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THE DESIGN OF BARRICADES FOR HAZARDOUS PRESSURE SYSTEMS

C. V. Moore

February 5, 1965

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ABSTRACT

Procedures are given for the rational design of barricades for hazardous pressure systems. Methods are given for estimating the initial velocities of missiles produced by exploding pressure vessels, and for determining the penetrating effects of these missiles on materials normally used for barricade construction. Methods are also given for estimating effective blast pressures produced by the explosion of pressure vessels. Charts and diagrams to assist in performance of the calculations are included. Some checks of the design methods against experimental data are presented.

THE DESIGN OF BARRICADES FOR HAZARDOUS PRESSURE SYSTEMS

C. V. Moore

1. INTRODUCTION

1.1 Use of Barricades

It is sometimes necessary to operate experimental pressure containing equipment which present hazards not accounted for by existing industrial pressure vessel codes. (An example is a test section used for investigating heat transfer phenomena in which fission heat is simulated by passing electric current through the pressure retaining walls.)

In such cases, personnel hazards can be reduced to the level provided by industrial codes by interposing suitable barricades between the pressure retaining walls and personnel. Such barricades must, of course, be adequate for the purpose or they may, in fact, increase hazards by becoming missiles themselves.

1.2 General Barricade Design Method

The design method outlined in this report is that one first determines what one is barricading against (including the methods by which failure is anticipated), and then evaluates a proposed design of barricade to determine its adequacy.

The evaluation process is something of a trial and error operation since the first proposed design may either be inadequate or excessive.

The trial and error process could be eliminated by restricting consideration to only certain types of barricades (e.g., steel plates). It is felt, however, that to do so would be unduly restrictive.

The evaluation of the adequacy of a barricade is divided into two phases; resistance to penetration or perforation by missiles produced by an exploding pressure vessel, and resistance to the blast effects produced by release of the pressurized fluid inside the pressure vessel. (Complications due to release of flammable fluids are not treated in this report but should be considered, when applicable.) The evaluation of missile resistance is given first since, in most cases, barricades which will be adequate for missile resistance will be more than adequate for blast resistance.

2. RUPTURE CONDITIONS

The methods given below for evaluation of barricade adequacy require consideration of the amount of energy released during the pressure vessel rupture. This amount of energy is a function of the mode of failure assumed for the pressure vessel.

For example, if a rapid chemical reaction is anticipated which is expected to be too fast to be relieved by normal pressure relief devices, one might expect an explosion in which the temperature and pressure of the fluid builds up at a rate which is too fast to transfer heat to the walls of the pressure vessel. Thus the walls of the pressure vessel will remain essentially at the initial temperature and failure will occur when the pressure is high enough to equal the rupture pressure of the vessel at the initial temperature. If the initial temperature is the design temperature for the vessel then, for ASME Code vessels, the rupture pressure will normally be about four times the design pressure.

As another example, consider a vessel for which no mechanism is available by which the pressure can be raised above the design pressure - but which is subjected to severe thermal cycling stresses so that failure by fatigue is feared. It is thus assumed that the vessel ruptures suddenly at design temperature and pressure. The energy released is then assumed to be that released by isentropic expansion of the contained fluid from design conditions to one atmosphere.

As another example, consider a vessel with electrically heated walls where failure by overheating of the walls is anticipated. Pressures are limited to design pressures by pressure relief devices, but the wall is weakened by increased temperature (resulting, say, from loss of flow of internal fluid or low liquid level) until rupture occurs at a temperature at which the tensile strength of the wall material equals the pressure stress. This temperature would be determined by consulting data for the high temperature short-time tensile properties of the wall material, and the initial energy content of the fluid would be obtained at this temperature and design pressure from steam charts or from other thermodynamic data.

