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TECHNICAL REPORT BRL-TR-3012

BRL

SURVEY OF AIRBLAST DATA RELATED TO UNDERGROUND MUNITION STORAGE SITES

CHARLES N. KINGERY

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This report presents results of an in-depth review of the research, both experimental and theoretical, related to the problem of establishing a quantity-distance criteria for accidental explosions occurring in underground munition storage sites.

Six different methods proposed for calculating the safe inhabited building distance were reviewed. Using the same loading density and site configuration, distances were calculated and comparisons were made. The present standard published in the DDESB Safety Manual appears overly conservative while one of the methods proposed by a Norwegian report is under-conservative.

Three of the six methods relied on results obtained from research conducted with small scale models of underground storage sites. The other three methods are based on an empirical approach where the origin and methodology for the equations are not clear.

The weaknesses in all methods are discussed and a recommendation is made for what the author considers the best method.

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22a. NAME OF RESPONSIBLE INDIVIDUAL: CHARLES N. KINGERY

22b. TELEPHONE *(Include Area Code)*: (301) 278-4914

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1. INTRODUCTION

1.1 Background. The peak overpressure associated with a blast wave, propagating from an accidental explosion in an underground munition storage site, is the damaging mechanism that governs the distance at which inhabited buildings may be located. There is a range of peak overpressure, from 50 millibars (0.725 psi) to 86 millibars (1.2 psi), which has been established as the criterion for acceptable damage to an inhabited building. NATO countries, in general, use the 50 millibars while the United States use 86 millibars. There are also different methods used to predict the distance one might expect these peak overpressures. These differences in the peak overpressure for acceptable damage and the methods for predicting the distance at which this pressure would occur are of primary interest to this report.

1.2 Objectives. The objectives of this study are to determine the rationale for current criteria for both the U.S. and NATO countries, to assess weaknesses in the different approaches, and to establish a new recommendation based on scientific experiments and theoretical calculations.

2. RESULTS

2.1 Literature Search. An extensive literature search was made and a total of 24 reports reviewed in detail. These are listed as References 1-24. These reports included small scale and shock tube experiments, and computer calculations.

2.2 Chamber Pressure and Exit Pressure. The various parameters that govern the blast propagation outside of an underground tunnel are the storage chamber dimensions and volume, passageway dimensions and volume, mass and type of explosive stored, exit pressure, tunnel diameter, and the angle off of the zero-degree axis.

The mass of explosive and volume of the storage chamber are needed to establish the loading density. One of the Norwegian reports[5] concentrated on the build-up of pressure in the storage chamber by measuring the pressure versus time for different loading densities, types of explosive, and vent areas. The experimental results compared quite well with the output from Proctor's INBLAST computer code.[6] Although the chamber pressure is one of the important parameters and depends on loading density, early equations, developed to predict the exit pressure from the tunnel, used loading density rather than chamber pressure.[7] The equation established for predicting the exit pressure is approximated by

$$P_w \quad 24(Q/V_t)^{0.66}, \qquad (1)$$

where

P_w = exit pressure, bars

Q = explosive mass, kg

V_t = total volume, m^3.

In English units, the equation becomes

$$P_w = 2172\ (W/V_t)^{0.66}, \qquad (2)$$

where P_w = exit pressure in psi,

W = explosive mass in lbs,

and V_t = total volume in ft^3.

When the passageway or exit tunnel cross-section is smaller than the chamber cross-section, then an attenuation of the shock was considered and other equations for P_w were developed.[7]

$$P_w = 12.1\ (Q/V_t)^{0.607}\ (A_j/A_c)^{0.19}, \qquad (3)$$

where A_j = area of exit tunnel,

A_c = area of storage chamber at exit

(See Figure 1),

and P_w = bar, Q = kg, and V_t = m^3.

In English units, the equation becomes

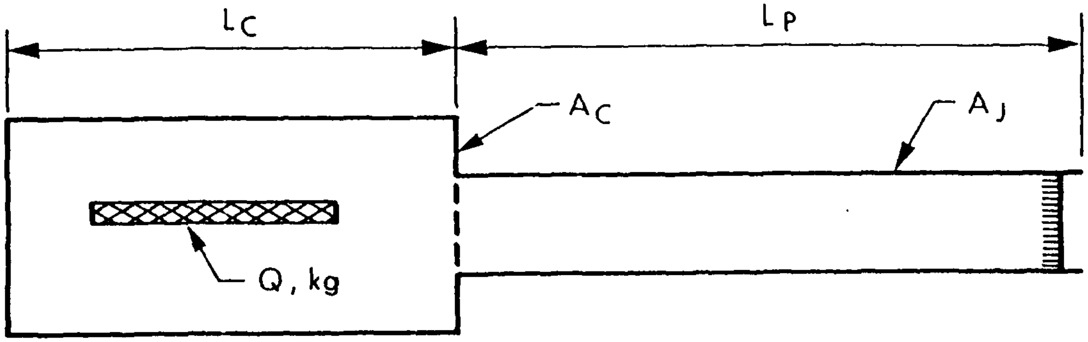
$$P_w = 943\ (W/V_t)^{.607}\ (A_j/A_c)^{0.19}, \qquad (4)$$

where P_w = psi, W = lbs, and V_t = ft^3.

In Reference 17, a new equation was developed to predict the exit pressure P_w. This equation is:

$$P_w = 16.4\ (Q/V_t)^{0.54}\ (A_j/A_c)^{0.24}. \qquad (5)$$

As can be seen, this is a variation of Equation 3. A comparison of Equations 3 and 5 shows that at the lower loading densities, Equation 5 predicts higher values for P_w, while at higher loading densities ($Q/V_t > 30$), Equation 3 predicts higher values of P_w.



$V_C = A_C \times L_C$, m^3

$V_P = A_J \times L_P$, m^3

$V_T = V_C + V_P$, m^3

Q/V_C = CHAMBER LOADING DENSITY, kg/m^3

Q/V_T = TOTAL VOLUME LOADING DENSITY, kg/m^3

$kg/m^3 \times 0.0624 = lbs/ft^3$

Figure 1. Storage Site Considerations

Equation 3			Equation 5		
W/V_t	A_j/A_c	P_w	W/V_t	A_j/A_c	P_w
10	.23	37	10	.23	40
30	.23	72	30	.23	72
50	.23	98	50	.23	95
100	.23	150	100	.23	138

A method developed at BRL considers the total volume pressure P_{Vt} as the governing parameter rather than the loading density. Of course, the loading density and type of explosive must be known in order to determine the total volume pressure (P_{Vt}). The INBLAST computer code is an excellent way to predict the chamber pressure for a given explosive and storage density. In the BRL method, the total volume is used in the equation and the same attenuation factor using A_j/A_c also appears in the equation, as follows:

$$P_w = 1.1\ (P_{Vt})^{0.83}\ (A_j/A_c)^{0.19}, \qquad (6)$$

where P_w and P_{Vt} are in bars.

