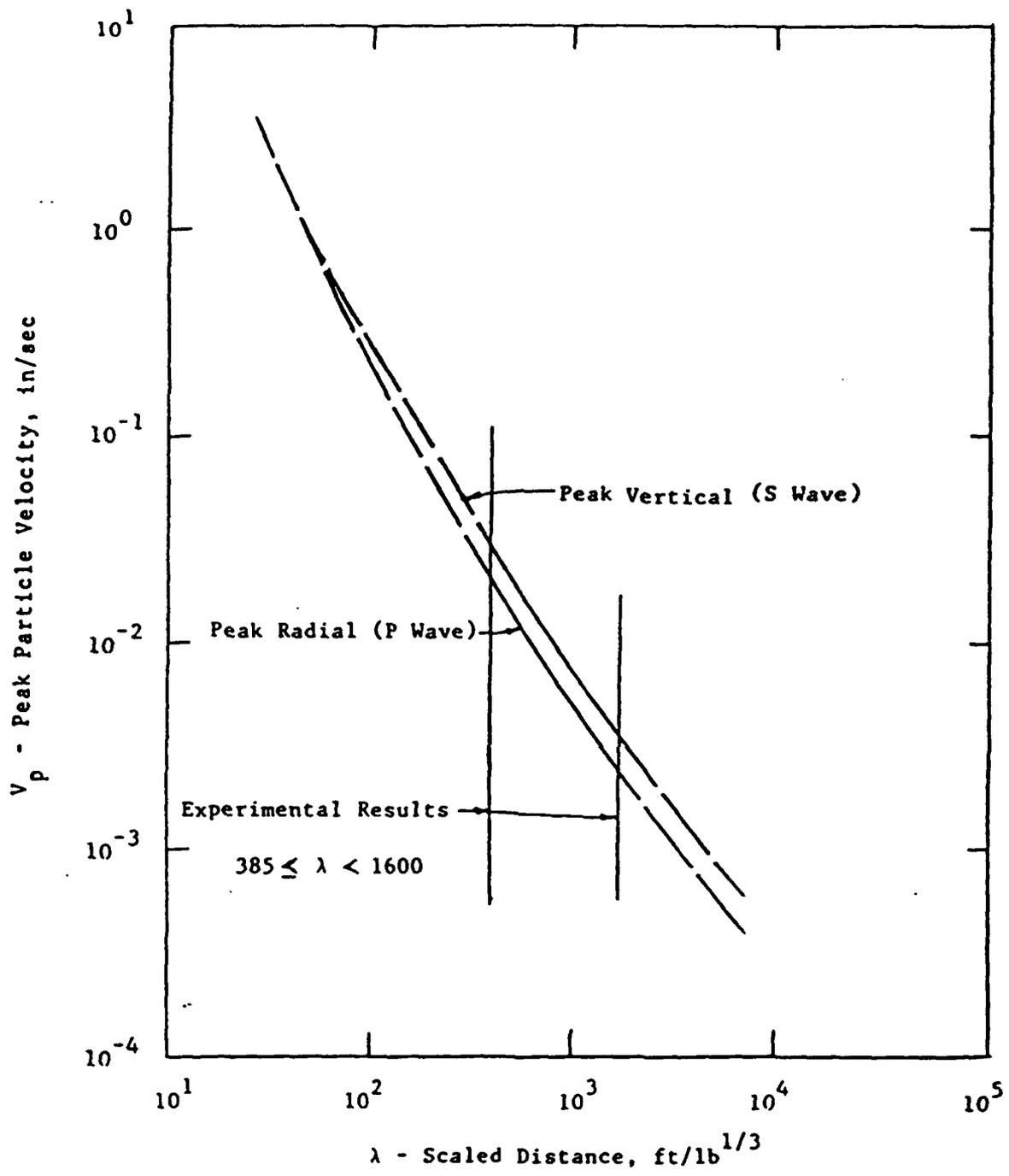|	Particle Velocity, in./sec		
Frequency Hz	Perceptible and Capable of Startling	Interferes with Human Activity	Possible Damage to Health and/or Safety
4	1.4	4.4	8.8
8	0.7	2.2	4.4
20	0.7	2.2	4.4

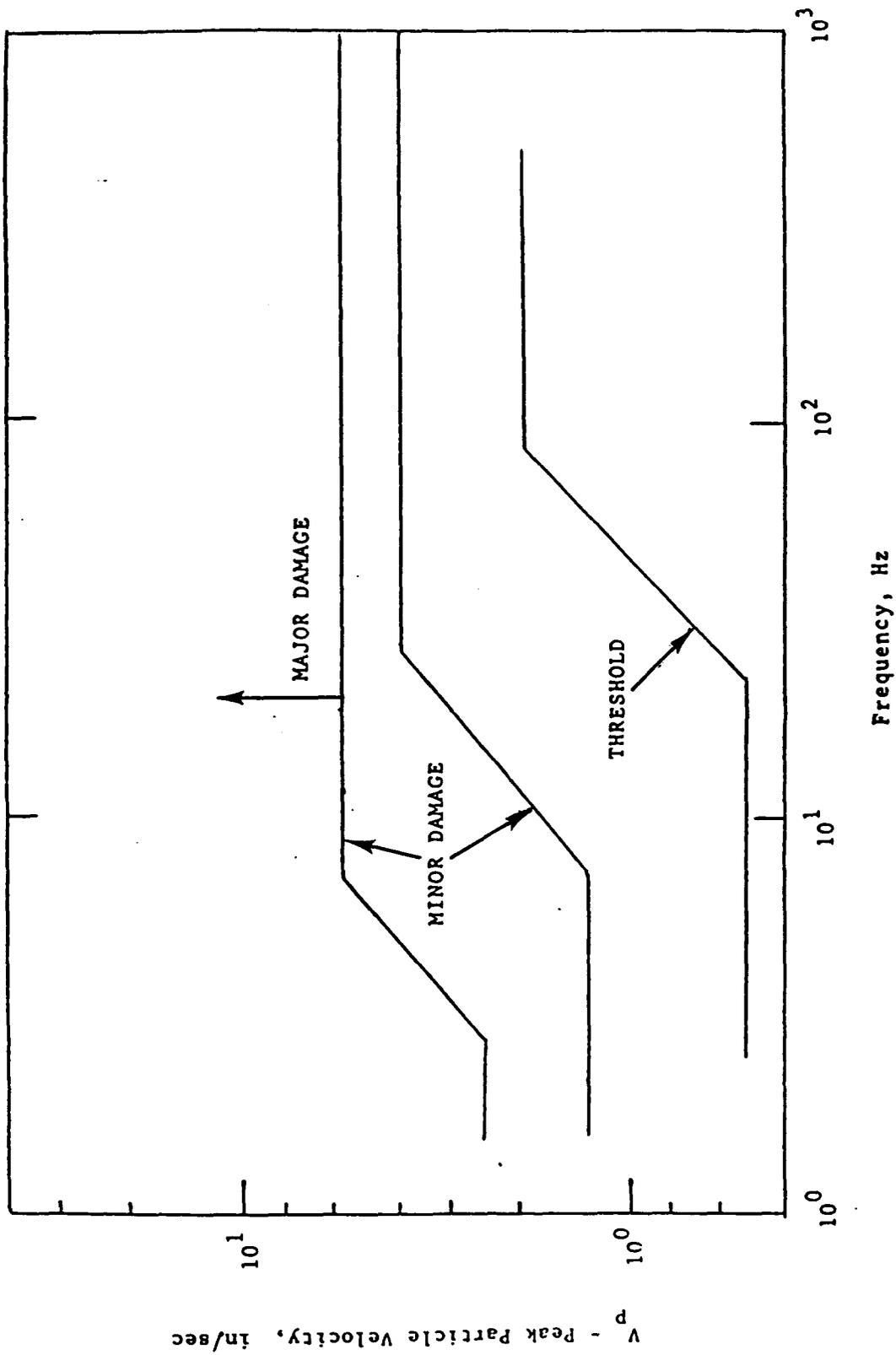Figure 4.8   Peak particle velocity versus scaled distance (far-out).

