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SAFETY DISTANCES FOR THE UNDERGROUND
DEMOLITION OF EXPLOSIVE ORDNANCE

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INTRODUCTION

1.   The Australian Defence Force has an explosive ordnance disposal mission that encompasses the disposal and destruction of stray explosive ordnance (EO), improvised explosive devices and also unexploded ordnance (UXO) resulting from its own training and operational activities. There have at times been requirements to detonate EO close to structures or on ranges not large enough to contain the resulting fragmentation and debris. In these situations, EOD personnel have provided "public" protection by either sandbagging the EO or by burying it prior to detonation. Safety distances applicable, depths of burial and protective measures, have largely been "rule of thumb" based on previous experience.

2.   The Australian Army, supported by the other Armed Services, and with the aim of aligning these EOD procedures on a more scientific basis, approached the Australian Ordnance Council for guidance. The Materials Research Laboratory (MRL) of the Defence Science and Technology Organisation was tasked to consider the requirement. As a result the Australian Army's Proof and Experimental Establishment at Graytown Victoria, conducted confirmatory trials to test the MRL recommendations.

AIM

3.   The aim of this paper is to advise the MRL recommendations for safety distances applicable for underground demolition of EO and to report the results of confirmatory trials.

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THE INITIAL TASK

Standards and Limitations

4.   Prior to tasking research establishments, the effects of an underground explosion were itemised and safety criteria allocated. The following effects were considered:

    a.   air blast,

    b.   noise,

    c.   atmospheric focussing of blast and noise,

    d.   primary and secondary fragmentation effects ie consideration of the fragments produced by the EO as well as soil and debris ejecta, and

    e.   seismic phenomena.

5.   The Australian Defence Force is extremely safety conscious especially in matters relating to explosives. In explosives demolition matters that could affect members of the public, safety is of the highest standard. Consequently, any safety distances recommended should meet the following criteria:

    a.   **Air Blast** Overpressures at the nominated safety distance should not exceed 200 Pascals. This overpressure is the onset of possible damage to windows (one window in a thousand could expect to be damaged) though normally this overpressure would only cause windows and dishes to rattle[1,2]. It is considered appropriate as EOD teams may have to operate in civilian controlled areas or adjacent to important national buildings.

    b.   **Noise** Noise at the nominated distances would be unlikely to exceed 140 db and though quite loud, provided it was not repetitive, would only constitute a nuisance value.

    c.   **Atmospheric Focussing** This phenomena is related to weather conditions at the time of detonation, and in particular temperature inversion. EOD personnel are already trained to consider its effects and consequently, the phenomena will not be discussed further in this paper.

d. **Fragmentation** Fragmentation at the safety distance was not to exceed the currently accepted hazard density criteria for surface demolitions[3][4] ie one hazardous fragment per 56 m^2 where a hazardous fragment has an energy greater than 79 Joules.

e. **Seismic Effects** The current Australian Standard[5] providing guidance on blasting adjacent to buildings and structures, recommends peak particle velocities ranging from 2 mm s^{-1} (at historical or important buildings), 10 mm s^{-1} (at standard housing) to 25 mm s^{-1} (for commercial and industrial structures).

6. **Explosives Limits** The largest anticipated individual item in service that may have to be destroyed underground is the Mk 84 HE bomb (Net explosive quantity [NEQ] about 590 kg TNT equivalent). Smaller items such as artillery projectiles, grenades and improvised explosive devices would also be destroyed. Hence EOD operators should be provided guidance for demolition of NEQs between 0.5 and 600 kg.

Task Elements

7. As a consequence of the above factors, the Explosives Division of the Australian Department of Defence's Materials Research Laboratory (MRL) was tasked to:

a. conduct an initial literature search to provide data useful to the determination of underground demolition safety distances,

b. assess air blast, fragmentation/debris throw and ground shock factors,

c. derive procedures to determine the required safety distances,

d. plan a confirmatory trial (if deemed necessary by MRL), and

e. prepare an "aide-memoir" for use in the field by EOD personnel.

PRELIMINARY RESEARCH

8. The research task at MRL was conducted by Mr Doug Oliver and he was initially assisted by Ms A. Kennett. Following a review of unclassified literature, Mr Oliver advised[6][7] that safety distances could be derived using the following procedures.

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However, much of the information is old and would require verification by a fairly simple experimental program.

Air Shock

9.   Reports on the suppression of air shock by burial are not numerous and those acquired and examined by MRL were sometimes contradictory in their conclusions.

10.   Vortman[8] (1968) gives a valuable discussion of air shock from underground explosions and analyses a number of tests to deduce blast suppression factors. This is the best data we could find as far as it goes. However the data terminates at ground ranges of 8 m.kg$^{-1/3}$ and these ranges may be too short for EOD purposes (eg for a 20 kg charge, the data applies only to ranges up to 22 m, for a 500 kg charge up to 64 m). Some research quoted by Vortman indicates that overpressures may also depend on the nature of the ground. For information, the Vortman curve is at Figure 1.