In English units, this translates to:

$$P_w = 1.733\ (P_{Vt})^{0.83}\ (A_j/A_c)^{0.19} \qquad (7)$$

where P_w and P_{Vt} are in psi.

A plot of P_{Vt} (psi) versus w/v_t (lb/ft^3) is presented in Figure 2 for both TNT and PETN. This is to illustrate that the chamber pressure for each specific explosive should be calculated rather than using a TNT equivalence factor. In this illustration, PETN shows a lower efficiency than TNT at the low loading densities, but becomes higher above a loading density of 0.08 lbs/ft^3. The total volume pressures as a function of loading density for various explosives are listed in Table 1. This table was taken from Reference 19.

When Equation 6 is compared with Equation 5, the values of the predicted exit pressures for Equation 6 are larger at the higher loading densities.

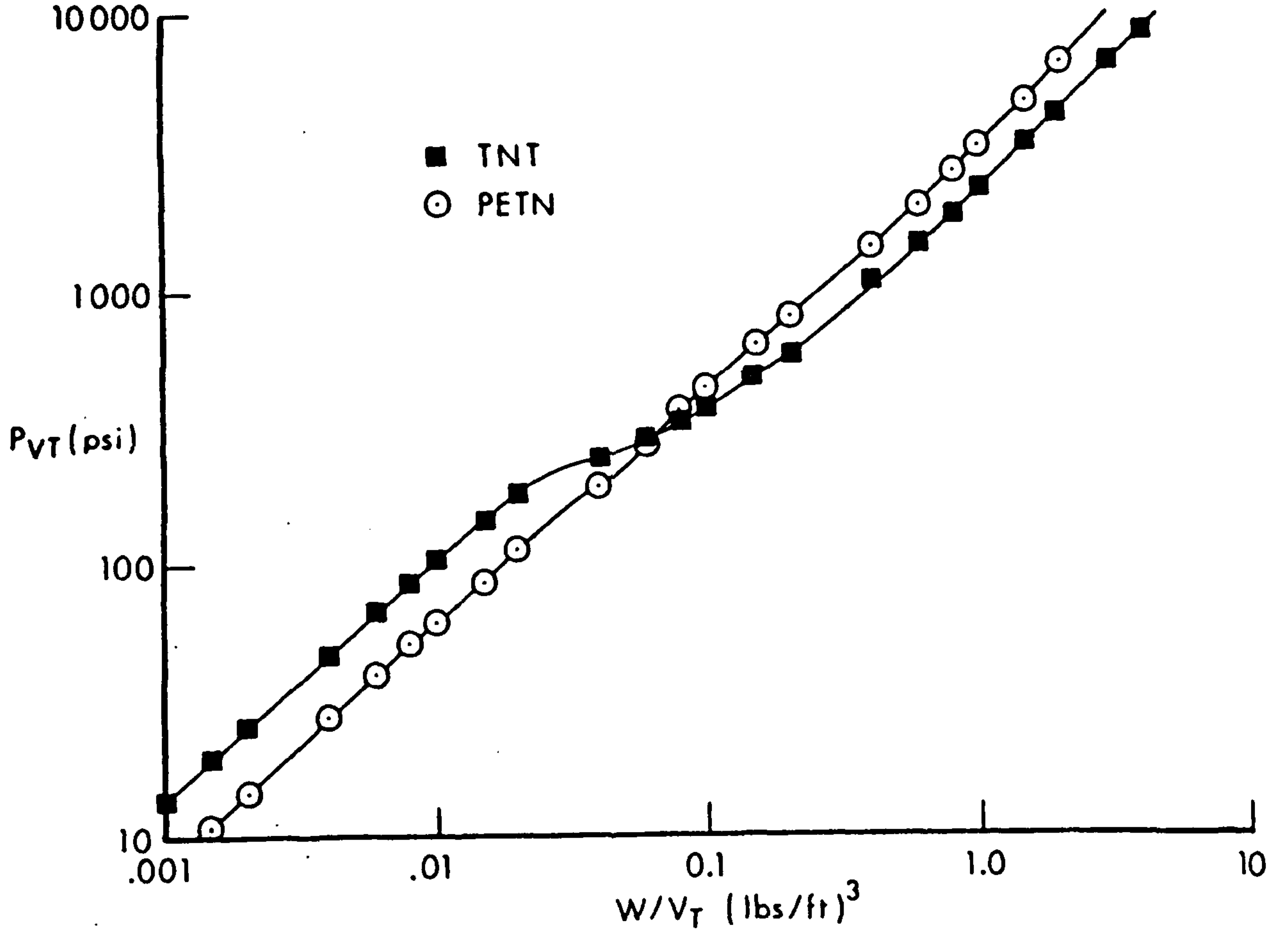


Figure 2. Chamber Pressure (P_{VT}) versus Loading Density (W/V_T)

TABLE 1. Static Overpressure as a Function of Loading Density from Explosions in Confined Spaces