3. MISSILE RESISTANCE OF BARRICADES

3.1 Estimation of Initial Missile Velocities

a. Energy Method. An expression derived from energy relationships for the initial velocities of fragments of exploding casings filled with explosives which has been found by experiment to be reasonably accurate is (from Gurney, reference 8.1.2 and Sterne, reference 8.1.4):

$$V_o = \sqrt{2ER} \tag{1}$$

where, for cylinders

$$R = \frac{C/N}{1 + C/2N} \tag{2}$$

for spheres

$$R = \frac{C/N}{1 + 3C/5N} \tag{3}$$

and, for "sandwiches"

$$R = \frac{C/N}{1 + C/3N} \tag{4}$$

where $2E$ = Energy function = 6900 ft/sec for TNT
C = Explosive weight
N = Case weight (both sides, for "sandwiches")
V_o = Initial velocity, ft/sec

In deriving this expression, it was assumed that, for a given explosive, a constant fraction of the energy released on detonation of the explosive is converted to kinetic energy - which is imparted to the fragments and to the expanding fluid. For TNT this fraction was found to be about 60 per cent of the calculated energy which would be released by isentropic expansion of the fluid to one atmosphere.

This expression may be used to estimate the velocities of fragments of exploding pressure vessels by assuming that the same fraction of available energy is transformed into kinetic energy for fluids other than those resulting from the detonation of high explosives. This assumption is believed to be conservative. (See Appendix A for some checks of the accuracy of this assumption against published data for pressure vessel explosions.)

The expression then becomes

$$V_o = 1.092 \sqrt{E_f R} \quad \text{ft/sec} \qquad (5)$$

where E_f = Available energy released by isentropic expansion of pressurized fluid to one atmosphere on per-unit mass basis, ft-lb/slug (see Figure 1, Curve A, for saturated water).

In the event a portion of the interior of the pressure vessel is occupied by an inert material, such as steel, the energy, E_f, and the "explosive" weight, C, should be reduced proportionally.

b. Initial Velocities of Fragments of Cylindrical Pressure Vessels Containing Saturated Water. The initial velocities of fragments of long cylindrical pressure vessels constructed of steel (or material with a similar density to steel, 490 lbs/cu ft) filled with saturated water at various temperatures have been determined from Equation (5), and are presented on Figure 2 as a function of the ratio of the inside diameter of the vessel to its wall thickness.

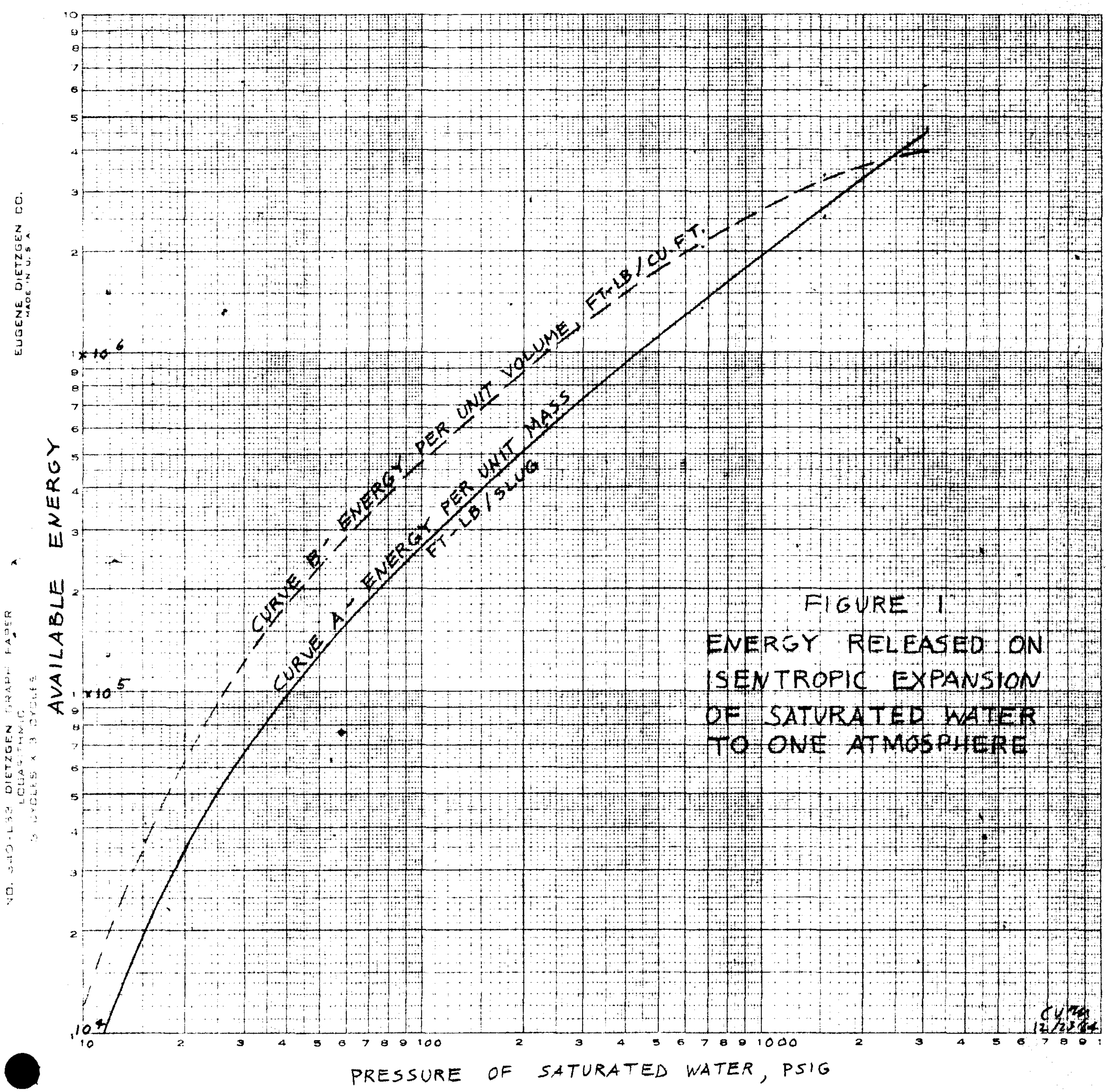
For subcooled water (water which is pressurized up to 1000 psi above the saturation pressure corresponding to its temperature), Figure 2 can be used with only a few per cent error by using the curve corresponding to the temperature of the subcooled water.