11.   Bishoff[9] (1968) provides at Figure 2, data originating from the US Department of Defense Explosives Safety Board. This data suggests inter alia that peak overpressures may be enhanced rather than diminished by shallow burial. This may be true as air shock can arise from a precursor ground shock as well as from the venting of the explosive gases. MRL considers that at depths of burial below 0.2 m.kg$^{-1/3}$ the probability of such behaviour can be ignored at ranges of interest in EOD tasks.

12.   At Figure 3 is a graphical solution proposed by Perkins and Jackson[10] in 1964. The source of information is not revealed but the data makes blast pressure predictions that are between the Vortman and Bishoff estimates and which extend to ground ranges beyond either.

13.   None of the above data provides a general rule that can confidently be recommended. Of the data, the Bishoff procedure seems preferable to that of Perkins and Jackson because it predicts higher peak overpressures and is therefore likely to err towards enhanced safety. However, extrapolation from any of the data without experimental verification is risky.

Fragmentation

14.   Information on the dispersal of missiles from buried explosives is given by Vortman[11] in 1967 and quoted by Johnson[12] (1971) in the graphical form reproduced at Figure 4. Results deduced from the graph are credible, eg a charge of 500 kg buried to 3 m would give a missile range of 540 m. However as is not certain how "missiles" are defined, it would be advisable

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for EOD operators applying this graph to add a contingency safety
factor of 25% to the ranges deduced from it.

Seismic Effects

15.   Possibly the best guide to the probability of seismic
shock damage to a structure is the peak particle velocity in the
earth at the site of the structure. The peak particle velocity
(V_p) is the vector sum of the three velocity components and, when
not measured directly by an instrument, may be determined from
the formula:

$$V_p = (V_x^2 + V_y^2 + V_z^2)^{1/2}$$

where V_x, V_y and V_z are the instantaneous components of particle
velocity on x, y and z axes respectively.

16.   In 1980, the US Bureau of Mines recommended[13] that V_p
should not exceed 13 mm/s at typical US housing sites. The
current Australian standard specifies 10 mm/s with lower limits
in certain circumstances - see para 5e above.

17.   For field expedients, MRL advises that any form of seismic
damage is likely to be negligible beyond a distance of 32
"distance units" where a distance unit is a distance in metres
numerically equal to the square root of the charge mass in
kilograms. At this distance V_p is approximately 5 mm/s. Note that
square root scaling applies here rather than the more usual cube
root scaling.

TRIAL REQUIREMENTS

Trial Outline

18.   On considering the above advice from MRL, the Australian
Ordnance Council tasked the Army's Proof and Experimental
Establishment at Graytown in Victoria to conduct a limited trial
to provide data to be compared with the theoretical
considerations. Army's Engineering Development Establishment was
tasked to obtain overpressure and seismic data.

19.   The trial consisted of a series of fourteen test
detonations of stacked modified (the boosters and fuzing systems
were removed) Mines Anti-tank Mk5(AUST) buried at various depths
and with differing burial procedures. Two surface test firings
were conducted for calibration purposes. Mines were prepared for
detonation as shown at Figure 5. Each charge was 19 kg NEQ TNT
and 37 mm projectiles were taped to each charge to simulate

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fragmentation. Additional projectiles were buried adjacent to the top mine in the stack. The mines were placed at three depths ie one metre, one point five metres and two metres, in three burial modes:

a. buried (backfilled) in an augered 60 cm diameter post hole;

b. buried in a parallel sided, back hoed trench; and

c. placed in an open parallel sided trench but not buried (1.5 m only).

Data Requirements

20. **Overpressure** Overpressures for each detonation were measured by dynamic transducers and Anderson Blasgages at 32 m and at 40+/- 1 m from ground zero.

21. **Fragmentation** The magnetic bearing and distance from GZ of the 37 mm projectiles, and crater ejecta greater than 500 g was to be recorded after each detonation. Depending on burial depth, a surface fragment search was conducted to 480 m (1 m burial), 260 m (1.5 m burial) and 110 m (2 m burial).

22. **Seismic Vibration** Seismic vibrations were recorded by a vertically oriented geophone, and a set of concrete embedded axial accelerometers, both at 140 +/-2 m from GZ.

23. **Meteorological Data** Immediately before each firing, temperature (°C), barometric pressure, relative humidity, surface wind speed and direction were recorded.

24. **Supplementary Data** Demolition site survey and cartographic data were recorded and soil density determined at nominated burial depths (2092 kg.m^3). Sound pressure levels were recorded at 288 +/-1 m from GZ and both normal speed and high speed videos of each detonation were recorded.

TRIAL RESULTS AND EVALUATION

General

25. Data arising from the trial was initially collated by Proof and Experimental Establishment Graytown[14]. Reduction and initial analysis was conducted by Army's Engineering Development Establishment[15]. A provisional final analysis and recommendations were made by Mr Doug Oliver of MRL[16]. A summary of the trial

results follows.

