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PRELIMINARY DESIGN PROCEDURES FOR SUPPRESSIVE SHIELDS

by

Arthur F. Spencer
James L. McKivrigan

Manufacturing Technology Directorate

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DEPARTMENT OF THE ARMY
Headquarters, Edgewood Arsenal
Aberdeen Proving Ground, Maryland 21010

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Suppressive shields are designed to provide a full spectrum of protection for hazardous manufacturing operations in ammunition plants. This report presents preliminary design procedures for quick approximations of shield size and structural response to particular blast situations. It also includes pertinent data on existing shield designs and a consolidated list of references on suppressive shielding.

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PREFACE

The work presented in this report was authorized under MM&T Project 57X1264, Advance Technology for Suppressive Shielding of Hazardous Production and Supply Operation.

CONTENTS

PRELIMINARY DESIGN PROCEDURES FOR SUPPRESSIVE SHIELDS

I. INTRODUCTION.

Suppressive shields are steel structures designed to contain the hazardous effects resulting from detonation or deflagration of high explosive (HE) and pyrotechnic charges. These designs use vented walls to minimize structural loading. (The effective open area may be very small in some designs compared to the total wall area, i.e., 0.2%).

Shield groups have been developed to provide a full spectrum of protection for hazardous manufacturing operations in ammunition plants. These shields totally contain fragments and significantly reduce the external overpressure and/or thermal threat. The shield groups are superior to the conventional concrete barricades because of advantages such as increased safety and a reduction in size, weight, and cost for the majority of applications.

The purpose of this report is to provide a consolidated reference source for making quick, approximate shield designs. Where practical, the required tables and graphs are included, and all equations are referenced. Example problems are provided to prevent confusion concerning units.

Section II discusses and summarizes the Hopkinson scaling laws which is an important tool in the development of suppressive shielding technology. Testing of scaled models represents a tremendous cost savings by yielding data which can be related to full-scale designs.

Section III presents step-by-step methods for calculating blast loads and blowdown time. Also, it presents the Fano equation for equivalent charge weight as a function of actual charge and casing weight.

Section IV covers the response of structural members to dynamic loads, including dynamic shear. The members analyzed are typically those found in the 1/4-scale shield group I structure, i.e., beams and rings. Newmark's equivalent stiffness technique, which is used in this handbook, is a simple method that yields good results.

Section V presents a step-by-step method for calculating blast pressure external to the shield. This section is primarily based on work done by the Southwest Research Institute.

Section VI discusses the fragment hazard and gives a method for calculating penetration depths of primary fragments. It also discusses the secondary fragment hazard.

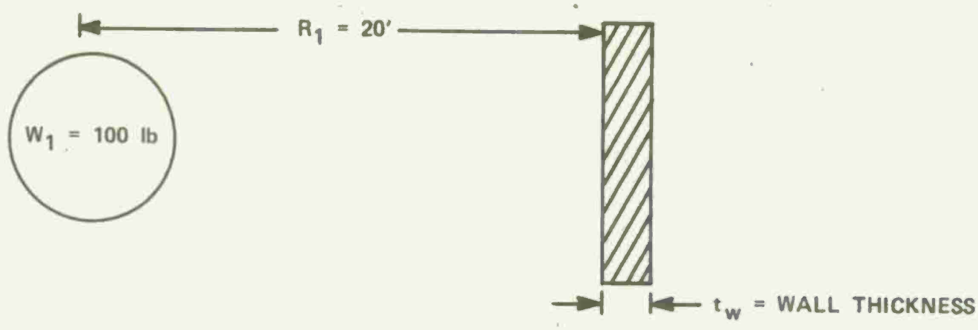
Section VII describes each shield group. It gives the major data of each shield: physical dimensions, weight, unit cost (man-hours), charge weight, design blast loading and test results, fragment stopping protection, and effective vent area.

A list of all suppressive-shield-related references is given in the selected references.

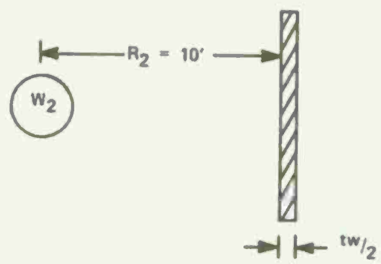
An index of symbols are in the glossary.

II. SCALING LAWS.

For a full-scale blast situation, where W is the charge weight and R is the distance from the center of the explosive source, the system may be scaled down (or up) according to certain scaling laws. For example, let $W_1 = 100$ lb and $R_1 = 20$ ft as shown:



In order to simulate an experiment with a half-scale model of this system (i.e., $R_2 = 10$ ft), W_2 must be determined as shown:



The Hopkinson scaling law defines the scaled distance $Z = R/W^{1/3}$. For each Z, a unique set of R and $W^{1/3}$ values exists and the blast pressure will be the same for any combination of R and $W^{1/3}$ whose ratio yields the same Z value. In the example:

$$Z = \frac{R_1}{W_1^{1/3}} = \frac{20}{(100)^{1/3}} = 4.31 \text{ ft/lb}^{1/3}$$

$$\text{setting } \frac{R_2}{W_2^{1/3}} = 4.31 \quad \text{yields } W_2 = \left(\frac{R_2}{4.31}\right)^3 = \left(\frac{10}{4.31}\right)^3 = 12.5 \text{ lb}$$

Therefore, the peak blast pressure from a 12.5-lb charge at 10 ft will be the same as that from a 100-lb charge 20 ft away.

It is important to note in the above example that although the peak blast pressure is the same in both models, the duration of the blast load and, hence, the loading impulses are different. Time is directly proportional to the scale factor as demonstrated below:

$$\frac{T_1}{W_1^{1/3}} = \frac{T_2}{W_2^{1/3}}$$

$$\frac{T_2}{T_1} = \left(\frac{W_2}{W_1}\right)^{1/3} = \left(\frac{12.5}{100}\right)^{1/3} = 0.5$$

$$T_2 = 0.5 T_1$$

Therefore, the reflected impulse loading is one-half as much on the scale model even though the peak blast pressures are the same.

A summary of the scaling laws is as follows (Ref 81):

Scaling Relationships

(1) $Z = \frac{R}{W^{1/3}}$ = constant

(2) $\frac{T}{W^{1/3}}$ = constant, where T = time

(3) $\frac{I_R}{W^{1/3}}$ = constant, where I_R = reflected impulse

(4) $(P_{SO})_1 = (P_{SO})_2$, where P_{SO} = side-on overpressure

(5) $(P_R)_1 = (P_R)_2$ where P_R = reflected pressure

(6) $(P_{QS})_1 = (P_{QS})_2$*, where P_{QS} = quasi-static pressure.

In order to model the structural response, structural members in a suppressive shield must be scaled as well as the overall dimensions of the structure. (That is, members in a 1/4-scale model must have a similar shape but be 1/4 the size). A properly scaled structure and charge weight will provide the same stresses and strains that would be experienced in the full-scale structure.

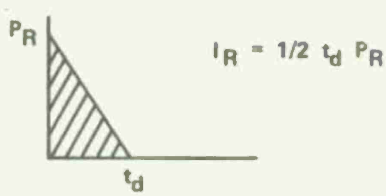
III. BLAST LOADING CALCULATIONS.

A. Parameters.

Quasi-static pressure, P_{QS}, is the pressure inside a partially or completely confined structure which develops from the combustion of gases produced by detonation products and heat generated by blast wave reflections.

Peak positive incident or side-on pressure, P_{SO}, is the abrupt pressure increase from ambient caused by the blast wave.

Peak positive reflected pressure, P_R, is the pressure produced at the shield wall by the blast wave which lasts for the duration of the wave, t_d. Although t_d decays exponentially, it is usually approximated by a triangular pulse. Reflected impulse, I_R, is the impulse associated with a completely reflected incident wave and has units of pressure-time. For a triangular pulse, I_R is simply the area under the curve, as shown:



*This will be true as long as the ratio of the charge weight-to-volume remains constant.

Parametric calculations in this section are based on centrally located bare spherical charges.

B. Explosive Materials Equivalency.

Blast wave parameters from different explosives can be approximated by comparison with an equivalent weight of some standard explosive, usually, TNT. The ratio of the weight of TNT to that of a given explosive which produces the same effect is given in table 1 for both peak pressure and impulse. For example, 1.1 lb of TNT is required to produce the same side-on blast pressure as would 1 lb of Comp B.

Table 1. Equivalent Weight Ratios for Free-Air Effects

Material	*Peak pressure* P_{so}	*Impulse* i_s
Comp A-3	1.09	1.07
Comp B	1.10	1.06
Comp B/TiH_2 (70/30)	1.13	1.13
Cyclotol (70/30)	1.14	1.09
Explosive D	0.85	0.81
HBX-1	1.21	1.21
HBX-3	1.16	1.25
H-6	1.27	1.38
Minol II	1.19	1.17
Pentolite	1.17	1.15
Picratol	0.90	0.93
RDX/Wax (98/2)	1.19	1.16
RDX/Wax (95/5)	1.19	1.16
TNT	1.00	1.00
TNETB	1.13	0.96
Torpex II	1.24	1.20
Tritonal (80/20)	1.07	1.11

C. Cased Charge Equivalent Weight.

Bare charge simulators can be used in shield testing to provide overpressure* characteristics equivalent to those from cased charges without the adverse effects associated with fragmentation. The modified Fano equation, below, gives the equivalent charge weight as a function of actual charge (Refs 20 and 87).

For

$$M/W < 0.53 \ , \ W' = W\left[1 - \frac{(M/W)^2}{(1 + M/W)}\right]$$

For

$$0.53 < M/W \ , \ W' = W\left[0.47 + \frac{0.53}{(1 + M/W)}\right]$$

Where

W' = Effective charge weight, lb

W = Weight of explosive in munition, lb

M = Metal weight, lb

These equations are shown graphically in figure 1.

*Fano equivalency does not apply to quasi-static pressure.