c. Autoclave Heads. For autoclave heads, a simple method of estimating the head kinetic energy which is believed to be conservative is to assume that the full rupture pressure acts on the bottom surface of the head during motion of the head from its initial position for a distance equal to the diameter of the opening generated by its removal.

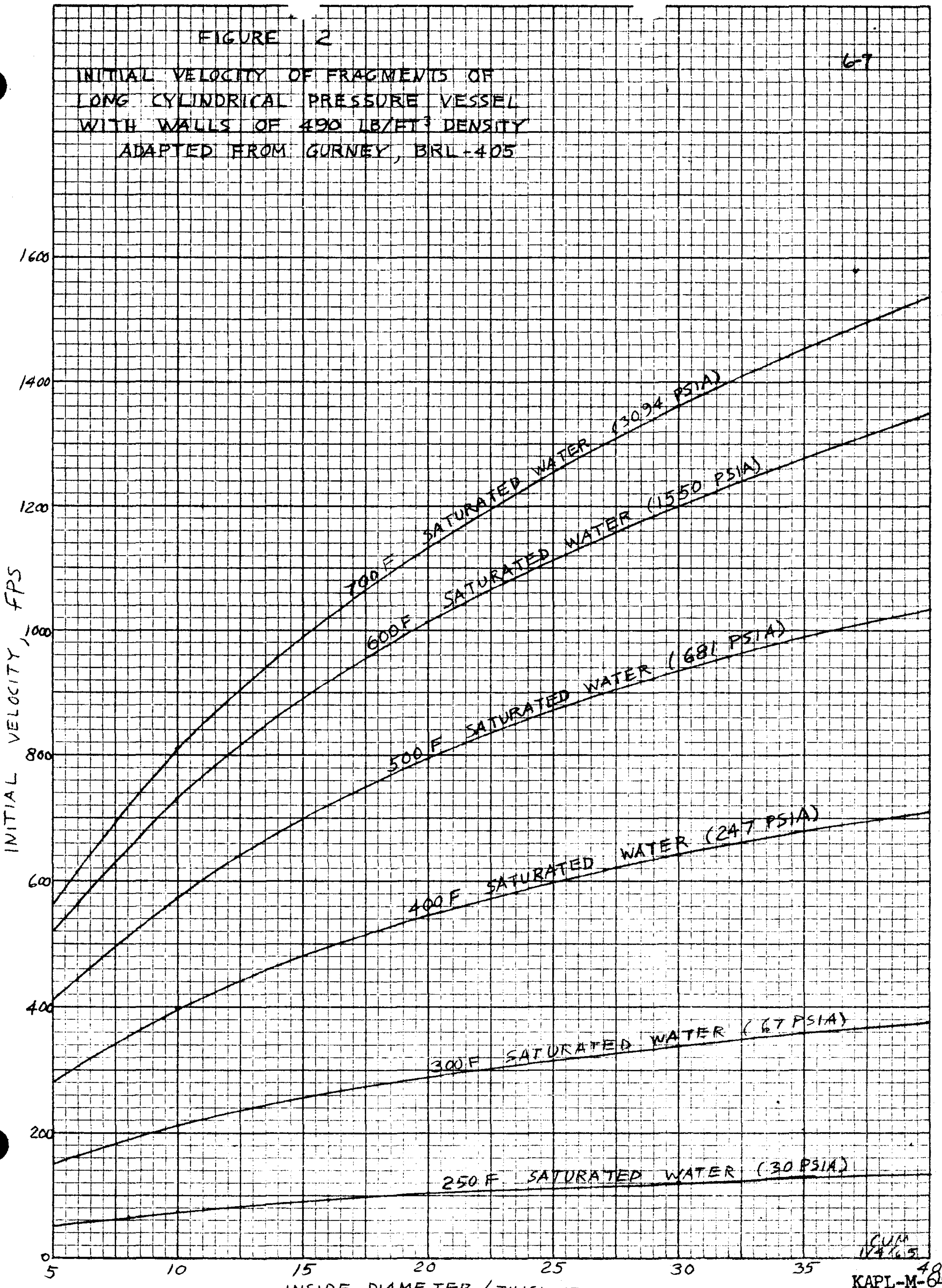
Making these assumptions, the kinetic energy of the head is given by