Figure 4.9 Residual type structural damage levels as a function of peak particle velocity and frequency (adapted from Bureau of Mines, RI 8507 as reported by Siskind, et al).

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4.9.8. ETL 1110-1-142 defines, in a quantitative sense, the level of human response to particle motions occurring at different frequencies. It also provides structural tolerances for residential-type dwellings. In March 1972, Engineer Manual (EM) 1110-2-3800 specified 2 in./sec as the lower limit of particle motion where the threshold of damage would occur; this damage criterion obviously is not frequency dependent. The Federal Register of 13 December 1977 gave 1 in./sec as the lower limit of damage, also not frequency dependent. The Federal Register of 8 March 1983 gave particle-velocity criteria that are frequency dependent. Basically, these criteria say that damage can occur with lower particle velocities with low frequencies, e.g., at 1 Hz, a particle velocity 0.5 in./sec constitutes a threshold-damage level. At 100 Hz, 2 in./sec constitutes the threshold level. These criteria are all displayed in Figure 4.10.

Summary of Part IV

4.10 Explosion effects relating to airblast, noise and ground shock as a function of distance from the source are well enough documented for $\lambda < 50$ for charges at or very near ground surface. An impressive data base is available from which to develop graphic (empirical) models to describe blast effects within this domain. Unfortunately, for greater scaled distance and deeper burials, wherein lies the real interest for munitions disposal, the data base is not as extensive. Thus, for charges placed deeper than $\lambda_c = -1$, where ground motion is enhanced and airblast diminished, the present prediction capability will necessarily rely less upon data and more upon extrapolations and judgmental inferences. In this regard, the proposed experimentation should serve to strengthen prediction capability.
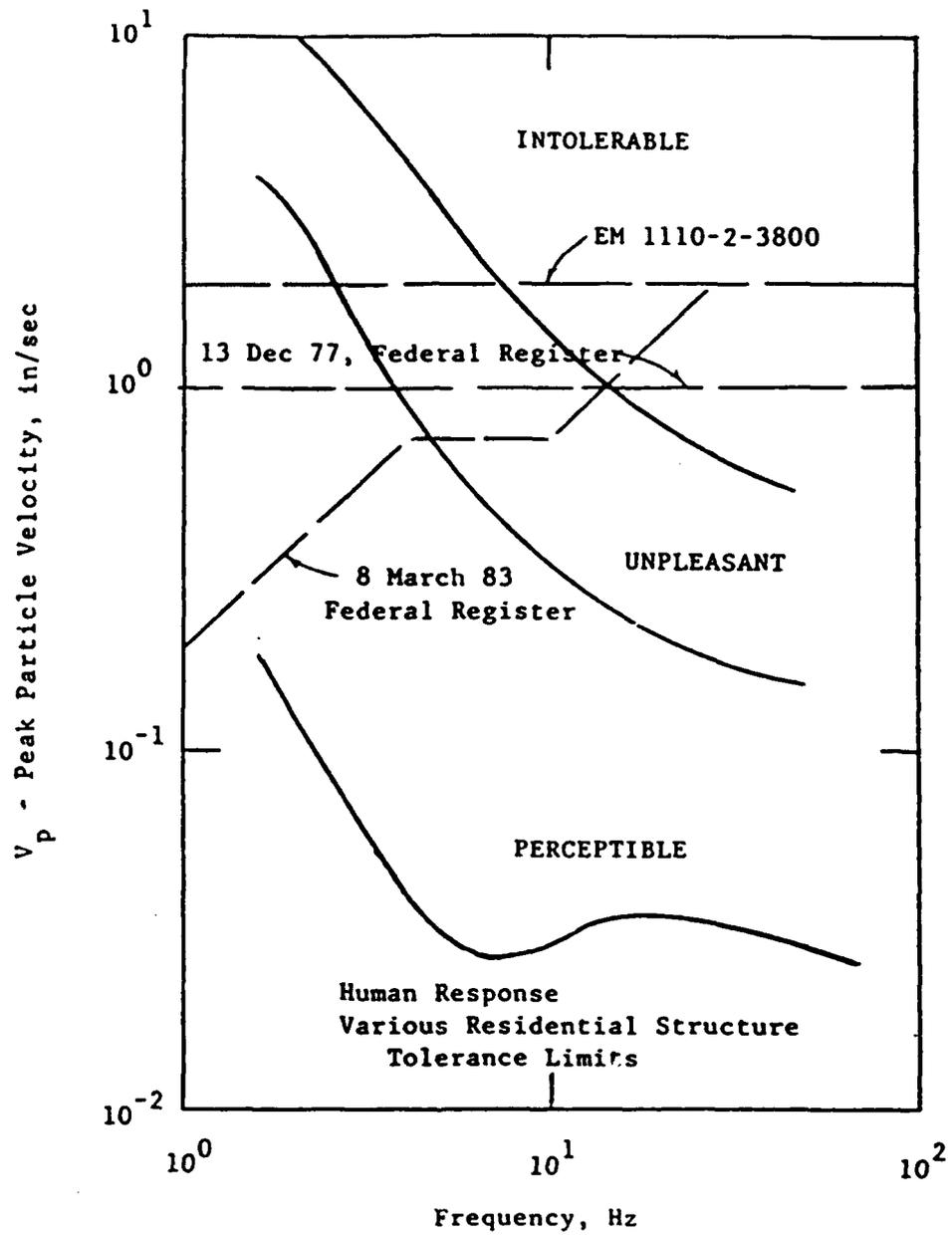
Figure 4.10 Tolerance levels of peak particle velocity
versus frequency.

