Probability of Prevention of Explosive Propagation and Personnel Injury by Protective Walls

by:
C. E. McKNIGHT
PICATINNY ARSENAL, DOVER, N. J.

Abstract & Introduction

This paper deals with the details of calculating the probability of detonation occurrence in an explosive (acceptor) system or personnel injury resulting from detonation of an adjacent explosive system (donor) when the donor is separated from the acceptor or personnel by an intervening protective wall.

The capacity of a wall to confine explosions can be measured by the probability of occurrence of the secondary explosion or personnel injury at the opposite side of the wall. In all cases of flying fragments, either steel or concrete, both large and small, knowledge of the fragment size, velocity, acceptor distance-from-wall, acceptor size and acceptor sensitivity lead to a calculated probability of propagation.

The theory upon which the fragment probability rests is based on determining the mass-velocity distribution of the fragments and calculating how many could cause a detonation by virtue of their mass and velocity, if impact occurs. When the fragments are large, like spalls and chunks of a wall, the level of kinetic energy or momentum of the chunks is used to determine if they could cause detonation. Having determined the number of "potent" fragments, the number of them that can be expected to result in impact, the distances and acceptor sizes can be used to calculate a probability of detonation or damage to personnel due to fragments.

As a less important cause of damage, blast from the donor may reach the acceptor or personnel. Since blast is continuous, and not discrete, as in the case of fragments, the "explosion pressure" at the acceptor is a measure of the capacity of the walls for safety. If the donor explosive weight, wall height and distances from the wall are known, the "explosion pressure" at the acceptor or personnel area is calculable. The pressure being continuous, the probability is unity that the acceptor will "feel" the pressure. Therefore, from the pressure sensitivity of the acceptor, or the pressure tolerance of personnel, an assessment of "safe" or "unsafe" can be made.

The final assessment in all cases is "safe" or "unsafe" to the acceptor regardless of how much damage would occur to the wall. The degree of protection to be afforded the acceptor must be specified in each case. Having decided upon an acceptable level of safety, the design of protective walls can proceed with a great deal of insight into the question of whether the thickness, height or minimum permitted distances are realistic.

Probability of Detonation Propagation

In an explosive system failure to prevent detonation propagation may take place in various ways summarized for convenience in Table 1.

TABLE 1

Modes of Failure in Explosive System

Donor Effect	Mechanism	Input to Acceptor (Output from Mechanism)
1. Blast	A. Direct	Blast
	B. Walls	
	1. Leakage	Blast, reduced
	2. Shear (punching)	Secondary missiles
	3. Spalling	Secondary missiles
	4. Collapse	Secondary missiles
2. Primary Missiles	A. Direct	Primary missiles
	B. Walls	
	1. Perforation	Secondary missiles Slowed primary missiles
	2. Spalling	Secondary missiles
3. Miscellaneous		

The presence of unknown effects renders the situation typical for the use of probability as a means of comparing safety design calculations and of terminating or evaluating a safety design of structures to handle large amounts of explosive.

It is our basic assumption that a donor detonation has occurred. An interaction with the acceptor must occur by way of at least one of the mechanisms. Following impact, the acceptor sensitivity to missiles or blast must be such that the impact results in detonation. Thus if P_i and P_S are the probabilities of impact and sufficient impact respectively, these being independent events, the probability of detonation by way of any one mechanism alone is

$$P_{Dn} = (P_i \times P_S)_n$$

where n refers to the mode of failure in question. For all modes together, the probability is that of a mutually exclusive set of events. The overall probability of detonation is, P_o (see Nomenclature List)

$$\begin{aligned} P_o &= \sum^{n} P_{Dn} - \text{Interactions} \\ &= (P_i\ P_S)_{B1} + (P_i\ P_S)_{B2} + (P_i\ P_S)_{B3} + (P_i\ P_S)_{B4} \\ &\quad (P_i\ P_S)_{M1} + (P_i\ P_S)_{M2} \\ &\quad - \text{interactions.} \end{aligned}$$

The interactions are the corrections to be applied for the fact that since any one mode may cause detonation, the overall probability of detonation is less than the simple sum of probabilities of all possible events. It is sufficient to consider this term zero since its maximum for any pair of events cannot be greater than the greater of the two. A zero value is conservative.

