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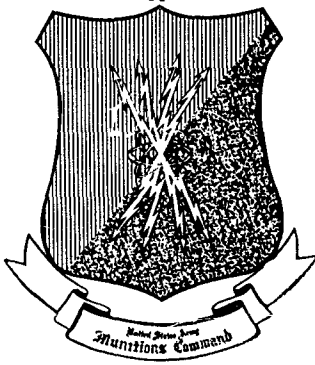
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TECHNICAL MEMORANDUM 1063

ANALYSIS
OF
CERTAIN ASPECTS
OF
PROTECTIVE WALL DESIGN

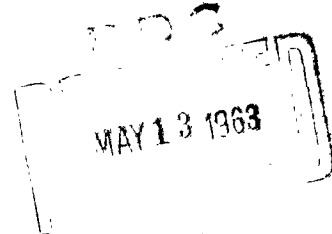
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FEBRUARY 1963

PICATINNY ARSENAL
DOVER, NEW JERSEY



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AMMUNITION GROUP

ANALYSIS
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OF
PROTECTIVE WALL DESIGN

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FEBRUARY 1963

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FOREWORD

The material contained in this Technical Memorandum was the subject of a presentation made during the Explosive Safety Seminar on High Energy Solid Propellants at the Langley Research Center, Virginia, 7-9 August 1962, and was published in the seminar's official minutes.

SUMMARY

This paper deals with two aspects of the Picatinny Arsenal program for establishment of safety design criteria, each of which is concerned with optimization of cubicle-type protective structures for manufacture and storage of explosives and/or high energy propellants. The first part of the paper considers the relative protection effectiveness of different materials of construction. The second part deals with determination of optimum explosive charge distribution within a cubicle for minimization of explosion effects. Illustrative examples are presented in each case.

ADDENDUM

Subsequent to the presentation of this paper in August, 1962, certain revisions have been made to the relationships defining blast reflection factors used in the illustrative examples. Based on these revisions, reflection effects as described in this paper are conservative. Moreover, these revisions do not alter the design principles discussed in this paper.

**PART I: COMPARISON OF EFFECTIVENESS OF SANDWICH-TYPE
CONSTRUCTION AND STANDARD REINFORCED CONCRETE
CONSTRUCTION FOR PROTECTIVE WALLS**

Various phases of the Picatinny Arsenal safety design criteria program have been discussed at the three previous Safety Seminars. For purposes of a very quick review let us look at Figure 1 which schematically outlines the various phases and status of our overall program. All the analytical phases of this work, including the most complex structural design phase, have now been essentially completed. We have developed detailed design relationships which represent a major step forward toward permitting a systematic, quantitative approach to the solution of virtually any problem relating to protection against propagation of explosions, personnel injury and materiel damage. This is of particular significance in the light of today's high energy propellant systems with attendant problems of designing safe, economical manufacturing plants, missile storage facilities and launching sites. Let me emphasize at this point, that although the design relationships developed are based upon very extensive correlation of a very great amount of actual data as well as theoretical approaches, these relationships must be specifically confirmed by actual tests before they can be reliably applied. As indicated on the chart, a portion of these tests is currently in progress. We are also just getting underway with a model scale test program to confirm the analytically developed structural design relationships.

Let us now consider, generally, the various possible locations of an explosive charge (i.e. a potential explosion) relative to a protective wall, as shown on

Figure 2. First we may have a situation where the charge is located close to the wall but sufficiently high above ground level, so that the wall is subjected essentially to a free air blast effect. Secondly, the charge may again be located relatively close to the wall, but also close to ground level, so that the wall is subjected to a combination of free air blast and ground reflection effects. In both cases, the wall is subjected to a non-uniform loading over its surface, with concentration of blast effects in the general area normal or almost normal to the charge. The third possibility is location of the charge far enough away from the wall so that the wall is subjected to a plane shock wave, i. e. uniform blast loading over its entire surface.

In most cases of ordnance interest (e. g. operating bays, storage cubicles), explosive charges will be located close to the protective wall and probably close to ground level. Our analytical work indicated that it is under these conditions that most severe damage to the wall occurs, not only for the obvious reason of charge proximity, but also because of intense effects resulting specifically from the non-uniform wall loading (e. g. punching out of very large concrete masses having substantial velocities). Figure 3 summarizes the various possible modes of wall failure. By way of confirmation, results of large scale tests recently conducted by the Armed Services Explosives Safety Board have strongly demonstrated that, for close-in effects, the degree of protection afforded by standard reinforced concrete walls in thicknesses up to several feet is far below what might previously have been expected based on, for example, plane wave theory. As a matter of fact, it may be said, based on these large scale tests, that standard reinforced concrete walls are

not adequate and/or practical for protection against close-in explosions involving charges of more than a few hundred pounds. Design of a protective wall for close-in charge locations based on the assumption that the wall is subjected to a plane shock wave, would be, therefore, an over-simplification leading to a serious underestimate of the potential degree of damage and/or likelihood of propagation.

It follows from the preceding discussion, that a means of improving the effectiveness of protective structures is to design overall explosive-protection systems so that protective walls are subjected to plane blast wave loading only, or so that this condition is approached. If we were to limit ourselves to standard reinforced concrete walls, this could be accomplished only by locating the explosive material at relatively great distances from the protective walls (i. e. using the air as an attenuator). As you might guess, and as I will show later in an illustrative example, this approach would be impractical, even prohibitive in many cases, because of construction costs and real estate requirements. A more attractive approach would be to use a type of construction material more effective than concrete as an attenuator, having the additional advantages of (1) substantial mass (unlike air) which would absorb energy during translation resulting from blast loading (like concrete), and (2) being highly frangible, or initially finely subdivided, so that (unlike concrete) it would not transfer any appreciable portion of its acquired kinetic energy during impact with another explosive charge or other material. Dry sand or earth meet all these requirements. Based on the use of such materials in protective structures, our analytical studies have resulted in design relationships which

quantitatively show the substantial benefits which they make possible. Referring again to large scale tests recently conducted by the Armed Services Explosives Safety Board, these included tests with (1) storage cubicles constructed of sandwich-type walls, i. e. each side of the cubicle consisting of a layer of sand held between two reinforced concrete walls and (2) storage cubicles consisting of metal multiplate arches with continuous earth cover and earth fill between them. Results with both structures, and particularly with the multi-plate arches, clearly indicated their advantages over conventional reinforced concrete walls in terms of protection effectiveness and economy.

In order to illustrate the application of our design relationships, including the plane wave aspects previously discussed, let us consider a typical design problem. We will assume a three-sided cubicle constructed with sandwich-type walls consisting of a three feet thick layer of sand held between two one-foot thick reinforced concrete walls (Figure 4). The requirement imposed upon this cubicle will be that it must offer adequate protection to personnel and/or materiel on the outside of the rear wall against the damaging effects of detonation of a 400 pound explosive charge inside the cubicle. In other words, the inside dimensions of the cubicle must permit location of the charge relative to the interior walls in a manner which will virtually prevent any substantial damage to the outside face of the rear wall. It should be noted that this requirement is much more severe than a requirement for prevention of explosion propagation only, since the latter would permit a substantial degree of damage to the outside face of the wall. Figure 5 summarizes all

the conditions assumed for the illustrative example.

Step 1. Consideration must first be given to total protection against spalling. It may be assumed that if spalling does not occur, punching will not occur. Figure 6 is a chart relating threshold conditions necessary for prevention of spalling in terms of explosive charge weight (W), scaled charge distance (linear distance divided by cube root of charge weight) from wall in question (Z_A), and concrete wall thickness (T). It should be noted that, throughout this paper, the Z subscript A by itself refers to normal scaled distance from the charge to the wall in question. In considering our sandwich rear wall, the portion of interest here is the outside one-foot thick concrete wall. As can be seen from the chart, spalling of this wall will not occur beyond a free air $Z_{A(out)}$ value of 2.5. This value approaches the threshold condition for plane wave loading.

Step 2. Preliminary calculations (not detailed in this paper) indicate that for $Z_{A(out)} = 2.5$ the outside one foot thick concrete wall would not withstand the blast load because of excessive shear stresses acting at the base support. It is necessary, therefore to place the charge at a free air scaled distance from the outside concrete wall of $Z_{A(out)} \approx 3.0$. Under these conditions, this wall is subjected to plane wave blast loading.

Step 3. From Figure 7 determine the normal pressure (P_R) and scaled impulse per unit area ($\bar{I}_R$) loading on the front face of the outside concrete wall for $Z_{A(out)} \approx 3.0$.

$$P_R = 500 \text{ psi}$$

$$\bar{I}_R = 70 \text{ psi-ms/lb. } 1/3$$

Step 4. Calculate scaled thicknesses of concrete ($T/W^{1/3}$) and sand ($T_E/W^{1/3}$).

$$T/W^{1/3} = 1.0/400^{1/3} = 0.136$$

$$T_E/W^{1/3} = 3.0/400^{1/3} = 0.41$$

Step 5. Figure 8 is a chart for determination of attenuation of peak pressure in sand and concrete as a function of scaled thickness. The solid family of lines refer to concrete, while the broken lines refer to sand. Starting at a point corresponding to the front face of the outside concrete wall locate the point on a broken line corresponding to $T_E/W^{1/3} = 0.41$ and $P_R = 500$. Read vertically upward from this point to the point on a solid line corresponding to $T/W^{1/3} = 0.136$. From this point read horizontally to determine peak pressure (P_F) at the front face of the inside concrete wall.

$$P_F = 5500 \text{ psi}$$

It should be noted that this chart accounts for coupling effects between the sand and concrete.

Step 6. Figure 9 is a chart similar to the chart shown on Figure 8, except that it is used for determination of attenuation of scaled impulse per unit area in sand and concrete. By a procedure similar to that used in Step 5, determine scaled impulse per unit area ($\bar{I}_F$) at the front face of the inside concrete wall.

$$\bar{I}_F = 500 \text{ psi-ms/lb.}^{1/3}$$

Step 7. Determine, from Figure 7, the scaled normal distance from the front face of the inside concrete wall corresponding to $P_F(Z_{A(in)} \text{ (pressure)})$ and $\bar{I}_F(Z_{A(in)} \text{ (impulse)})$.

$$Z_{A(in)} \text{ (pressure)} = 1.10$$

$$Z_{A(in)} \text{ (impulse)} = 0.80$$

Therefore $Z_{A(in)} \text{ (pressure)} = 1.10$ is controlling scaled distance.