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Bibliography for Part IV

Day, J. Donald and Joachim, C. E.; "Cable Vulnerability Study," MP SL 81-19; U.S. Army
Engineer Waterways Experiment Station, Vicksburg, Mississippi. Aug. 1981.

This report describes the vulnerability of buried electronic cables exposed to various underground
stress levels induced by MK-82 bomb explosions (250 kilograms). The report also includes
airblast measurements obtained at various scaled distances from the explosions.

Dowding, Charles H.; "Blast Vibration Monitoring and Control," Prentice-Hall International Series in
Civil Engineering and Engineering Mechanics; Prentice-Hall Inc., Inglewood Cliffs, NJ.

This is general textbook on blast and shock effects which includes a complete treatment of the
explosion process beginning with detonations chemistry and physics and the propagation into the
surrounding media.

Engineer Manual; "Systematic Drilling and Blasting for Surface Excavations," EM 1110-2-3800;
Office Chief of Engineers; Corps of Engineers; Department of the Army; Washington, D.C. Mar.
1972.

The Engineer Manual discusses the mechanics of blasting, explosives and their properties,
drilling, basic surface blasting techniques, modifying blasting techniques to fit geological
conditions, damage prediction and control, and drilling and blasting in rock excavation by
contract.

Engineer Technical Letter (ETL)(1110-1-142); "Blasting Vibration Damage and Noise, Prediction and
Control," U.S. Army Corps of Engineers; Department of the Army; Washington, D.C. Sep. 1989.

This ETL details blast levels that cause damage; it also relates blast peak overpressure versus
noise and describes noise/pressure levels that cause physical harm, frc⁻ discomfort to fatalities
from overpressure.

Ingram, James K.; "CENSE Explosion Test Programs: CENSE 2, Explosions in Soil," TR N-77-6;
Weapons Effects Laboratory; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
Dec. 1977.

The objective of CENSE 2 was to study the effects of burst position on ground shock, stress,
airblast, and cratering in soil (clayey silt). Nine tests were conducted using 300-lb spherical cast
TNT explosive charges. Burst positions ranged from an elevated (airburst, noncratering) charge
position of +10.8 ft ($1.61 W^{1/3}$) to burial at a depth of -10.8 ft ($1.61 W^{1/3}$). Apparent craters
were measured on all tests. Surface airblast was measured on Events 1 through 6, but not on the
buried events (Events 7 through 9).

Jackson, Willis F.; "Airblast in the Crater Region, Project ESSEX, Phase I," BRL MR 2524; U.S.
Army Ballistic Research Laboratories, Aberdeen Proving Ground, MD. Aug. 1975.

A series of four subsurface detonations of gelled nitromethane of nominal 10-ton yield (TNT
equivalent) was performed during Phase I of the ESSEX Program. The purpose of these tests was

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to determine the effects of different stemming conditions, charge burial depths and geology on a wide range of blast and shock parameters. This report presents the results of airblast overpressure measurements taken in the crater region of each detonation.

Joachim, C. E.; "Structures in an Arctic Environment, Airblast and Subsurface Shock from High Explosive Tests," TR 1-649; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Oct. 1964.

During the summer of 1962, two 4180-, one 1860-, and one 500-lb C-4 charges; two 36-lb C-3 charges, and nine 256-lb TNT charges were detonated on or near the snow surface in the vicinity of Camp Century on the Greenland Ice Cap. Airblast pressure-time measurements were made to determine pressure loading on the snow surface, and acceleration-time measurements were made to determine motion near the snow surface.

Kaplan, Kenneth; "The Meaning of Simultaneity of Detonation with Respect to the Application of Quantity Distance Regulations," URS Systems Corporation; Burlingame, CA (Published in the Ninth Explosives Safety Board Seminar). 1967.

This paper describes a test series conducted to investigate shock waves generated from nonsimultaneous detonations as compared to those from simultaneous detonations; how this information affects quantity-distance regulations is also discussed. It was found that explosions need not take place simultaneously in order to be the complete equivalent of a simultaneous explosion. The formation of a single shock wave from two explosions occurs even if the time between the explosions is long. At some distance from any charge -- even one formed by disparate components -- if all the material detonates, the shock wave will be sharp, smooth, and single. Quantity-distance regulations must consider all explosives present in an area, not just that present in one bay.

Kuzmina, N. V., et al.; "Seismic Effect of Eruptive Explosions in Nonrock Coherent Ground," A paper included in the Monograph: "Problems of Engineering Seismology," Edited by Medreder, S. V. (Prof.); Consultant Bureau; New York, NY.

A general discussion of wave motions accompanying an explosion: first, in an infinite medium; second, in a half space; and finally, in layered media. Particle motions from longitudinal and transverse waves (body waves) are discussed.

Murrel, D. W. and Skinner, F. W.; "Long-Range Blast Effects from Munition Disposal Operations at Raritan Arsenal, New Jersey," Letter Report; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Jul. 1991.

The letter report describes the procedures, results, and analysis of long-range blast effects during munition disposal operations at Raritan Arsenal, New Jersey. Threshold damage levels are given for human perception, minor damage and major damage.

Perkins, Beauregard, Jr. and Jackson, Willis F.; "Handbook for Prediction of Airblast Focusing," Report No. 1240; Ballistic Research Laboratories, Aberdeen Proving Ground, MD. Feb. 1964.