STATIC OVERPRESSURE (P_{V_t}) psi

w/v_t (lbs/ft^3)	TNT	Pentolite	Comp B	Tritonal	H-6	HBX-1	HBX-3	RDX	PETN	Tetryl	Worse Case Unknown
1×10^{-4}	1.36	1.05	1.08	1.67	1.57	1.54	1.86	0.85	0.74	1.11	1.86
1.5	2.04	1.57	1.62	2.49	2.36	2.31	2.79	1.27	1.10	1.66	2.79
2.0	2.71	2.09	2.16	3.32	3.14	3.08	3.71	1.69	1.47	2.21	3.71
4.0	5.40	4.17	4.31	6.61	6.25	6.14	7.39	3.38	2.93	4.41	7.39
6.0	8.09	6.24	6.45	9.85	9.32	9.16	11.0	5.05	4.39	6.60	11.0
8.0	10.7	8.30	8.58	13.0	12.3	12.1	14.4	6.73	5.84	8.78	14.4
1×10^{-3}	13.3	10.3	10.7	16.1	15.2	15.0	17.8	8.39	7.29	10.9	17.8
1.5	19.5	15.2	15.7	23.4	22.2	21.9	25.8	12.5	10.9	16.1	25.8
2.0	25.4	20.0	20.6	30.3	28.8	28.4	33.3	16.4	14.3	21.1	33.3
4.0	47.0	37.4	38.6	55.3	52.8	52.1	60.4	31.2	27.3	39.4	60.4
6.0	66.6	53.4	55.2	77.6	74.3	73.4	84.4	44.8	39.3	56.1	84.4
8.0	85.0	68.4	70.7	98.2	94.2	93.2	106.2	57.7	50.6	71.8	106.2
1×10^{-2}	102.4	82.7	85.6	117.4	112.8	111.7	126.4	70.1	61.4	86.8	126.4
1.5	142.7	116.1	120.5	160.8	155.1	154.0	171.2	99.5	87.0	122.0	171.2
2.0	179.9	147.1	153.1	199.4	193.1	192.2	210.2	127.3	111.0	154.7	210.2
4.0	242.3	257.9	267.6	272.4	283.8	277.7	285.9	229.1	198.4	265.3	285.4
6.0	282.9	317.5	324.8	323.0	340.3	334.2	316.2	323.2	278.2	321.7	340.3
8.0	323.9	372.3	381.6	364.2	385.0	381.0	341.3	413.3	354.3	377.8	413.3
1×10^{-1}	367.6	427.0	438.2	402.7	426.7	425.3	384.3	482.9	428.2	433.7	482.9
1.5	475.6	563.2	579.0	492.3	524.2	530.4	489.5	649.4	607.8	573.0	649.4
2.0	582.6	699.0	717.7	577.4	617.1	631.5	592.8	815.8	770.4	711.9	815.8
4.0	1007	1241	1268	903.7	1023	1024	986.2	1482	1390	1261	1482
6.0	1430	1780	1816	1223	1449	1410	1355	2148	2009	1807	2148
8.0	1853	2318	2364	1541	1874	1811	1724	2814	2629	2352	2814
1×10^{0}	2275	2857	2911	1859	2299	2210	2093	3481	3248	2898	3481
1.5	3331	4202	4279	2650	3361	3230	3018	5146	4797	4260	5146
2.0	4386	5548	5647	3441	4423	4251	3942	6812	6346	5623	6812

Equation 5		Equation 6
Q/V_t	P_w, bar	P_w, bar
10	40	38
30	72	90
50	95	137
100	138	250

This increase in the value of the exit pressure may be justified because it can be seen in Figure 2 that as the loading density increases, the chamber pressure, P_{Vt} , increases quite rapidly.

2.3 Outside Pressure. A method for predicting the pressure propagating outside of the tunnel exit and along different radials was developed and presented in Reference 10. The basic equation is presented as follows:

$$\Delta P/P_w = 1.24\ (R/D_t)^{-1.35}/\ 1 + (\theta/56)^2 \ , \tag{8}$$

where ΔP = pressure at target in bar or psi,

P_w = exit pressure in bar or psi,

R = distance to target in m or ft,

D_t = tunnel diameter in m or ft,

and θ = angle in degrees, off zero axis.

Equation 8 has been plotted in Figure 3, along with data points taken from experiments reported in References 10, 11, and 14-17. It is interesting to note that data from References 11 and 14-16 were generated from shock waves exiting from shock tubes.

In practical use, the desired parameter is the distance R at which a selected pressure would occur. Therefore, Equation 8 may be rewritten as:

$$R = D_t \left(\frac{\Delta P}{1.24\ P_w} \right)^{-0.74} \left[1 + \frac{\theta}{56}{}^{2} \right]^{-0.74} . \tag{9}$$