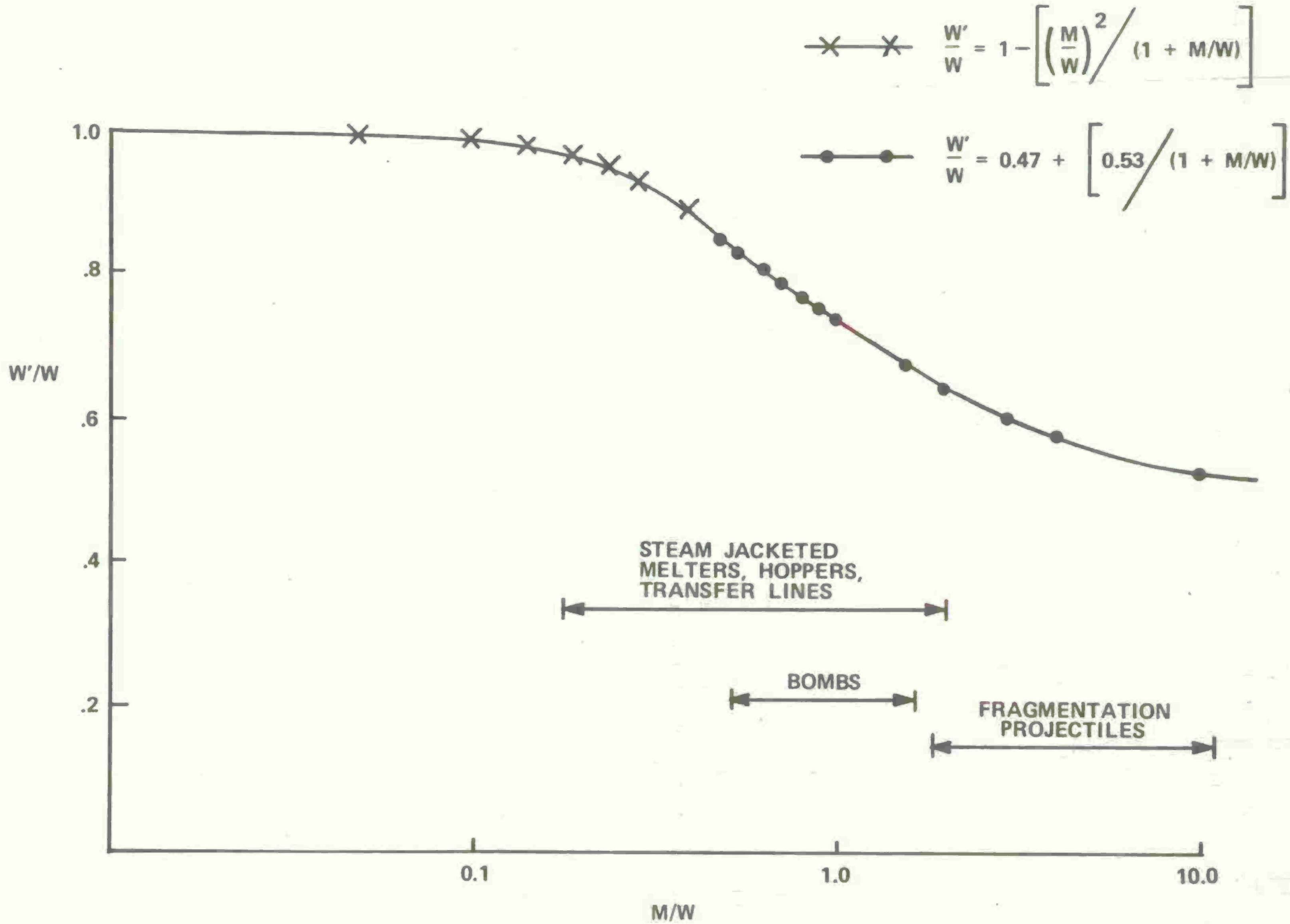


Figure 1. Fano Equivalent Weight Ratio

Example (Fano equivalent charge weight)

Simulate an 81-mm mortar explosion in a suppressive shield without damaging the shield with fragmentation; i.e., use a bare charge with a Fano effective weight.

$$W = 2.1 \text{ lb of explosives in the mortar}$$

$$M = 3.818 \text{ lb case weight}$$

$$M/W = 1.82 \text{ or}$$

$$W' = W\left[0.47 + \frac{0.53}{(1 + M/W)}\right]$$

$$= 2.1\left[0.47 + \frac{0.53}{1 + 1.82}\right] = 1.38 \text{ lb}$$

D. Quasi-Static Pressure.

Tests with HE charges in partially vented chambers with small venting areas have shown that for suppressive shields applied to detonation charges only, venting has no significant influence on the maximum pressures recorded but does affect blowdown time. To calculate the charge weight-to-volume ratio (W/V) and to determine the maximum quasi-static pressure rise, use one of the methods given below. Note also calculated examples given below.

1. A curve developed from two sources of test data using Comp B explosives is shown in figure 2. This data was taken in two different domains of W/V. Figure 2 implies that for $W/V<0.003$, complete oxidation occurs; for $W/V>0.1$, the only oxidizer available is that in the explosive itself; and for W/V between 0.003 and 0.1, partial oxidation results (Ref 28). Because of insufficient experimental data in the partial oxidation regime, it is impossible to accurately predict quasi-static pressure in that range.

2. A conservative calculation for the quasi-static pressure is given by:

$$P_{QS} = 2410\left(\frac{W}{V}\right)^{0.72}$$

This curve (taken from figure 4-65, TM 5-1300) is based on TNT and assumes complete energy conversion.

Example (P_{QS} calculation)

For

$$W = 20 \text{ lb Comp B}$$

$$V = 6458 \text{ ft}^3$$

$W/V = 20/6458 = .0031$ (from figure 2) $P_{QS} = 33$ psi.

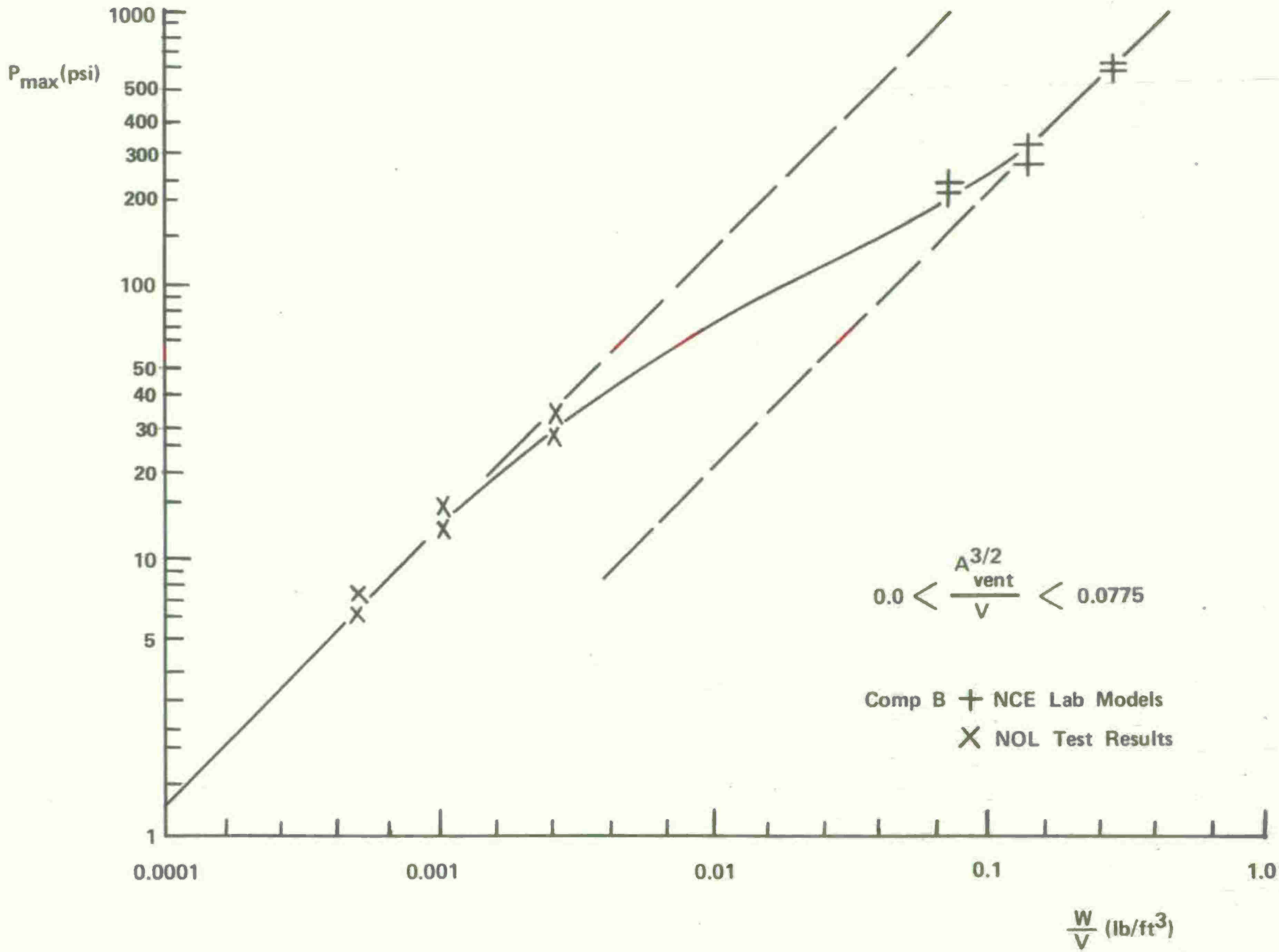


Figure 2. Quasi-Static Pressure Rise Inside an Unvented Enclosure (Ref 28)

The TM 5-1300 equation gives

$$P_{QS} = 2410\left(\frac{W}{V}\right)^{0.72} = 38 \text{ psi}$$

This result is higher for two reasons:

1. The information provided in TM 5-1300 is based on TNT which has a higher heat of combustion.

2. The information provided in TM 5-1300 assumes complete energy conversion.

E. <u>Blowdown Time.</u>

The time required for the quasi-static pressure in a suppressive shield to vent down to ambient pressure is the blowdown time.

The procedure for calculating blowdown time is outlined below.

1. Calculate the volume of the shield, V, and P_{QS}.

2. Calculate A_{vent}. (See section V.)

3. Enter figure 3 with (A_{vent}/V) for the value of $(t/P_{QS}{}^{1/6}V^{1/3})$.

4. Solve for blowdown time, t.

<u>Example</u> (blowdown time calculation)

For

$$V = 6458 \text{ ft}^3, A = 2312 \text{ ft}^2, P_{QS} = 10 \text{ psi}$$

$$A_{vent} = 3\% \text{ of total area} = .03(2312) = 69.4 \text{ ft}^3$$

$$\frac{A_{vent}{}^{3/2}}{V} = \frac{(69.4)^{3/2}}{6458} = .09$$

And so

$$\frac{t}{P_{QS}{}^{1/6}V^{1/3}} = \frac{3.2 \text{ msec}}{(\text{psi})^{1/6}\text{ft}^{1/3}\text{ft}}$$

Or

$$t = 3.2(10)^{1/6}(6458)^{1/3} = 87.5 \text{ msec}$$

Therefore, 87.5 msec from detonation, the quase-static pressure will vent down to ambient pressure.