Step 8. Determine reflection effects coming from side walls of cubicle and ground, which enhance blast loading on the rear wall. (Since the method for arriving at the appropriate reflection factor (R_I) is detailed in PART II of this paper, it will not be given at this point).

$$R_I = 2.5$$

Step 9. Calculate effective weight of charge (W_e)

$$W_e = R_I W = 2.5 \times 400 = 1000 \text{ lbs.}$$

Step 10. Using the value of W_e from Step 9 and $Z_{A(in)} \text{ (pressure)}$ from Step 7, calculate the normal distance (d) from the center of the charge to the front face of the inside wall required for the desired protection.

$$d = Z_{A(in)} \text{ (pressure)} \times (W_e)^{1/3} = 1.10 \times 1000^{1/3} = 11 \text{ feet}$$

Step 11. Recalculate scaled thicknesses of concrete and sand corresponding to W_e .

$$T/W_e^{1/3} = 1/10 = 0.1$$

$$T_E/W_e^{1/3} = 3/10 = 0.3$$

Step 12. From Figure 7, determine $\bar{I}_F$ corresponding to $Z_A = 1.10$. Calculate I_F using W_e value from Step 9.

$$\bar{I}_F(Z_{A(in)}(\text{pressure})) = 295 \text{ psi-ms/lb. }^{1/3}$$

$$I_F(Z_{A(in)}(\text{pressure})) = 295 (1000)^{1/3} = 2950 \text{ psi-ms.}$$

Step 13. Using values of P_F and $\bar{I}_F$ from Steps 5 and 12, respectively, and the scaled thickness values from Step 11, redetermine P_R and $\bar{I}_R$ by a method similar to that used in Steps 5 and 6. Calculate I_R using W_e value from Step 9.

$$P_R = 650 \text{ psi}$$

$$\bar{I}_R = 55 \text{ psi-ms/lb. }^{1/3}$$

$$I_R = 55 (1000)^{1/3} = 550 \text{ psi-ms.}$$

Step 14. Determine from Figure 7, the scaled normal distance from the front face of the outside concrete wall corresponding to $P_R(Z_{A(out)}(\text{pressure}))$ and $\bar{I}_R(Z_{A(out)}(\text{impulse}))$.

$$Z_{A(out)}(\text{pressure}) = 2.8$$

$$Z_{A(out)}(\text{impulse}) = 3.6$$

Therefore, $Z_{A(out)}(\text{pressure}) = 2.80$ is controlling scaled distance for use in subsequent calculations relating to flexural failure of the outside concrete wall.

We must now check the outside concrete wall for flexural capacity and reinforcement required. This flexural analysis involves determination of the following:

a. bending or moment stresses

b. shear stresses consisting of (1) pure shear (cracking normal to the wall) and (2) diagonal tension (cracking at approximately 45°) and (3) bond (pulling out of reinforcing rods).

These calculations (not detailed in this paper) indicate the necessary degree of reinforcement for moment capacity (rods) to be 0.6 percent. The calculations also indicate that stirrups are necessary in order to avoid failure in diagonal tension.

Figure 10 is a summary of results calculated for the rear sandwich wall as compared with results which would have been obtained with a 5-foot solid concrete wall. It is clear that the substantially greater normal distance between charge and wall required with solid concrete to prevent spalling would result in a much larger cubicle than is required with sandwich wall construction.

**PART II: DETERMINATION OF WALL RESPONSES TO BLAST EFFECTS
FROM EXPLOSIVE CHARGES DISTRIBUTED IN A CUBICLE
TYPE STRUCTURE**

This portion of the paper deals with the determination of the magnitude of blast loads in terms of pressure and impulse imposed on a protective wall as a result of detonation of an explosive charge located close to the wall. More specifically, consideration will be given to the often encountered situation where several like charges are to be placed in a storage bay and it is desired to determine the optimum charge distribution for minimization of pressure and impulse loads acting on the walls. It will be conservatively assumed that, regardless of their distribution within the bay, all the charges will detonate in the event of an accident.

This illustrative analysis will consider three typical distributions of four 200 pound explosive charges within a three-sided cubicle. Through stepwise calculations in each case we will determine the net combined maximum pressure and impulse loading on the rear wall in the event of explosion of the donor charges. For comparison purposes, the following conditions have been assumed constant for each case:

- a. Three sided storage cubicle 16 feet long, 16 feet wide and 12 feet high.
- b. Geometric center of charge configuration located midway between the two side walls of the cubicle.

c. Distance of geometric center of charge configuration to rear wall (4.5 feet).

d. Height of charges above ground (3 feet).

The three different charge arrangements to be considered are as follows:

CASE 1: All four charges are clustered in the center of the cubicle. For all practical purposes the donor charge may be considered as a single symmetrical charge, the center of which is the geometric center of the cluster, and the mass of which is equal to the total mass of the individual charges.

CASE 2: The charges are distributed symmetrically in two groups of two charges each, one group behind the other.

CASE 3: The charges are distributed symmetrically in two groups of two charges each, all the charges lying along a straight line parallel to the rear wall.

For all three charge locations the rear wall is subjected to a combination of free air blast effects and reflected blast effects from adjacent sections of the structure, which enhance the rear wall loading. In order to account for reflection effects, it is necessary to determine, for each donor charge, the reflection factor which is applied as a multiplier to the actual donor charge weight. This reflection factor is defined as the ratio of an equivalent weight of the donor charge detonated in free air to the actual weight of donor charge detonated close to a

reflecting surface, the equivalent charge producing essentially the same pressure and impulse loading on the wall in question as the actual donor charge. For utilization of such reflection factors, the type of wall being considered as well as the location of the charge in relation to this wall, to the other cubicle walls, and to the ground must be known. In the specific examples to be considered in this paper, reflections on the rear wall resulting from reflection interactions between the two side walls may be considered negligible in comparison to direct reflections from the side walls to the rear wall.

Figure 11 is a chart relating reflection factors for walls restrained on two sides (e. g. side walls of the cubicle) or three sides (e. g. rear wall of the cubicle) to (1) scaled distance of the charge (linear distance divided by cube root of charge weight) from the wall being investigated (Z_A), (2) scaled distance between the center line of the wall in question and the adjacent wall (Z_P), (3) ratio of the distance between the charge and the nearest adjacent wall to the length of the wall in question (L/l), and (4) charge height to wall height ratio (h/H). As can be seen from the chart this factor may be of relatively great magnitude for large charges close to the wall. Therefore, failure to take them into account in the calculation of blast loads on the wall may lead to seriously inadequate design of a structure to withstand these loads.

CASE 1 of our illustrative example will now be considered. This is shown schematically on Figure 12.

Step 1 Calculate normal scaled distance between the geometric center of the charges and the wall in question $Z_A = \frac{d}{W^{1/3}} = \frac{4.5}{800^{1/3}} = 0.485 \text{ ft/lb.}^{1/3}$.

Step 2 Calculate scaled distance between the center of the cubicle and the side wall (Z_B) $Z_B = \frac{8.0}{800^{1/3}} = 0.86$

Step 3 Using the values for Z_A and Z_B determine the reflection coefficient from Figure 11. For the conditions indicated, namely $Z_A = 0.485$, $h = H/4$, $Z_B/Z_A = 1.8$, the reflection coefficient would lie between lines 1 and 2 on the reflection chart. Interpolating between these two lines, we obtain a reflection coefficient (R_I) = 3.5.

Step 4 Calculate equivalent charge weight (W_e) and corrected scaled distance ($\dot{Z}_A$). $W_e = W \times R_I = 800 \times 3.5 = 2,800 \text{ lbs.}$

$$\dot{Z}_A = 4.5/2,800^{1/3} = 0.32$$

Step 5 From chart relating pressure (P_T) and scaled impulse per unit area ($\bar{I}_T$) to scaled distance (Figure 7), determine pressure and impulse loads on rear wall for corrected scaled distance.

$$\bar{I}_T = 2,000 \text{ psi-ms/lb.}^{1/3}$$

$$P_T = \underline{38,000 \text{ psi}}$$

Calculate impulse per unit area

$$I_T = \bar{I}_T \times W^{1/3} = 2,000 \times 2,800^{1/3} = \underline{28,000 \text{ psi-ms}}$$

Let us now consider CASE 2 as shown schematically in Figure 13. This

example will illustrate the method for determining mass and location of a single equivalent charge which would produce essentially the same pressure and impulse loads on the rear wall as the four actual charges in the indicated configuration. It will also serve to compare the blast load produced by this configuration with the blast load from a single charge cluster as presented in CASE 1.

Step 1. Calculate scaled distance between each charge and the rear wall.

$$Z_A(W_a) = Z_A(W_b) = 3/200^{1/3} = 0.515$$

$$Z_A(W_c) = Z_A(W_d) = 6/200^{1/3} = 1.03$$

Step 2. Calculate scaled distance Z_B between the center of the cubicle and the side walls $Z_B = 8.0/200^{1/3} = 1.37$

Step 3. Using the values of Z_A and Z_B from Steps 1 and 2 calculate the value of Z_B/Z_A for each charge

$$Z_B/Z_A(W_a) = Z_B/Z_A(W_b) = 1.37/0.515 = 2.66$$

$$Z_B/Z_A(W_c) = Z_B/Z_A(W_d) = 1.37/1.03 = 1.33$$

Step 4. Using the values from Steps 1 through 3 determine the reflection factors for each charge from Figure 11.

$$\text{for } W_a \text{ and } W_b, R_I = 2.25 \text{ (} L/1 = 2.6 \text{)}$$

$$(Z_B/Z_A = 2.66)$$

$$\text{for } W_c \text{ and } W_d, R_I = 2.75 \text{ (} L/1 = 2.6 \text{)}$$

$$(Z_B/Z_A = 1.33)$$

Step 5. Calculate equivalent weight of the individual charges using the

respective values of reflection coefficient R_I from Step 4.

$$\dot{W}_a = \dot{W}_b = 2.25 \times 200 = 450 \text{ lbs.}$$

$$\dot{W}_c = \dot{W}_d = 2.75 \times 200 = 550 \text{ lbs.}$$

Step 6. Using the values obtained in Step 5 for each charge calculate the adjusted normal scaled distance between each charge and the rear wall.

$$\dot{Z}_A(\dot{W}_a) = \dot{Z}_A(\dot{W}_b) = 3.0/450^{1/3} = 0.40$$

$$\dot{Z}_A(\dot{W}_c) = \dot{Z}_A(\dot{W}_d) = 6.0/550^{1/3} = 0.74$$

Step 7. Using the adjusted values from scaled distance from Step 6 and equivalent weights from Step 5 determine, from Figure 7 the impulse on the wall normal to each equivalent charge

$$\bar{I}(\dot{W}_a) = \bar{I}(\dot{W}_b) = 1,350$$

$$\bar{I}(\dot{W}_c) = \bar{I}(\dot{W}_d) = 550$$

$$I(\dot{W}_a) = I(\dot{W}_b) = \bar{I}(\dot{W}_a) \times \dot{W}_a = \bar{I}(\dot{W}_b) \times \dot{W}_b = 1,350 \times 450^{1/3} = 10,300 \text{ psi-ms}$$

$$I(\dot{W}_c) = I(\dot{W}_d) = 550 \times 550^{1/3} = 4,500 \text{ psi-ms}$$

Step 8. Sum up charges in each group to determine equivalent group charge

$$\dot{W}_a + \dot{W}_c = \dot{W}_b + \dot{W}_d = 450 + 550 = 1,000 \text{ lbs.}$$

Step 9. Sum impulse for each group to determine equivalent group charge normal impulse at points A and B (refer Figure 13, for this step and subsequent steps)

$$I_A(\dot{W}_{ac}) = I_B(\dot{W}_{bd}) = 10,300 + 4,500 = 14,800 \text{ psi-ms}$$