This handbook sets forth the procedures and techniques for gathering and evaluating the meteorological data necessary for predicting the focus of airblast from surface or near-surface explosions, and it describes simple devices to speed the calculations. In Appendix A, all the graphs necessary for the evaluation are gathered for easy reference. In Appendix B, 87 sets of vertical velocity gradients and the resulting sound ray paths are assembled for rapid determination of focal distance. These should cover most of the conditions to be expected throughout the continental United States.

Raspet, Richard and Bobak, Michael T.; "Procedures for Estimating the Flat-Weighted Peak Level Produced by Surface and Buried Charges," TR N-88/07; U.S. Army Construction Engineering Research Laboratory, Champaign, IL. Aug. 1988.

In this report, procedures are described for estimating immediate noise impacts of demolition and explosive operations. The three-step procedure involves estimating the peak level at a range of interest, based on data for TNT, then calculating two correction factors, one for the type and weight of explosive and one for depth of burial.

Reed, Jack W.; "Predictions of Nuisance Damage and Hazard from Accidental Explosions During Trident Missile Flight Tests," Sandia Report No. 79-0626; Sandia Laboratories, Albuquerque, NM. Mar. 1980.

Threshold overpressure levels for damage is discussed for long-duration blast waves as well as for short-duration waves. Probability of window breakage is discussed and defined for various levels of blast intensity.

Reed, Jack W.; "Explosion Airblast Predictions on a Personal Computer and Application to the Henderson, Nevada Incident," Ground Motion and Seismic Division, Sandia National Laboratories; Albuquerque, NM. (Published in the Minutes of the Twenty-Third Explosives Safety Board Seminar, Vol. I, Aug. 1988.

A computer program written for IBM-PC and compatible computers to predict the airblast from explosions is presented. The program, BLASTO, produces overpressure-distance curves for a variety of conditions. Explosives may be point charges at any height above or depth below ground. Buried charges may be distributed in sheet or HEST configurations. An explosion on 4 May 1988 at the Pacific Engineering Company's (PEPCON) AP plant in Henderson, Nevada, is evaluated using BLASTO.

Richmond, D. R. and Fletcher, E. R.; "Blast Criteria for Personnel in Relation to Quantity-Distance," (Published in the Minutes of the Thirteenth Explosives Safety Board Seminar, Sep. 1971.

Airblasts can produce injuries by three mechanisms: (1) from the overpressure effect itself; (2) from blast displacement of the individual; and (3) from missiles in the form of building debris, casing fragments, and crater ejecta that are hurled by the explosion. Thermal effects must also be considered in close proximity to small explosions. This paper presents blast criteria for a man standing in the open, primarily to determine the direct overpressure and displacement effects in terms of quantity-distance. In order to put these criteria in the proper perspective, some

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information on crater ejecta is also included. Blast effects for personnel inside structures is also discussed.

Sauer, F. and Stubbs, T.; "Application of FAE Technology to the Design of Nuclear Airblast Simulation Experiments," DNA Report No. 4327F; Physics International Company; San Leandro, CA. Aug. 1977.

The detonation of fuel aerosols and vapors in air is investigated with respect to the applicability of this type of explosion to generating an airblast simulation at 1-KT nuclear airburst explosion. Extensive investigations into existing overpressure and overpressure-impulse data from weaponized FAE's and carefully controlled hemispherical balloon detonations has allowed a comparison of the fuel-air explosives with both condensed explosives (TNT and nitromethane) and a predicted 1-KT nuclear surface burst. The report presents peak overpressure and impulse curves for 1-KT nuclear surface burst along with HE experimental support data.

Siskind, David E., et al.; "Vibration Environment and Damage Characterization for Houses in McCutchenville and Daylight, Indiana," Contract Research Report, U.S. Bureau of Mines, Twin Cities Research Center, MN. Feb. 1990.

Strange, John N. et al.; "ESSEX Diamond Ore Research Program, Summary Report of the ESSEX Program, Volume I, Phenomenology and Effects," WES TR N-78-5; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Dec. 1978.

The ESSEX program, a research effort whose primary objective was to study the Effects of Subsurface EXplosions, was accomplished during a 5-year period beginning in FY 1973. The program documented the phenomenology and effects of subsurface explosions that occurred at intermediate depths of burial (from roughly one-third optimum to one and one-half optimum) and made assessments of these effects on various types of targets, principally those of interest to tactical military operations.

This report summarizes individual technical reports that present the re-sults of the three-phased experimental program of ESSEX, along with those reports resulting from the study of the vulnerability of various generic classes of targets. Volume I treats the phenomenology and effects of the ESSEX detonations, and Volume II describes the response of the various target types.

Swisdak, Michael M., Jr.; "Explosion Effects and Properties, Part 1 - Explosion Effects in Air," Chapter 15, "Airblast From Underground Explosions," NSWC/WOL/TR 75-116; Naval Surface Weapons Center, White Oak, Silver Spring, MD. Oct. 1975.

A brief presentation of relations for peak overpressure from underground explosions as a function of adjusted ground range. The adjusted ground range is a function of ground range, yield, soil specific gravity and depth of burial.

Zaker, T. A.; "Far Field Overpressures from Closely Spaced Sequential Detonations," IIT Research Institute; Chicago, IL. (Published in the Minutes of the Eleventh Explosives Safety Board Seminar; Sep. 1967.

This paper describes an investigation of the air blast produced by sequentially detonated high explosive charges. Criteria are established relating the coalescence of successive blast waves to explosion time delay, charge weight, and distance from the explosion site.

Zheng, Li; "Safety Distance for a Person Under Action of Air Shock Waves," Engineering Design and Research Institute (Published in the Minutes of the Twenty-Fourth Explosives Safety Board Seminar). Aug. 1990.

In this paper, the acceleration response spectrum of a near-field strong explosion seism from a linear charge is given. Also provided is a method for calculating the attendant seismic force. These data include the seismic accelerations measured at near-field for explosions in granite, a conglomerate, and yellow soil, and from building response data measured from single-story and multi-story buildings.

The author also describes injury levels for various animals exposed to widely differing airblast overpressures.