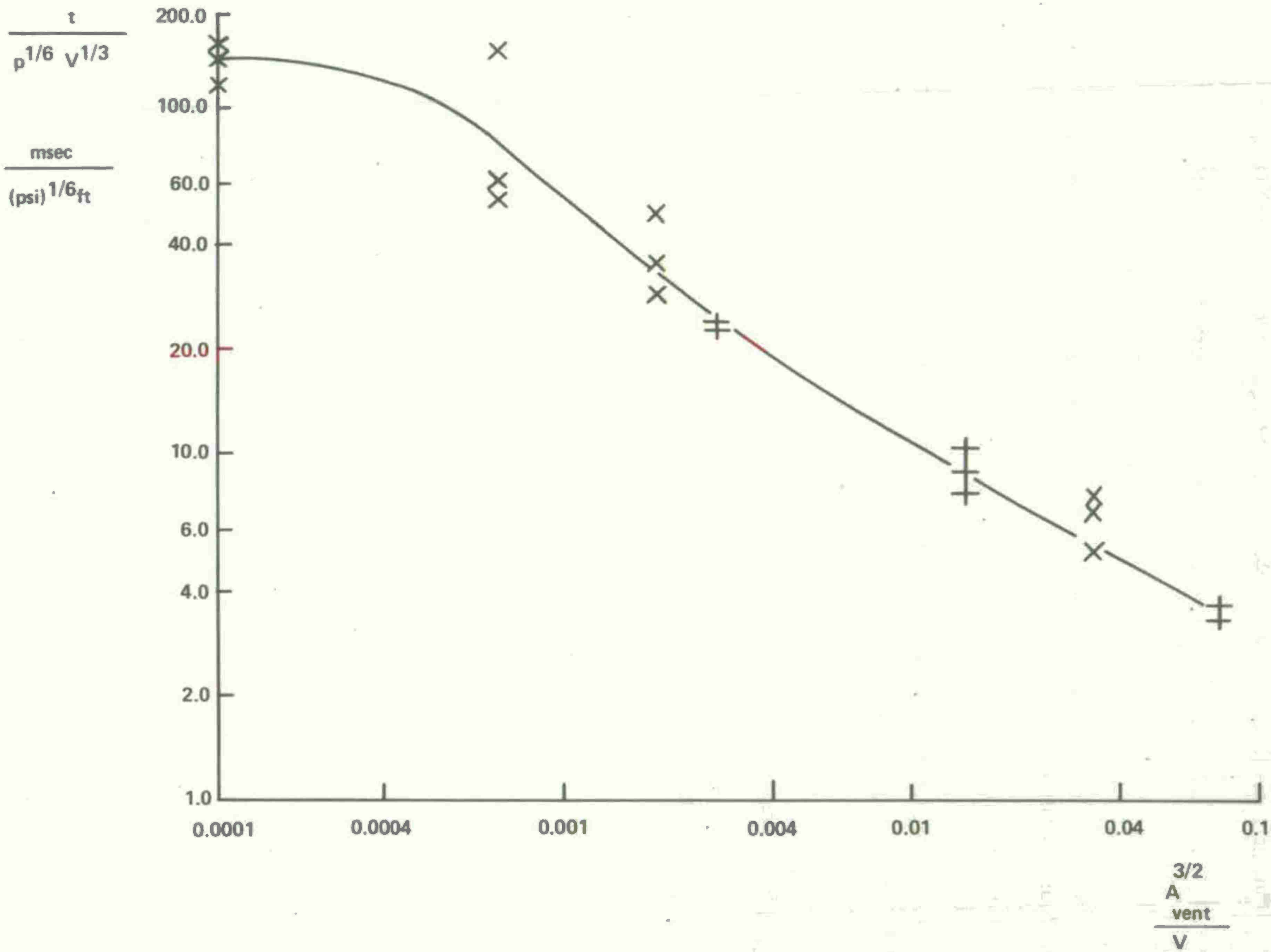


Figure 3. Scaled Blowdown Time for Vented Structure (Ref 28)

F. Side-on and Reflected Pressures.

Calculate scaled distance, $Z = \frac{R}{W^{1/3}}$, determine P_{SO} by one of the following:

1. Goodman's air blast data (Ref 84) (based on pentolite explosion in free air)

2. TM 5-1300, figure 4-5 (based on TNT explosion in free air)

3. TM 5-1300, figure 4-12 (based on hemispherical TNT surface explosion which is higher than free air due to surface reflections).

G. Impulse and Reflected Pressure Duration.

Same as above except for Goodman's data where dimensions incorporating units of time must be scaled, i.e.:

$$t_d, I_S, I_R = (\text{table value}) \cdot (W^{1/3})$$

Example (blast parameter calculations)

For

$$W = 5 \text{ lb TNT}$$

$$R = 10 \text{ ft}$$

From table 1 the pentolite equivalent weight ratio is 1.17.

$W = 5/1.17 = 4.27$ lb of pentolite is equivalent to 5 lb of TNT.

$$Z = \frac{R}{W^{1/3}} = \frac{10}{(4.27)^{1/3}} = 6.16$$

From Goodman's data:

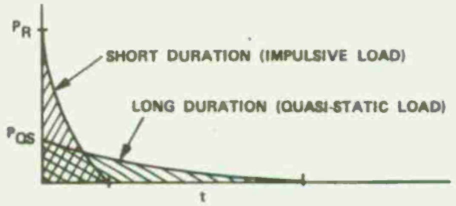
$$I_R = 23.143(4.27)^{1/3} = 37.6 \text{ psi-msec}$$

$$P_R = 62.2 \text{ psi}$$

$$t_d = 1.282(4.27)^{1/3} = 2.08 \text{ msec}$$

$$P_{SO} = 20.8 \text{ psi}$$

The quasi-static pressure and reflected pressure have a combined effect on the suppressive structure. Graphically the two pressures overlap as shown:



Both short- and long-duration effects are taken into account in the structural response section of this handbook (Ref 85).

IV. STRUCTURAL RESPONSE.

A. Newmark's Method.

Newmark's method, which is a simple engineering approximation, yields a reasonable solution for determining the dynamic response of structures. This approach generally replaces a given structure with a dynamically equivalent system. The load-mass factor K_{LM} which equates structural elements to an ideal spring-mass system and the equivalent unit stiffness of the system K_E are the transformation factors (Refs 35, 51, 82, 85).

The resistance of a structure is defined as the internal force tending to restore the structure to its unloaded static position. This function approximates the real case where plastic hinges are formed at high stress points. External work is the product of the time-dependent force and the maximum displacement. To satisfy the law of conservation of energy, the external work minus the internal work is equated to the change in kinetic energy.

From the equation of motion discussed above, equations have been developed for pressure loads of long, short, and combined durations. These cases are discussed in the following structural response calculations.

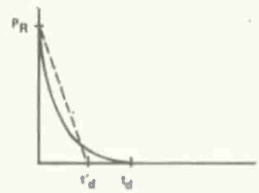
B. Structural Response Calculations (Beams).

The procedure for calculating structural response is outlined below.

1. Calculate P_{QS}, P_R, and I_R. (See Section III.)

2. Newmark's method is based on an idealized triangular reflected impulse; therefore, the idealized reflected pressure duration t'_d is

$$t'_d = \frac{2I_R}{P_R}, \text{ as shown below}$$



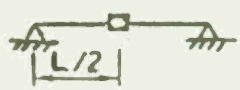
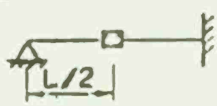
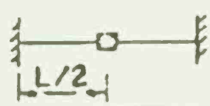
3. Select a structural member and calculate its natural period of vibration, T_N:

a. Use applicable equation given in table 2, or

b. Use equation 6-15 in TM 5-1300,

$$T_N = 2\pi \sqrt{\frac{K_{LM} m}{K_E}} \quad \text{where } m = \text{unit mass, } \frac{\text{psi-ms}^2}{\text{in.}}$$

Table 2. Natural Period of Vibration for Steel Beams (Ref 51)

Member	Period
	$T_N = 0.64\ L^2 \sqrt{\frac{W}{gEI}}$
	$T_N = 0.91\sqrt{\frac{W_c}{g}\ \frac{L^3}{EI}}$
	$T_N = 0.42\ L^2 \sqrt{\frac{W}{gEI}}$
	$T_N = 0.61\sqrt{\frac{W_c}{g}\ \frac{L^3}{EI}}$
	$T_N = 0.28\ L^2 \sqrt{\frac{W}{gEI}}$
	$T_N = 0.45\sqrt{\frac{W_c}{g}\ \frac{L^3}{EI}}$

Where:

T_n = Period, sec
W = Support weight (including beam) per unit length
W_c = Total weight concentrated at midspan
E = Modulus of elasticity
I = Moment of inertia
g = Gravitational constant (386 in./sec^2)

4. Calculate ultimate unit resistance, $r\mu$, using the applicable equation in table 3 where M_P is the plastic moment capacity and is given by

$$M_P = F_{dY} Z$$

Where F_{dY} is the dynamic yield strength of the material (F_{dY} for mild steel is 42,000 psi), and Z is the plastic section modulus (Ref 83).

For standard I-shaped sections (S, W, and M shapes)

Z = 1.15 times the elastic section modulus.

For plates or rectangular cross-section beams

Z = 1.5 times the elastic section modulus.

5. Calculate the ductility ratio, μ, which is the maximum deflection, X_m, divided by the elastic deflection X_e ($\mu = X_m/X_e$) (Ref 85):

a. For short duration only (neglecting P_{QS} effects)

$$\frac{T_N\sqrt{2\mu-1}}{\pi t'_d} = \frac{P_R}{r_u} \quad (t'_d < T_N/3).$$

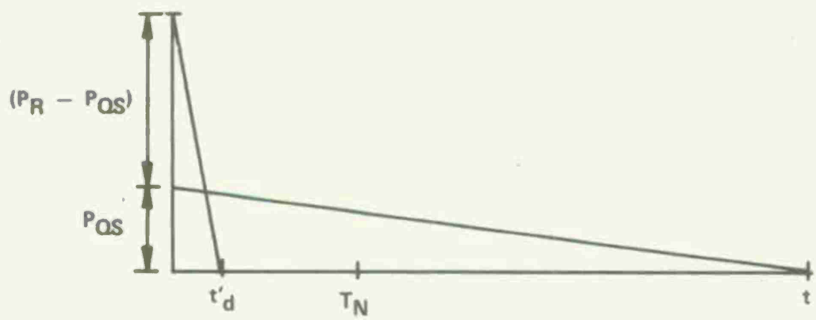
b. For long duration only

$$\frac{P_{QS}}{r_u} = 1 - \frac{1}{2\mu} \quad (t \gg T_N)$$

c. For short and long duration (Ref 85).

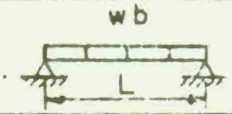
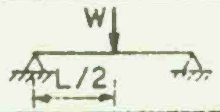
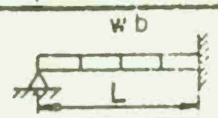
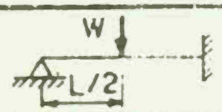
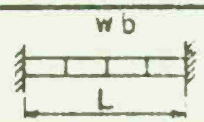
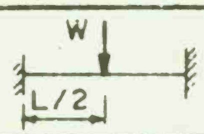
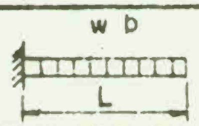
$$\left(\frac{\dfrac{P_R - P_{QS}}{r_u}}{\dfrac{T_N\sqrt{2\mu-1}}{\pi t'_d}}\right)^2 + \left(\frac{\dfrac{P_{QS}}{r_u}}{1-\dfrac{1}{2\mu}}\right) = 1 \quad \left(\begin{matrix} t'_d < T_N/3 \\ t \gg T_N \end{matrix}\right)$$

where



6. If the μ calculated above is not satisfactory, select another structural member size and repeat steps 2 through 4 until μ meets the design requirements. A guide for design criteria is given as follows:

Table 3. Ultimate Resistance and Stiffness of Beam Elements (Ref 28)

Member And Load Configuration	Ultimate Flexural Resistance	Equivalent Elastic Stiffness
	$r_u b L = 8.0 \frac{M_p}{L}$	$K_E = \frac{384 EI}{5L^3}$
	$R_u = 4.0 \frac{M_p}{L}$	$K_E = \frac{48 EI}{L^3}$
	$r_u b L = 12.0 \frac{M_p}{L}$	$K_E = \frac{160 EI}{L^3}$
	$R_u = 6.0 \frac{M_p}{L}$	$K_E = \frac{106 EI}{L^3}$
	$r_u b L = 16.0 \frac{M_p}{L}$	$K_E = \frac{307 EI}{L^3}$
	$R_u = 8.0 \frac{M_p}{L}$	$K_E = \frac{192 EI}{L^3}$
	$r_u b L = 2.0 \frac{M_p}{L}$	$K_E = \frac{8 EI}{L^3}$
	$R_u = \frac{M_p}{L}$	$K_E = \frac{3 EI}{L^3}$

Where:

b = Width of contributory loading area
M_p = Plastic moment capacity
r_u = Ultimate resistance per unit area
R_u = Ultimate total resistance
w = Load per unit area
W = Total concentrated load

The ductility ratio indicates if the structural members will be reusable, namely (Ref 83, 86):

$\mu \leq 1$ - Elastic design.