Step 10. Using the values of $\dot{W}$ and I from Steps 8 and 9 calculate the scaled values of the impulse load above

$$\bar{I}(\dot{W}_{ac}) = \bar{I}(\dot{W}_{bd}) = 14,800/1,000^{1/3} = 1,480$$

Step 11. Using the value $\bar{I}$ from Step 10 determine the value of $\dot{Z}_A$ from Figure 7 for each group. Calculate the actual distance ($\dot{d}$) between the wall and the equivalent charges

$$\begin{aligned}\dot{Z}_A(\dot{W}_{ac}) &= \dot{Z}_A(\dot{W}_{bd}) = .40 \\ \dot{d}_{AC} &= \dot{d}_{RD} = .40 \times 1,000^{1/3} = 4.0 \text{ ft.}\end{aligned}$$

Step 12. Using the values of $\dot{W}$ from Step 9 calculate the total equivalent charge of the entire system

$$\dot{W}_{abcd} = 1,000 + 1,000 = 2,000 \text{ lbs.}$$

Step 13. Calculate the slant distances between the wall and the equivalent group charges. Calculate the scaled values of these distances using the value of $\dot{W}$ of step 8. Calculate the angles (α) formed by the lines defining these scaled distances and the normal distance between the equivalent group charges. (See Figure 13).

$$\begin{aligned}\dot{d}_{AD} &= \dot{d}_{BC} = (4^2 + 4^2)^{1/2} = 5.65 \text{ ft.} \\ \dot{Z}_{AD} &= \dot{Z}_{BC} = 5.65/1000^{1/3} = 0.565 \\ \tan \alpha_C &= \tan \alpha_D = 4/4 = 1.0\end{aligned}$$

$$\alpha_C = \alpha_D = 45^\circ$$

Step 14. Figure 14 is a chart relating impulse per unit area as a function of scaled distance and angle of incidence α . Using the scaled distance and angle of incidence computed in Step 13 and this chart, determine, the scaled impulse load, for each equivalent group charge, acting at a point on the wall normal to the charge, which is due to the other equivalent group charge. Calculate the actual impulse loads using the values of $\dot{W}$ from Step 8

$$\bar{I}_A(\dot{W}_{bd}) = \bar{I}_B(\dot{W}_{ac}) = 335$$

$$I_A(\dot{W}_{bd}) = I_B(\dot{W}_{ac}) = 335 \times 1000^{1/3} = 3,350 \text{ psi-ms}$$

Step 15. Calculate the total impulse acting on points A and B using impulse values from Steps 9 and 14. Calculate total scaled impulse.

$$\frac{I_A(\dot{W}_{bd}) + I_A(\dot{W}_{ac})}{I_A(\dot{W}_{bd}) + I_A(\dot{W}_{ac})} = \frac{14,800 + 3,350}{18,150} = \frac{18,150}{18,150} = 1.0$$

$$\frac{I_B(\dot{W}_{bd}) + I_B(\dot{W}_{ac})}{I_B(\dot{W}_{bd}) + I_B(\dot{W}_{ac})} = \frac{18,150}{18,150} = 1.0$$

Step 16. Based upon the scaled impulse load calculated in Step 15 determine from Figure 14 the scaled slant distance between the total equivalent charge of the whole system and points A and B. Calculate the actual distance using $\dot{W}$ value from Step 12.

$$\dot{Z}_{OA} = \dot{Z}_{OB} = 0.4$$

$$d_{OA} = d_{OB} = 0.4 \times 2000^{1/3} = 5.0 \text{ ft.}$$

Step 17. Calculate angle β

$$\sin \beta = d_{AT}/d_{AO} = 2.0/5.0 = 0.4$$

$$\beta = 24^\circ$$

(Available data indicates a sudden change in impulse patterns occurs at an angle of 40° . If this value is less than 40° , as is true in this case, it is valid to determine a single equivalent point on the wall at which the total equivalent charge for the entire system exerts maximum impulse. If, on the other hand, this angle is 40° or greater this assumption is not valid, as will be covered further under CASE 3.)

Step 18. Using the slant distance from Step 16 calculate the normal distance and scaled normal distance between the wall and the total equivalent charge of the entire system. Determine the maximum local scaled impulse and pressure of the entire system acting on the rear wall from Figure 7. Calculate maximum local impulse using $\dot{W}$ value from Step 12.

$$\dot{d}_{OT} = (\dot{d}_{OA}^2 - \dot{d}_{AT}^2)^{1/2} = (5.0^2 - 2.0^2)^{1/2} = 4.58 \text{ ft.}$$

$$\dot{Z}_A(\dot{W}_{abcd}) = 4.58/2000^{1/3} = 0.360$$

$$\bar{I}_T = 1700$$

$$P_T = 34,000 \text{ psi}$$

$$I_T = 1700 \times 2000^{1/3} = \underline{21,400 \text{ psi-ms}}$$

We will now consider CASE 3 as shown schematically on Figure 15. As will be shown in this example, the distribution of individual charges in a straight line along the rear wall does not result in a single concentration of loading on the wall, but rather two distinct points of concentration of lesser magnitude.

Step 1. By a series of calculations similar to those used in CASE 2 up to Step 10 we arrive at the following:

$$\dot{W}_{ab} = \dot{W}_{cd} = 1150 \text{ lbs.}$$

$$d_{EG} = d_{FH} = 4.25 \text{ ft.}$$

$$\dot{Z}_A(\dot{W}_{ab}) = \dot{Z}_A(\dot{W}_{cd}) = 0.405 \text{ ft/lb.}^{1/3}$$

$$I_E(\dot{W}_{ab}) = I_F(\dot{W}_{cd}) = 15,700 \text{ psi-ms}$$

(Refer to Figure 15 for this step and subsequent steps).

Step 2. Calculate distances d_{GF} and d_{HE} and corresponding scaled distances using $\dot{W}$ value from Step 1.

$$d_{GF} = d_{HE} = (4.25^2 + 8^2)^{1/2} = 9.0 \text{ ft.}$$

$$\dot{Z}_{GF} = \dot{Z}_{HE} = 9.0/1150^{1/3} = 0.86$$

Step 3. Calculate angle α

$$\tan \alpha = d_{AD}/d_{EG} = 8.00/4.25 = 1.87$$

$$\alpha = 62^\circ$$

Step 4. Using the scaled distance and angle of incidence from Steps 2 and 3, determine from Figure 14 the scaled impulse load, for each equivalent group charge, acting at a point on the rear wall normal to the charge, which is due to the other equivalent group charge. Calculate the actual impulse loads using value of $\dot{W}$ from Step 1.

$$\bar{I}_E(\dot{W}_{cd}) = \bar{I}_F(\dot{W}_{ab}) = 180$$

$$I_E(\dot{W}_{cd}) = I_F(\dot{W}_{ab}) = 180 \times 1150^{1/3} = 1900 \text{ psi-ms}$$

Step 5. Calculate total equivalent charge for entire system using $\dot{W}$ values from Step 1.

$$\dot{W}_{abcd} = \dot{W}_{ab} + \dot{W}_{cd} = 1,150 + 1,150 = 2,300 \text{ lbs.}$$

Step 6. Calculate the total impulse acting on points E and F using impulse values from Steps 1 and 4. Calculate scaled impulses corresponding to these values, using $\dot{W}$ value from Step 5.

$$\begin{aligned} \frac{I_E(\dot{W}_{ab}) + I_E(\dot{W}_{cd})}{\dot{W}_{abcd}} &= \frac{I_F(\dot{W}_{cd}) + I_F(\dot{W}_{ab})}{\dot{W}_{abcd}} = 15,700 + 1,900 = 17,600 \text{ psi-ms} \\ \frac{I_E(\dot{W}_{ab}) + I_E(\dot{W}_{cd})}{\dot{W}_{abcd}} &= \frac{I_F(\dot{W}_{cd}) + I_F(\dot{W}_{ab})}{\dot{W}_{abcd}} = 17,600/2,300^{1/3} = 1,330 \end{aligned}$$

Step 7. Using the total scaled impulse value from Step 6, determine from Figure 14, the scaled distance for the total equivalent charge weight acting at points E and F. Calculate the actual distance using the $\dot{W}$ value from Step 5.

$$\begin{aligned} \dot{Z}_{OE} &= \dot{Z}_{OF} = 0.43 \\ \dot{d}_{OE} &= \dot{d}_{OF} = 0.43 \times 2300^{1/3} = 5.6 \text{ ft.} \end{aligned}$$

Step 8. Calculate angle ϕ

$$\sin \phi = \dot{d}_{ET}/\dot{d}_{OE} = 4.0/5.6 = 0.72$$

$$\phi = 46^\circ$$

Since this angle is greater than 40° , we cannot assume that the total equivalent charge for the entire system exerts a single maximum impulse at one point on the wall (see CASE 2, Step 16). The overall resultant effect must therefore be considered to be two points of equal maximum impulse per unit area (E and F),

due to the total equivalent charge. This value was previously calculated in Step 6 as 17,600 psi-ms. It is important to note that this maximum value is substantially less than it would be in a similar situation where a single maximum value (i.e. where β is less than 40°) would apply.

$$\text{Thus } I_T = \underline{17,600 \text{ psi-ms}}$$

$$P_T = \underline{26,000 \text{ psi}} \text{ (from Figure 7)}$$

A summary of results for CASES 1, 2 and 3 is presented in Figure 16. It is clear that for a given total charge weight composed of individual charges, distribution of charges within a given cubicle results in significant reduction of blast loading on the walls as compared to clustering the charges. In our particular example in which only the rear wall was considered, distribution of charges in a straight line parallel to this wall appears to be particularly advantageous. It is important to note, however, that to complete the design analysis each charge configuration would have to be considered relative to each wall of the cubicle to result in an optimum configuration for the protection desired.

The next step in the design procedure would be calculation of wall responses in terms of spalling, punching, flexural failure, total destruction, and primary missile penetration. These calculation procedures were illustrated in papers presented at the previous Explosives Safety Seminars and are included in the minutes thereof.

We feel, very strongly, that the safety design criteria program represents a major, and long-needed, step forward in ordnance technology. Progress to date

shows every promise of far-reaching and continuing benefits to all the services, defense agencies, and private industry with respect to (1) permitting most effective use of existing storage and manufacturing facilities and (2) minimization of protective construction costs for new facilities and missile launching sites.

REFERENCES

1. **Industrial Engineering Study to Establish Safety Design Criteria For Use In Engineering of Explosive Facilities and Operations** (Report to be Published), Ammann & Whitney, Consulting Engineers; under Contract DA-28-017-501-ORD-3889 for Process Engineering Laboratory, Picatinny Arsenal; 1961.
2. **Loading Characteristics of Air Blasts from Detonating Charges**; S. A. Granstrom, Transactions of Royal Institute of Technology; Stockholm, Sweden; 1956.