Notations Used in Part IV

c	Velocity of Sound in air, ft/sec
db	Decibels
I	Unit impulse, psi-msec
I'	Scaled unit impulse, psi msec $lb^{-1/3}$
k	Constant
P, p	Peak overpressure, psi, $lb/in.^2$
P_o	Atmospheric pressure, psi
T	Temperature, $\cdot$F
V_p	Peak particle velocity, in./sec
V_p^x	Peak particle velocity (radial component) in./sec
V_p^z	Peak particle velocity (vertical component) in./sec
λ	Scaled distance, $ft/lb^{1/3}$
λ_c	Scaled depth of burst, $ft/lb^{1/3}$ (minus sign denotes) charge <u>below</u> ground)

PART V: SUMMARY

5.1   The approach used in this literature survey has been to develop each of the major parts of the research problem so as to stand alone. The emphasis in Parts II-IV has been upon introduction and brief explanation of literature that appear to be helpful in predicting explosion hazards from proposed munitions-disposal procedures.

5.2   Part II describes geological features which might well influence munition-disposal procedures. It is something of a check list of things to consider in choosing a disposal site, especially for installations that may not have experience in disposal procedures. Included is an elementary explanation of seismic phenomena, intended as background for the discussions in Part IV. The references are purposely general in nature, since we expect that disposal sites will vary widely in locations and geology.

5.3   Part III addresses what may commonly be the dominant hazard in munitions disposal, the ejection of munitions-casing fragments and natural ejecta, including foreign objects embedded in the soil. In order to provide the analyst with tools for a predictive model for safe distance, it was necessary to combine results of different experiments, thus degrading confidence. Nevertheless, a prediction procedure is suggested for cohesive soils; the main problems will come in extending the procedure to other soils. Experience was also found which indicates that any metal fragments that might be embedded in the cratered soil will travel further than natural ejecta, but probably with reduced densities (fragments per unit area). Lastly, the problem of primary casing fragments was reviewed, and a suggested procedure for hazardous-particle range and areal density is presented. Solution of this part of the problem, however, is dependent upon acquisition of more information during the detailed analysis to follow this survey.

5.4   In Part IV, damage/injury predictions for airblast, noise, and ground shock are developed. For these blast phenomena, we reviewed the various safety standards and made suggestions as to appropriate compromises. Happily, it appears that adequate prediction capabilities will exist for most disposal environments. However, additional experiments are strongly recommended to allow refinement of these capabilities, especially in the far-out effects region.

5.5   It cannot at present be stated with any assurance which of the above effects will govern safe distances. For any given situation, it seems likely that any one of the three major hazards -- ejecta/fragmentation, airblast, or ground shock -- could possibly dominate. As noted in various

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c	Velocity of Sound in air, ft/sec
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I	Unit impulse, psi-msec
I'	Scaled unit impulse, psi msec $lb^{-1/3}$
k	Constant
P, p	Peak overpressure, psi, $lb/in.^2$
P_o	Atmospheric pressure, psi
T	Temperature, $\cdot F$
V_p	Peak particle velocity, in./sec
V_p^x	Peak particle velocity (radial component) in./sec
V_p^z	Peak particle velocity (vertical component) in./sec
λ	Scaled distance, $ft/lb^{1/3}$
λ_c	Scaled depth of burst, $ft/lb^{1/3}$ (minus sign denotes) charge below ground)

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places, additional data and/or references are needed to fully analyze the data and thereby resolve the answer to such questions. From this preliminary look, however, it seems certain that, compared to surface detonations, burial of munitions for explosive disposal will offer a very marked improvement, permitting such operations to be conducted within drastically reduced areas and with improved and statistically established safety levels.

APPENDIX A: PROPOSAL FOR RESEARCH: HAZARDS FROM
THE DETONATION OF BURIED ORDNANCE

1. **REQUIREMENT**: The Department of Defense Explosives Safety Board (DDESB) surveys on the order of 900 installations throughout CONUS and OCONUS. About half of these installations have ammunition and explosives disposal areas. In most cases, explosives safety quantity-distance siting requirements for these disposal areas could be reduced if the attenuation effects on fragment throw distances, as a function of depth of burial, were properly quantified.

2. **OBJECTIVE**: The objective of this proposed study is to develop a methodology for determining the explosives safety Quantity-Distance (Q-D) relations for sites where ammunition is to be detonated as a means of disposal, based on the depth of burial of the ammunition.

3. **PRODUCTS**: A prediction model will be developed to provide reliable estimates of fragment and debris hazard ranges from the detonation of buried munitions in quantities of 7 to 100 kg (net explosive weight). These estimates will, in turn, establish the desired separation distances from safe disposal of the munitions. The safe separation distances will be specified for different quantities of munitions involved in a detonation, for different munition cover depths (i.e., depths of burial), and for a variety of soil types that may be encountered at ammunition disposal sites. The fragment and debris hazard ranges will be supplemented by hazardous fragment density prediction curves (i.e., the number of hazardous impacts of fragments/debris per square metre of surface area). The reliability of estimates provided by the predictive model will be determined in the following manner. The model will be used to generate data for a test which was not included in the original data set. To be considered "reliable," the predictions must match the test data within ± 15 percent. Further, when differences do occur, the predictions must be biased to the conservative side.

4. **APPROACH**:

   a. *Literature Survey*: A literature survey will be performed to assemble and evaluate all available existing information, including experimental data and analyses, which will (a) establish the current "state-of-the-art" for predicting fragment/debris hazards from the detonation of buried munitions, (b) provide a "point-of-departure" for developing the desired prediction model, and (c) identify current gaps in the experimental data base needed to develop a complete model.

   b. *Initial Model Development*. The framework for an improved prediction model will be developed. Input and output information sets will be defined, as shown in Figure 1. The model will

be flexible in nature, to specify different outputs for different input combinations. For example, if the type and quantity of munition rounds and the soil type are known (as an input set), the model will specify (as an output set) the hazard ranges to be expected for a range of burial depths. If the munition type and soil type are known and an allowable hazard range is already established, the model will specify different quantities of munitions that can be detonated for a range of burial depths. Some of the functions which relate the output values to input information will still be loosely defined, at this point, depending on the available experimental data. Figure 2 illustrates an example problem.

c. <u>Experimental Plan</u>. A series of experiments will be performed to provide the additional data needed to adequately define the functional relations. The tests will probably be conducted at three existing disposal sites, with differing soil types. The technical measurements to be made are described in detail in Section 5.