$\mu \leq 3$ - Reusable members, little or no permanent deformation.

$3 < \mu < 6$ - Reusable members, moderate damage.

$6 \leq \mu$ - Non-reusable, severe damage.

The maximum deflection, X_m, can be determined by

$$X_m = \mu X_e$$

where X_e is the equivalent elastic deflection.

The maximum strain, ϵ_m, can be determined by

$$\epsilon_m = \mu \epsilon_e$$

where ϵ_e is the equivalent elastic strain.

Example (structural response of an I-beam)

Blast loads - $P_R = 5000$ psi $\quad I_R = .38$ psi-sec

$$P_{QS} = 250 \text{ psi and } t = 0.3 \text{ sec}$$

$$t'_d = \frac{2I_R}{P_R} = .00015 \text{ sec}$$

S5 I-beam - (fixed-fixed)

$\omega = 14.75$ lb/ft
$b = 3.284$ in.
$I = 15.2$ in.^{4}
$S = 6.09$ in.^{3}
$L = 30$ in.
$E = 30 \times 10^6$ psi
$F_Y = 36{,}000$ psi
$F_{dY} = 42{,}000$ psi

Calculate natural period of vibration, T_N -

$$T_N = 0.28\, L^2 \sqrt{\frac{\omega}{gEI}} \quad \text{where } g = 386 \text{ in./sec}^2$$

$$= 0.28\,(30)^2 \sqrt{\frac{(14.75/12)}{(386)(30 \times 10^6)(15.2)}} = .00067 \text{ sec}$$

Calculate ultimate unit resistance, r_u -

$$r_u = 16.0 \frac{M_P}{bL^2} = 16.0 \frac{ZF_{dY}}{bL^2}$$

$$= 16.0 \frac{(1.15)(6.09)(42,000)}{(3.284)(30)^2} = 1593 \text{ psi}$$

Determine amount of deformation past the elastic limit; μ (use short- and long-duration equation since $t'_d = .00015 < T_N/3 = .00022$ and $t \gg T_N$) -

$$\left(\frac{\frac{P_R - P_{QS}}{r_u}}{T_N \frac{\sqrt{2\mu-1}}{\pi t'_d}}\right)^2 + \left(\frac{\frac{P_{QS}}{r_u}}{1 - \frac{1}{2\mu}}\right) = 1$$

$$\left(\frac{(5000 - 250)/1593}{.00067 \frac{\sqrt{2\mu-1}}{3.14(.00015)}}\right)^2 + \left(\frac{250/1593}{1 - \frac{1}{2\mu}}\right) = 1$$

$$\left(\frac{2.10}{\sqrt{2\mu-1}}\right)^2 + \left(\frac{.16}{1 - \frac{1}{2\mu}}\right) = 1$$

$$\frac{4.41}{2\mu-1} + \frac{.32\mu}{2\mu-1} = 1$$

$$4.41 + .32\mu = 2\mu - 1 \text{ or } \mu = 3.22$$

Therefore, the maximum deflection is 3.22 times the equivalent elastic deflection and the member would be reusable since $\mu < 6$.

Determine the maximum deflection, X_m (Ref 51)

$$X_e = \frac{R_u}{K_E}$$

Where

R_u = Ultimate total resistance

K_E = Equivalent elastic stiffness

From table 3 $R_u = r_u bL$ and $K_E = \frac{307 \, EI}{L^3}$

Therefore,

$$X_e = \frac{r_u bL^4}{307 \, EI} = \frac{(1593)(3.284)(30)^4}{(307)(30 \times 10^6)(15.2)} = 0.03 \text{ in.}$$

$$X_m = \mu X_e$$

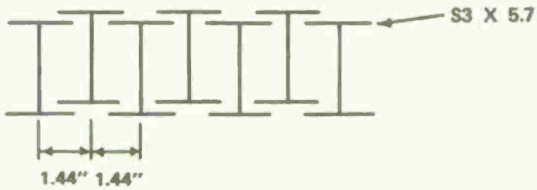
$$= 3.22(.03) = 0.10 \text{ in.}$$

Therefore, maximum deflection will be 0.06 in. and will occur at the center of the beam, and the maximum strain will be

$$\epsilon_m = \mu\epsilon_e = \mu\left(\frac{F_{dY}}{E}\right) = 3.22\left(\frac{42{,}000}{30\times10^6}\right) = 0.0045\ \mu\text{m/in.}$$

or 4,500 μm/in

Example (interlocking I-beams).



Blast loads - $P_R = 3150$ psi

$P_{QS} = 200$ psi

$t'_d = .00032$ sec

S3 I-beam - (fixed-fixed)

$\omega = 5.7$ lb/ft

$b = 2.33$ in.

$I = 2.52$ in.^{4}

$S = 1.68$ in.^{3}

$L = 60$ in.

$E = 30\times10^6$ psi

$F_Y = 36{,}000$ psi

$F_{dY} = 45{,}000$ psi

Assume equal load distribution on inner and outer beams (Refs 85, 89):

$$r_u = \frac{16\,M_P}{b'L^2} = \frac{16\,ZF_{dY}}{b'L^2}$$

$$= \frac{16(1.15)(1.68)(45{,}000)}{1.44(60)^2} = 268\text{ psi}$$

where b′ is the effective flange width.

$$T_N = 0.28\,L^2\sqrt{\frac{\omega}{gEI}} \quad \text{where } g = 386\text{ in./sec}^2$$

$$= 0.28\,(60)^2\sqrt{\frac{(5.7/12)}{(386)(30\times10^6)(2.52)}} = .0041\text{ sec}$$

Determine amount of deformation past the elastic limit, μ (use the short- and long-duration equation since $t'_d = .00032 < T_N/3 = .0014$ and $t \gg T_N$)

$$\left(\frac{\dfrac{P_R - P_{QS}}{r_u}}{\dfrac{T_N\sqrt{2\mu-1}}{\pi t'_d}}\right)^2 + \left(\frac{\dfrac{P_{QS}}{r_u}}{1-\dfrac{1}{2\mu}}\right) = 1$$

$$\left(\frac{\frac{3150-200}{268}}{.0041\frac{\sqrt{2\mu-1}}{\pi(.00032)}}\right)^2 + \left(\frac{\frac{200}{268}}{1-\frac{1}{2\mu}}\right) = 1$$

$$\frac{7.28}{2\mu-1} + \frac{1.49\mu}{2\mu-1} = 1$$

$$7.28 + 1.49\mu = 2\mu - 1 \quad \text{or} \quad \mu = 16$$

Determine the maximum deflection:

$$X_e = \frac{r_u b' L^4}{307\ EI}$$

$$= \frac{(268)(1.44)(60)^4}{(307)(30\times 10^6)(2.52)} = 0.22 \text{ in.}$$

$$X_m = \mu X_e$$

$$= 16(0.22) = 3.52 \text{ in. maximum deflection}$$

Maximum strain $\epsilon_m = \mu\epsilon_e$

$$= 16\left(\frac{F_{dY}}{E}\right) = 16\left(\frac{45{,}000}{30\times 10^6}\right) = 0.024 \text{ in./in.}$$

or 25,000 μ in./in.

C. Structural Response of Rings Supporting Beams (Figure 4).

The deformation of steel rings supporting cylindrical structures with interlocking or stacked beams can be conservatively estimated by neglecting the energy absorbed in deformation of the beams (Ref 85). The procedure for calculating structural response follows.

1. Determine the natural period of vibration for the ring and the portion of beams it supports (Ref 85)

$$T_N = 2\pi\sqrt{\frac{W_T}{K_g}}$$

Where K is the stiffness coefficient and

$$K = \frac{A_R E}{(R_R)^2}$$

W_T = Ring and supported beam weight per circumferential in., lb/in.

A_R = Cross-sectional area of ring, in.^{2}

R_R = Radial distance to ring centerline, in.

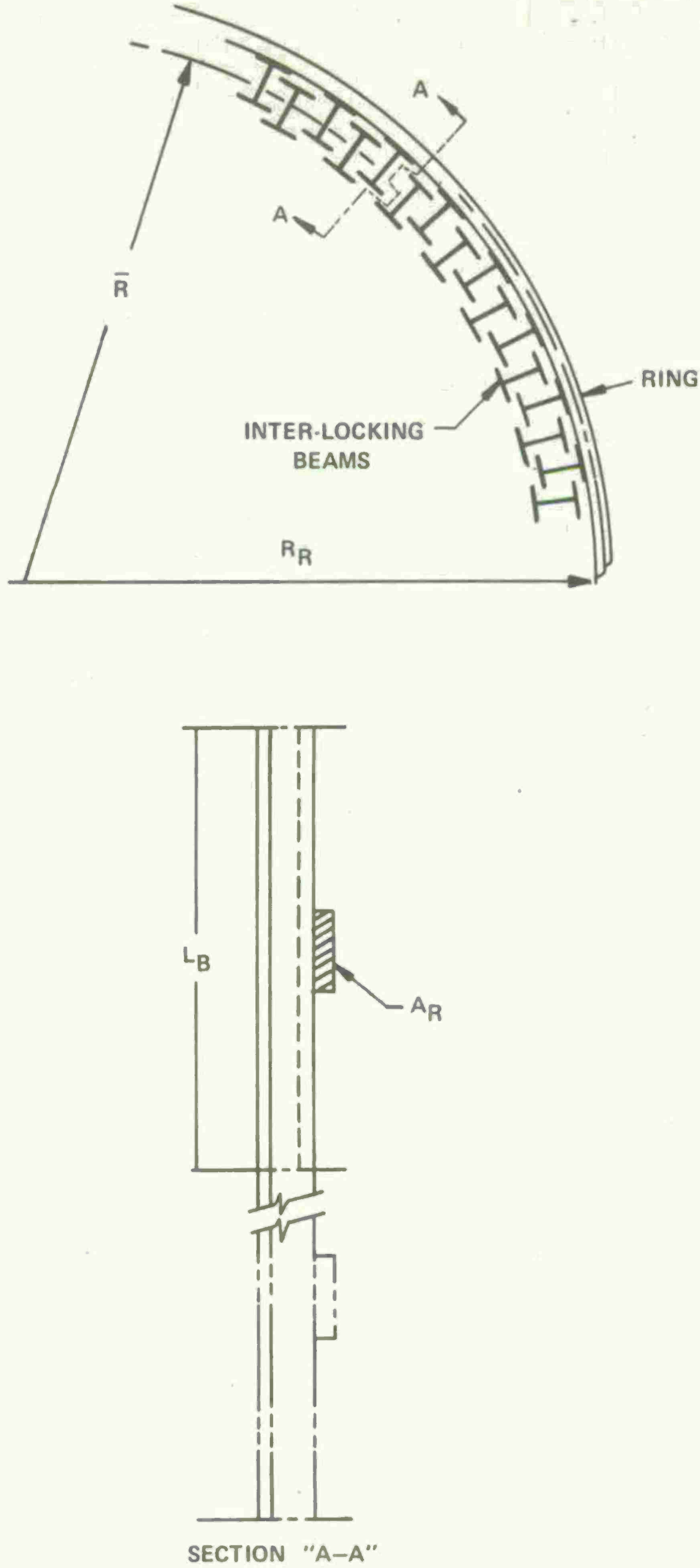


Figure 4. Geometry of Beams and Rings in the Cylinder Wall (Ref 31)

2. Calculate the ultimate unit resistance (Ref 85)

$$r_u = \frac{\sigma_c A_R}{L_B R_W}$$

where

σ_c = Circumferential stress, psi

R_W = Radius to inside wall, in.