The probability of impact due to blast is considered 1.0 in every case in which blast occurs as an input to the acceptor. This occurs only in two cases; blast without walls, and leakage around walls. The probability of detonation due to blast when impact is certain depends upon the blast sensitivity of the acceptor. This is determined by using various weight and distances between a donor explosive and many acceptors. The number of goes and no-goes at each distance-weight combination is recorded and a superficial probability of detonation is computed from the percentage of goes. This much of the procedure is subject to check by experimentation at a relatively reasonable cost.

To establish the probability region of interest to safety calculations the experimental, superficial probabilities are correlated simultaneously with distance and weight using a suitable multiple regression function. In this way the locus of probabilities in the region of 10^{-2} to 10^{-4}% are located in distance-weight coordinates. These values would be impossible to verify, except at great cost because of the large number of trials that would be required. Nevertheless they reflect actual sensitivity experience and represent an objective approach to safety determination. For the blast sensitivity of the example used in this paper, the standard normal probability function was used in log-log coordinates with a transformation of the distance parameter. The distance transformation was required to make the desired function reflect the experimental fact that the probabilities do not increase or decrease indefinitely with distance.

The case B2, shear failure resulting in punching, is a case of secondary missile damage. Analytical studies have shown the method if the weight and velocity of a punched-out piece of the donor and wall dimensions are known. As this piece leaves the wall it may go in any direction from the center, thus "searching" an area that can be calculated by assuming an 80° cone from the point of punching. The area of the base of this cone will be designated the search area, A_S. The probability for impact of any one punched-out piece is the ratio of the acceptor area to the search area. The piece is visualized as breaking into halves, thirds, quarters, etc. each in turn. Large pieces can cause detonation by a glancing hit, this is allowed for by increasing the acceptor area to include itself and the space occupied by the punched-out piece on all sides around the acceptor.

The probable number of effective hits is then

$$N = N_x \frac{A_{AL}}{A_S} = N_x \frac{(2\ dm + da)^2}{(1.67\ d)^2}$$

The probability of at least one hit is then the probability of missile impact,

$$P_{iB2} = 1 - e^{-N}$$

The sensitivity of acceptors to large missile like chunks of concrete can be based on kinetic energy or on a related function in an approximate but satisfactory manner. As with blast sensitivity one plots the kinetic energy at which various weights and velocities have caused detonations, fits a suitable regression curve to the go-no-go data and extrapolates to the region of low probability. A function that has been used is:

$$\log \log P_{SB2}/100 = \log \frac{1}{K.E.} + \text{const.}$$

For each of the above described pieces the probability based on sensitivity is found. Since the weight of halves is half that of the original piece, the sensitivity becomes less dangerous, but the number of missiles becomes greater, causing an increase in P_{iB2}. The maximum $(P_i \times P_S)_{B2}$ is taken as the value for probability of detonation due to failure mode B2.

Likewise for spalling and collapse, analytical methods permit the prediction of the kind of secondary missiles that are generated due to blast from the donor. A probability of impact in each case and the probability of detonation based on sensitivity are then found and their products taken. In this way all the probabilities of detonation, either by missile or blast, associated with blast impact to the wall are found.

If the donor is cased it can produce primary missiles striking against the wall. A wall may be perforated by the largest missiles. If so, the velocity versus size distribution is found by calculating the residual velocity of the missile for a selection of perforating weights. From fragment collection studies on the donor one finds the number of missiles having weights equal to or greater than the smallest perforating piece.

Experimental data from firing fragments of various sizes at various velocities into acceptors gives a missile sensitivity curve that is conveniently taken as representing a detonating probability of 1.0 (of course, if the data are known to be the 50% points widely used in vulnerability studies a probability of 0.50 could be used instead of 1.0). When using a fixed value for the sensitivity probability, only those missiles having the required weight or velocity are considered in getting the impact probability. Since detonation, if impact occurs, may be considered certain in safety calculations for these selected missiles,

$$P_{iM1} = 1.0$$

The number of missiles of any given weight which proceed from the donor is found from fragment collection experiments to be predictable if the dimensions of the donor are known. The missiles are somewhat more direction than an even spherical distribution; the probability of any one impacting the acceptor is the presented area of the acceptor per unit spherical surface area of sphere around the donor, corrected for directional effect. The result is that the probable number of missiles impacting the acceptor is,

$$N = 0.1N_x \frac{A_A}{d^2}$$

where the factor 0.1 is to correct for directional effects, N_x is the number of missiles which could cause detonation if impact takes place, A_A is acceptor presented area and d is distance from acceptor to donor.