FIGURES

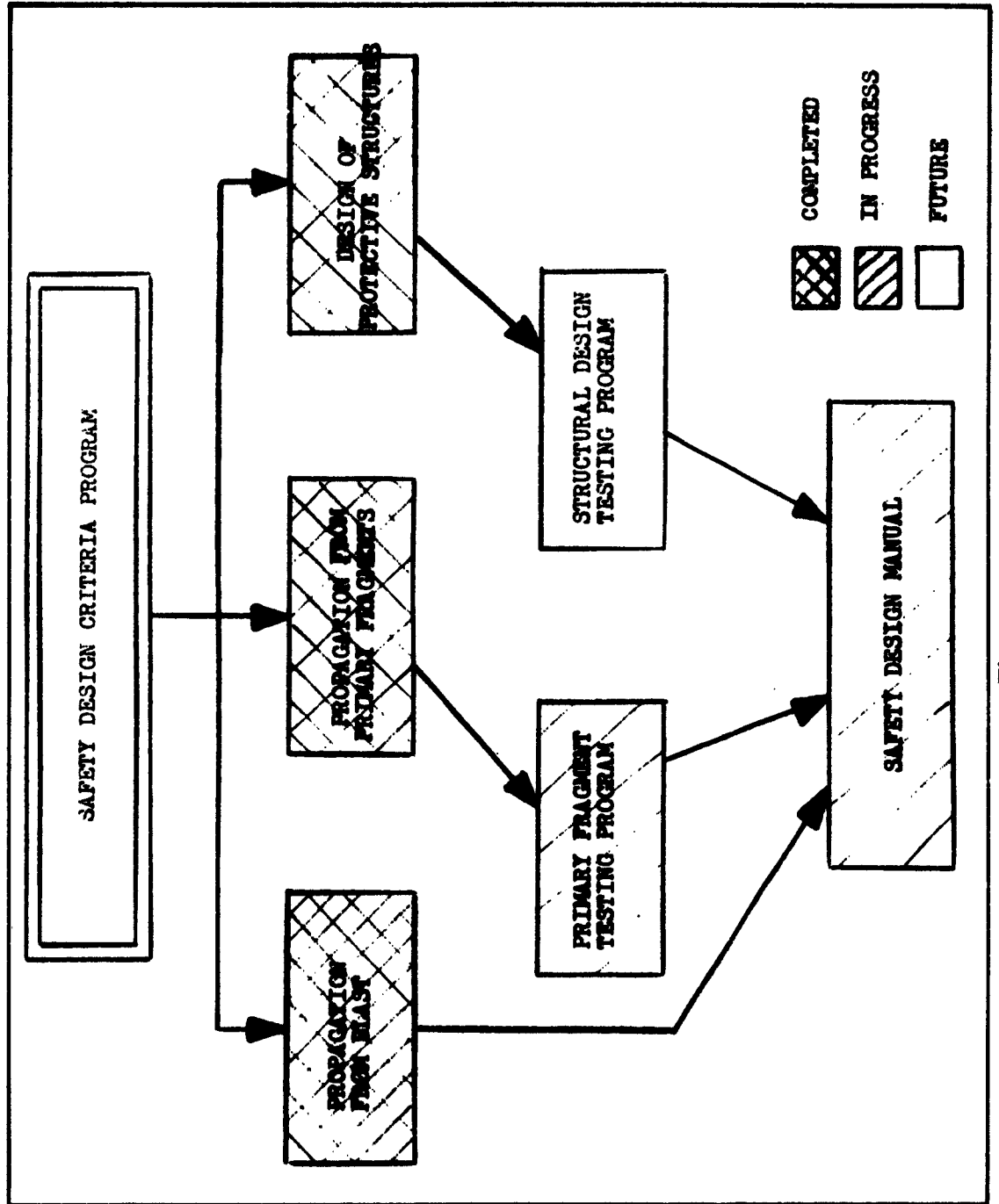


Figure 1

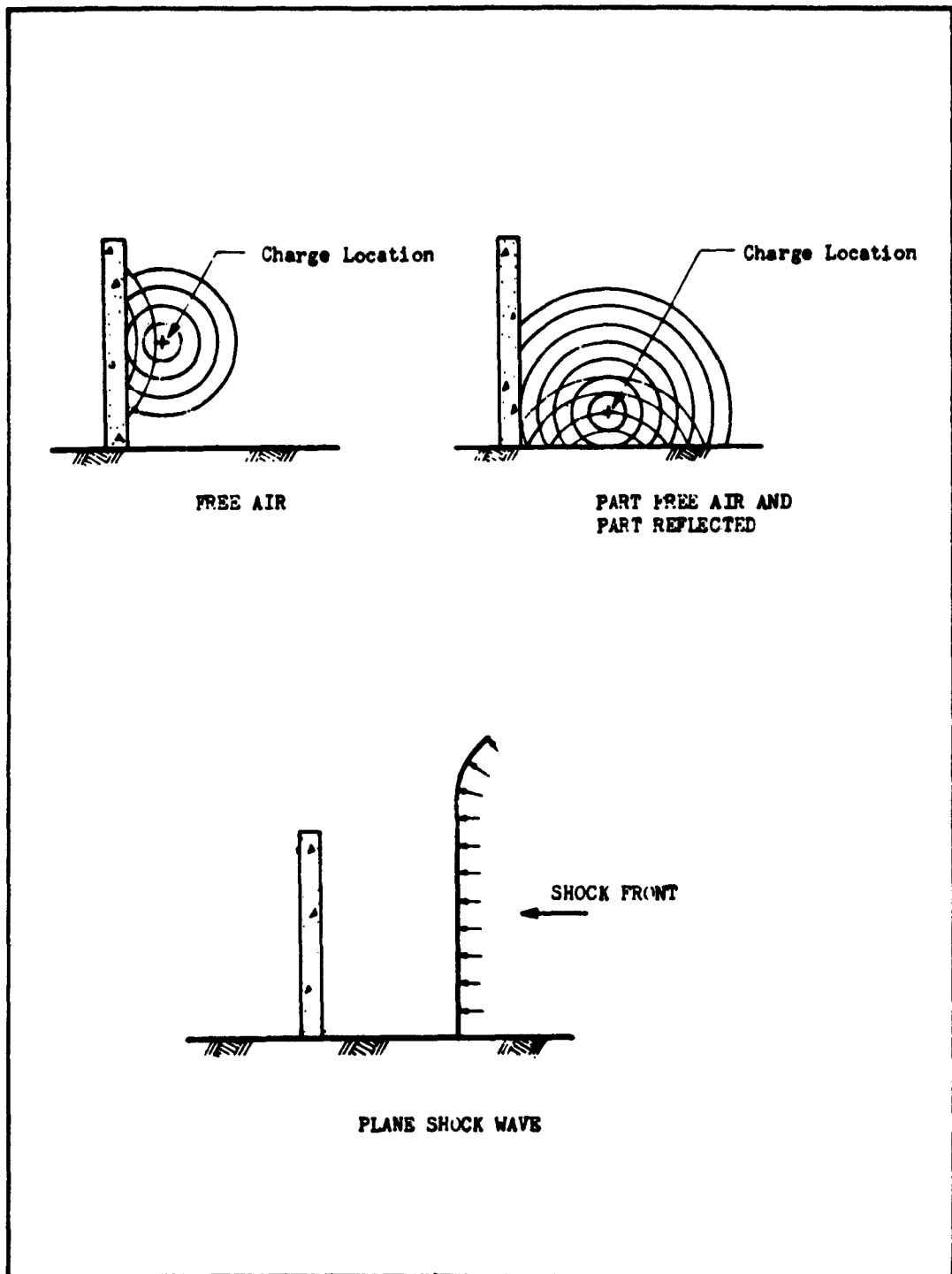


Figure 2

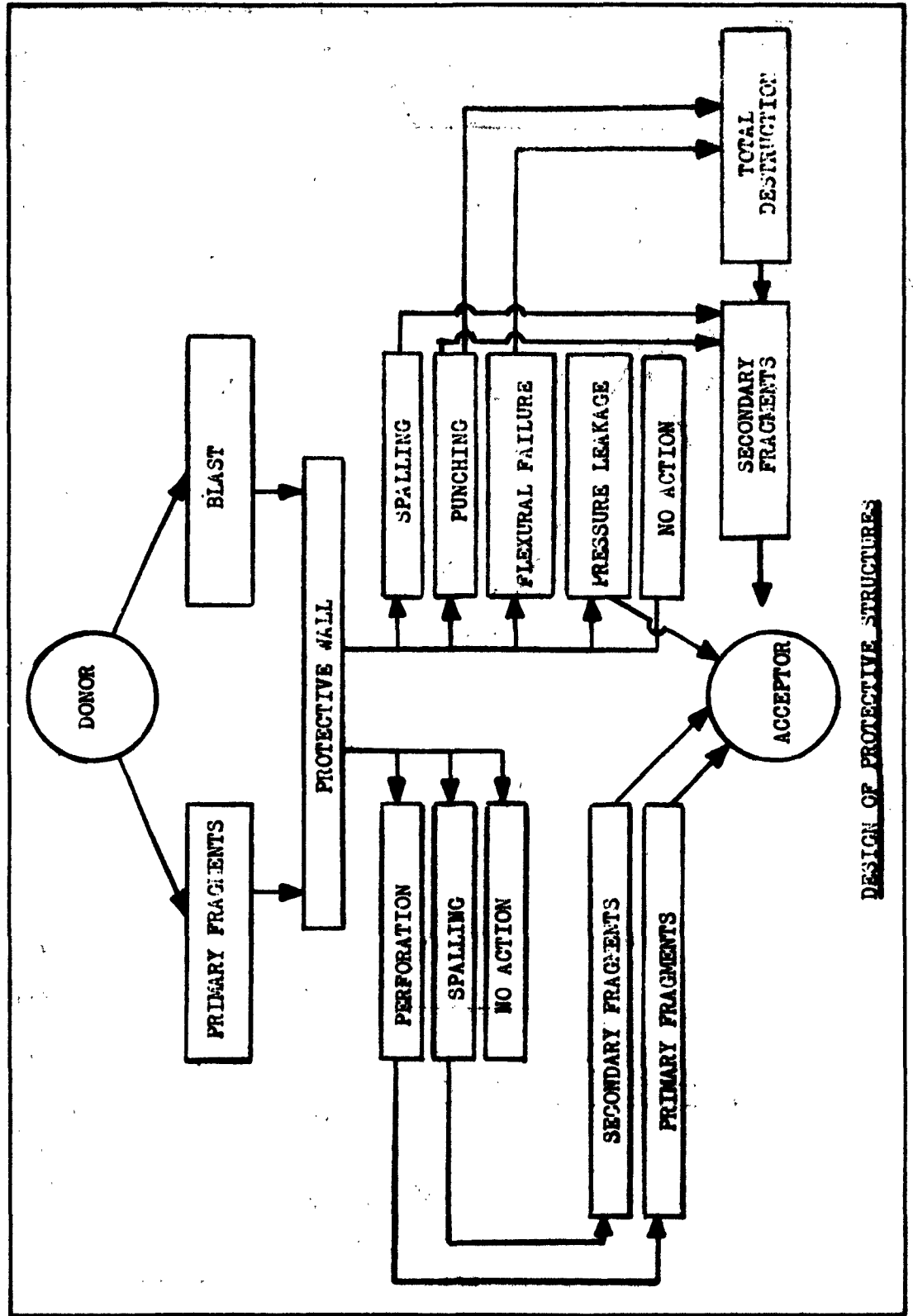
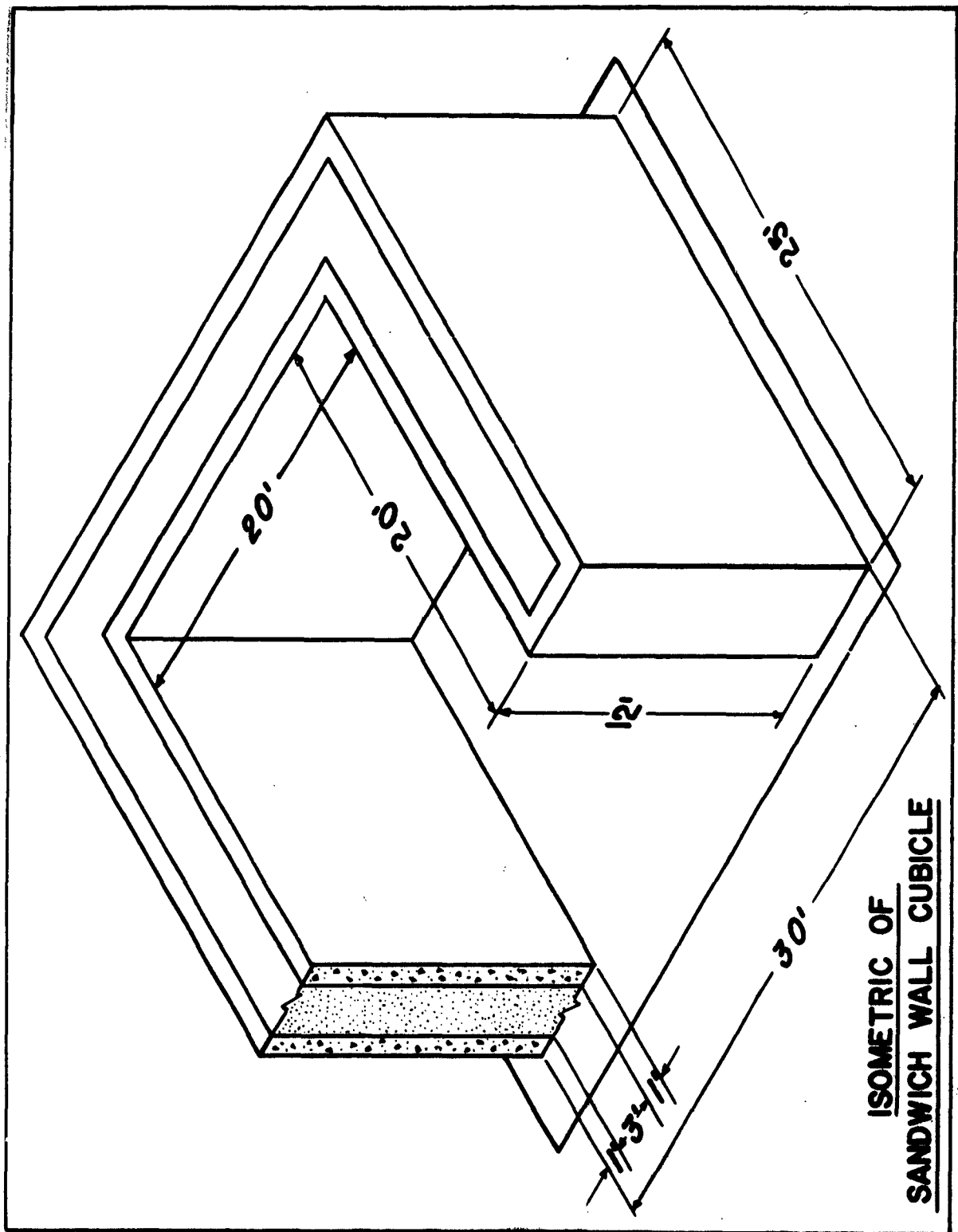