L_B = Length of supported portion of beams, in.

A_R = Ring cross-sectional area, in.^{2}

3. Determine the amount of deflection past the equivalent elastic deflection, μ, using the equation given in section IV.

$$\left(\frac{\frac{P_R - P_{QS}}{r_u}}{\frac{T_N \sqrt{2\mu - 1}}{\pi t'_d}} \right)^2 + \left(\frac{\frac{P_{QS}}{r_u}}{1 - \frac{1}{2\mu}} \right) = 1$$

4. If μ is not satisfactory, increase the number of rings or the ring cross-sectional area and repeat steps 1 through 3.

<u>Example</u> (rings supporting interlocking beams)

Suppose we have a structure, as shown in figure 7, with the following information:

I-beams S3 × 5.7

Rings 2.25 in. × 5 in.

$E = 29 \times 10^6$ psi

$W_T = 9.05$ lb/in.

$R_R = 71.125$ in.

$R_W = 67.5$ in.

$\sigma_c = 42{,}000$ psi

$L_B = 30$ in.

$P_R = 3150$ psi

$P_{QS} = 163$ psi

$t'_d = .32$ msec

$A_R = 11.25$ in.^{2}

$$K = \frac{A_R E}{(R_R)^2}$$

$$= \frac{(11.25)(29 \times 10^6)}{(71.125)^2} = 64{,}492 \text{ psi}$$

$$T_N = 2\pi \sqrt{\frac{W_T}{K_g}}$$

$$= 2\pi \sqrt{\frac{9.05}{(64{,}492)(386)}} = 3.788 \text{ msec}$$

$$r_u = \frac{\sigma_c A_R}{L_B R_W}$$

$$= \frac{(42{,}000)(11.25)}{(30)(67.5)} = 233 \text{ psi}$$

$$\left(\frac{\dfrac{P_R - P_{QS}}{r_u}}{\dfrac{T_N\sqrt{2\mu-1}}{\pi t'_d}}\right)^2 + \left(\frac{\dfrac{P_{QS}}{r_u}}{1 - \dfrac{1}{2\mu}}\right) = 1$$

$$\left(\frac{\dfrac{3150 - 163}{233}}{\dfrac{3.788\sqrt{2\mu-1}}{\pi(.32)}}\right)^2 + \left(\frac{\dfrac{163}{233}}{1 - \dfrac{1}{2\mu}}\right) = 1$$

$$\left(\frac{3.40}{\sqrt{2\mu-1}}\right)^2 + \left(\frac{.70}{1 - \dfrac{1}{2\mu}}\right) = 1$$

$$\frac{11.56}{2\mu-1} + \frac{1.4\mu}{2\mu-1} = 1 \text{ or } \mu = 21$$

Determine the ring deflection:

$$\Delta\text{Length} = \frac{\sigma_c A_R(2\pi R_R)}{A_R E}$$

$$= \frac{42{,}000(11.25)\pi(142.250)}{11.25(29 \times 10^6)} = .647 \text{ in. at the elastic limit.}$$

$$\Delta\text{Diameter} = \frac{.647}{\pi} = .206 \text{ in. or } \Delta\text{Radius} = .103 \text{ in. at the elastic limit.}$$

Since $\mu = X_m/X_e$ then $X_m = \mu X_e$

$$= 21(.103) = 2.16 \text{ in.}$$

This means that the ring's radius will increase by 2.16 in. if the ends of the beams are not supported.

D. Dynamic Shear.

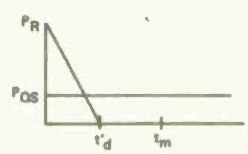
The procedure for calculating the dynamic shear is given below.

1. Calculate the time of maximum deflection, t_m (Ref 51)

$$t_m = \frac{\frac{1}{2} P_R t'_d}{r_u - P_{QS}}$$

It is assumed that the maximum shear occurs when the beam reaches maximum deflection (Refs 51, 86)

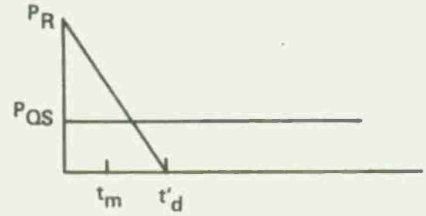
2. For $t_m > t'_d$



Calculate the maximum total load at the t_m

$$P_t = P_{QS} bL$$

3. For $t_m < t'_d$



Calculate the maximum total load at time, t_m

$$P_t = \left(\frac{t'_d - t_m}{t'_d} \right) P_R bL + P_{QS} bL$$

4. Calculate the maximum resistance, R_m, of the structural member using table 3 or table 4. Calculate the dynamic reaction V using table 4. The maximum shear stress will be the dynamic reaction divided by A_w (Refs 51, 85, 86).

5. The yield capacity of steel beams in shear is

$$V_p = F_{dV} A_w$$

where F_{dV} is the dynamic shear yield strength (equal to 0.55 F_{dY}, Ref 83) and A_w is the area of the web. For I-shaped beams and similar flexural members with thin webs, only the web area between flange plates should be used in calculating A_w.

6. As long as the dynamic reaction does not exceed V_p, I-shaped sections can be considered capable of achieving their full plastic moment. If V is greater than V_p, the web area is inadequate and either the web must be strengthened or a different section should be selected.

Example (shear calculations).

From the previous example on the structural response of an S5 I-beam with

$$P_R = 5000 \text{ psi}$$
$$P_{QS} = 250 \text{ psi}$$
$$t'_d = .00015 \text{ sec}$$
$$r_u = 1593 \text{ psi}$$

Calculate the time to maximum deflection

$$t_m = \frac{\tfrac{1}{2} P_R t'_d}{r_u - P_{QS}} = \frac{\tfrac{1}{2}(5000)(.00015)}{1593 - 250} = .0003 \text{ sec}$$

since $t_m > t'_d$

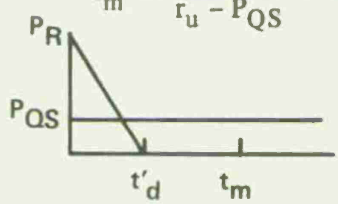
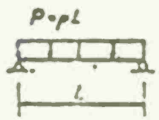
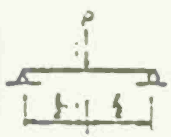
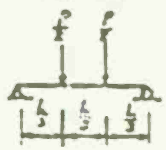


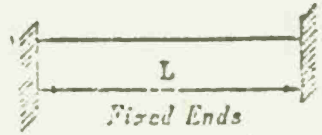
Table 4A. Dynamic Design Factors for Beams (Ref 51)

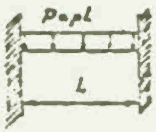
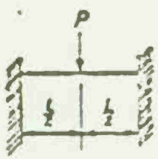
Simply-Supported

Loading Diagram	Strain Range	Load Factor K_L	Mass Factor K_M		Load-Mass Factor K_{LM}		Maximum Resistance R_m	Spring Constant k	Dynamic Reaction V
			Concentrated Mass *	Uniform Mass	Concentrated Mass *	Uniform Mass			
	Elastic	0.64		0.50		0.78	$\frac{8M_p}{L}$	$\frac{384EI}{5L^3}$	0.39 R+0.11P
	Plastic	0.50		0.33		0.66	$\frac{8M_p}{L}$	0	$0.38R_m+0.12P$
	Elastic	1	1.0	0.49	1.0	0.49	$\frac{4M_p}{L}$	$\frac{48EI}{L^3}$	0.78 R−0.28P
	Plastic	1	1.0	0.33	1.0	0.33	$\frac{4M_p}{L}$	0	$0.75R_m-0.25P$
	Elastic	0.87	0.76	0.52	0.87	0.60	$\frac{6M_p}{L}$	$\frac{56.4EI}{L^3}$	0.62 R−0.12P
	Plastic	1	1.0	0.56	1.0	0.56	$\frac{6M_p}{L}$	0	$0.75R_m-0.25P$

* Equal parts of the concentrated mass are lumped at each concentrated load.

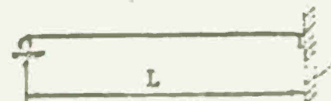
Table 4B. Dynamic Design Factors for Beams (Ref 51)



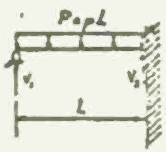
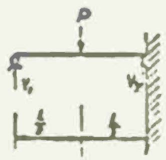
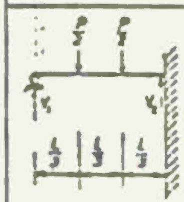
Loading Diagram	Strain Range	Load Factor K_L	Mass Factor K_M		Load-Mass Factor K_{LM}		Maximum Resistance R_m	Spring Constant k	Effective Spring Constant k_E		Dynamic Reaction V
			Concentrated Mass*	Uniform Mass	Concentrated Mass*	Uniform Mass			Elastic	Plastic	
	Elastic	0.53		0.41		0.77	$\frac{12M_{Ps}}{L}$	$\frac{384EI}{L^3}$	$\frac{264\ EI}{L^3}$	$\frac{307\ EI}{L^3}$	0.36R+0.14P
	Elasto-Plastic	0.64		0.50		0.78	$\frac{8}{L}(M_{Ps}+M_{Pm})$	$\frac{384EI}{5L^3}$	$R_{mf} = \frac{22M_P}{L}$		0.39R+0.11P
	Plastic	0.50		0.33		0.66	$\frac{8}{L}(M_{Ps}+M_{Pm})$	0			$0.38R_m+0.12P$
	Elastic	1	1.0	0.37	1.0	0.37	$\frac{4}{L}(M_{Ps}+M_{Pm})$	$\frac{192EI}{L^3}$			0.71R-0.21P
	Plastic	1	1.0	0.33	1.0	0.33	$\frac{4}{L}(M_{Ps}+M_{Pm})$	0			$0.75R_m-0.25P$

* Concentrated mass is lumped at the concentrated load.