Overpressures/Air Blast

26.   Mean overpressures in kPa recorded at the trial are at Tables 1 and 2.

Table 1 - Mean Overpressure Readings at 32 m from GZ (kPa)

Depth (m)	Filled Trench	Filled Hole	Open Trench	Predictions Ref 17	Ref 8	Ref 12
1.0	0.58	0.65	NR	0.52	0.44	1.45
1.5	0.62	0.54	10.4	0.18	0.2	0.75
2.0	0.62	0.62	NR	0.6	0.09	0.49

Table 2 -Mean Overpressure Readings at 40 m from GZ (kPa)

Depth (m)	Filled Trench	Filled Hole	Open Trench	Predictions Ref 17	Ref 8	Ref 12
1.0	0.63	0.41	NR	0.38	0.41	1.11
1.5	0.43	0.36	8.41	0.14	0.19	0.58
2.0	0.45	0.38	NR	0.03	0.08	0.38

27.   In Table 1, there appears to be some inconsistency in the range of overpressures recorded for the filled trench and this is still under consideration. The recorded results were compared with predictions from References 9 and 10 as well as those references specified in the prediction columns of the tables above. Values calculated from these references did not improve on those predicted. The predictions give an order of magnitude accuracy notwithstanding the observed inconsistencies. This is probably all that can be expected since they were based on data obtained from large charges and consequently suffer a scaling effect. The high overpressures from the unfilled trench is noteworthy. It would take a ground reflection factor of about 1.7 to achieve similar results from a 19 kg NEQ surface burst. This was not expected.

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Noise Levels

28.   Table 3 provides noise levels (dBA) recorded at 288 m from ground zero. This data cannot be interpreted in terms of overpressure or any other characteristic which damage potential could be assessed. The noise level data is provided for information only. They show that explosions are noisy, that open trenches are noisier than filled ones and that depth of burial (at the scaling used for the trial) doesn't suppress noise much.

Table 3 - Sound Pressure Levels (dB) at 288 m

Depth (m)	Filled Trench	Filled Hole	Open Trench
1.0	100+[a][b]	92.4	NR
1.5	92.7	92.1	112.5+
2.0	95.5+	99.7[b]	NR

Notes:

(a) a "+" sign indicates level meters over-ranged. Values will be higher than indicated.

(b) only one useful recording obtained.

Fragmentation

29.   A tabulated summary of fragment throw distance data and predicted distances is at Table 4. There was some difficulty in identifying earth debris and it is probable that many substantial clods were projected beyond the 37 mm shot limits shown in the table.

Table 4 - Maximum Fragmentation Throw (m)

Depth (m)	Filled Trench	Filled Hole	Prediction (Ref 11)
1.0	159	113 (187*)	317
1.5	63	40	183
2.0	51	29	68

[*Clod of earth: all others 37 mm projectiles]

30.   The predictions are based on the Vortman Curve[11]. This curve has done remarkably well considering that it is presumably based on much larger charges. Rough calculations suggest the projectiles from the 1.0 m deep charges had an exit velocity of about 60 m.s^{-1} at an exit angle of 65° above the horizontal. A clod from the same area and weighing about two or three kilograms could be projected to about 190 m. Note also that the maximum projectile throw from trench burials exceeds that from holes. There are a number of possible reasons for this, but at this stage of the data analysis, these would be guesses.

31.   Explosions in the 1.5 m deep open trench produced no acceptable fragment throw data. It therefore seems reasonable to accept this geometry as a charge surrounded by a barricade rather than as a buried charge. This geometry could prove useful if EOD tasks must be performed amongst fragment-sensitive structures. However, such an arrangement is exceptionally noisy.

Seismic Effects

32.   Tables 5 and 6 provide seismic data recorded by tri-axial accelerometer and a vertical geophone, both sited at 140 +/-2 m from GZ, respectively.

Table 5 – Mean Maximum Particle Velocity mm.s^{-1} –Accelerometer

Depth (m)	Filled Trench	Filled Hole	Open Trench
1.0	6.7	8.0	–
1.5	6.0	8.1	NR
2.0	6.8	6.4	–

Table 6 – Mean Maximum Particle Velocity mm.s^{-1} – Geophone

Depth (m)	Filled Trench	Filled Hole	Open Trench
1.0	4.3	3.6	–
1.5	3.6	4.3	7.9
2.0	3.7	2.8	–

33.   Consider first the accelerometer data which is the primary seismic data from this trial. The particle velocity for holes seems to be slightly higher than for trenches, but the difference is not significant. Nor is there any significant effect due to burial depth. Pending completion of data analysis, we may provisionally assume these data to be all from a common distribution with a calculated mean of 7.06 mm.s^{-1} and a standard deviation of 2.42 mm.s^{-1}. If, as seems likely, this distribution is gaussian, no more than 8 shots per 1000 will give particle velocities over 10 mm.s^{-1} at this distance and in this terrain. The mean of 7 mm.s^{-1} may be compared with the prediction at paragraph 17 that at $32*NEQ^{1/2}$, the maximum particle velocity would be approximately 5 mm.s^{-1}. $(32*19^{1/2} = 139.5$ m).

34.   Unfortunately, there is no accelerometer data for the two open trench shots. This is regrettable as these velocities may have been exceptionally high. The geophone data in Table 6, which gives the vertical component of the seismic motion, is roughly half the vector sum data from the accelerometers. Where comparison is possible, we might guess that the velocity from the open trenches would be twice the geophone figures, ie about 15 mm.s^{-1}. While velocities less than 10 mm.s^{-1} are probably acceptable, velocities of the nature of 15 mm.s^{-1} would more than likely be unacceptable to State authorities.