Figure 3



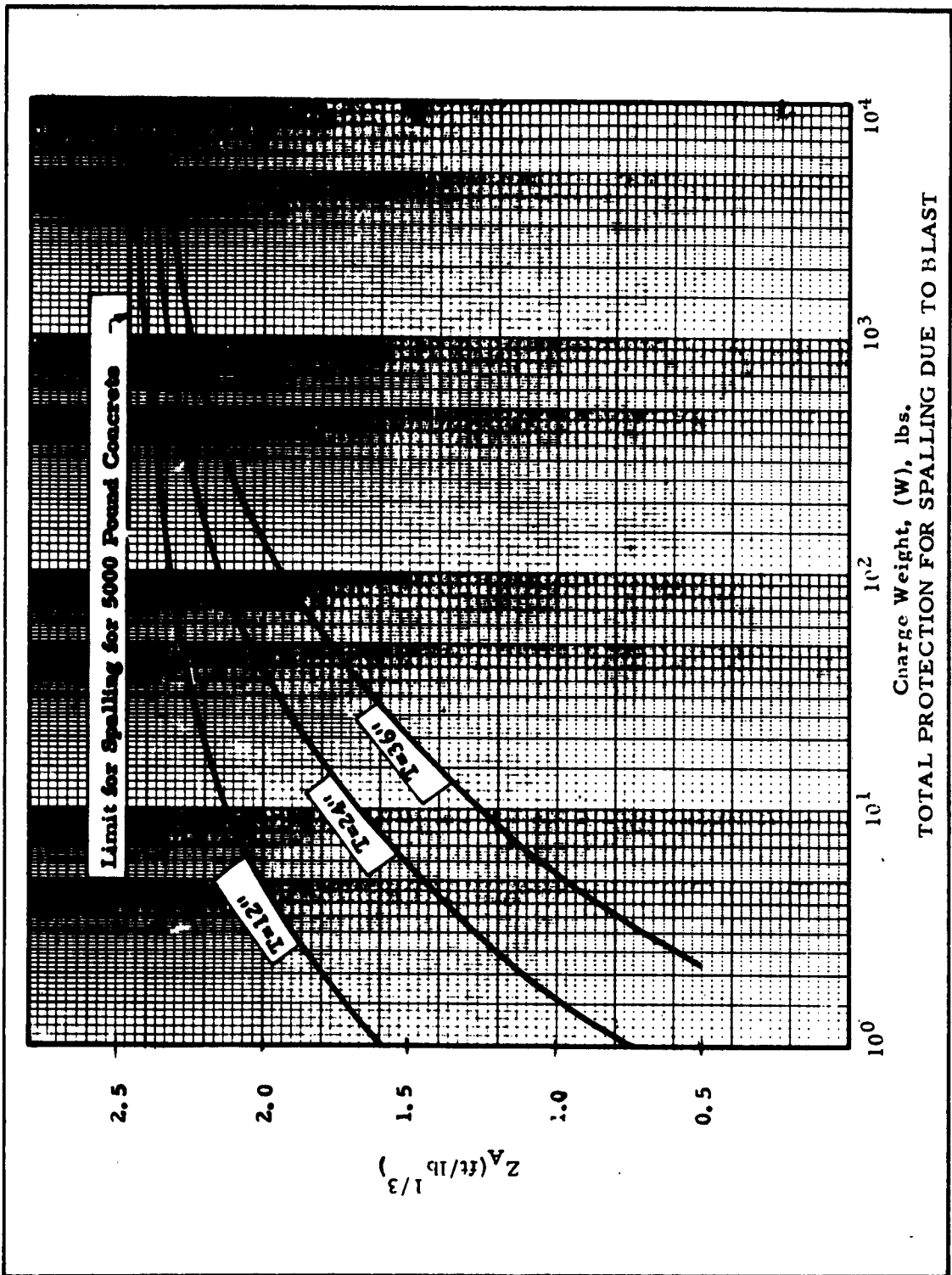
PART I - ILLUSTRATIVE EXAMPLE

CONDITIONS ASSUMED

- | | |
|---|--|
| 1. EXPLOSIVE CHARGE (DONOR) WEIGHT | 400 LBS. |
| 2. WALL HEIGHT | 12 FT. |
| 3. WALL LENGTH AND WIDTH | 20 FT. |
| 4. CHARGE HEIGHT ABOVE GROUND | 3 FT. |
| 5. CONCRETE STRENGTH | 5,000 PSI |
| 6. STEEL STRENGTH | 50,000 PSI |
| 7. SAND DENSITY | 100 LBS./CU. FT. |
| 8. SEISMIC VELOCITY OF SHOCK THROUGH SAND | 2,000 FT./SEC. |
| 9. WALL CONSTRUCTION | 3' SAND LAYER
SANDWICHED BETWEEN
TWO 1' REINFORCED
CONCRETE WALLS |

REQUIRED

1. MINIMUM DISTANCE BETWEEN THE INSIDE CONCRETE WALL AND CENTER OF THE CHARGE.
2. PERCENT AND KIND OF REINFORCEMENT IN THE CONCRETE WALL TO RESIST FLEXURAL FAILURE.