$$E_K = 0.0654\, D^3 P \quad \text{ft-lb} \qquad (6)$$

where D = Diameter of opening - inches
P = Pressure in system at time of rupture - psig



AVAILABLE ENERGY
PRESSURE OF SATURATED WATER, PSIG
CURVE B - ENERGY PER UNIT VOLUME, FT-LB/CU.FT.
CURVE A - ENERGY PER UNIT MASS FT-LB/SLUG
FIGURE 1
ENERGY RELEASED ON ISENTROPIC EXPANSION OF SATURATED WATER TO ONE ATMOSPHERE
EUGENE DIETZGEN CO. MADE IN U.S.A.
DIETZGEN GRAPH PAPER LOGARITHMIC 3 CYCLES X 3 CYCLES



70X100 1/10 Inch Divisions
GENERAL ELECTRIC COMPANY, SCHENECTADY, N. Y., U.S.A.
PN-521-A (8-50)

The associated velocity is

$$V_o = 2.05\sqrt{\frac{PD^3}{W}} \quad \text{ft/sec} \qquad (7)$$

where W = Weight of autoclave head - lbs

d. Attachments. If a piece of equipment such as a pressure gage or thermocouple well becomes dislodged, it will be accelerated by a jet of expanding fluid from the resultant opening in the vessel.

Procedures for predicting the velocities of such missiles are given in reference 8.1.13.

Predicted velocities of such missiles of various sizes and weights propelled from vessels filled with saturated water at 2000 psia are shown on Figure 3 (taken from reference 8.1.13).

e. Rocket Type Missiles. Rocket type missiles are those which discharge fluid while flying through the air. An example of such a missile would be a length of pipe closed at one end and open at the other which is initially filled with a pressurized fluid. The fluid discharges from the open end, accelerating the pipe.

The kinetic energy of such missiles may be conservatively estimated by assuming that the initial available energy of the fluid (taken, for water, from Curve B of Figure 1) is the final kinetic energy of the missile.