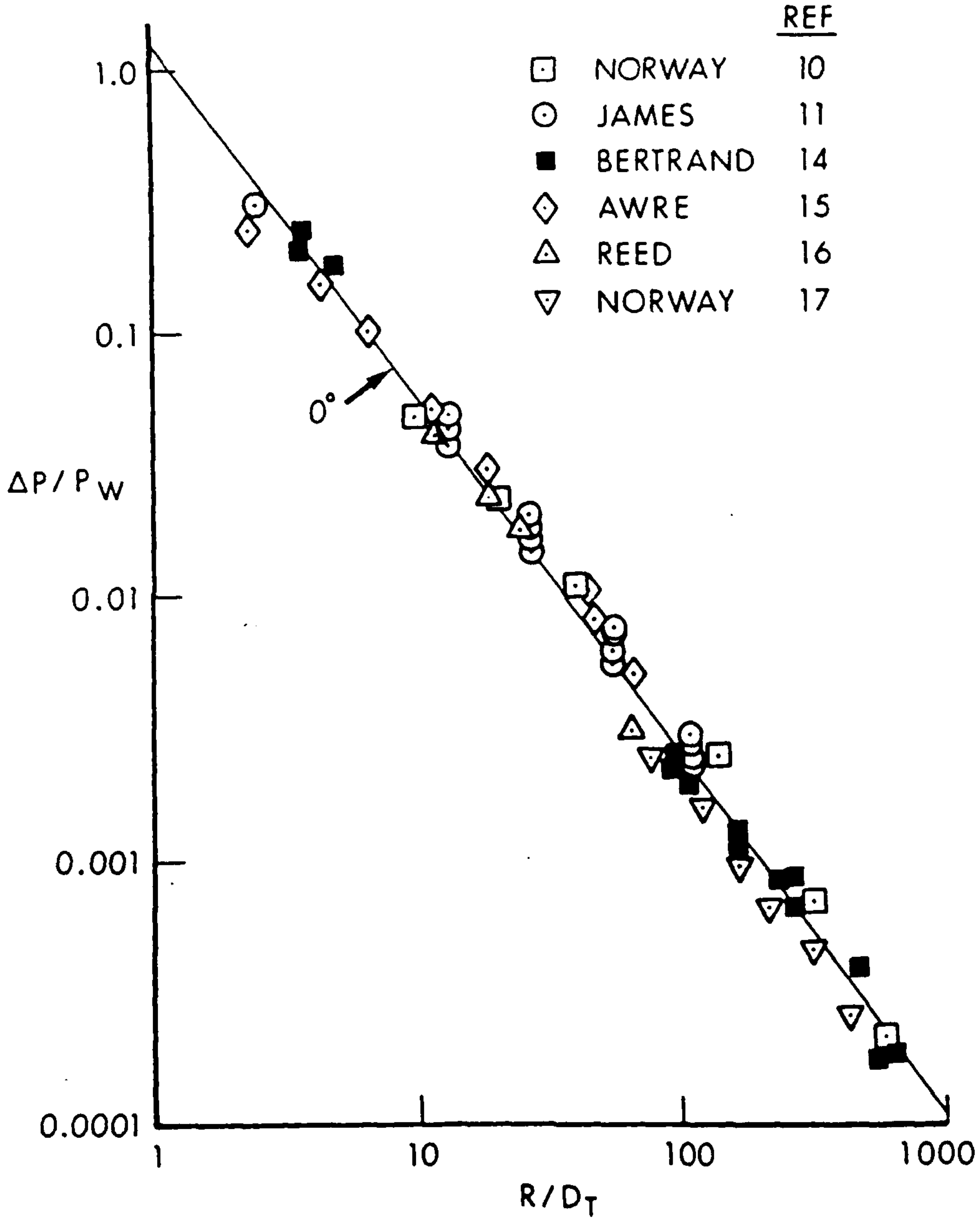


Figure 3. Δ P/P$_W$ versus R/D$_T$ Along Different Radials

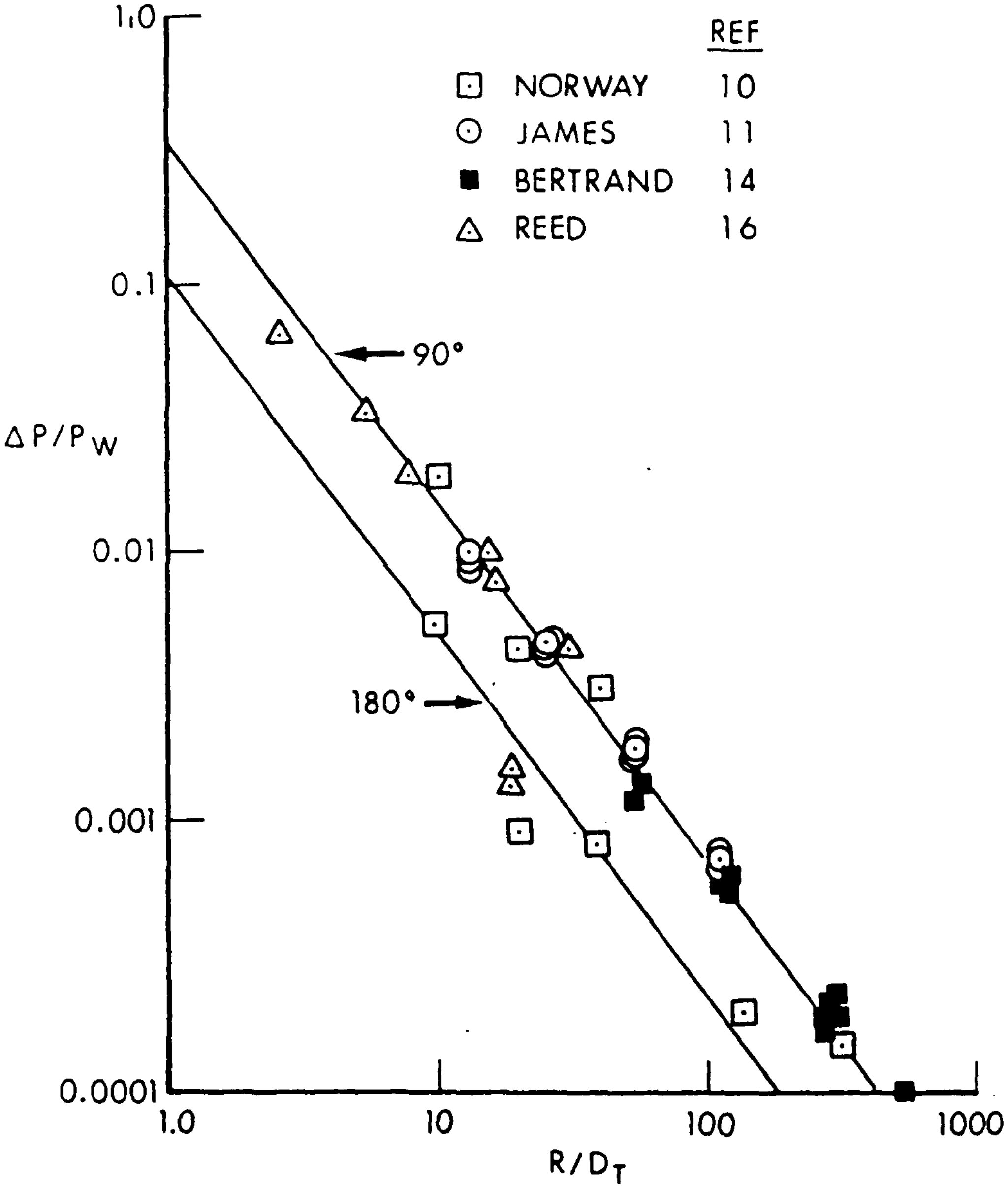


Figure 3. $\Delta P/P_W$ versus R/D_T Along Different Radials (continued)

These equations were developed by the Norwegians and presented in Reference 10. The distance R_o along the zero line for a given pressure may be multiplied by the attenuation factor,

$$AF = \left[1 + \left(\frac{\theta}{56}\right)^2\right]^{-0.74} ,$$

to obtain the distance along any radial at which the same given pressure might be expected. This attenuation factor AF is plotted versus angle off the zero axis in Figure 4. The dashed lines in Figure 4 represent the present attenuation system where sectors are used rather than a continuous attenuation.

A second method was proposed by the Norwegians.[17] In this report, equation in the form of Equation 8 was presented.

$$\Delta P/P_w = (1.2987\ R/D_t)^{-1.2987}(kn), \qquad (10)$$

where kn is an attenuation factor for different sectors. 0^o-30^o: kn = 1 and 30^o-60^o: kn = 0.74.

If we put Equation 10 into the form of Equation 9, then we have:

$$R = D_t\ (0.77)\ (P_w/\Delta P)^{0.77}(kn). \qquad (11)$$

When values of R/D_t and $\Delta P/P_w$ from this equation are compared with Figure 3, they fall below the curve established for Equation 8. The attenuation factors for distance k versus angle sectors are 0-30: kn = 1, 30-60: kn = 0.89, 60-90: kn = 0.67, 90-120: kn = 0.5, and 120-180: kn = 0.25.