PEAK PRESSURE AND SCALED IMPULSE vs SCALED DISTANCE

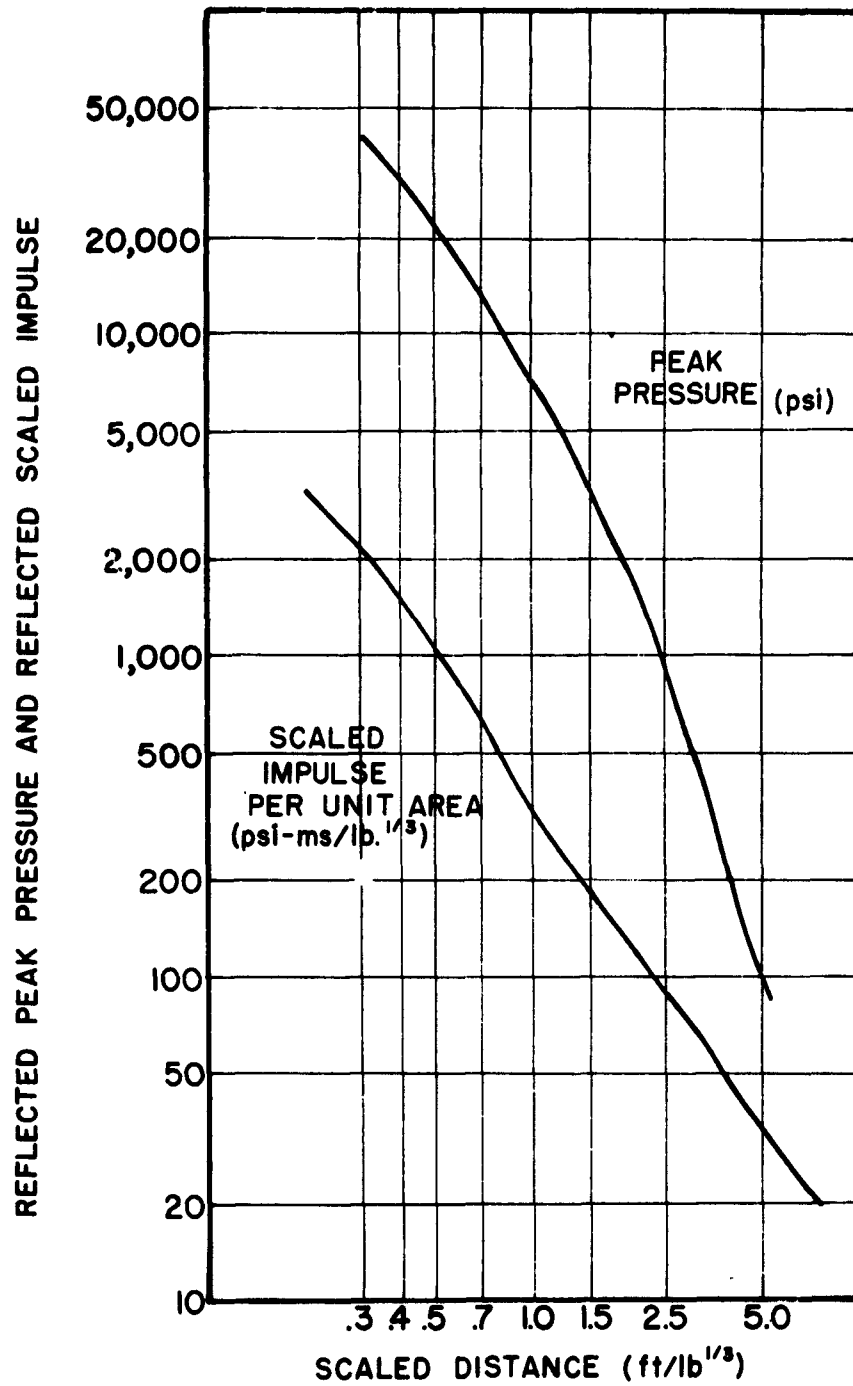


Figure 7

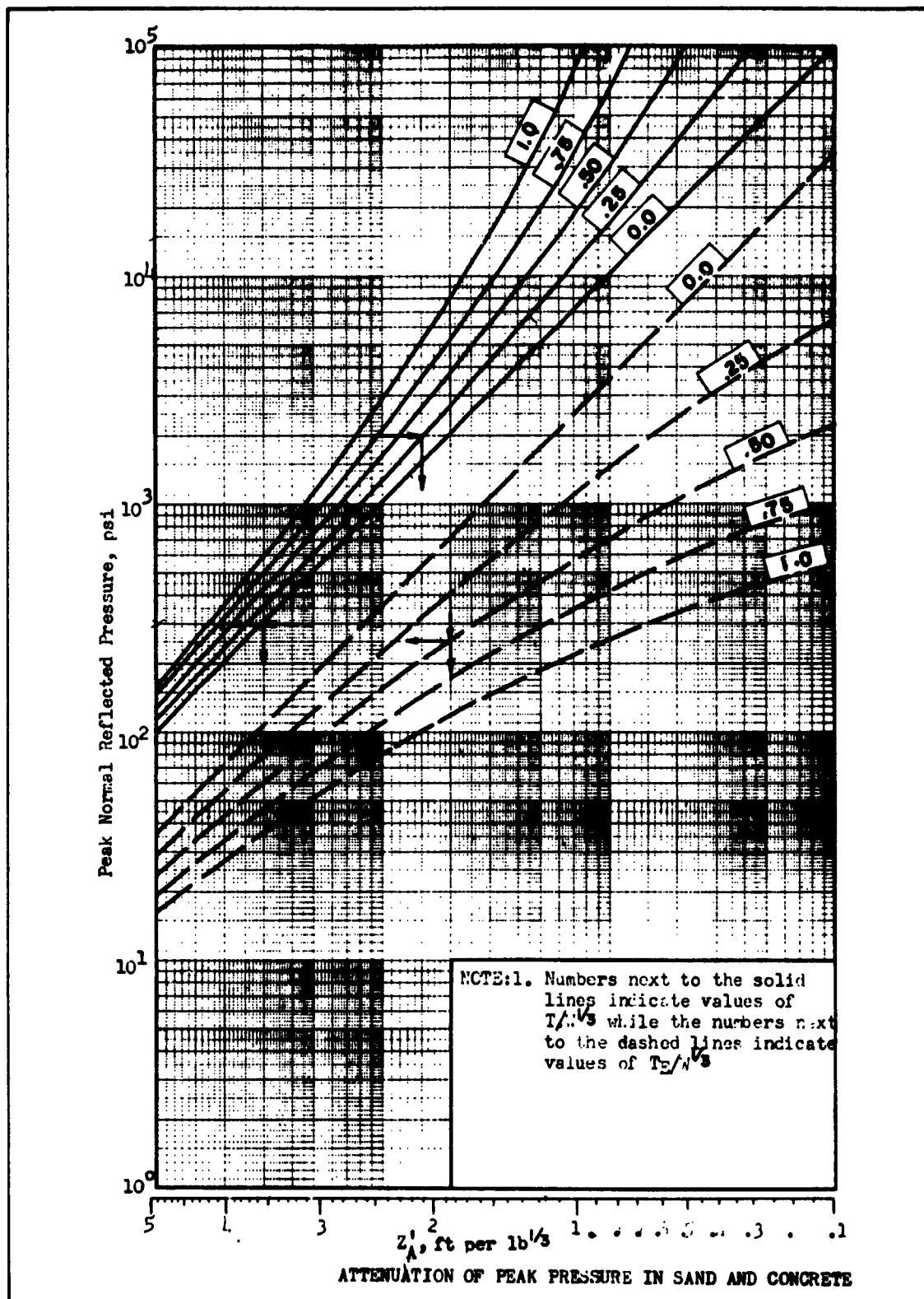


Figure 8

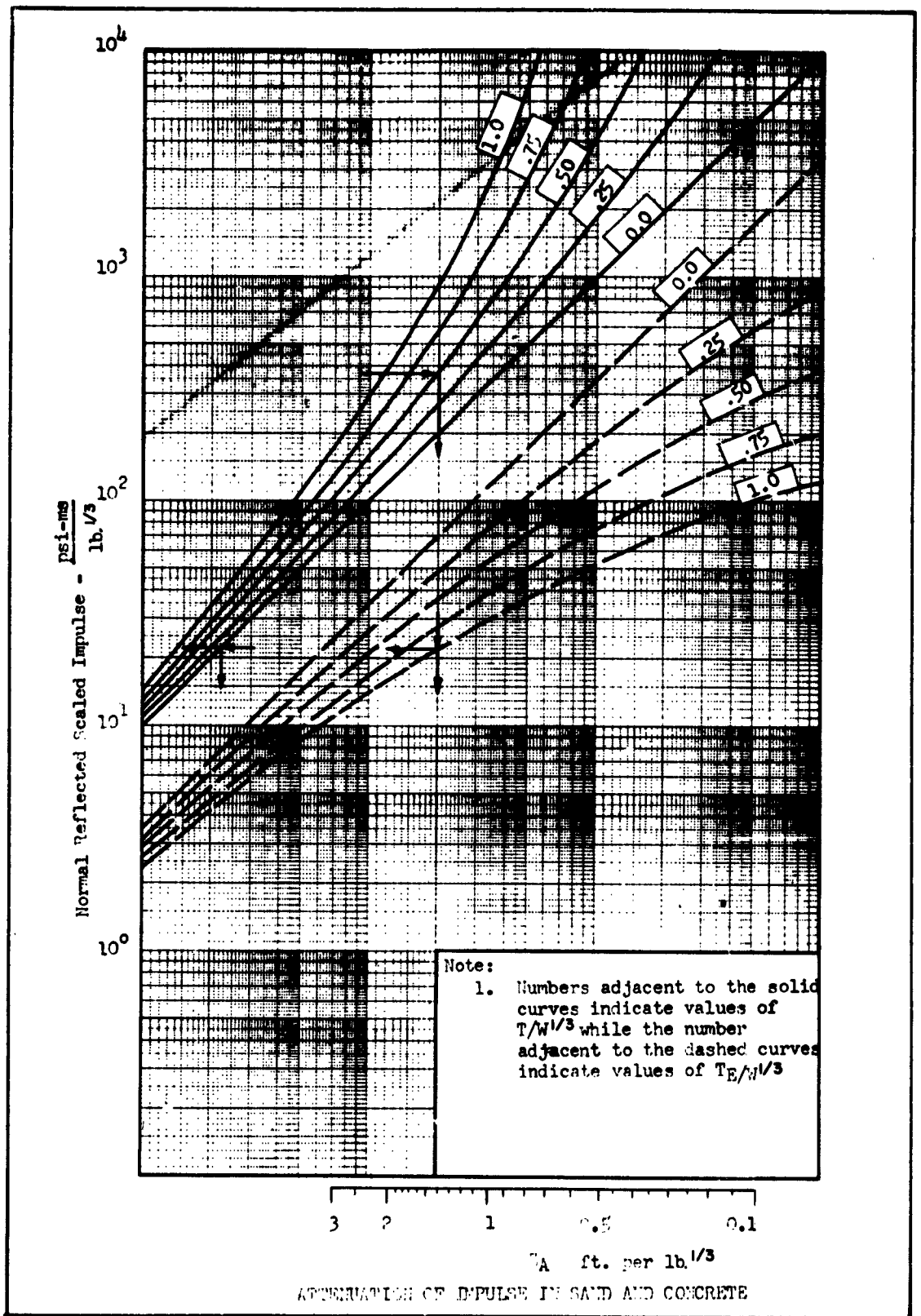