To find N_x, the residual velocity from the wall and weight of the perforating missiles is compared to the sensitivity curves. Their intersection defines the smallest "effective" missile. The fragment velocity studies then permit calculating N_x, the number of missiles having weight equal to or greater than that of the minimum effective missile. N is the expected number of impacts. The chance of only one impact is, as before, (see Figure 1).

$$P_{iM1} = 1-e^{-N}$$

Spalling due to missiles is handled like spalling due to blast. Thus all probabilities of impact and of detonation due to sensitivity are found. A set of possible values is shown in Table 2, the table of combined and overall probability.

TABLE 2

Overall Probability

Missiles	Impact Prob.		Sensit. Prob.		Combined (product)	
Perforation	P_{iM1}	.005	P_{SM1}	1.0	$(P_iP_S)_{M1}$	0.005
Spalling	P_{iM2}	-	P_{SM2}	0	$(P_iP_S)_{M2}$	0
Blast						
Leakage	P_{iB1}	1.0	P_{SB1}	.03	$(P_iP_S)_{M1}$	.03
Punching	P_{iB2}	.02	P_{SB2}	.50	$(P_iP_S)_{M2}$	.10
Spalling	P_{iB3}	.002	P_{SB3}	.30	$(P_iP_S)_{M3}$	.0006
Collapse	P_{iB4}	.30	P_{SB4}	.40	$(P_iP_S)_{M4}$	.120
					P_o =	0.2556

The overall probability of detonation, with probability interaction conservatively taken as zero, is 25%. This would be considered unsafe. The designer must now pick on the high probabilities and redesign so as to increase the safety of the explosive system, or declare its impossibility. In the later case he has ample proof for his position.

This analysis points out that not only must every mode of failure be safe, but all must be safe enough with a margin to allow for additivity.

Typical figures in Table 2 indicate that spalling is unimportant. This is believed to be the situation in many cases, but it should be considered at the start of every new problem.

It should be pointed out that the attempt at safety calculations involving propellants and explosives in a state of development may be defeated by the lack of sensitivity data, i.e. by a state of complete ignorance as to whether a new high energy composition might be detonable. A method has been devised to test small samples for the ability to detonate if burning starts. In this procedure a transition pressure is found for any propellant which correlates with the detonability of conventional high explosives. Propellants and explosives can thus be classified as mass-detonating or not using the procedure in one of the references.

The probability calculation represents a balance between the following parameters and any parameters which may be subsidiary to these:

Acceptor:	Wall:	Donor:
Area	Thickness	Distance
Distance	Height	Case
Case		Material
Material and Wt.		Explosive output
Sensitivity		Blast
Blast		Missile
Missile		Velocity
Chunks		

Depending upon the relative magnitude of these parameters, the various modes of failure assume greater or less importance. Thus the effect of some fifteen or twenty factors is evaluated objectively in one figure, the overall probability of detonation, P_O.

A major advantage of reducing the tangible effects to an objective figure is that the tangible considerations can be handled as a matter of routine, leaving the intangible factors to be reduced by judgement of those who are most experienced in the industry. An additional advantage is that when large uncertainties are shown to exist due to lack of data, a proper justification and allocation of funds for large programs can be prepared.

Personnel protection follows the principle given here with the additional restriction that the probabilities should be reduced to the equivalent of zero by designing so that the calculated number of missiles, punchings, and spalls are less than one (i.e. effectively zero); and designing blast resistant shelters to protect against blast and leakage.

NOMENCLATURE

A_A = presented area of acceptor, sq. ft.

A_{AL} = lethal area of acceptor, sq. ft.

A_S = area searched by missiles after punching, sq. ft.

d = distance from source of missile to acceptor, ft.

d_m = diameter of missile due to punching, ft.

d_r = diameter of round acceptor, ft.

e = base of natural logarithms.

K.E. = kinetic energy of large missile at acceptor, ft.-lbs.

N = probable number of impacts

N_x = number of missiles having weight and velocity suitable for causing detonation if an impact occurs.

P = probability of impact or detonability or both associated with a given mechanism of transfer or mode of wall failure.

