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TECHNICAL MEMORANDUM 1311

PROBABILITY OF PREVENTION OF EXPLOSIVE PROPAGATION AND PERSONNEL INJURY BY PROTECTIVE WALLS

CHARLES E. McKNIGHT

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MARCH 1964

PICATINNY ARSENAL
DOVER, NEW JERSEY

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PROBABILITY OF PREVENTION OF EXPLOSIVE PROPAGATION AND PERSONNEL INJURY BY PROTECTIVE WALLS

BY

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MARCH 1964

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FOREWORD

This Technical Memorandum was presented at the 145th National Meeting of the American Chemical Society in New York City in September 1963.

The paper was given as part of the Symposium on Explosives and Hazards and Testing of Explosives organized by Dr. M. A. Cook of the University of Utah and Intermountain Research and Engineering Company. The symposium was under the auspices of the Division of Fuel Chemistry, with R. S. Montgomery of the Dow Chemical Company as chairman, and J. D. Clendenin of U. S. Steel Corporation as program chairman.

A preliminary version of the paper is recorded in Volume 7, Number 3 of the Division of Fuel Chemistry preprints. The present composition of the paper includes typographical and technical corrections resulting from discussion and critical reading subsequent to presentation.

Formal publication of this paper and others of the symposium is expected as a separate ACS volume.

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ABSTRACT

If a first explosive, the donor, detonates, the detonation may cause damage to a second body of explosive, the acceptor, in the form of a second detonation, or it may cause injury to personnel. The details of calculating the probability of second detonation or injury in the presence of an intervening protective wall are explained.

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 distance 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 assessement 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 PREVENTION OF EXPLOSIVE PROPAGATION AND PERSONNEL INJURY BY PROTECTIVE WALLS

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

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

I. FAILURE MODES AND PROBABILITY

It is our basic assumption that a donor detonation has occurred.

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		

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 (mechanism) of failure in question. For all modes together, the probability is that of a mutually exclusive set of events. The over-all probability of detonation is P_o (see Nomenclature List and Table 2 for meaning of symbols):

$$P_o = \sum^{n} P_{Dn} - \text{Interactions}$$

$$= (P_i\ P_S)_{B1} + (P_i\ P_S)_{B2} + (P_i\ P_S)_{B3} + (P_i\ P_S)_{B4}$$

$$(P_i\ P_S)_{M1} + (P_i\ P_S)_{M2}$$

$$- \text{interactions}$$

The interactions are the corrections to be applied for the fact that since any one mode may cause detonation, the over-all 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 lesser of the two. A zero value is conservative.

II. BLAST

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 weights 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.

A. PUNCHED-OUT MISSILES DUE TO BLAST

The case B2, shear failure resulting in punching, is a case of secondary missile damage. Analytical studies have shown the method of determining the weight and velocity of a punched-out piece if the donor, weight, distance 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 in the plane of the acceptor 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 <u>all</u> sides around the acceptor in the plane of the acceptor.

The probable number of effective hits is then

$$N = P_{iB2(1)} N_x = N_x \frac{A_{AL}}{A_s} = N_x \frac{(2\text{ dm} + \text{da})^2}{(1.67\text{ d})^2}$$

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

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

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:

$$\log \log P_{SB2}/100 = k_1 \log KE + k_2$$

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, causing a decrease in P_{SB2}; 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.

B. SPALLING- AND COLLAPSE- MISSILES DUE TO BLAST

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. The number and size of spalls follows from the magnitude of impulse loading compared to the tensile strength of the wall material. A simple approximation to the size of pieces in total collapse is provided by studies on large slab break-up: the number of missiles is simply taken as one (whole wall), two (equal half-pieces of the wall) three (equal thirds), four, etc. and treated as given above under Case B2.

III. PRIMARY MISSILES

A. PRIMARY MISSILES AFTER PERFORATION

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 a fixed value for the sensitivity probability is used, 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,

$$P_{SM1} = 1.0$$

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 directional than would be given by 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,

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

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

To find N_x, the weight of the perforating missiles and their residual velocity from the wall are compared to those of the sensitivity curves. The intersection (Figure 1) 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 impacting missiles out of N_x effective missiles. The chance of only one impact, is, as before,

$$P_{IM1} = 1-e^{-N}$$

B. SPALLING DUE TO PRIMARY MISSILES

Spalling due to missiles is handled like spalling due to blast. The size and velocity of the spall are calculated analytically. The probability of impact is found from size and distance. The probability of detonation due to sensitivity is found as already described. The probability of detonations due to both impact and sufficient impact (sensitivity) is taken as the product of the two individual probabilities to give $(P_I\ P_S)_{M2}$. When acceptor sensitivity is considered it may be found that the spalls are so slight that they represent virtually no possibility of detonation. In such a case, calculation of impact probability is rendered unnecessary.

IV. OVER-ALL PROBABILITY OF DETONATION

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 over-all probability.