Table 4C. Dynamic Design Factors for Beams (Ref 51)



Simply-Supported and Fixed

Loading Diagram	Strain Range	Load Factor K_L	Mass Factor K_M		Load-Mass Factor K_{LM}		Maximum Resistance R_m	Spring Constant k	Effective Spring Constant k_E		Dynamic Reaction V
			Concentrated Mass*	Uniform Mass	Concentrated Mass*	Uniform Mass			Elastic	Plastic	
	Elastic	0.58		0.45		0.78	$8M_{Ps}/L$	$185EI/L^3$	$\frac{153EI}{L^3}$	$\frac{160EI}{L^3}$	$V_1=0.26R+0.12P$ $V_2=0.43R+0.19P$
	Elasto-Plastic	0.64		0.50		0.78	$\frac{4}{L}(M_{Ps}+2M_{Pm})$	$\frac{384}{5}EI/L^3$			$V_1=V_2=0.39R+0.11P$
	Plastic	0.50		0.33		0.66	$\frac{4}{L}(M_{Ps}+2M_{Pm})$	0	$R_{mf}=\frac{14.6M_P}{L}$		$V_1=V_2=0.38R_m+0.12P$
	Elastic	1.0	1.0	0.43	1.0	0.43	$16M_{Ps}/3L$	$107EI/L^3$	$\frac{104EI}{L^3}$	$\frac{160EI}{L^3}$	$V_1=0.54R+0.14P$ $V_2=0.25R+0.07P$
	Elasto-Plastic	1	1.0	0.49	1.0	0.49	$\frac{2}{L}(M_{Ps}+2M_{Pm})$	$48EI/L^3$			$V_1=V_2=0.78R-0.28P$
	Plastic	1	1.0	0.33	1.0	0.33	$\frac{2}{L}(M_{Ps}+2M_{Pm})$	0	$R_{mf}=\frac{6.63M_P}{L}$		$V_1=V_2=0.75R_m-0.25P$
	Elastic	0.81	0.67	0.45	0.83	0.55	$6M_{Ps}/L$	$132EI/L^3$	$\frac{117.5EI}{L^3}$	$\frac{122EI}{L^3}$	$V_1=0.17R+0.17P$ $V_2=0.33R+0.33P$
	Elasto-Plastic	0.87	0.76	0.52	0.87	0.60	$\frac{2}{L}(M_{Ps}+3M_{Pm})$	$\frac{56EI}{L^3}$			$V_1=V_2=0.62R-0.12P$
	Plastic	1	1.0	0.56	1.0	0.56	$\frac{2}{L}(M_{Ps}+3M_{Pm})$		$R_{mf}=\frac{9.52M_P}{L}$		$V_1=0.56R_m-0.25P$ $V_2=0.56R_m+0.13P$

* Equal parts of the concentrated mass are lumped at each concentrated load.

$$P_t = P_{QS} bL$$

$$= 250(3.284)(30) = 24{,}630 \text{ lb}$$

$$R_m = r_u bL$$

$$= (1593)(3.284)(30) = 156{,}942 \text{ lb}$$

$$V = 0.38\, R_m + 0.12\, P_t = 62{,}594 \text{ lb}$$

The yield capacity is

$$V_P = F_{dV} A_w \quad \text{where } A_w = 5(.494) = 2.47$$

$$= 0.55\, F_{dY} A_w$$

$$= 0.55\,(42{,}000)(2.47)$$

$$V_P = 57{,}057 \text{ lb} < 62{,}594 \text{ lb}$$

Since $V_P < V$, the beam will not be capable of achieving its full plastic moment before failing by shear. Select a larger beam with a yield capacity greater than 62,594 lb.

V. BLAST PRESSURE EXTERNAL TO SHIELD

The external side-on overpressure is a function of charge weight, standoff distance, shield size, and the effective vent area ratio, α_e. The procedure for calculating blast pressure follows.

1. Calculate effective vent area ratio, α_e.

   a. Figure 5 gives equations to calculate α for a variety of vented elements.

   b. From Ref 35:

$$\frac{1}{\alpha_e} = \frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \ldots + \frac{1}{\alpha_n}$$

2. A curve fit to side-on pressures outside the suppressive structures is shown in figure 6. The resulting equation is (Ref 35):

$$P_{SO} = 957\left(\frac{1}{Z}\right)^{1.66}\left(\frac{R}{X}\right)^{0.27}\left(\alpha_e\right)^{0.64}$$

where

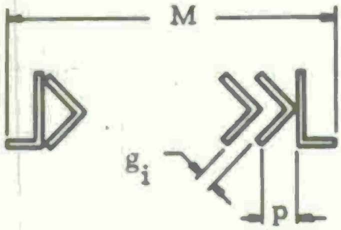
X = width of suppressive cube or diameter of suppressive cylinder, ft
R = standoff distance from charge, ft
Z = scaled distance, $\text{ft/lb}^{1/3}$

This equation is valid for the following parameter ranges

$$2.93 \leq Z \leq 21.3$$

$$0.69 \leq R/X \leq 4.55$$

$$0.01 \leq \alpha_e \leq 0.13$$



$A_{vent} = \ell \sum_{1}^{n} g_i / N$

ℓ = length of element

p = projected length of angle

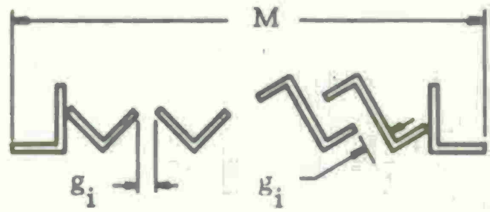
N = 2 or 4 (see text)

A_{wall} = LM

L = length of wall

$\alpha = A_{vent}/A_{wall}$

(a) NESTED ANGLES



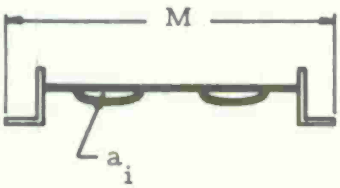
$A_{vent} = \ell \sum_{1}^{n} g_i$

n = number of openings

A_{wall} = LM

$\alpha = A_v/A_w$

(b) SIDE-BY-SIDE ANGLES OR ZEES



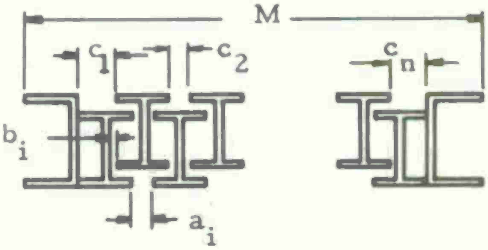
$A_{vent} = \sum_{1}^{n} a_i / 2$

a_i = open area of louvre

A_{wall} = LM

$\alpha = A_v/A_w$

(c) LOUVRES



$A_{v_1} = 2\ell \sum_{1}^{n} a_i$

$A_{v_2} = A_{v_3} = 2\ell \sum_{i}^{n} b_i$

$A_{v_4} = 2\ell \sum_{1}^{n} c_i$

$\alpha_1 = A_{v_1}/A_w, \ldots$

(d) INTERLOCKED I-BEAMS

Figure 5. Definition of Effective Area Ratio for Various Structural Elements (Ref 35)

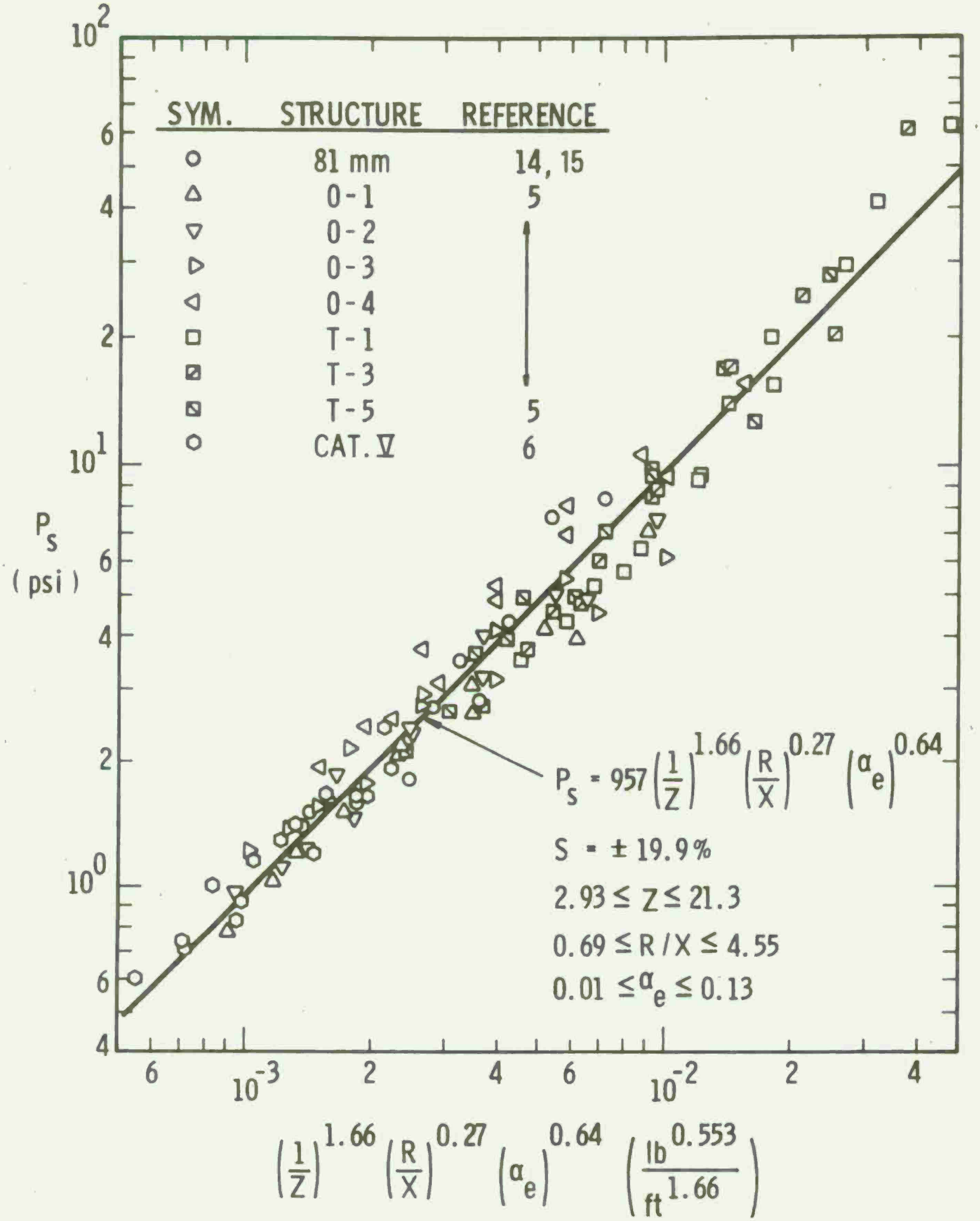


Figure 6. Curve Fit to Side-On Pressures Outside Suppressive Structures (Ref 35)

3. A curve fit to scaled side-on impulse outside a structure is shown in figure 7. The resulting equation is (Ref 35):

$$\frac{I_S}{W^{1/3}} = 2.18 \left(\frac{1}{Z}\right)^{0.98} \left(\frac{R}{X}\right)^{0.008} \left(\alpha_e\right)^{0.45}$$

and is valid for the following ranges

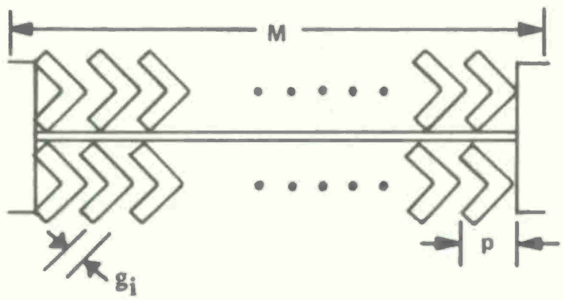
$$2.93 \leq Z \leq 15.0$$
$$1.16 \leq R/X \leq 4.55$$
$$0.008 \leq \alpha_e \leq 0.13$$

4. For particular configurations, i.e., nested angles, perforated plates, or interlocking I-beams, slightly more accurate curve fits and equations are presented (in Ref 35) for P_{SO} and I_S outside the suppressive structure.

Example (external blast pressure calculation)

Consider a 6- X 6- ft two-layered, nested angle shield with two 30% perforated plates in between ($\alpha = .3$).