Equations 10 and 11 were developed from small scale experiments and the data falls along the calculated curve, but it is recommended in this report that Equation 9 be used to calculate the distance at which selected peak overpressures should occur. This recommendation is based on the fit of data from other sources as shown in Figure 3.

2.4 Other Methods Considered. There are two other methods that were proposed for consideration as criteria for predicting the distance at which an inhabited building could be located.

The first method was submitted by the Norwegians.[20] The basic equation to predict the distance to expect a peak shock pressure of 50 mbar is as follows:

$$R_o = 18.8\ (Q/V)^{0.265}\ (Q/nk)^{0.283}, \qquad (12)$$

where Q = explosive mass in kilograms,

V = volume of storage chamber, m^3,

n = 1 when storage site has only one exit, or when there are more than one and the blast waves interact.

n = 2 when there are more than two exits and the blast waves are not expected to interact.

k = 3 if the branch passageway between the storage chamber and the main passageway has the following characteristics:

- crosssectional area is not greater than 1/2 the main passageway area,
- length is not less than 2/3 of the required interval, and
- the angle between main passageway and branch passageway is within the interval of 60° to 120°.

k = 1 for all other cases.

Equation 12 covers the section 0° to 30°. For sector 30° to 60°, the constant 18.8 is reduced to 16.9; from 60° to 90°, 18.8 becomes 12.5; from 90° to 120°, 18.8 becomes 8.1; and for 120° to 180°, the constant 18.8 is reduced to 4.7. These attenuation factors for distance are the same as the dashed lines in Figure 4. A comparison of this method with other methods will be presented later in this report.

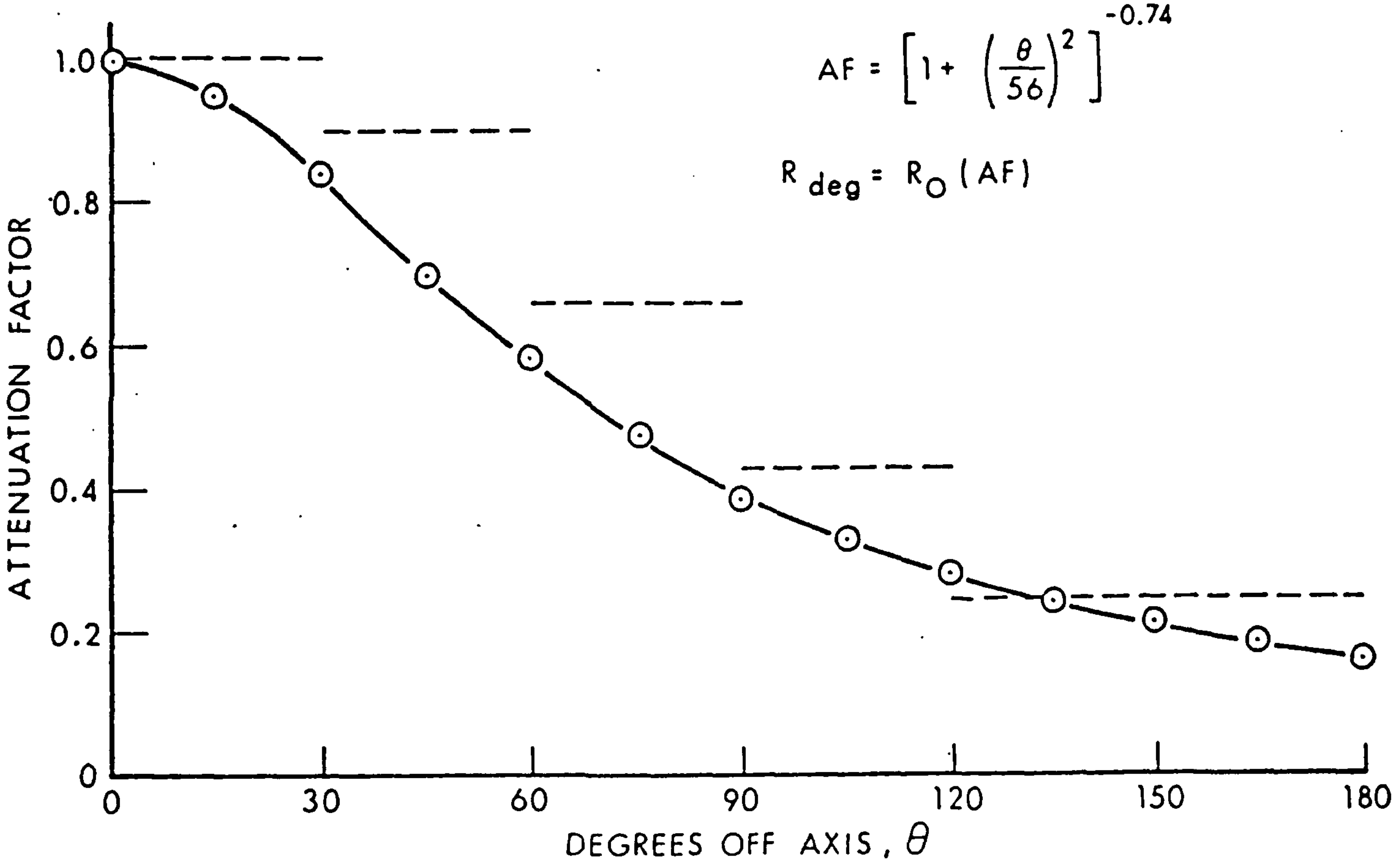


Figure 4. Attenuation Factor versus Degrees Off-Axis

A second method which is quite similar to the one just discussed was proposed by Paul Price, DOD Explosives Safety Board.[21] This equation is presented as follows:

$$R_o = F_y\ (W/V)^{0.265}\ (W/nk)^{X_y}, \tag{13}$$

where F_y is a function of explosive mass,

X_y is a function of explosive mass,

W = explosive mass in pounds, lbs,

and V = volume of storage chamber, ft^3.

n and k have the same definition as given in the previous method.

When calculating R_o for various charge masses, these factors are listed below:

0-100000		100000-250000		250000-500000	
F_y	X_y	F_y	X_y	F_y	X_y
92	0.283	5.29	0.531	115	0.283

This calculation for R_o includes the 0° to 30° sector. For the other sectors, use the dashed line attenuation factors given in Figure 4.