CONCLUSIONS

35.   The results of the trial reported above are still being analysed and as a result, only some tentative conclusions can be offered at this stage. These are:

    a.   the Vortman curve for estimating debris throw appears suitable for use when determining safety distances for buried EOD operations, however it would be prudent to increase calculated distances by a 25% factor.

    b.   Hole burials appear to cast debris to a shorter distance than trench burials.

    c.   Peak overpressures estimated from various formulae and graphs give "ball park" figures but are not precise probably due to scaling effects. They appear to over estimate the decrease in overpressure due to depth of burial.

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d. The $32 \times NEQ^{1/2}$ rule for avoiding seismic damage fulfils expectations in the conditions for experiments conducted to date.

36. For open trench shots, overpressures are similar to surface bursts and shots are very noisy compared with buried demolitions. Seismic shock is noticeably higher, when measured by particle velocity, than for buried explosions. Fragment dispersal appears insignificant but this needs confirmation by separate experiment.

ACKNOWLEDGMENTS

JJG 9 Aug 90

FIGURES

1. Suppression of Peak Overpressures from Venting Gases - Vortman (1968)

2. Blast Pressure vs Distance for Explosions in Soil at Various Scaled Depths - Bishoff (1968)

3. Air Blast Overpressures vs Distance for Various Depths of Burial of Explosives - Perkins and Jackson (1964)

4. Prediction of Maximum Missile Range for Detonation of Buried Charges - Vortman (1967)

5. Mine Firing Configuration - Underground Demolition Trial 1990

REFERENCES

1. Reed J.W. (1982) "Blast Predictions for Coyote Canyon Explosions" Minutes of the 20th US DDESB Explosives Safety Seminar Vol 1 pp 169-201 (August 1982)

2. Imperial Chemical Industries (ICI) Australia - Blasting Tables Edition 2

3. NATO AC/258 "Manual on NATO Safety Principles for the Storage of Ammunition and Explosives 1977" Part II (as amended)

4. Australian Ordnance Council Proceeding 7/81 (Amdt No 2) "Restricted Airspace Above Explosives Facilities" dated 20 April 1982

5. Australian Standard AS 2187.2-1983 "SAA Explosives Code Part 2- Use of Explosives" pp 15 and 32

6. Australian Department of Defence Materials Research Laboratory Type F Task Report 64/4/1 "Quantity Distances for Underground Demolitions" dated 20 December 1985

7. Australian Department of Defence Materials Research Laboratory Type F Task Final Report 64/4/1 "Safety Distances for Underground Demolition of Explosive Ordnance" dated 26 October 1988

8. Vortman L.J. (1968) "Air Blast for Underground Explosions as a Function of charge Burial" Ann New York Academy of Science Vol 152 Art. 1 (1968) pp 362 - 377

9. Bishoff F.M. (1968) "Practical Solution to Problem of Computing Safety Zones for Cave Storage of Mass Detonating Ammunition and Explosives" Ann New York Academy of Science Vol 152 Art. 1 (1968) pp 43 - 50

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11. Vortman L.J. (1967) "Maximum Missile Ranges for Surface and Buried Explosions" Sandia Laboratories Alburquerque NM Report SC-RR-67-616 (September 1967)

12.   Johnson S.M. (1971) "Explosives Excavation Technology" US Army Engineer Nuclear Cratering Group NCG Technical Report No 21 (June 1971) {also quotes pertinent paper by J.W. Reed]

13.   Siskind D.E., Stagg M.S., Kopp J.W. and Dowding C.H. "Structural Response and Damages Produced by Ground Vibration from Surface Mine Blasting" US Bureau of Mines Report of Investigation RI-8507 (1980)

14.   Australian Army Proof and Experimental Establishment Graytown letter R980/500/626 dated 26 May 90

15.   Australian Army Engineering Development Establishment draft Report LD2844 for Task LD7603 "Measurement of Blast Overpressures, Ground Vibration and Sound Pressure Levels during Underground Demolitions for the Australian Ordnance Council" (June 1990)

16.   Australian Department of Defence Material Research Laboratory "Notes on Buried EOD Trial of May 1990" by Mr D. Oliver dated 1 August 1990

17.   "Hazards of Chemical Rockets and Propellant Handbook" Vol 1 AD889763 CPIA/194 May 1972 pp 2-44 [AS DOD CP library AACA 23386 U]