That is

$$E_K = v \; E_V \quad \text{ft-lbs} \qquad (8)$$

where E_K = Kinetic energy of rocket type missile - ft-lbs
v = Volume of water which produces the jet - cu ft
E_V = Available energy per unit volume from Figure 1, Curve B - ft-lb/cu ft

The corresponding velocity of the missile is

$$V_o = \sqrt{\frac{2\,gE_K}{W}} \quad \text{ft/sec} \qquad (9)$$

where g = Acceleration of gravity - ft/sec^2
W = Weight of missile after discharge of water - lbs

A somewhat more sophisticated analysis by Porzel may be found in reference 8.2.3.

Missiles of this type can acquire such high velocities that it is impractical, in many cases, to design barricades to withstand them. Fortunately, in most cases, the probabilities of such missiles occurring can be economically reduced to acceptable levels by suitably anchoring the potential missiles. Such anchors should be capable of withstanding forces equal to the cross-sectional areas of the missiles multiplied by the expected pressures at rupture.

f. General Method. The methods of missile velocity estimation described above are believed to give generally conservative results. In the event the barricades necessary to restrain these missiles are uneconomically massive, more elaborate and less conservative calculations may be desirable. Some examples of such calculations are given in references 8.1.13, 8.2.3, 8.3.a.1, 8.3.a.3, 8.3.a.4, 8.3.a.6, and 8.3.a.15.

In most of these examples a set of differential equations is prepared relating the forces acting on the missiles during expansion of the vessel contents to the pressures occurring during some assumed thermodynamic sequence of events. Normally, a digital computer is required for solution of the equations.

3.2 Missile Shapes

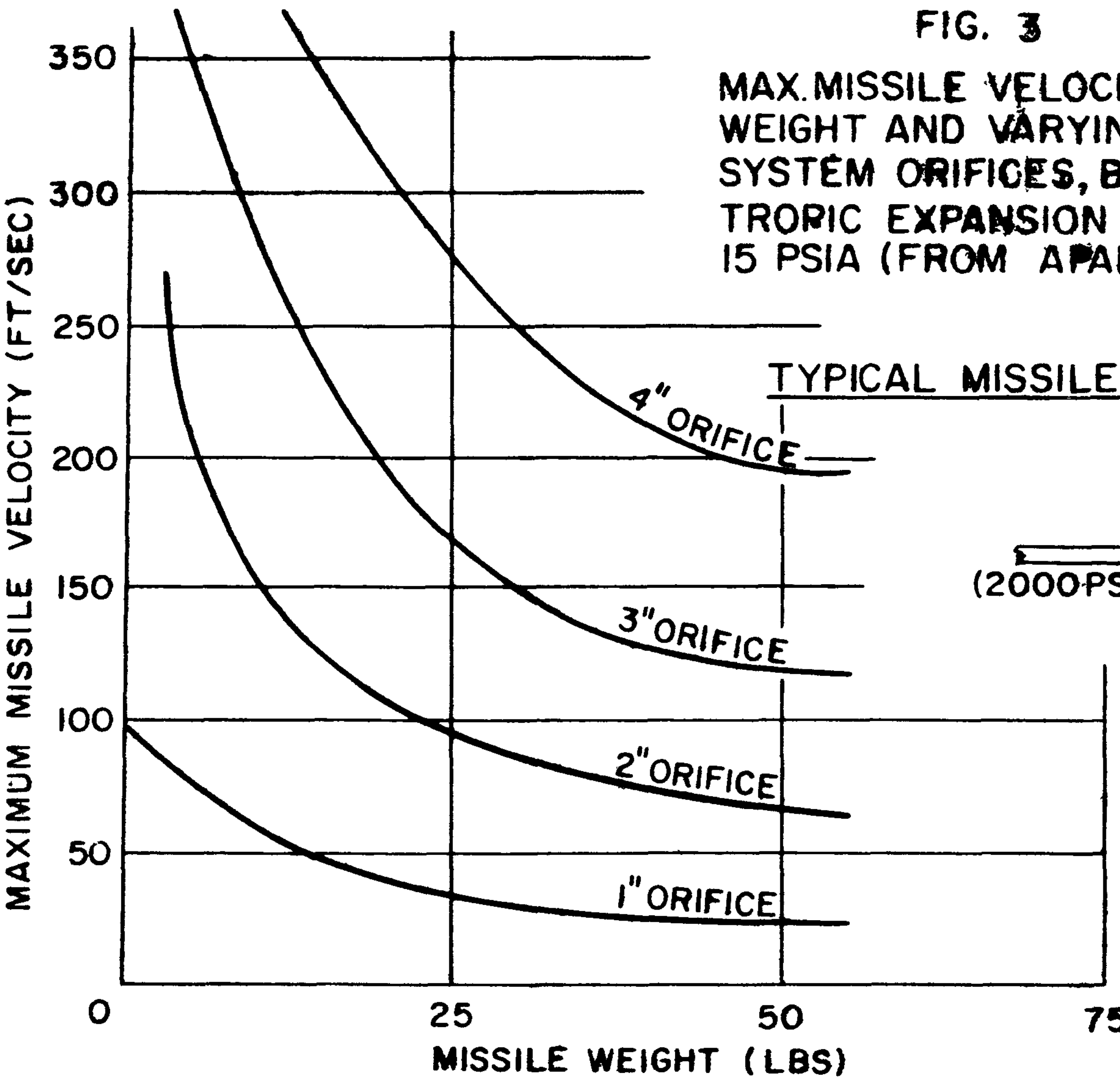
In some cases, the shapes of missiles produced by exploding pressure vessels will be obvious (such as autoclave heads). In other cases, however, (such as fragments of a cylindrical shell) the shapes and sizes of the missiles will not be obvious.