Find α_e



where

$$n + 1 = 100 \text{ (1/4-by 1-in. angles)}$$
$$g_i = .25 \text{ in.}$$
$$p = .7 \text{ in.}$$
$$N = 2$$
$$M = 72 \text{ in. (total width)}$$
$$L = 72 \text{ in. (total height)}$$
$$l = 70 \text{ in. (angle length)}$$

Since there is approximately one opening per projected length, p (for closer nested angles with about two openings per projected length use N = 4).

$$A_{vent} = l\sum_{1}^{n} g_i/N = 70(99)(.25)/2 = 866 \text{ in.}^2$$

$$A_{wall} = LM = (72)(72) = 5184 \text{ in.}^2$$

$$\alpha_1 = \alpha_4 = A_{vent} / A_{wall} = 866/5184 = .17$$

$$\frac{1}{\alpha_e} = \frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \frac{1}{\alpha_3} + \frac{1}{\alpha_4} = \frac{1}{.17} + \frac{1}{.3} + \frac{1}{.3} + \frac{1}{.17}$$

$$\alpha_e = .05$$

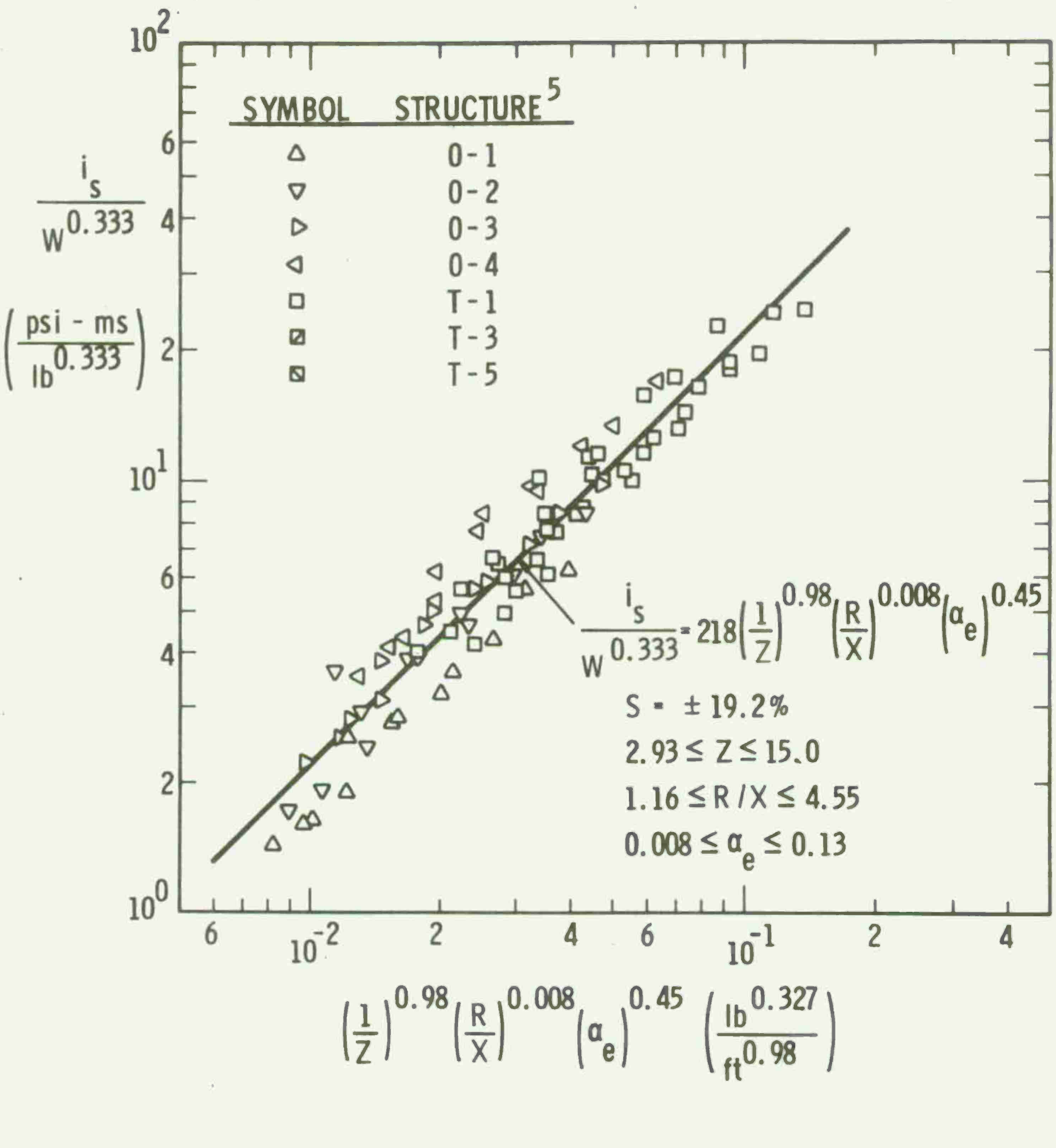


Figure 7. Curve Fit to Scaled Side-On Impulse Outside of Suppressive Structures (Ref 35)

with $\alpha_e = .05$ and a charge weight of 2 lb, determine the side-on pressure outside the suppressive structure at a standoff distance of 10 ft from the charge.

$$Z = \frac{R}{W^{1/3}} = \frac{10}{(2)^{1/3}} = 7.94$$

$$\left(\frac{1}{Z}\right)^{1.66}\left(\frac{R}{X}\right)^{0.27}\left(\alpha_e\right)^{0.64} = \left(\frac{1}{7.94}\right)^{1.66}\left(\frac{10}{6}\right)^{0.27}\left(.05\right)^{0.64} = .005$$

And from figure 6

$$P_S = 5 \text{ psi.}$$

VI. FRAGMENTS.

A. Fragment Classification.

Primary fragments are pieces of the casing, container, or other structure which contain the explosive material and which is in physical contact with the explosive. In most cases, these fragments arrive at the suppressive shield wall prior to the shock wave.

Secondary fragments are missiles consisting of items which were not in initial physical contact with the explosive material. These objects are accelerated by the blast wave and, due to inertial resistance, will arrive at the suppressive shield wall behind the initial shock wave.

B. Primary Fragments.

1. Determine gurney energy constant, $\sqrt{2E'}$, for the type of explosive material (TM 5-1300, table 4-2).

2. Calculate initial velocity of primary fragments, V_o, using the appropriate equation (TM 5-1300, table 4-3).

3. Determine striking velocity, V_s

a. For $R < 20$ ft $V_s \approx V_o$.

b. For $R > 20$ ft (refer to TM 5-1300, figure 4-74) for V_s, see next step for W_f calculation.

4. Calculate primary fragment weight, W_f

a. For explosives with cylindrical containers, use TM 5-1300, equation 4-14 (see paragraph 4-22 for discussion of cylindrical containers).

b. W_f must be estimated for all other shapes.

5. Calculate penetration depth into mild steel (Ref 13)

a. For chunky fragments ($L/D \approx 1$)

$$P = .112\, W_f^{1/3}\, (.001\, V_s)^{4/3}$$

b. For rod or ban-like fragments ($L/D > 1$)

$$P = .112\, W_f^{1/3}\, (.001\, V_s)^{4/3}\, (L/D)^{5/8}$$

The equation was developed from a series of experiments conducted within the following limits:

Fragment weights	W_f	= .197 to .310 oz.
Fragment velocities	V_s	= 1690 to 3775 ft/sec
Plate thickness	t_w	= .125 to .375 in.

Extrapolation up to $W_f = 16$ oz and V_s 7200 ft/sec has been found to be in good agreement with recent data from tests with fragment weights and velocities of this magnitude.

Example (primary fragment penetration calculation).

For 50 lb Comp B charge encased in a spherical container, find the penetration depth into mild steel:

Assume

$$W/W_c = 1$$

Gurney energy constant, $\sqrt{2E'} = 7880$ ft/sec

Initial fragment velocity, $V_o = \sqrt{2E'} \left[\dfrac{W/W_c}{1 + 3W/5W_c}\right]^{1/2} = 6230$ ft/sec

Assume striking velocity, $V_s = V_o = 6230$ ft/sec

Estimate maximum fragment weight, $W_f = 0.3$ oz (chunky)

Calculate penetration depth, P

$$P = .112\, W_f^{1/3}\, (.001\, V_s)^{4/3}$$

$$= .112\, (.3)^{1/3}\, [(.001)(6230)]^{4/3} = .86 \text{ in.}$$

Therefore, a total mild steel thickness of 0.86 in. is required to stop all chunky fragments. If the fragments are rod shaped, the penetration depth will increase by a factor of $(L/D)^{5/8}$.

C. Secondary Fragments.

1. Calculate penetration depth as described for primary fragments. The result will be conservative because (Ref 13):

a. Fragment acceleration is calculated on the basis of I_R which is the highest possible pressure.

b. Assumed that I_R is acting on the side of the bar.

c. Assumed that the bar rotates in flight and strikes the barrier on end.

d. Assumed that the fragment experiences no velocity decay due to aerodynamic drag.

2. The secondary fragment hazard is under further study at Ballistics Research Laboratory, Aberdeen Proving Ground, and a final report will not be available at the time of this publication.

VII. SHIELD GROUPS.

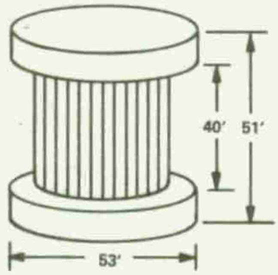
An overview of shield groups 1 through 7 is given as follows:

Shield Group	Hazard Parameter		Representative Applications	Level of Protection*
	Blast	Fragmentation		
	psi side-on			
1	500	Severe	Porcupine Melter (2000 lb plus 2 pour units 250 lb each	Reduce blast pressure at intraline distance by 50%
2	500	Severe	HE bulk (750 lb) Minute Melter	Reduce blast pressure at intraline distance by 50%
3	500	Moderate	HE bulk (37 lb) Detonators, fuzes	Category I hazard** at 6.2 ft from shield
4	200	Severe	HE bulk (9 lb) Processing rounds	Category I hzaard** at 19 ft from shield
5	50	Light	30 lb Illuminant Igniter slurry mixing HE processing (1.84 lb)	Category I hazard** at 3.7 ft from shield
6	2000	Light	Laboratory, handling, and transportation	Category I hazard** at 1 ft from shield
7	200	Moderate	Flame/fireball attenuation	Category I hazard** at 5 ft from shield

*All shield groups contain all fragments.
**Mil Std 882, 15 Jul 69 (2.3 psi level).

A detailed description of the shield groups is given on the following pages.

Group No. 1



Inside dimensions: 45 ft diameter, 40 ft high

Weight: 5,760,000 lb

Type construction: Built-up structure using I-beams and concrete roof (w/steel liner)

Per unit cost: 84,144 man-hours, approximate $1,100,000 (est)

Charge weight (Comp B):

a. Design 2,500 lb
b. Proof (25% overcharge) 3,125 lb

Reflected impulse:

		Calculated	Measured
a.	Design	1685 psi-msec	—
b.	Proof	2022 psi-msec	—

Reflected pressure:

		Calculated	Measured
a.	Design	2728 psi	—
b.	Proof	3198 psi	—

Quasi-static pressure:

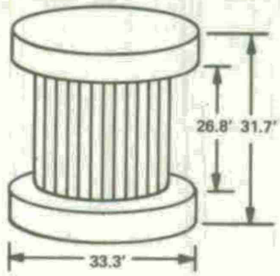
		Calculated	Measured
a.	Design	145 psi	—
b.	Proof	165 psi	—

Blowdown time (design): 2 sec with α_e = 0.4% (total)

Total steel thickness (fragment stopping): 4 in.