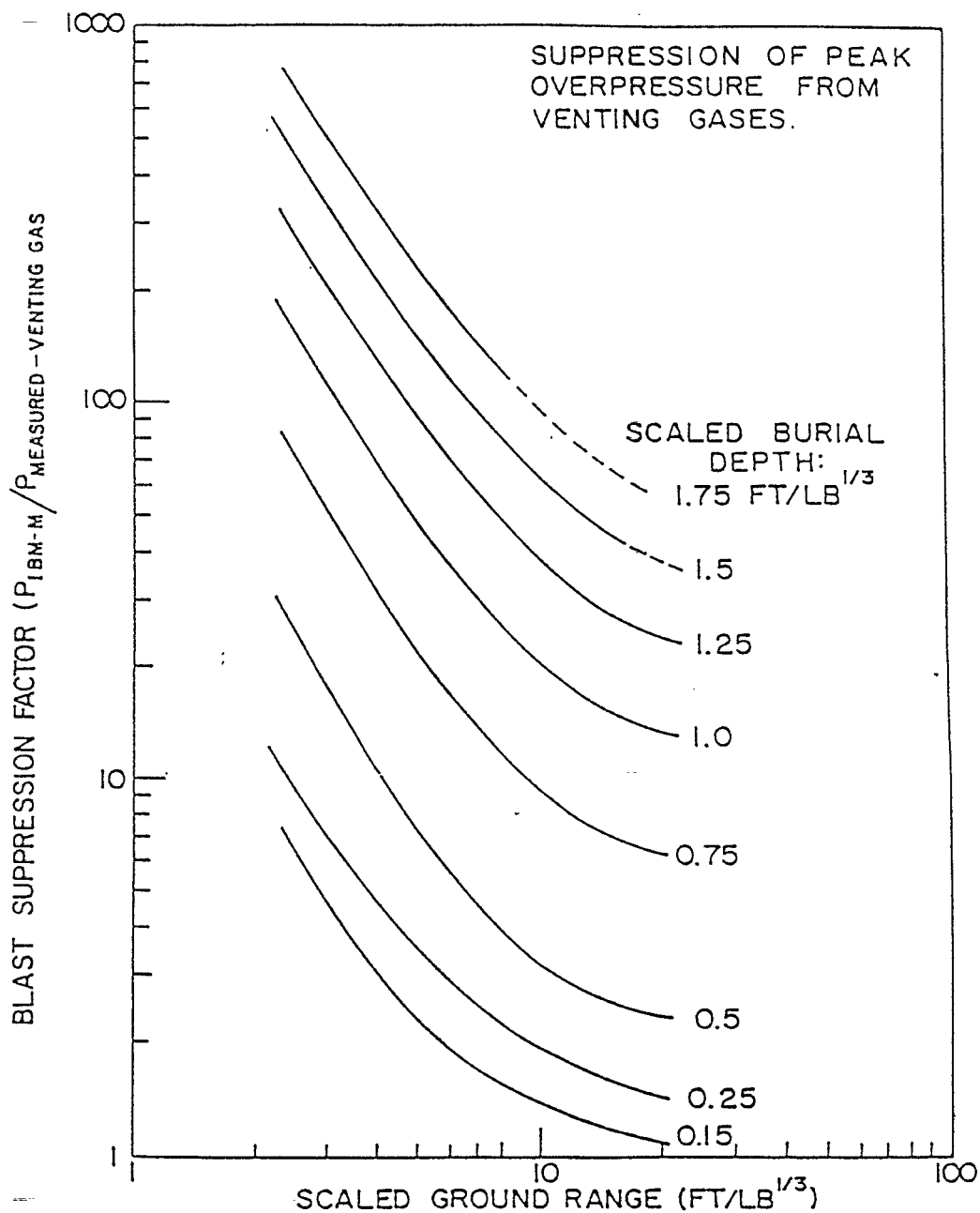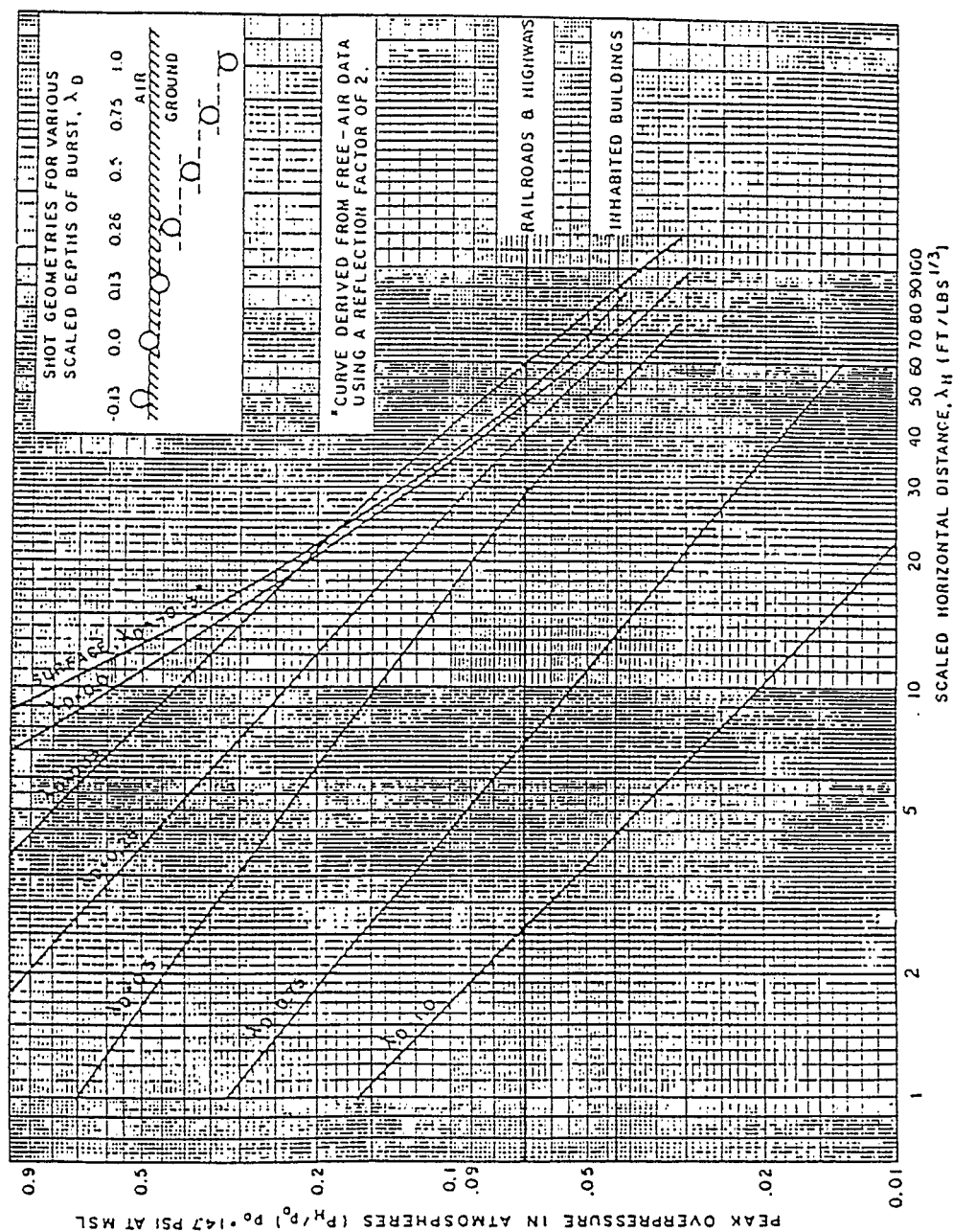SUPPRESSION OF PEAK OVERPRESSURE FROM VENTING GASES.