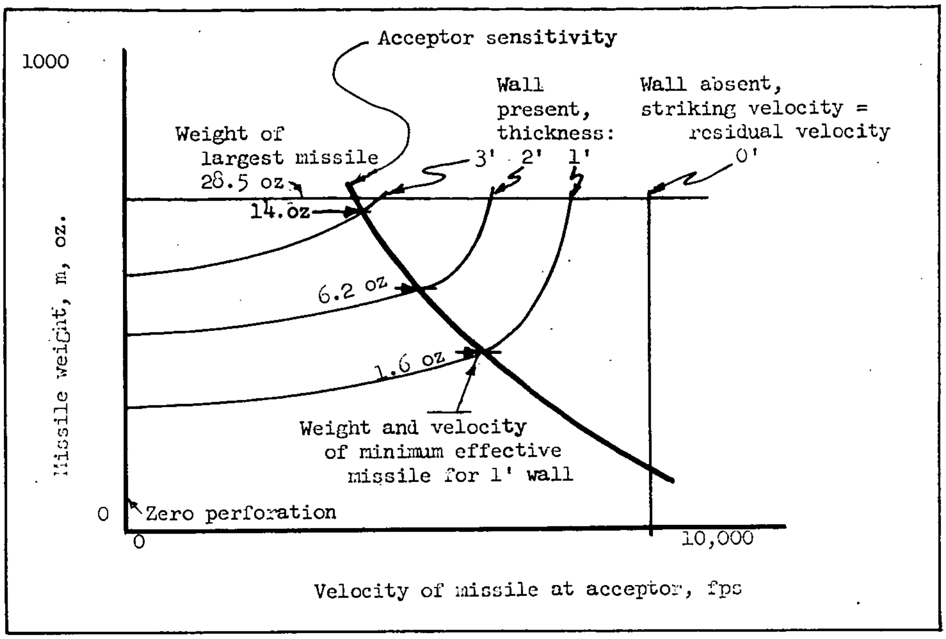
Subscripts to P:

i = impact; S = sensitivity (detonability); M = missile donor effect;

B = blast donor effect; n = 1,2, etc. acceptor effect tabulated below;

D = detonation.

	Probability of Impact	Sensitivity Probability (Detonability)	Combined
General case	P_{in}	P_{Sn}	$(P_iP_S)_n$
Specified mechanisms			
Missiles: perforation	P_{iM1}	P_{SM1}	$(P_iP_S)_{M1}$
spalling	P_{iM2}	P_{SM2}	$(P_iP_S)_{M2}$
Blast: leakage	P_{iB1}	P_{SB1}	$(P_iP_S)_{B1}$
punching	P_{iB2}	P_{SB2}	$(P_iP_S)_{B2}$
spalling	P_{iB3}	P_{SB3}	$(P_iP_S)_{B3}$
collapse	P_{iB4}	P_{SB4}	$(P_iP_S)_{B4}$



Illustrative Numerical Quantities *

Missile weight m ounces	Number of effective missiles, N_x, heavier than m	Probable number of hits for each wall, N	Probability of detonation for each wall, P_{iM2}
28.5	1	0.0058	0.005
14.0	15	0.0861	0.57
6.2	184	1.06	0.65
1.6	1,800	10.4	1
0.0	26,500	-	-

* Actual quantities depend on all parameters in the explosive system.

Figure 1. Nomenclature and relationships for perforation of wall by missiles from donor explosive.

REFERENCES

1. Rindner, R. M. and Wachtell, S. Establishment of Safety Design Criteria for Use in Engineering of Explosive Facilities and Operations. Report No. 3: Safe Distances and Shielding for Prevention of Propagation of Detonation by Fragment Impact. Picatinny Arsenal Technical Report DB-TR: 6-60, December 1960 (Classified)

2. Ammann and Whitney, Consulting Engineers. Industrial Engineering Study to Establish Safety Design Criteria for Use in Engineering of Explosive Facilities and Operations: Wall Responses. Prepared for Picatinny Arsenal under Contract No. DA-28-017-ORD-3889, April 1963

3. McKnight, C. E., Shulman, L., and Wachtell, S. Establishment of Improved Standards for Classification of Explosives and Propellants, Report No. 1: A Method for Determination of Susceptability of Propellants and Explosives to Undergo Transition from Deflagration to Detonation. Picatinny Arsenal Technical Report DB-TR: 3-61, June 1961. Also available in ONR Symposium Report ACR-52, Vol. 2, p. 635, Third Symposium on Detonation, James Forrestal Research Center, Princeton University, September 1960 under sponsorship of Naval Ordnance Laboratory (White Oak) and Office of Naval Research.