In this latter situation, the recommended procedure is to assume that missiles having the greatest penetrating effect are produced. They will normally be the largest missiles which can be generated.

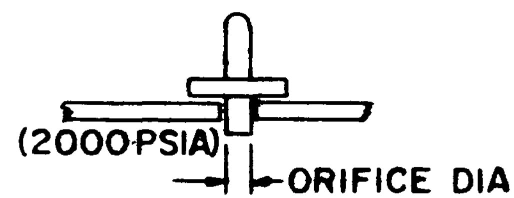
In the case of cylindrical shells constructed of ductile materials, the worst configuration is normally that generated by a longitudinal split of the shell followed by a flattening out of the cylinder into a flat plate (which is not a bad approximation of configurations produced in many accidents). The missile should be assumed to rotate in flight (if there is sufficient space available inside the barricade for such rotation) and to strike the barricade with a velocity parallel to the plane of the missile.

FIG. 3

MAX. MISSILE VELOCITY VS MISSILE WEIGHT AND VARYING PRESSURIZED SYSTEM ORIFICES, BASED ON ISENTROPIC EXPANSION FROM 2000 TO 15 PSIA (FROM APAE-63)



TYPICAL MISSILE CONFIGURATION



3.3 Perforation of Steel Plates

a. Missiles of Circular Cross-Section. References 8.1.9 through 8.1.11, and 8.1.14, 8.1.16, 8.1.18, and 8.1.20 report the results of an extensive series of tests conducted by the Stanford Research Institute in which rod shaped missiles traveling at velocities characteristic of missiles produced by pressure vessel explosions were impacted against square steel plates with edges clamped in relatively rigid frames (or "windows").

The results of these tests have been summarized in reference 8.3.a.17 which gives the following expression for the minimum energy per unit diameter of missile required for perforation of a steel plate:

$$\frac{E}{D} = U\,(0.344\,T^2 + 0.00806\,WT) \qquad (10)$$

where
E = Critical kinetic energy required for penetration - ft-lb
D = Diameter of missile - inches
U = Ultimate tensile strength of target plate - psi
T = Plate thickness - inches
W = Width of window - inches

This expression has been tested for validity within the following range of variables:

$$
\begin{aligned}
&0.1 < T/D < 0.8 && (a)\\
&0.002 < T/L < 0.05 && (b)\\
&10 < L/D < 50 && (c)\\
&5 < W/D < 8 && (d) \qquad (11)\\
&8 < W/T < 100 && (e)\\
&0.2 < W/L < 1.0 && (f)\\
&70\ \text{fps} < V_c < 400\ \text{fps} && (g)
\end{aligned}
$$

where
L = Missile length - inches
Vc = Missile velocity - fps

It should be used with caution if any of the variables fall outside the ranges given.

The limitations on width of window (which can be taken as the distance between parallel supports or stiffening members) will often be restrictive with common construction practice for spacing of structural members or when a membrane type of construction is used - as, for example, a cylindrical or spherical container without stiffening members, which possesses no obvious analog to window width.