FIGURE 1 - SUPPRESSION OF OVERPRESSURE (VORTMAN 1968)

Blast pressure vs. distance for explosions in soil at various scaled depths of burst.
(From U.S. Armed Services Explosives Safety Board   Technical Paper No. 8; Figure 3.1.1.)

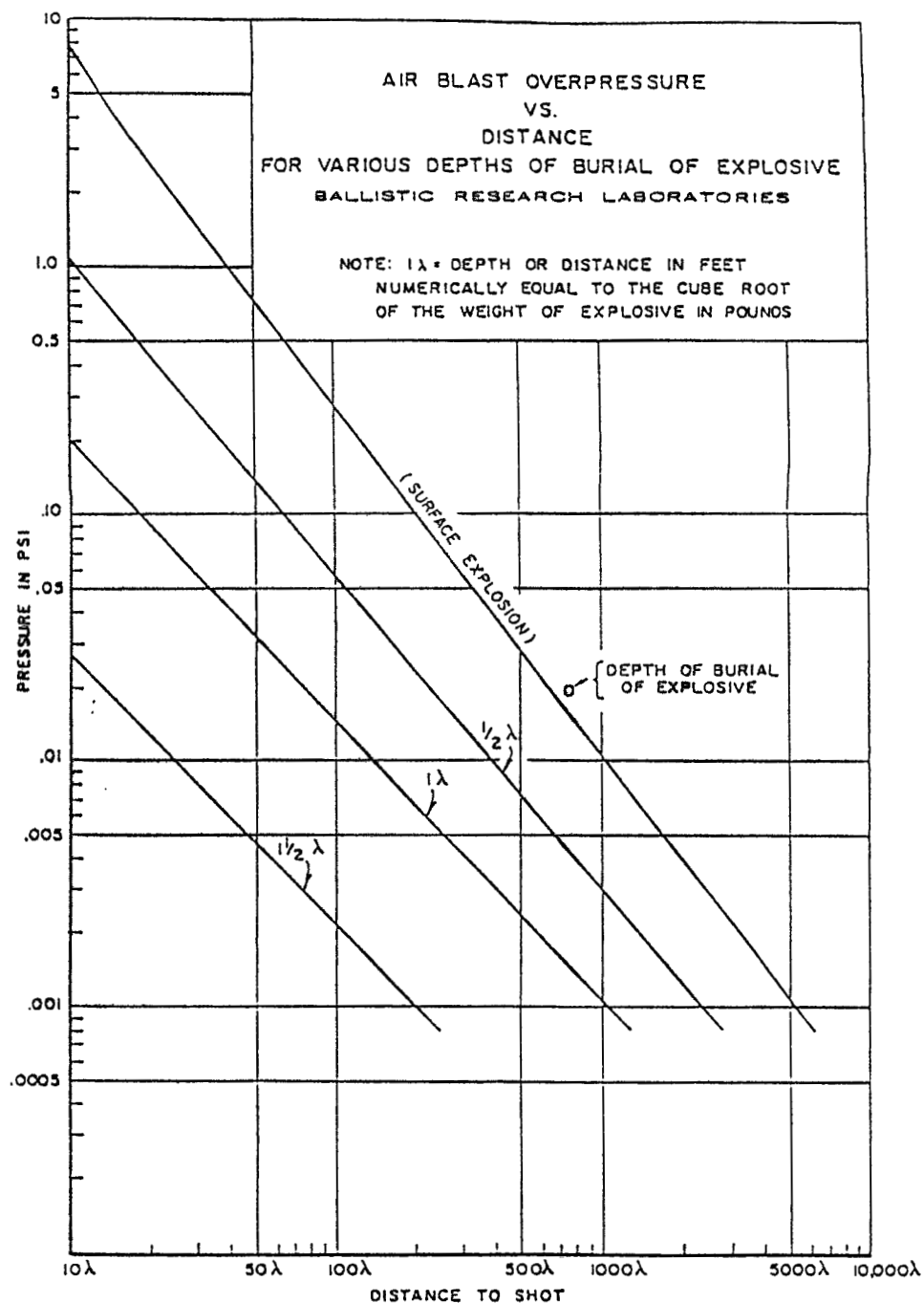FIGURE 2 - BLAST PRESSURE vs DISTANCE (BISHOFF 1968)