Since there are four test variables of interest (munition type, munition quantity, soil type, and burial depth), a complete set of tests covering each possible combination of variables would be prohibitive in cost. If it is assumed, for example, that four variations in each variable must be tested to establish meaningful relations, then $4 \times 4 \times 4 \times 4 = 256$ tests would be required. Consequently, several assumptions will be made to reduce the number of tests needed. These assumptions must, of course, be technically defensible, based on the literature study and analysis.

For example, previous research has shown that debris throw distances are closely related to the size of the crater from a buried explosion, with both being functions of the charge burial depth. As burial depth increases, the crater size increases and the throw range decreases, up to the "optimum" burial depth which produces the maximum crater size for a given charge in a given soil type. For further increases in burial depth, both the crater size and throw range rapidly decrease to zero, at what is termed the "containment" depth. Sufficient cratering data are available to provide "soil factors," by which a measured crater size in one soil type can be adjusted to predict the crater that would occur in a different soil type. Similar soil factors can be developed for debris throw ranges based on a very limited number of tests. If two such tests are needed, for each of four soil types, to establish a direct correlation with the cratering curves, then the total number of tests required becomes $(4 \times 4 \times 4) + (2 \times 4) = 72$.

Certain assumptions can also be applied to account for the number of munitions. Previous ejecta/debris studies for cratering tests have shown that the ejecta/debris range scales as the 1/6th root of the net explosive weight. This variation from standard cube root scaling essentially accounts

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for the effects of gravity and air drag on the ejection and ballistic flight of the debris pieces. Since the initial velocities of fragments may differ for different generic types of munitions, a limited number of tests should be conducted to verify or adjust the 1/6th scaling function for generically different munitions. If this requires four tests for each of four munition types (e.g., bombs, cluster munitions, mortar/artillery rounds, and mines), the total number of tests required becomes $4 \times 4 + (4 \times 4) + 8 = 40$.

The number of variables used in the preceding examples are merely presumed. The actual number of tests required for this program is estimated to be between 40 and 60. When choices must be made, worst case conditions (where practical) will be selected. For instance, a worst case HE load, such as Comp B will be used for a majority of the tests. Where it is likely that munitions may be placed in more than one orientation, then the test will be conducted using the worst case orientation.

d. <u>Final Model Development</u>. After completion of the experimental program, the completed data base will be used to extend, supplement, or create the parameter relations (i.e., algorithms) required by the prediction model. In addition, appropriate tables and graphs will be provided as guidelines for safe munition disposal.

5. <u>EXPERIMENTAL PROGRAM - TECHNICAL MEASUREMENTS</u>:

a. <u>Primary Fragment Range</u>. Surveys will be made on all tests to record the areal densities of munition fragments as a function of range and azimuth around the detonation point. After each test, the number of fragments above a size that has been determined to be hazardous (impact energy greater than 79 joules) within each sample area will be counted.

b. <u>Debris Range</u>. The soil cover over selected detonations will be seeded, in a controlled pattern, with artificial pieces of debris, simulating unexploded rounds, rocks, or other debris commonly found in the soil of ordnance disposal sites. Each piece will be marked with an identifying number to relate its posttest position to its pretest location. Figure 3 shows a typical seeding plan. The artificial debris will be cylinders fabricated of steel or aluminum bar stock, and painted bright colors to facilitate their recovery after the test.

c. <u>Airblast Levels</u>. Side-on airblast overpressures will be measured at five locations for selected tests. Because of the relatively low levels of airblast expected from the buried detonations, the gage canisters will be buried surface-flush, and the cables left uncovered.

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d. Noise Levels. Long-range noise levels will be measured with portable Sound Pressure Level (SPL) gages on selected tests. At least four ranges will be monitored to establish a data curve of decibels-versus-range, through the 140 db level. Weather data (temperature, barometric pressure, wind speed/direction, etc.) will be recorded for each test involving SPL measurements.

6. REPORTS. A progress report will be submitted to DDESB each quarter, describing the milestones accomplished and expenditures (actual versus planned), and detailing plans for the remainder of the fiscal year.

A final report will be submitted in draft form to DDESB for review and comments prior to publication. The final report will describe the results of each stage of the project, include a detailed description of the prediction model, and provide a table of proposed separation distances for buried ordnance disposal.

7. COST AND MILESTONE SCHEDULE. The proposed study will be conducted over a two-year period, at an estimated cost of $300K for the first year, and $180K for the second year. Figure 4 is a proposed milestone/cost schedule.

8. PERFORMING AGENCIES. The study will be conducted jointly by the Naval Surface Warfare Center, Silver Spring, MD, and the U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