Both of these methods have certain requirements which must be met. The first method states that the cross-section of the main passageway must not be larger in cross-section than 20 m^2, the tunnel roughness must be at least 5%, and the length of the passageway must be at least 100 meters. There are no corrections given for smaller area tunnels, shorter tunnels, or longer tunnels.

The method proposed by Paul Price does not specify tunnel cross-sectional area, but states that if the tunnel is longer than 330 feet, then reduce the distance R_o by 23%.

A third method for comparison is the current one in Reference 22. Distances in this standard are based on the equation:

$$R_o = 76(W_t)^{1/3}, \tag{14}$$

where $W_r = W/nk$.

n and k are similar to previous description.

R_o = range, ft, and

W = explosive stored, lbs.

The loading density, chamber volume, and passageway length or diameter are not required for this method of calculation.

3. COMPARISON OF RESULTS

3.1 Description of Method.

3.1.1 Method 1. This method is published in the current safety manual[22] and will be presented to show that in most test cases, it is very conservative. Equation 14 is used in Method 1.

$$R_o\ (ft) = 76\ (W_r/nk)^{1/3},$$

where R_o is the inhabited building distance for the 0^o-30^o sector (1.2 psi or 83 mbar).

3.1.2 Method 2. Method 2 was proposed by the Norwegians in Reference 20. In Method 2, Equation 12 is used as:

$$R_o\ (m) = 18.8\ (Q/V)^{0.265}(Q/nk)^{0.283}$$

This method was detailed in Section 2.4 above.

3.1.3 Method 3. This method is similar to Method 2, with the exception of a change in constants and exponents depending on the change in mass. In Method 3, Equation 13 is used.

$$R_o\ (ft) = 92\ (W/V)^{0.265}(W/nk)^{0.283}$$

This equation is used for a W of 0 to 100000 lbs. Here again, R_o applies to the 0^o to 30^o sector.

3.1.4 Method 4. This method is one proposed in Reference 7. It requires the geometry of the storage site and mass of explosive in order to calculate the exit pressure, P_w, and a second equation is used to calculate R_o. The first, Equation 4, is

$$P_w\ (psi) = 943\ (W/V_t)^{0.607}(A_j/A_c)^{0.19},$$

then Equation 9 in English units is:

$$R_o \text{ (ft)} = D_T \ (1.173)(\Delta P/P_w)^{-0.74},$$

then attenuation factors are applied for the different radials as presented in Figure 4.

3.1.5 Method 5. This method was also developed by the Norwegians.[17] Equation 5 in English units becomes:

$$P_w \text{ (psi)} = 1064 \ (W/V_t)^{0.54}(A_j/A_c)^{0.24};$$

then Equation 11 becomes:

$$R_o \text{ (ft)} = D_t \ (0.77)(P_w/\Delta P)^{0.77}$$

where R_o is used for the 0° to 30° sector. For 30°-60°, use 0.89 R_o, 60°-90° use 0.67 R_o, for 90°-120° use 0.50 R_o, and for 120° to 180° use 0.25 R_o.

3.1.6 Method 6. This method was developed at BRL and is being proposed as a new criterion for predicting the distance at which a specific peak overpressure should occur. The major difference in this method is that the pressure in the overall chamber and tunnel volume is used in Equation 7 rather than loading density.

$$P_w \text{ (psi)} = 1.733 \ (P_{Vt})^{0.83}(A_j/A_c)^{0.19}.$$

Then Equation 9, in English units, is:

$$R_o \text{ (ft)} = D_t \ (1.173)(\Delta P/P_w)^{-0.74}.$$

3.2 Comparision of Methods. A comparision of the six methods will be made where the initial storage site parameters are the same, so that a direct comparison can be made. We will assume there is only one tunnel exit, then n = 1 and the criteria are met to make k = 1. The exit tunnel diameter is 16.6 feet and calculations will be made for the distance to 1.2 psi and 0.725 psi (50 mbar). The ratio A_j/A_c from Figure 1 is 0.23.

3.2.1 Comparision of Six Methods - Increase in Charge Mass. In Table 2, the volume of the storage chamber and the passageway tunnel remained constant while the amount of explosive was increased from 2204 lbs to 11020 lbs, an increase of five times. The increase in distance ranged from a factor of 1.71 to 2.41. With the exception of Method 1, the spread of distances for the five other methods is within ± 11%.

TABLE 2. Comparison of Six Methods - Increase in Charge Mass

Method	Charge Mass W (lbs)	Loading Density W/V_c (lbs/ft^3)	W/V_t (lbs/ft^3)	1.20 psi R_o-ft	0.725 psi R_o-ft	P_w psi
1	2204	0.062	0.021	989	--	--
2	2204	0.062	0.021	--	436	--
3	2204	0.062	0.021	389	--	--
4	2204	0.062	0.021	386	561	68
5	2204	0.062	0.021	364	537	93
6	2204	0.062	0.021	444	644	82
1	11020	0.312	0.105	1691	--	--
2	11020	0.312	0.105	--	1052	--
3	11020	0.312	0.105	941	--	--
4	11020	0.312	0.105	797	1157	181
5	11020	0.312	0.105	709	1045	221
6	11020	0.312	0.105	800	1162	182

NOTE: Storage site dimensions constant.

3.2.2. Increase in Chamber Volume and Explosive Mass. In Table 3, the amount of explosive was increased by a factor of 10, and the chamber volume was increased by a factor of 10, so the loading density remained the same (0.624). The volume of the tunnel passageway was increased approximately 30%. This changed the loading density of the total volume from 0.211 to 0.499. The distances calculated for 1.2 and 0.725 psi at the 0.211 loading density are within ± 7% with the exception of Method 1. When the loading density of the total volume was changed to 0.499, the spread of distances increased to ± 20%. Methods 4-6 are usually quite consistent in that Method 5 calculates values that are less than the other two.

TABLE 3. Comparison of Six Methods - Increase in Charge Mass and Total Volume

Method	Charge Mass W (lbs)	Loading Density W/V_c (lbs/ft^3)	W/V_t (lbs/ft^3)	1.20 psi R_o-ft	0.725 psi R_o-ft	P_w psi
1	22040	0.624	0.211	2131	--	--
2	22040	0.624	0.211	--	1539	--
3	22040	0.624	0.211	1379	--	--
4	22040	0.624	0.211	1092	1586	277
5	22040	0.624	0.211	947	1397	322
6	22040	0.624	0.211	1080	1569	273
1	220400	0.624	0.499	4590	--	--
2	220400	0.624	0.499	--	2952	--
3	220400	0.624	0.499	2470	--	--
4	220400	0.624	0.499	1607	2334	467
5	220400	0.624	0.499	1356	1999	513
6	220400	0.624	0.499	1617	2348	471

NOTE: Explosive mass and chamber volume increased 10 times and total volume increased 4 times.