AIR BLAST OVERPRESSURE
VS.
DISTANCE
FOR VARIOUS DEPTHS OF BURIAL OF EXPLOSIVE
BALLISTIC RESEARCH LABORATORIES

NOTE: 1λ = DEPTH OR DISTANCE IN FEET
NUMERICALLY EQUAL TO THE CUBE ROOT
OF THE WEIGHT OF EXPLOSIVE IN POUNDS

(SURFACE EXPLOSION)

DEPTH OF BURIAL
OF EXPLOSIVE

½ λ

1 λ

1½ λ

PRESSURE IN PSI

DISTANCE TO SHOT

SUPPRESSION OF AIR BLAST OVERPRESSURE BY BURIAL OF EXPLOSIVE

FIGURE 3 - AIR BLAST OVERPRESSURES (PERKINS & JACKSON 1964)

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Prediction of maximum missile range from detonation of buried charges
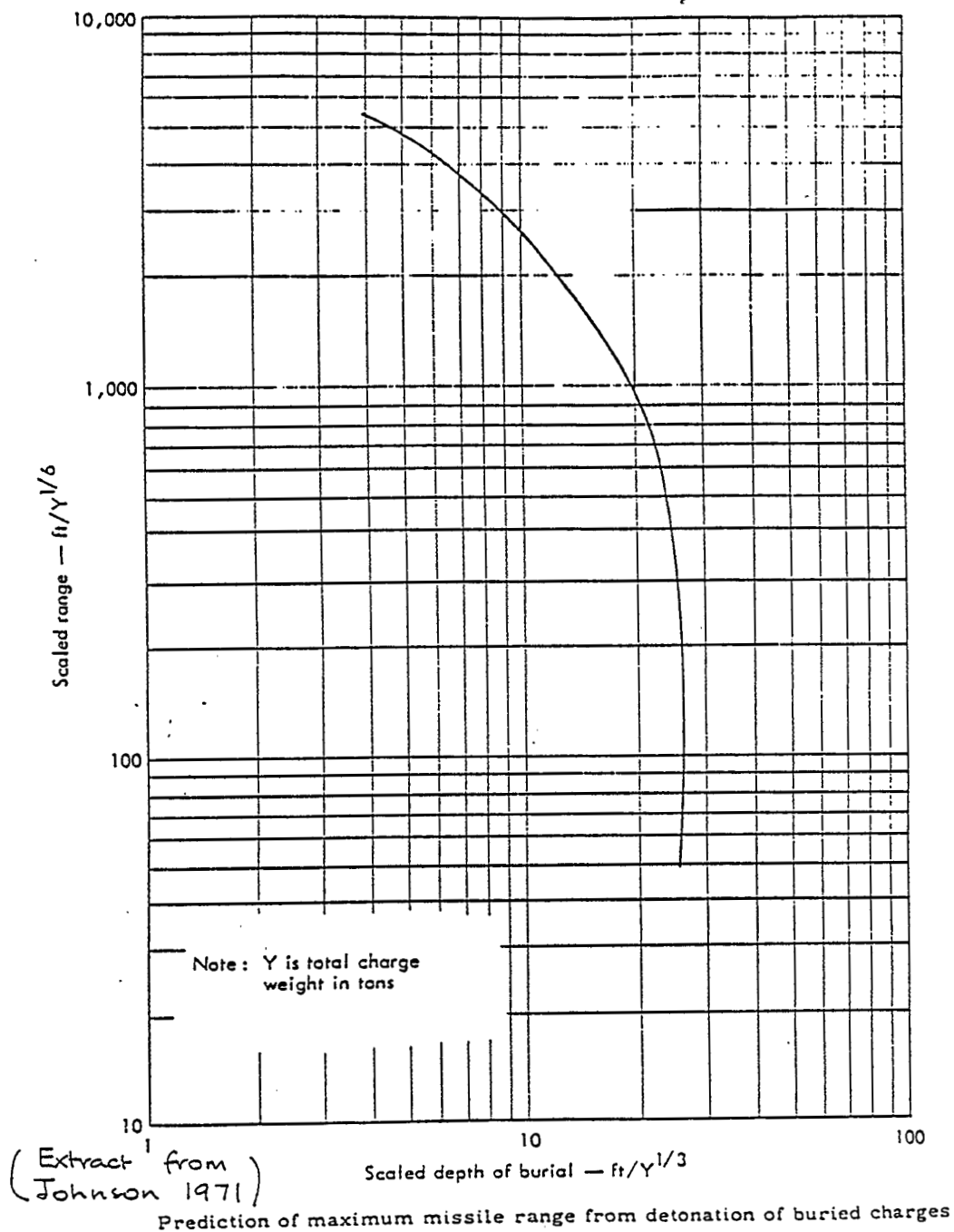
FIGURE 4 - MAXIMUM MISSILE RANGES (VORTMAN 1967)