FIGURE A-1

INPUT/OUTPUT INFORMATION SETS

a. Munition type

b. Quantity of munitions

c. Soil type

d. Munition burial depth

e. Fragment/debris hazard range

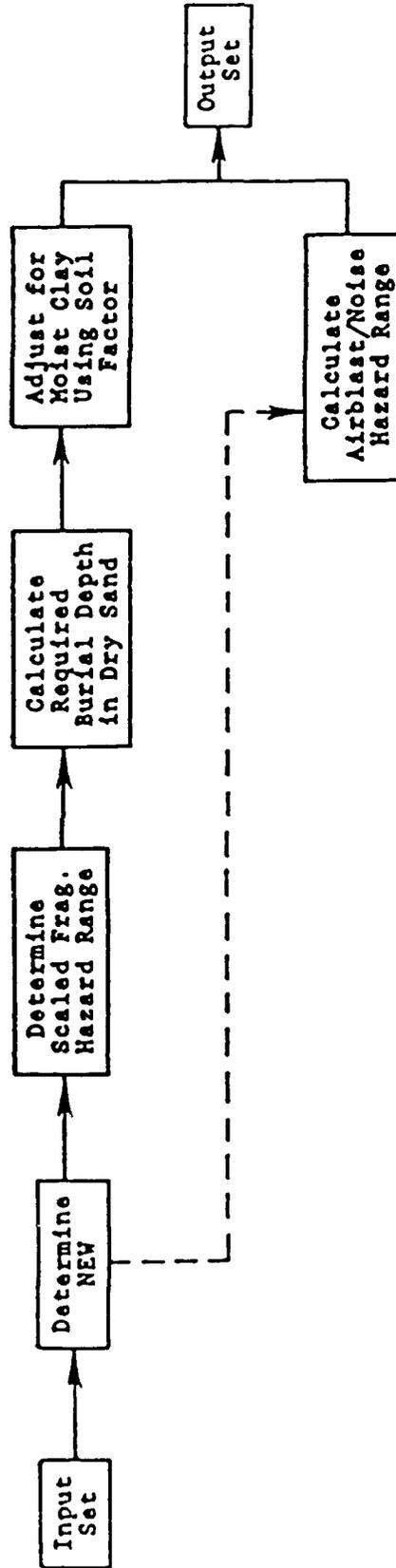f. Airblast/noise hazard ranges

| Item	Definition
a. Munition Type	Generic classification and specific identification of munitions; e.g., GP bombs (MK-82, 83, 84, etc.), HE artillery rounds (105 mm, 15... mm, etc.), HE mortar rounds (82 mm, 4.2-in., etc.), cluster bombs, etc., etc. (NOTE: A "worst case" HE load, such as Comp B explosive, will be assumed for each munition type).
	Example Input: "GP bomb, MK-82"
b. Quantity of Munitions	The number of rounds involved in a single detonation, plus the equivalent weight of additional explosives used to detonate the munitions.
c. Soil Type	The general classification of soil type in which the munitions will be detonated.
	Example Input: "Dry desert alluvium"
d. Munition Burial Depth	The depth (in metres) of soil cover placed (or required) over the buried munitions.
e. Fragment/ Debris Hazard Range	The maximum distance (in metres) from the detonation point at which fragments or debris thrown out by the detonation can be expected to be a hazard to unprotected personnel (one hazardous impact per 56 m^2).
	OR: the distance from a detonation point that has been established as the radius of the existing hazard area (personnel exclusion area) for a munition disposal site.
f. Airblast/ Noise Hazard Range	The maximum distance (in metres) from the detonation point at which (a) airblast can be expected to be a hazard to unprotected personnel or to structures, and (b) the distance at which the noise produced by the detonation will exceed an acceptable level (e.g., 140 db),
	OR: The radius of the existing airblast/noise hazard area at a munition disposal site.

EXAMPLE PROBLEM

REQUIREMENT: For a detonation of 24 rounds of 105 mm projectiles, determine the burial depth of the munitions required to limit the fragment hazard range to 250 m. The soil at the disposal site is a moist clay. A total of 1 kilogram of C-4 explosive will be used to initiate the munitions.
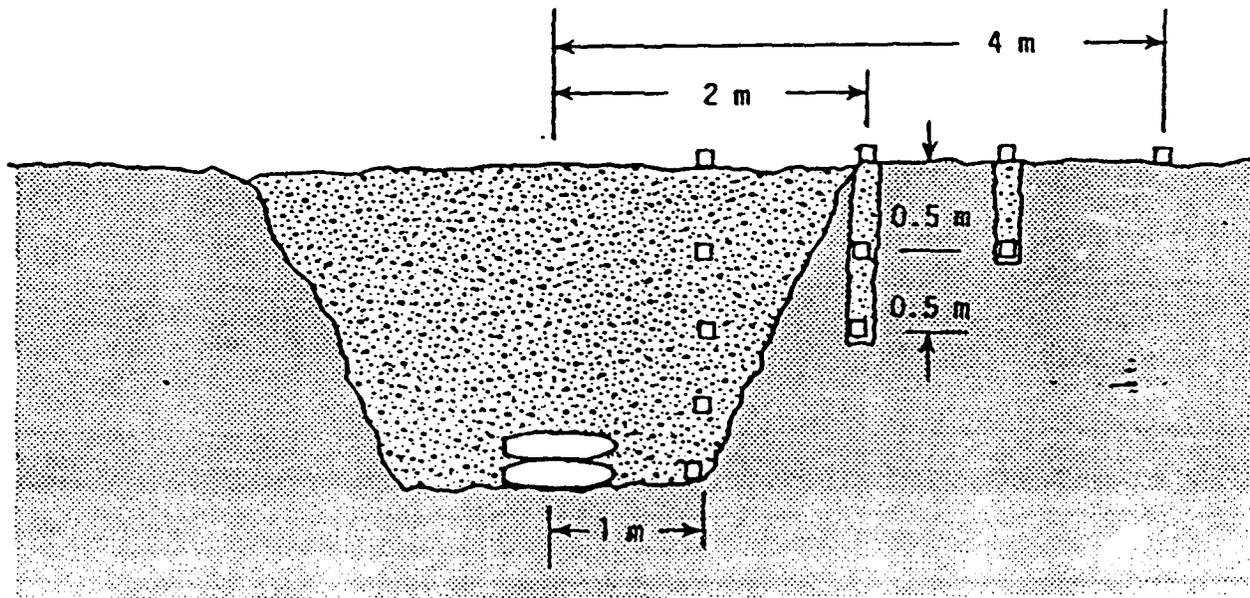
INPUT INFORMATION SET:
- Munition type - 105 mm artillery projectiles
- Munition quantity - 24 rounds
- Soil type - moist clay
- Fragment hazard range - 250 m