Figure 9

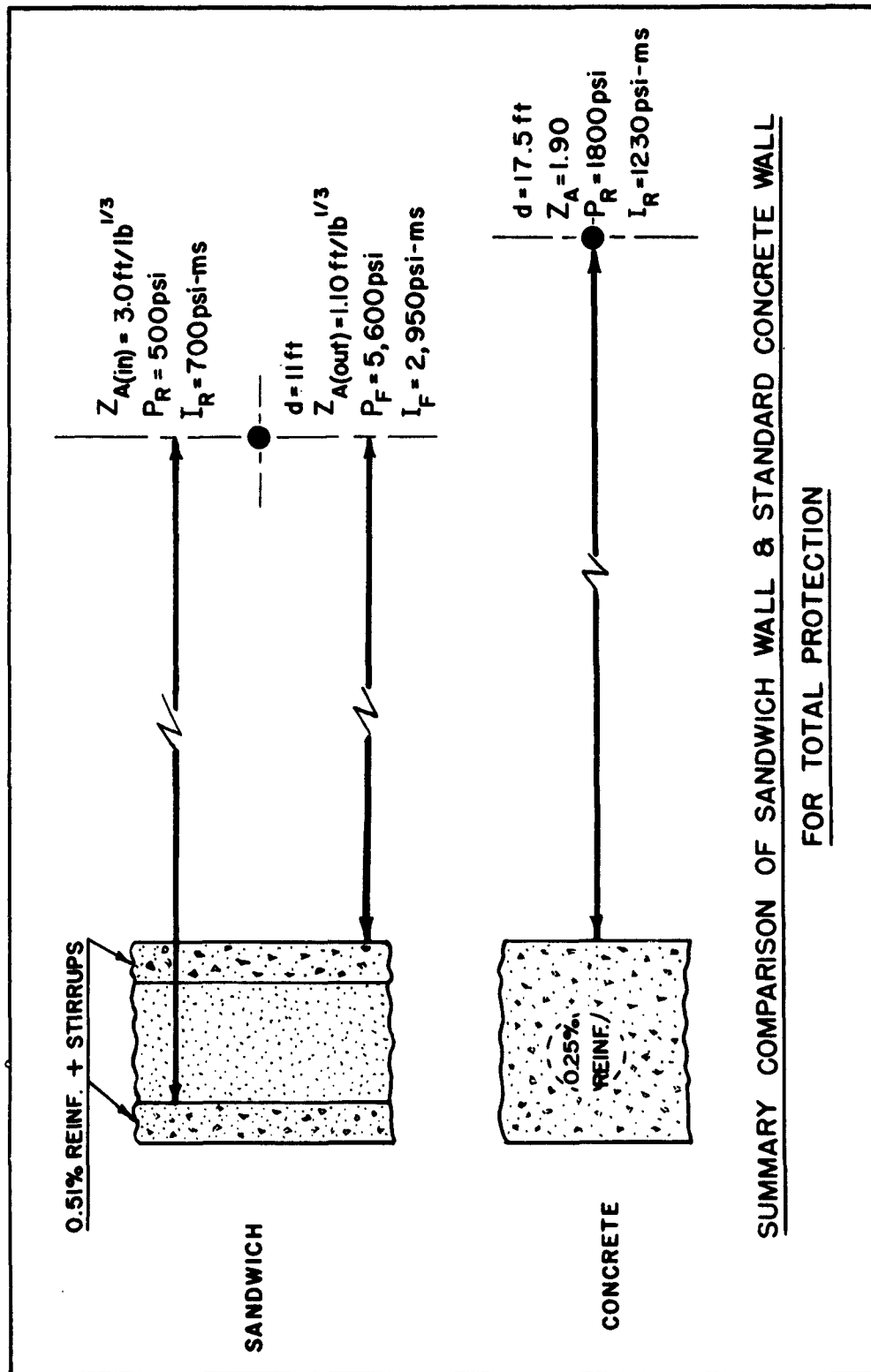


Figure 10

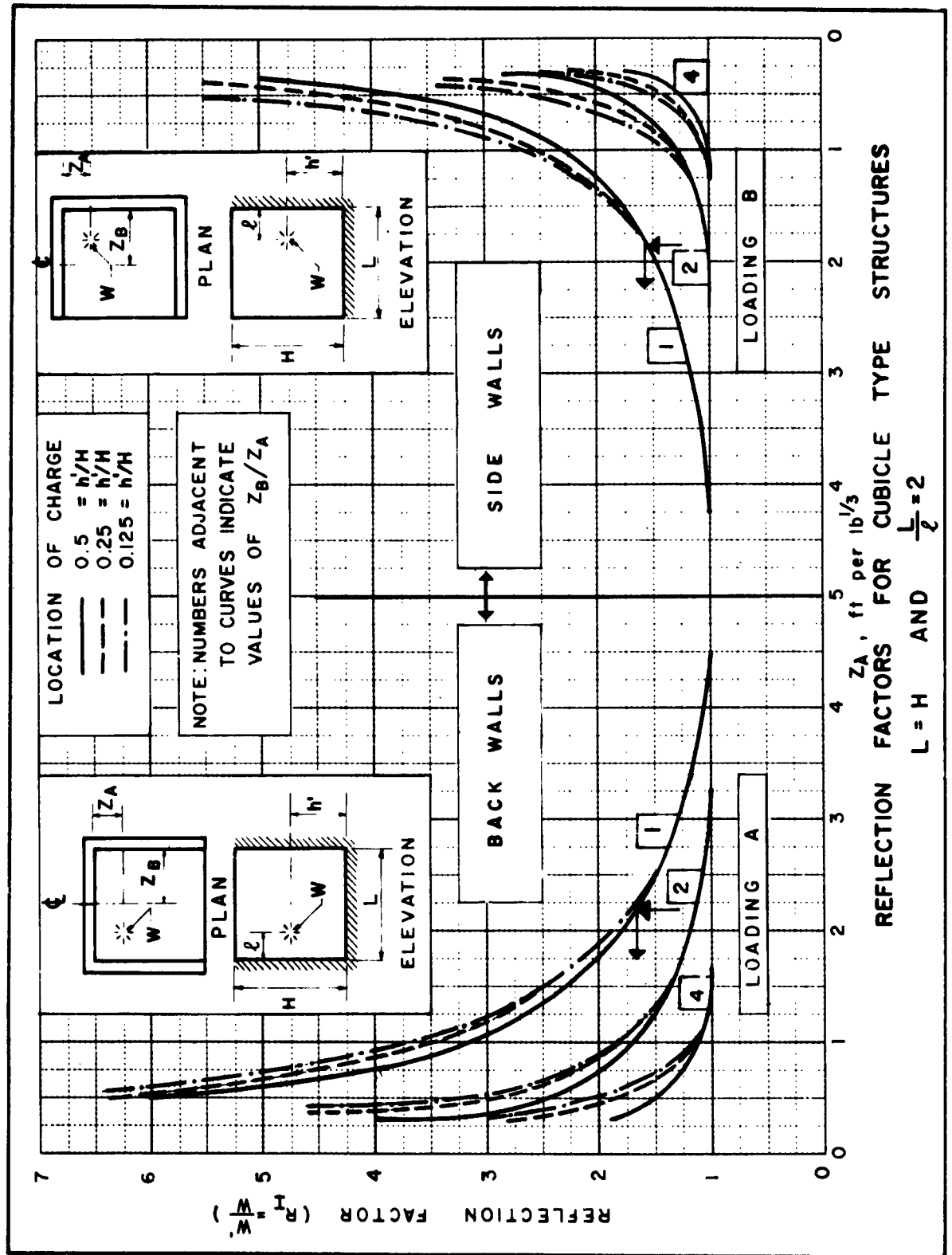
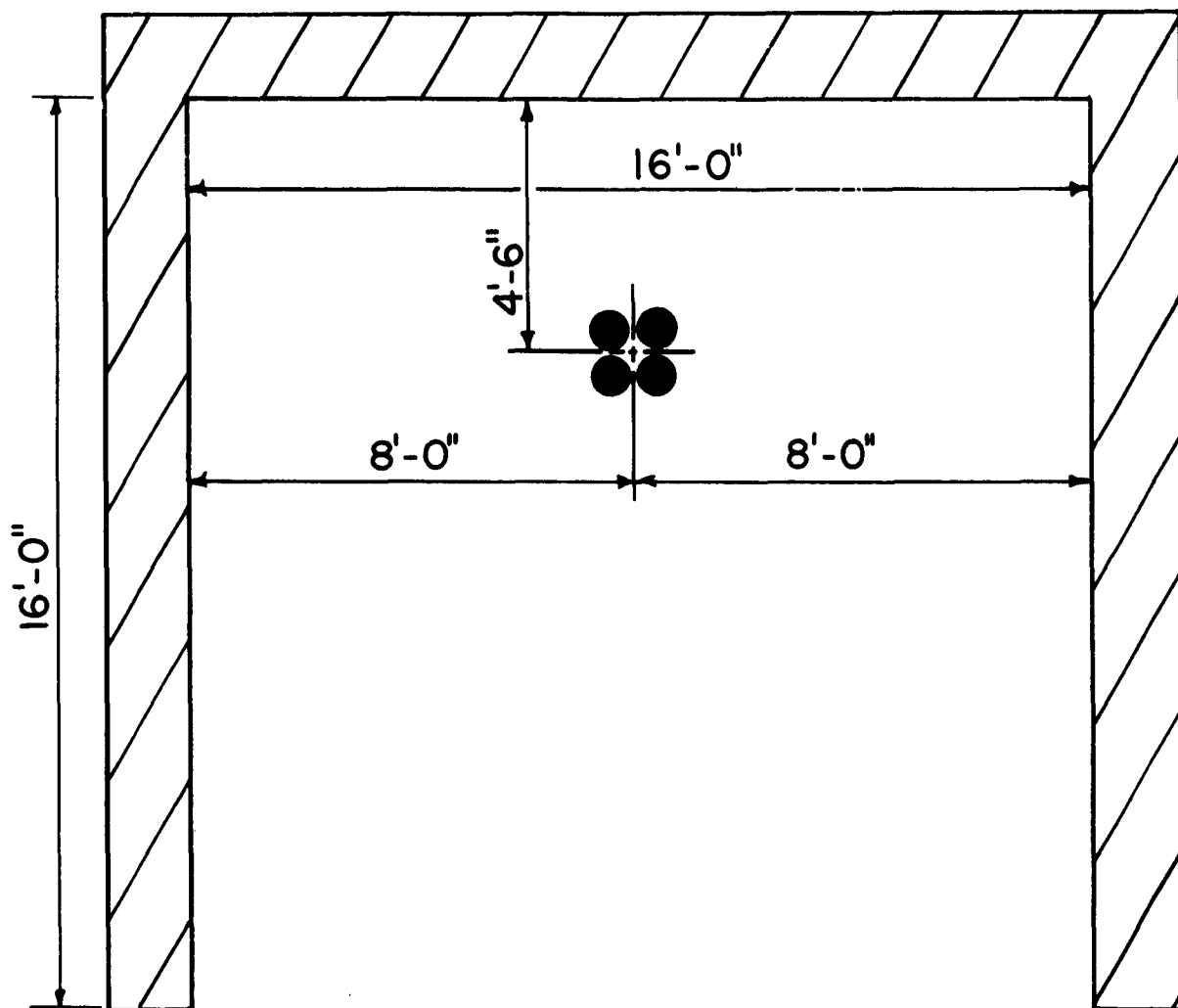
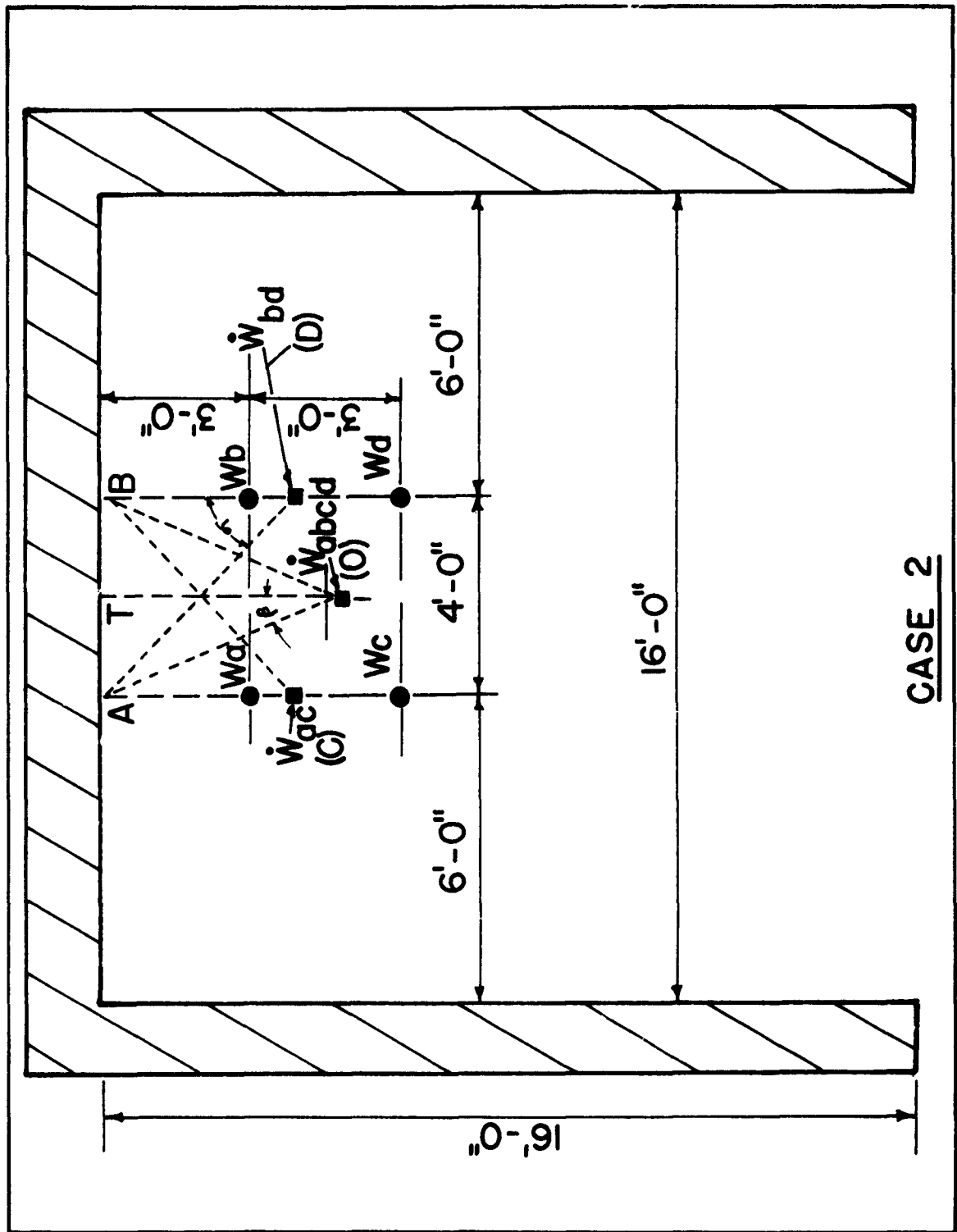