3.2.3 <u>Comparision of Six Methods - Decrease in Tunnel Diameter.</u> In table 4, the explosive mass was increased to 500000 lbs. The loading density of the chamber and total volume remained the same. The only difference is in the diameter of the exit tunnel. Here you can see that Methods 1-3, which do not use the tunnel diameter in their equations, have the same calculated distance, while Methods 4-6 show a reduction in distance of approximately 39%, which corresponds to the reduction in tunnel diameter.

Table 4. Comparision of Six Methods - Decrease in Tunnel Diameter

Method	Charge Mass W (lbs)	Loading Density W/V_c (lbs/ft^3)	Loading Density W/V_t (lbs/ft^3)	1.20 psi R_o-ft	0.725 psi R_o-ft	P_w psi	Tunnel Diameter (ft)
1	500000	6.24	4.99	6032	--	--	16.6
2	500000	6.24	4.99	--	6790	--	
3	500000	6.24	4.99	7609	--	--	
4	500000	6.24	4.99	4519	6561	1888	
5	500000	6.24	4.99	3535	5211	1780	
6	500000	6.24	4.99	6310	9161	2964	
1	500000	6.24	4.99	6032	--	--	10.0
2	500000	6.24	4.99	--	6790	--	
3	500000	6.24	4.99	7609	--	--	
4	500000	6.24	4.99	2722	3952	1888	
5	500000	6.24	4.99	2129	3139	1780	
6	500000	6.24	4.99	3800	5518	2964	

3.3 Tunnel Junctions. When there are two exit tunnels and they are separated enough so that there is no enhancement between them, in Equation 13 the value of n becomes 2. When Method 3 is used to calculate values in Table 2 for an explosive mass of 11020 lbs and a loading density of 0.312 lbs/ft^3, then R_o was calculated as 941 feet. If a value of n = 2 is used in Equation 13, the distance is reduced to 767 feet.

It is suggested by the author that a new approach be taken when there are tunnel branches or junctions. This new method would reduce the transmitted pressure by factors based on shock tube experiments. These reduction factors are presented in Figure 5 and are based on data in Reference 23. The 90^o tunnel junction data do not follow a simple equation and, therefore, the curve presented in Figure 6 should be used.

If we make a comparison between Methods 3 and 6 and assume a Y junction in the tunnel system that gives two exit tunnels that do not cause any exterior enhancement, then the inhabited building distance will change as follows. Using the 11020 lbs in Table 2, the distance using Method 3 is 941 feet. If we use n = 2 in Equation 13, this distance reduces to 767 feet. This is a reduction of approximately 18%.

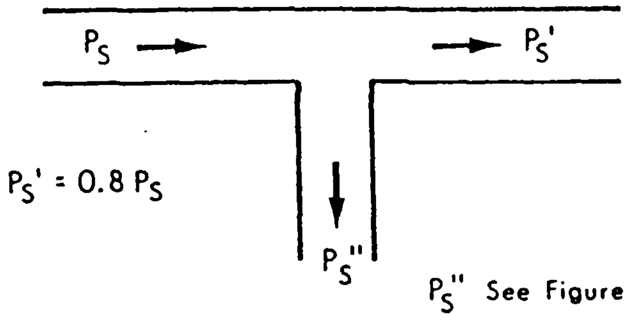
Now using Equation 7 to calculate P_w, we find P_w equal to 182 psi. With a Y junction as shown in Figure 5c, P_w would be multiplied by 0.65 to become 118 psi. With P_w equal to 118 in Equation 9, the inhabited building distance reduces from 800 feet down to 581 feet. This is a reduction of 27%.

This implies that using n = 2 may be conservative and that the 941 feet should reduce to 687 feet rather than 767 feet.

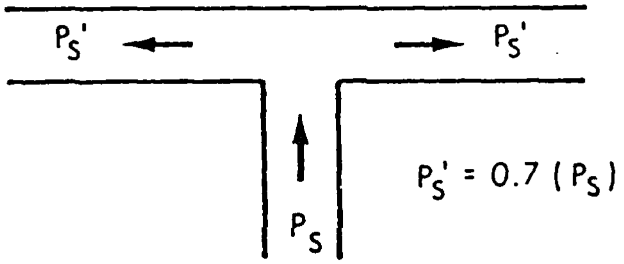
It should also be noted that with a tunnel junction as shown in Figure 5a, there would be different exit pressures at the end of the two tunnels. The inhabited building distance would also be different in front of the two exits.

The reduction in pressure propagating through the different junctions applies only if the tunnel cross sectioned area of each branch remains the same. In configurations where there is a reduction or increase in the cross section area of the tunnel, then these conditions should be treated on an individual basis.

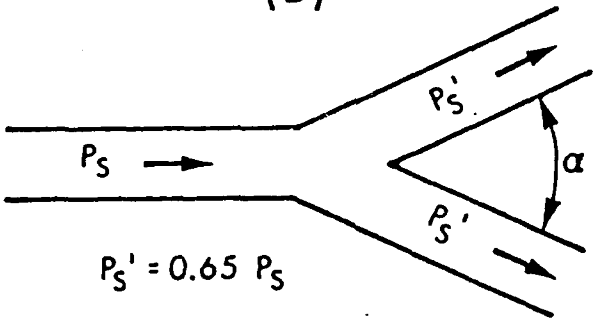
An extensive series of tests were conducted by Switzerland.[24] The values given in Figure 5 compare quite well with the results reported in Reference 24. The BRL value of transmitted pressure of 0.80 P_s in Figure 5a compares with a Reference 24 value of 0.83 P_s.