OUTPUT INFORMATION SET:
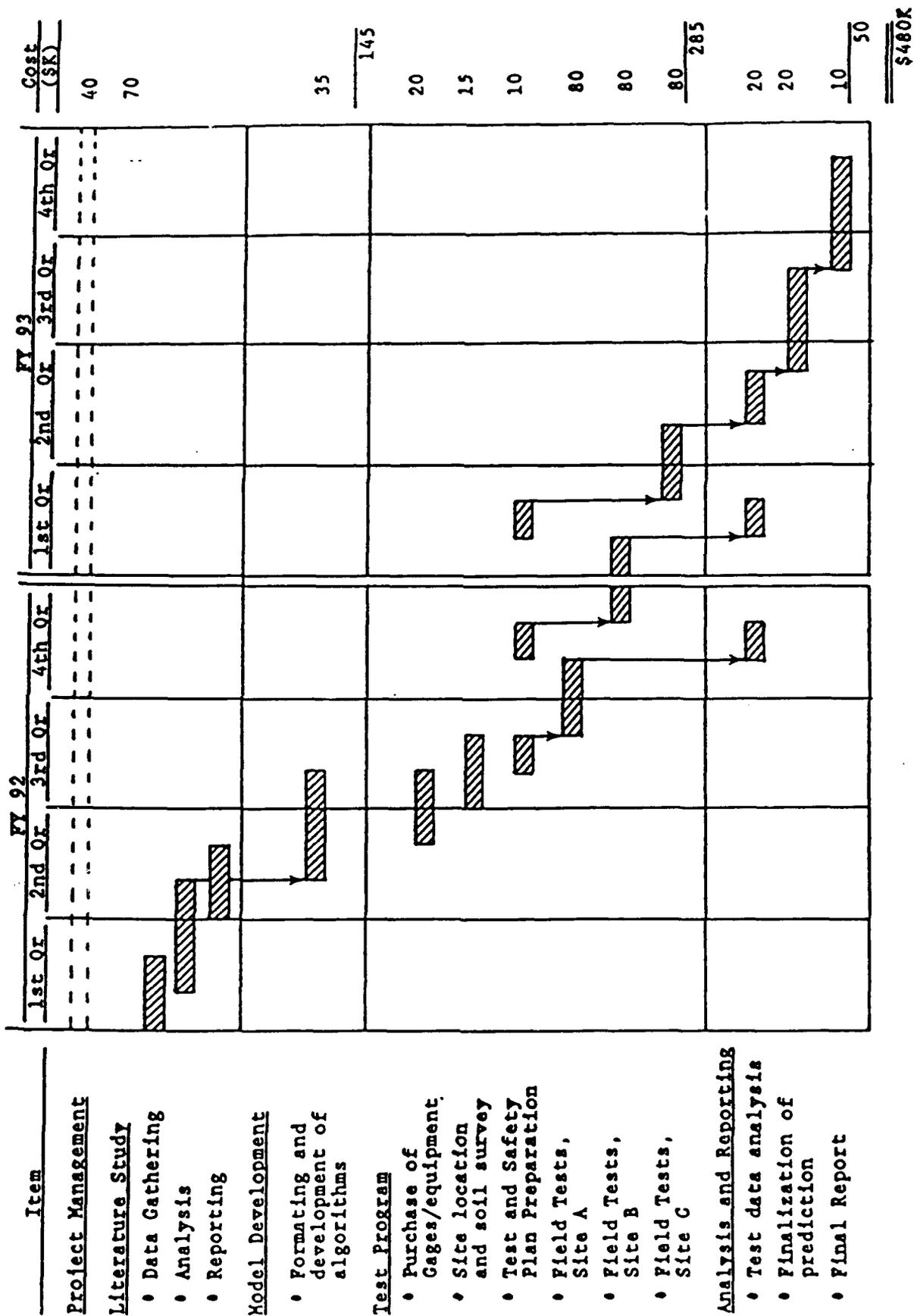- Required munition burial depth - 2.1 m
- Airblast/noise hazard range - 180 m

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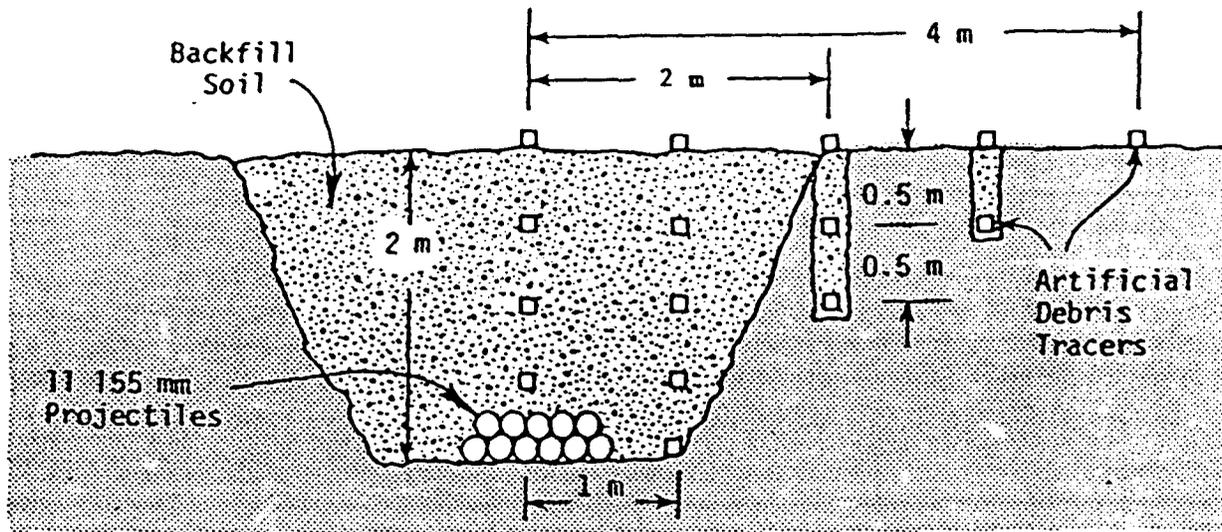
Figure A-3. Typical plan for seeding coded, artificial debris
tracers into testbed area.

FIGURE A-4

COST/MILESTONE SCHEDULE

Item	Cost ($K)
Project Management	
Literature Study	
• Data Gathering	40
• Analysis	70
• Reporting	
Model Development	
• Formatting and development of algorithms	35
	145
Test Program	
• Purchase of Gages/equipment	20
• Site location and soil survey	15
• Test and Safety Plan Preparation	10
• Field Tests, Site A	80
• Field Tests, Site B	80
• Field Tests, Site C	80
	285
Analysis and Reporting	
• Test data analysis	20
• Finalization of prediction	20
• Final Report	10
	50
	$480K

Time scale: FY 92 (1st Qr, 2nd Qr, 3rd Qr, 4th Qr) — FY 93 (1st Qr, 2nd Qr, 3rd Qr, 4th Qr)

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Existing explosive safety Quantity-Distance (Q-D) criteria do not consider the suppressive effects of burial on fragment/ejecta distribution and airblast hazards. The Q-D standoff could be significantly reduced and siting requirements simplified by introduction of this variation in explosive (shot) geometry. A comprehensive literature survey was conducted to assemble and evaluate all available information on the hazards from the detonation of buried munitions. The literature survey described herein evaluated the effects of geological features; fragment/ejecta hazards; and airblast, noise, and ground shock effects from buried detonation on Q-D hazard distances.

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