Figure 11



CASE 1

Figure 12



CASE 2

Figure 13

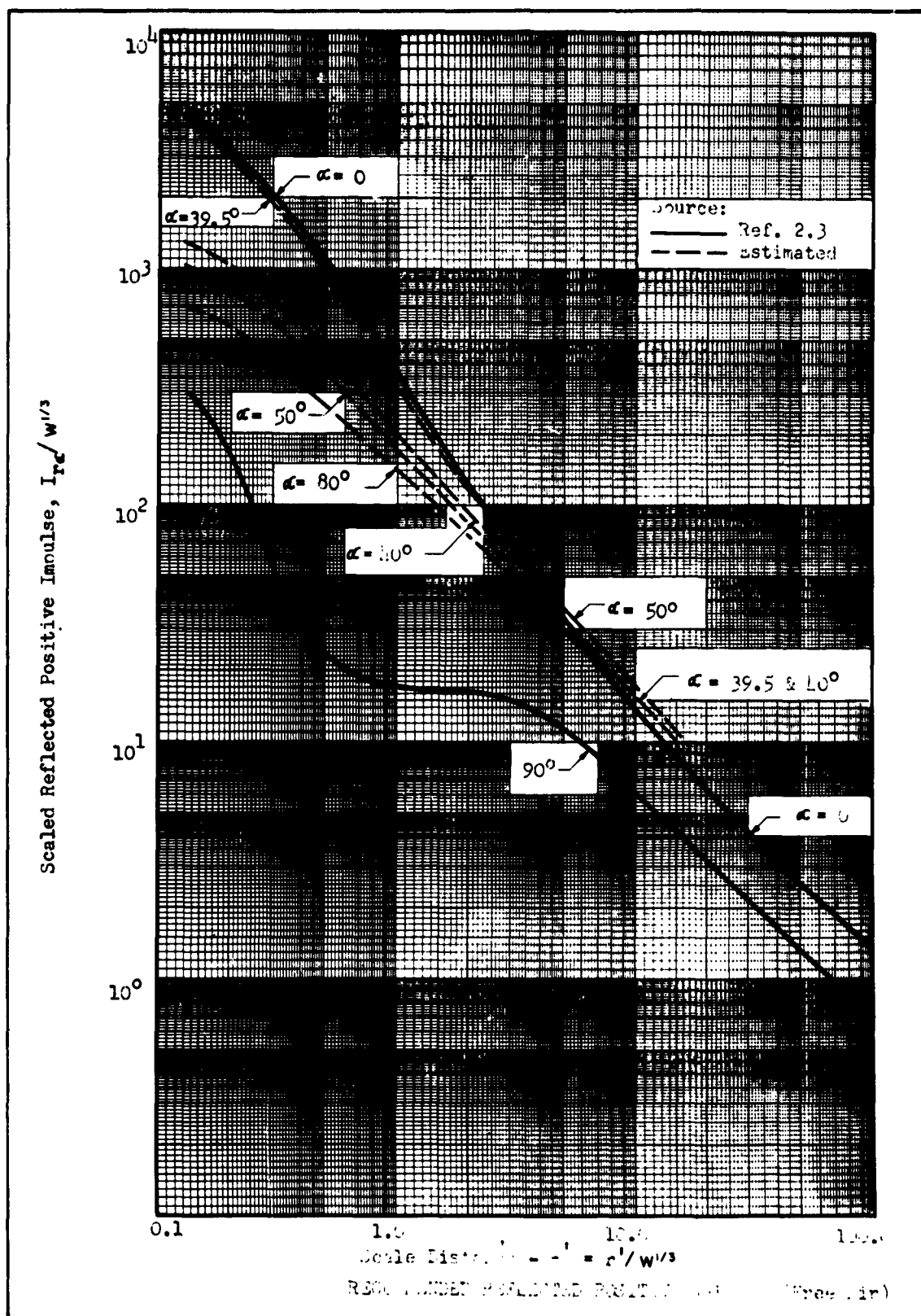
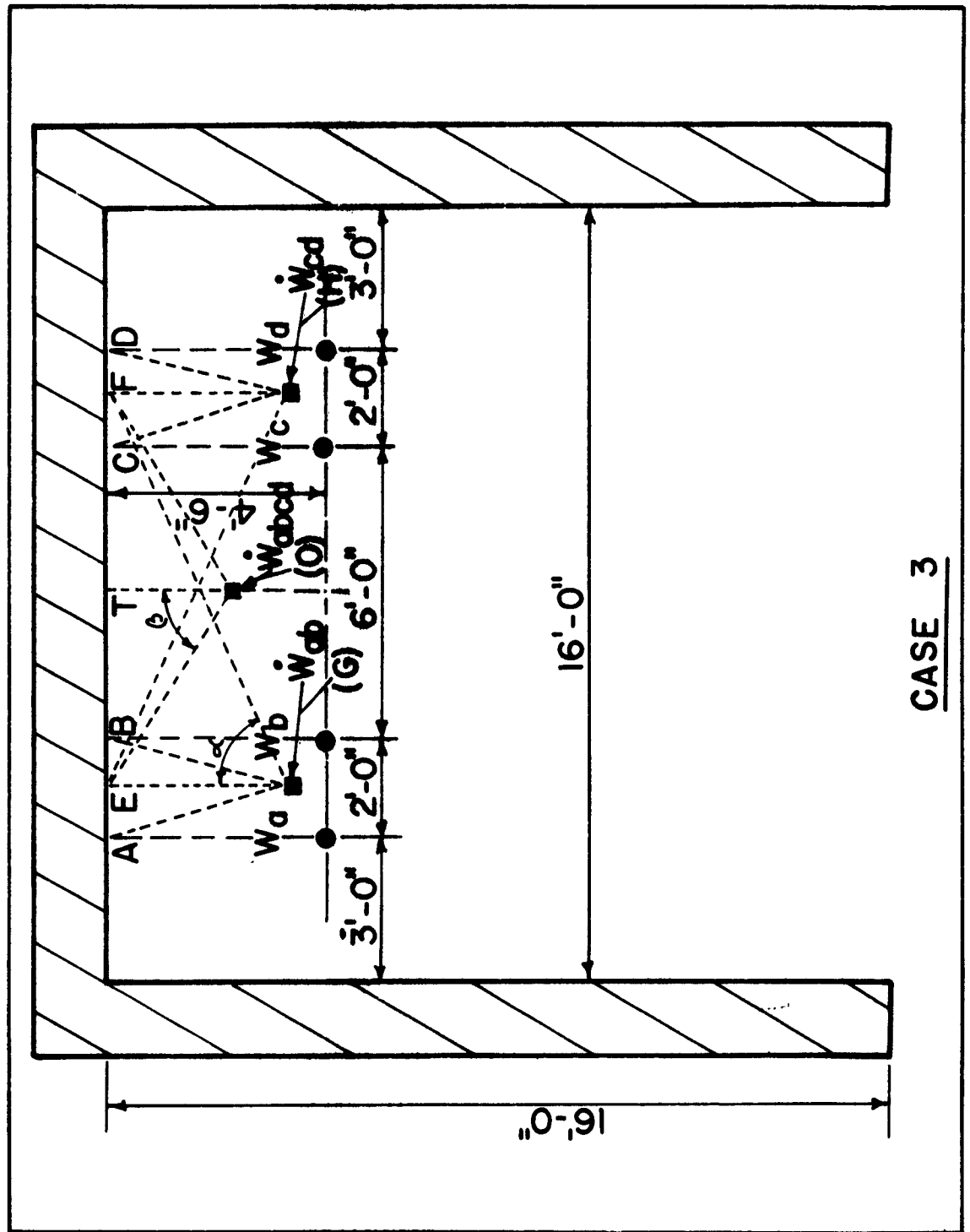


Figure 14



CASE 3

Figure 15

PART II - SUMMARY OF RESULTS

MAXIMUM IMPULSE
PER UNIT AREA, psi-ms MAXIMUM
PRESSURE, psi

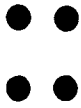
CASE 1		28,000	38,000
CASE 2		21,400	34,000
CASE 3		17,600	26,000

Figure 16

ABSTRACT DATA

ABSTRACT DATA

Accession No. AD

Picatinny Arsenal, Dover, New Jersey

**ANALYSIS OF CERTAIN ASPECTS OF PRO-
TECTIVE WALL DESIGN**

Leon W. Saffian, Richard M. Rindner

Technical Memorandum 1063, February 1963
46pp, figures.

Unclassified memorandum from the Process
Engineering Laboratory, Ammunition Group

Two aspects of the Picatinny Arsenal pro-
gram for establishment of safety design cri-
teria are discussed. Each is concerned with
optimization of cubicle-type protective
structures for manufacture and storage of
explosives and/or high energy propellants.

The first aspect considers the relative pro-
tection effectiveness of different construction
materials. The second part deals with deter-
mination of optimum explosive charge dis-
tribution, within a cubicle, for minimization
of explosion effects.

Illustrative examples are presented for each
case.

Since this presentation in August 1962, cer-
tain revisions have been made to the relation-
ships defining blast reflection factors used in
the illustrative examples. Based on these
revisions, reflection effects as described in
this paper are conservative. These revisions
do not alter the design principles originally
discussed.

UNCLASSIFIED

I. Safety design criteria

I. Saffian, Leon W.

II. Rindner, Richard M.

UNITERMS

Safety

Design

Protective

Walls

Optimization

Cubicle-type

Storage

High energy propellants

Effectiveness

Saffian, L. W.

Rindner, R. M.

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