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MINE FIRING CONFIGURATION

STRING
LOWERING
P&EE

TO
INITIATOR

GROUND
SURFACE

CORDTEX
(EQUAL LENGTHS FROM
JUNCTION TO BOOSTEF
-WHEN PLACING AVOID
SHARP BENDS)

PE4 BOOSTER
IN FUZE WELL

SHOT 37mm
(QTY. 4 SPACED AT 90°

ADHESIVE TAPE

MINES ATK MK5
W/O FUZE (QTY 5)

WOODEN SPACER

← 23 cm →

← 60 cm →
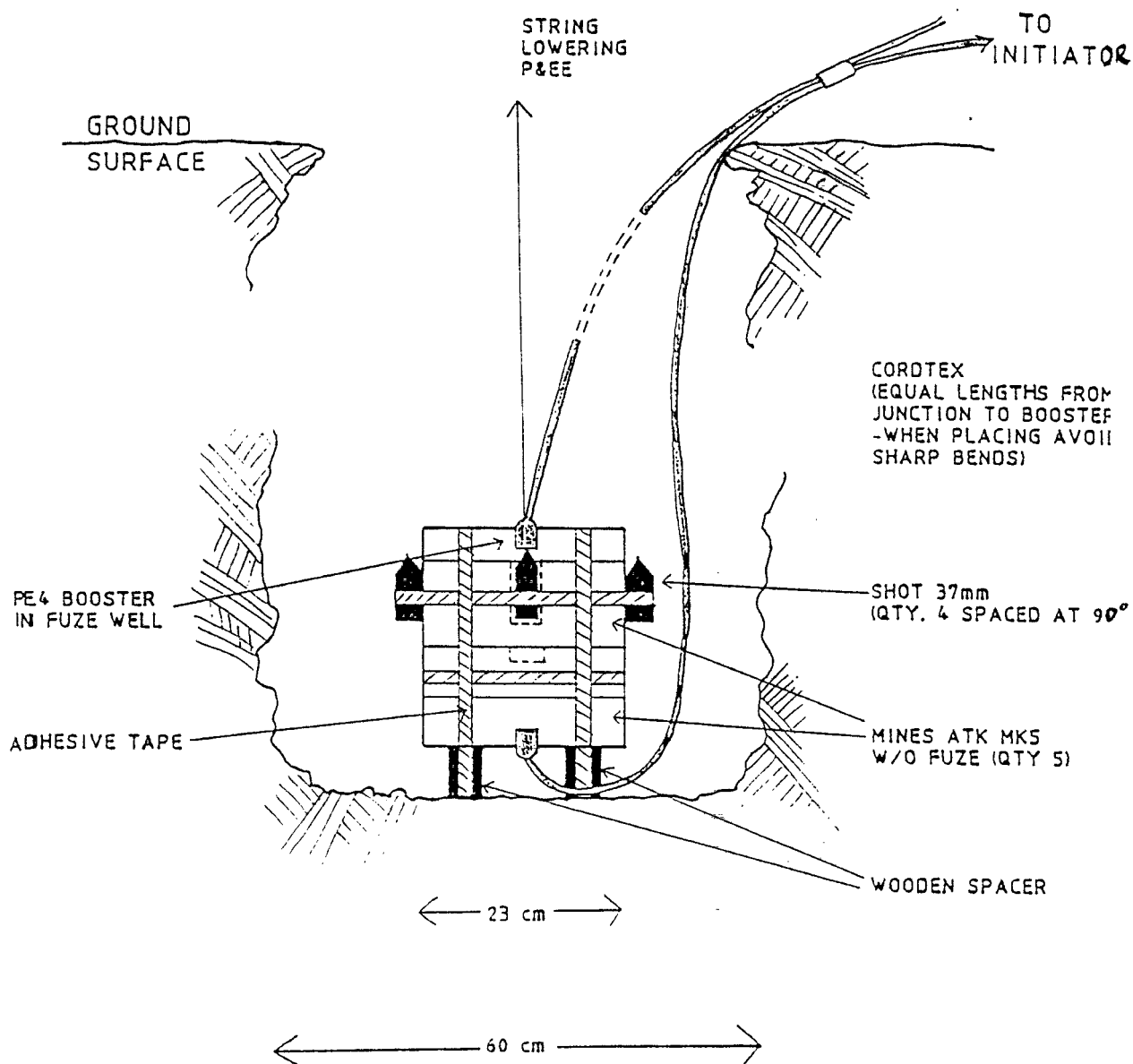
NOT TO SCALE

FIGURE 5 - MINE FIRING CONFIGURATION · UNDERGROUND
DEMOLITION TRIAL (1970)

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