Status: Preliminary design, not safety approved

Group No. 2



Inside dimensions: 30 ft diameter, 26.8 ft high

Weight: 1,581,840 lb

Type construction: Built-up structure using I-beams and concrete roof (w/steel liner)

Per unit cost: 32,496 man-hours, approximate $475,000 (est)

Charge weight (Comp B):

a. Design 750 lb
b. Proof (25% overcharge) 937.5 lb

Reflected impulse:

		Calculated	Measured
a.	Design	1128 psi-msec	—
b.	Proof	1354 psi-msec	—

Reflected pressure:

		Calculated	Measured
a.	Design	2728 psi	—
b.	Proof	3198 psi	—

Quasi-static pressure:

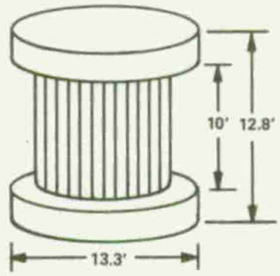
		Calculated	Measured
a.	Design	145 psi	—
b.	Proof	165 psi	—

Blowdown time (design): 2 sec with α_e = 0.4% (total)

Total steel thickness (fragment stopping): 2.7 in.

Status: Preliminary design, not safety approved

Group No. 3 (1/4-scale Shield Group 1)



Inside dimensions: 11.25 ft diameter, 10 ft high

Weight: 90,000 lb

Type construction: Built-up structure using I-beams and concrete roof (w/steel liner)

Per unit cost: 5,259 man-hours, approximate $75,000

Charge weight (50-50 pentolite):

a. Design 37 lb
b. Proof (25% overcharge) 45.7 lb

Reflected impulse: (sidewall)

		Calculated	Measured
a.	Design	414 psi-msec	—
b.	Proof	495 psi-msec	435 psi-mec

Reflected pressure: (sidewall)

		Calculated	Measured
a.	Design	2728 psi	—
b.	Proof	3198 psi	2386

Quasi-static pressure:

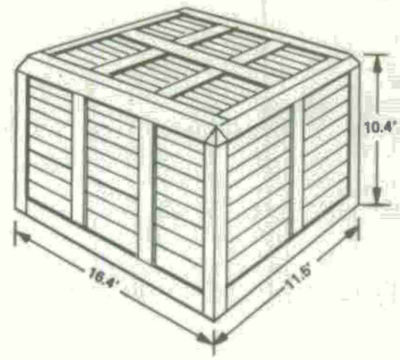
		Calculated	Measured
a.	Design	145 psi	—
b.	Proof	165 psi	187

Blowdown time (design): 2 sec — with α_e = 0.4% (total)

Total steel thickness (fragment stopping): 1 in.

Status: Safety approved.

Group No. 4



Inside dimensions: 9.2 ft wide X 13.1 ft long X 9.3 ft high

Weight: 79,159 lb

Type construction: Frame, nested angles and perforated panels.

Per unit cost: 6,500 man-hours, approximate $105,000

Charge Weight (Pentolite):

a. Design 9 lb
b. Proof (25% overcharge) 11.25 lb

Reflected impulse:

		Calculated	Measured
a.	Design	162 psi-msec	—
b.	Proof	194 psi-msec	—

Reflected pressure:

		Calculated	Measured
a.	Design	1387 psi	—
b.	Proof	1464 psi	1143 psi

Quasi-static pressure:

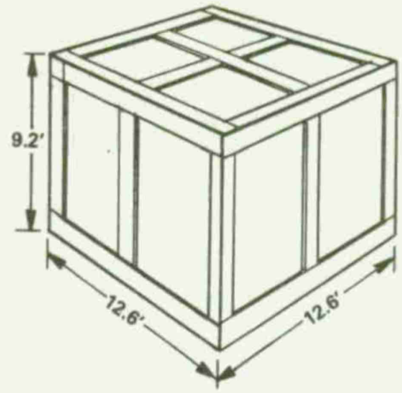
		Calculated	Measured
a.	Design	57 psi	37 psi
b.	Proof	63 psi	44 psi

Blowdown time (design): 88 msec — with α_e = 3.0% (total)

Total Steel thickness (fragment stopping): Maximum 2.17 in.
Minimum 1.46 in.

Status: Safety approved

Group No. 5



Inside dimensions: 10.4 ft wide X 10.4 ft long X 8.5 ft high

Weight: 16,772 lb

Type construction: Frame, angles, perforated plates and screens

Per unit cost: 3,174 man-hours, approximate $55,000

Charge weight (C-4):

a. Design 1.84 lb
b. Proof (25% overcharge) 2.44 lb

Reflected impulse:

		Calculated	Measured
a.	Design	44 psi-msec	54 psi-msec
b.	Proof	55 psi-msec	68 psi-msec

Reflected pressure:

		Calculated	Measured
a.	Design	368 psi	242 psi
b.	Proof	493 psi	346 psi

Quasi-static pressure:

		Calculated	Measured
a.	Design	24 psi	18 psi
b.	Proof	29 psi	33 psi

Blowdown time (design): 44 msec with α_e = 15.5% (panels).

Total steel thickness (fragment stopping): Maximum .427 in.
Minimum .125 in.

Status: Safety approved

Group No. 6

Inside dimensions: 2 ft diameter

Weight: 165 lb

Type construction: Mild steel sphere (no venting)

Per unit cost: 130 man-hours, approximate $2,500

Charge weight (50-50 pentolite)

a. Design 13.63 oz
b. Proof (25% overcharge) 17.04 oz

Reflected impulse*:

		Calculated	Measured
a.	Design	231 psi-msec	—
b.	Proof	276 psi-msec	—

Reflected pressure*:

		Calculated	Measured
a.	Design	835 psi	—
b.	Proof	926 psi	—

Quasi-static pressure:

		Calculated	Measured
a.	Design	600 psi	—
b.	Proof	680 psi	600 psi

Blowdown time (design): N/A with α_e=N/A

Total steel thickness (fragment stopping): .25 in.

Status: Safety approved

*Hydrostatic test to 1400 psi

Group No. 7

(Final design criteria not established for Group No. 7.)

Inside dimensions:

Weight:

Type construction:

Per unit cost: man-hours, approximate $

Charge weight ( ):

a. Design
b. Proof (25% overcharge)

Reflected impulse:

	Calculated	Measured
a. Design		
b. Proof		

Reflected pressure:

	Calculated	Measured
a. Design		
b. Proof		

Quasi-static pressure:

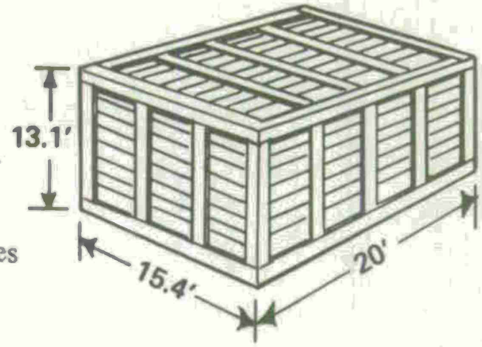
	Calculated	Measured
a. Design		
b. Proof		

Blowdown time (design): with α_e =

Total steel thickness (fragment stopping):

Status: Unfunded

Group No. 81 mm



Inside dimensions: 14 ft wide X 18.7 ft long X 12.4 ft high

Weight: 50,000 lb

Type construction: Box beams, Z-bars, and perforated plates

Per unit cost: 4,095 man-hours, approximate $80,000

Charge weight (C-4);

a. Design 6.72 lb
b. Proof (25% overcharge) 8.4 lb bare charge

Reflected impulse:

		Calculated	Measured
a.	Design	97 psi-msec	—
b.	Proof	115 psi-msec	95 psi-msec

Reflected pressure:

		Calculated	Measured
a.	Design	483 psi	—
b.	Proof	610 psi	379 psi

Quasi-static pressure:

		Calculated	Measured
a.	Design	23 psi	—
b.	Proof	28 psi	21 psi

Blowdown time (design): 82 msec   with α_e = 4.3 oz (total)

Total steel thickness (fragment stopping):

Status: Safety approved for two 81-mm mortor rounds – 4.2 lb Comp B

Safety approval has been requested for 6.72 lb of C-4 explosive based on a successful follow-on proof test of six 81-mm rounds.

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GLOSSARY

P_{SO}	–	Side-on pressure or peak positive incident pressure, psi
P_R	–	Reflected pressure or peak positive normal reflected pressure, psi
I_S	–	Positive incident impulse, psi-msec
I_R	–	Positive normal reflected impulse, psi-msec
W	–	Charge weight, lb
R	–	Radial distance from charge, ft
Z	–	Scaled distance ($Z = R/W^{1/3}$)
V	–	Chamber volume, ft^3
T_N	–	Effective natural period of vibration, sec
B	–	Peak pressure of equivalent triangular loading function, psi
r_u	–	Ultimate unit resistance, psi
W_c	–	Weight of explosives container, lb
W_f	–	Primary fragment weight, lb
V_o	–	Initial velocity of primary fragment, fPS
V_s	–	Striking velocity of primary fragment, fPS
P	–	Penetration depth, in.
t_d	–	Duration of impulse, sec
P_t	–	Maximum total load, lb
b	–	Loaded width of beam, in.
L	–	Length of beam or rod, in.
F_Y	–	Static yield strength, psi
F_{dY}	–	Dynamic yield stress, psi
F_{dV}	–	Dynamic yielding shear stress, psi
ω	–	Supported weight, lb/ft

t_m	–	Time when maximum deflection occurs, sec
W'	–	Fano effective charge weight, lb
M	–	Metal case weight, lb
X_e	–	Equivalent elastic deflection, in.
X_m	–	Maximum deflection, in.
μ	–	Ductility ratio, X_m/X_e
L_B	–	Length of the beam supported by one ring, in.
A_R	–	Ring cross-sectional area, in.^{2}
T	–	Time, sec
P_{QS}	–	Quasi-static pressure, psi
A_{vent}	–	Vent area of shield, ft^2
t	–	Blowdown time, msec
K_{LM}	–	Load-mass factor
K_E	–	Equivalent elastic stiffness, psi-in.
m	–	Unit mass, psi-msec^2/in.
E	–	Modulus of elasticity, psi
I	–	Moment of inertia, in.^{4}
S	–	Section modulus, in.^{3}
g	–	Gravitational constant, 386 in./sec^2
R_u	–	Ultimate total resistance, lb
A_w	–	Web cross-sectional area, in.^{2}
V_P	–	Yield capacity of a beam in shear, lb
α	–	Vent area ratio A_{vent}/A_{wall}
α_e	–	Effective vent area ratio
A_{wall}	–	Total wall area of shield, ft^2

D	–	Diameter of rod, in.
K	–	Stiffness coefficient, psi
A_R	–	Cross-sectional area of ring, in.^{2}
R_R	–	Radial distance to ring centerline, in.
R_W	–	Radial distance to inside wall, in.
σ_c	–	Circumferential stress, psi
L_B	–	Length of supported portion of beams, in.
M_P	–	Plastic moment, capacity, in.-lb
Z	–	Plastic section modulus, in.^{3}
t_w	–	Wall thickness, in.
t'_d	–	Idealized reflected pressure duration, sec
r_u	–	Ultimate unit resistance, psi
ϵ_m	–	Maximum strain, in./in.
ϵ_e	–	Elastic strain, in./in.
b'	–	Effective flange width, in.

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