TABLE 2

OVER-ALL PROBABILITY

Missiles	Impact Probability		Sensitivity Probability		Combined (product)	
Perforation	P_{iM1}	.005	P_{SM1}	1.0	$(P_i\ P_S)_{M1}$	0.005
Spalling	P_{iM2}	---	P_{SM2}	----	$(P_i\ P_S)_{M2}$	-----
Blast						
Leaking	P_{iB1}	1.0	P_{SB1}	0.3	$(P_i\ P_S)_{B1}$	0.03
Punching	P_{iB2}	0.02	P_{SB2}	0.50	$(P_i\ P_S)_{B2}$	0.10
Spalling	P_{iB3}	0.002	P_{SB3}	0.30	$(P_i\ P_S)_{B3}$	0.0006
Collapse	P_{iB4}	0.30	P_{SB4}	0.40	$(P_i\ P_S)_{B4}$	0.120
					P_o =	0.2556

The over-all probability of detonation, with probability interaction conservatively taken as zero, is 25%. This would be considered "unsafe", relative to some previously adopted value of P_o. 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 latter case he has ample proof for his position.

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 for any propellant is found which correlates with the detonability i.e., sensitivity of conventional high explosives. Propellants and explosives can thus be classified as mass-detonating or not using the procedure in one of the references.

V. PERSONNEL PROTECTION

Personnel protection follows the principles given here with the additional restriction that the impact 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.

VI. CONCLUSIONS

Performance of such an analysis discloses the unavoidable conclusion that not only must the wall be safe with respect to every mode of failure, but must be safe enough to allow a margin for additivity.

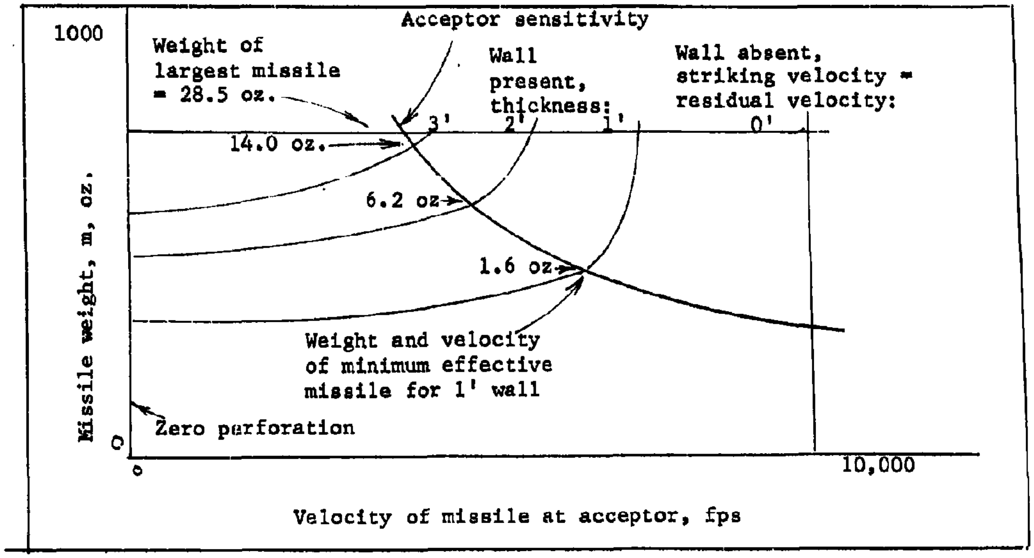
Typical figures in Table 2 indicate that spalling is unimportant. Although this is believed to be the situation in many cases, spalling should be considered at least at the start of every new problem.

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 judgment 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 can be prepared for large programs to investigate and remove the uncertainties.

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		Thickness
Thickness		Explosive Output
Sensitivity		Blast
Blast		Missile Velocity
Missile		Missile Weights
Chunks		

Depending upon the relative magnitude of these parameters, the various modes of failure assume greater or less importance. Thus the effect of some 15 or 20 factors is evaluated objectively in one figure, the over-all probability of detonation, P_O. Hence, the over-all probability of detonation propagation can be taken as a merit index to compare or evaluate safety aspects of structure designs.



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_{1M2}
28.5	1	0.0058	0.005 for 4" wall
14.0	15	0.0861	0.570 for 3" wall
6.2	184	1.06	0.650 for 2" wall
1.6	1,800	10.4	1.000 for 1" wall
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

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_a = diameter of round acceptor, ft.

e = base of natural logarithms

KE = 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

<u>Subscripts to P:</u>

i = impact

S = sensitivity (detonability)

M = missile donor effect

B = blast donor effect

n = 1, 2, etc. acceptor effect tabulated below

D = detonation

o = over-all

(1) this subscript in $P_{iB2(1)}$ refers to the probability of at least one fragment impacting

continued

NOMENCLATURE (CONT'D)

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

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ABSTRACT DATA

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Picatinny Arsenal, Dover, New Jersey

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Technical Memorandum 1311, March 1964, 14 pp. Unclassified report from the Processing Engineering Laboratory, Ammunition Engineering Directorate.

Given the occurrence of an initial large detonation in a storage or manufacturing facility for explosives, the probability of the spread of detonation can be estimated as a function of explosive quantity, barrier strengths and separation distances. Conversely these parameters can be established at values consistent with predetermined probabilities for safety.

The mechanisms of detonation propagation are classified and means described for assessing the hazard associated with each.

The analysis of detonation over-all probability provides a means of either automatic computer treatment or manual calculation of safety and it results in an index of safety for the judging of protective buildings, walls and magazines.

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Safety
Propagation
Probability
Storage
Missiles
Blast
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