90 Degree Side Tunnel
(A)



90 Degree Dead-end Tunnel
(B)



Y Junction
(C)

Figure 5. Transmitted Pressure versus Input Pressure for Various Tunnel Junctions

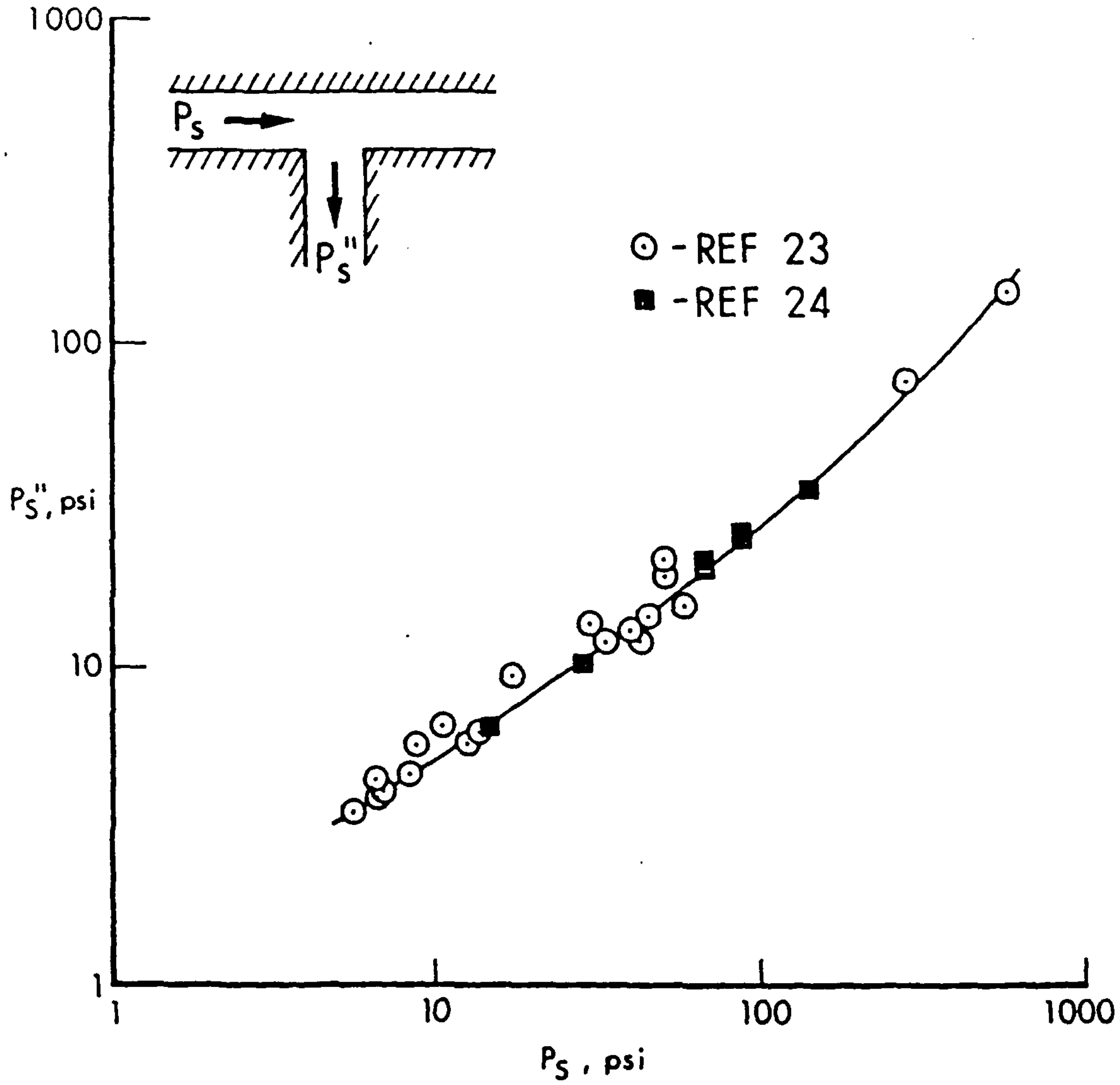


Figure 6. Incident versus Transmitted Shock Overpressure for Tunnel Joined to an Equal Area Tunnel

The side tunnel (Figure 5a) values from Reference 24 are plotted in Figure 6 along with the BRL-generated curve. The 90^o dead-end tunnel (Figure 5b) value for the transmitted shock is 0.7 P_s, while the Reference 24 value shows a spread of 0.57 P_s to 0.68 P_s, which appears to be partially a function of incident pressure. The Y junction transmitted pressure values from Reference 24 for equal to 15^o through 90^o range from 0.65 P_s at 14.5 psi down to 0.58 P_s at 130 psi. This compares with a value of 0.65 P_s developed in Figure 5c from BRL data in Reference 23.

4. CONCLUSIONS

4.1 Weaknesses. It is impossible to establish one or two equations that will be universally accepted and that fit all underground storage sites. This report has presented, discussed, and compared the results of six methods proposed for determining the safe, inhabited building distance. All methods have certain weaknesses, some more than others. In the opinion of the author, certain parameters should be known. These are as follows:

Storage Chamber Volume
Exit Tunnel Volume
Loading Density
Explosive Distribution and Containment
Chamber Pressure for Specific Explosives
Chamber Diameter
Tunnel Diameter
Tunnel Junctions (If any.)
Tunnel Roughness
Terrain Outside of Tunnel

All of these variables will affect in some way the overpressure propagated outside of the tunnel. One other variable not dealt with is the location, confinement, and point of initiation of the explosive source. The major portion of scaled model tests has been conducted with linear charges placed along the centerline of the chamber or near spherical charges placed near the entrance to the storage chamber. When in a real storage scenario, there will be pallets and boxes of munitions stored throughout the chamber and on the floor. Most of the munitions will have some kind of containment, from the thin skin of rocket motors to the thick casing of general purpose bombs. The effect of containment on the build-up of gas pressure within the storage chamber has not been fully addressed.

4.2 Recommendations. It has been shown that Methods 4 or 6 give the most consistent values, and the inhabited building distances vary only a few percent in the medium loading densities, i.e., less than 0.624 lb/ft^3. At the higher loading densities, it is recommended that Method 6 be used in any prediction calculation. It can be seen in Figure 2 that using the loading density (W/V_t) as an input parameter in Equation 4 will give different exit pressures, than using the static pressure (P_{Vt}), which is based on (W/V_t) as the input parameter in Equation 7.

Having available this list of ten variables, there is still no assurance that a precise prediction can be made. The methods presented here should be used as guides and not for planning and construction of new sites. When planning the location of a new site, it is recommended that a scaled model of the site be constructed and tests conducted to determine the range for inhabited buildings. This is also true where there may be a controversy over a specific, existing site.

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