In these cases, when the upper limits of window size are exceeded or when the window size is unknown, it is recommended that the smallest of the upper limits for W given by (11)d, (11)e, and (11)f be used in equation (10). That is, use the smallest of

$$W = 8D \qquad (a) \qquad (12)$$
$$W = 100T \qquad (b)$$
$$W = L \qquad (c)$$

If, as is usually the case, the required thickness is unknown and the other factors in equation (10) are known, then a more convenient form for this equation is

$$T = -0.0118W + \sqrt{1.38 \times 10^{-4}W^2 + 2.90 \frac{E}{DU}} \qquad (13)$$

b. <u>Missiles of Non-Circular Cross-Section</u>. The Stanford reports do not give rules for missiles of other than circular cross-section. It is believed, however, that it is reasonable to use the results obtained for circular cross-section missiles by converting non-circular missiles to "equivalent" circular missiles having the same ratio of length of perimeter to cross-sectional area.

For flat plate hitting edgewise having widths (perpendicular to the direction of velocity) which are large compared to the missile plate thickness, this conversion can be made by assuming that the plate has a penetrating effect the same as a rod having the same velocity and length (measured parallel to the rod velocity), and a diameter twice the thickness of the plate.

Making this conversion, then, and expressing the energy in terms of velocity, the above expression for E/D may be rewritten

$$T = -0.0118W + \sqrt{1.38 \times 10^{-4}W^2 + 0.0706 \rho t L V_p^2/U} \qquad (14)$$

where T = Plate thickness at which perforation barely takes place - inches
ρ = Density of missile - lbs/cu in
t = Thickness of missile plate - inches
L = Length of missile plate measured parallel to velocity - inches
V_p = Velocity of missile - ft/sec

c. Considerations Other Than Perforation. Even though a missile does not perforate a steel barricade, it may produce considerable rapid deformation in the vicinity of the area of impact. Such deformation may dislodge gauges, fasteners, or other materials mounted on the operators' side of the barricade and convert them into missiles. It is, therefore, recommended that the operators' side of steel plate barricades be kept free of any such attachments, and that operators' stations be kept back at least several inches from the surface of the barricade.

3.4 Penetration and Perforation of Concrete, Masonry and Sand

Penetration depth is the distance into a barricade which a non-perforating missile penetrates before coming to rest.

This distance is given (Amirikian, reference 8.1.5) by the modified Petry formula:

$$D' = KAV'R \tag{15}$$

where D' = Depth of penetration in slab of thickness T - ft
K = Material property constant from Table 1 - ft^3/lb
A = Sectional mass, weight of missile per unit cross-sectional area - lb/ft^2
V' = Velocity factor, from Figure 4
R = Thickness ratio, from Figure 5

For depths of penetration greater than two-thirds of the total slab thickness, scabbing (that is, expulsion of slab material from the operator side of the slab) may be anticipated. Thus, unless the barricade is made more than 1-1/2 times the predicted penetration depth, a steel plate should be anchored to the operator side of the barricade to prevent scabbing.

Nomograms by means of which the penetration of cylindrical missiles into concrete and soil may be estimated for missile velocities above 500 ft/sec are given in reference 8.1.3.

TABLE 1. VALUES OF PENETRATION COEFFICIENT (K) FOR VARIOUS MATERIALS

Material	$Ft^3\ lb^{-1}$
Limestone	5.36×10^{-3}
Concrete[1]	7.99×10^{-3}
Reinforced concrete[2]	4.76×10^{-3}
Specially-reinforced concrete[3]	2.82×10^{-3}
Stone masonry	11.72×10^{-3}
Brickwork	20.48×10^{-3}
Sandy soil	36.7×10^{-3}
Soil with vegetation	48.2×10^{-3}
Soft soil	73.2×10^{-3}

[1]Mass concrete with a crushing strength of 2,200 pounds per square inch.

[2]Normal reinforced concrete with a crushing strength of 3,200 pounds per square inch and 1.4 per cent of reinforcement.

[3]Specially-reinforced concrete with a crushing strength of 5,700 pounds per square inch and 1.4 per cent of reinforcement.

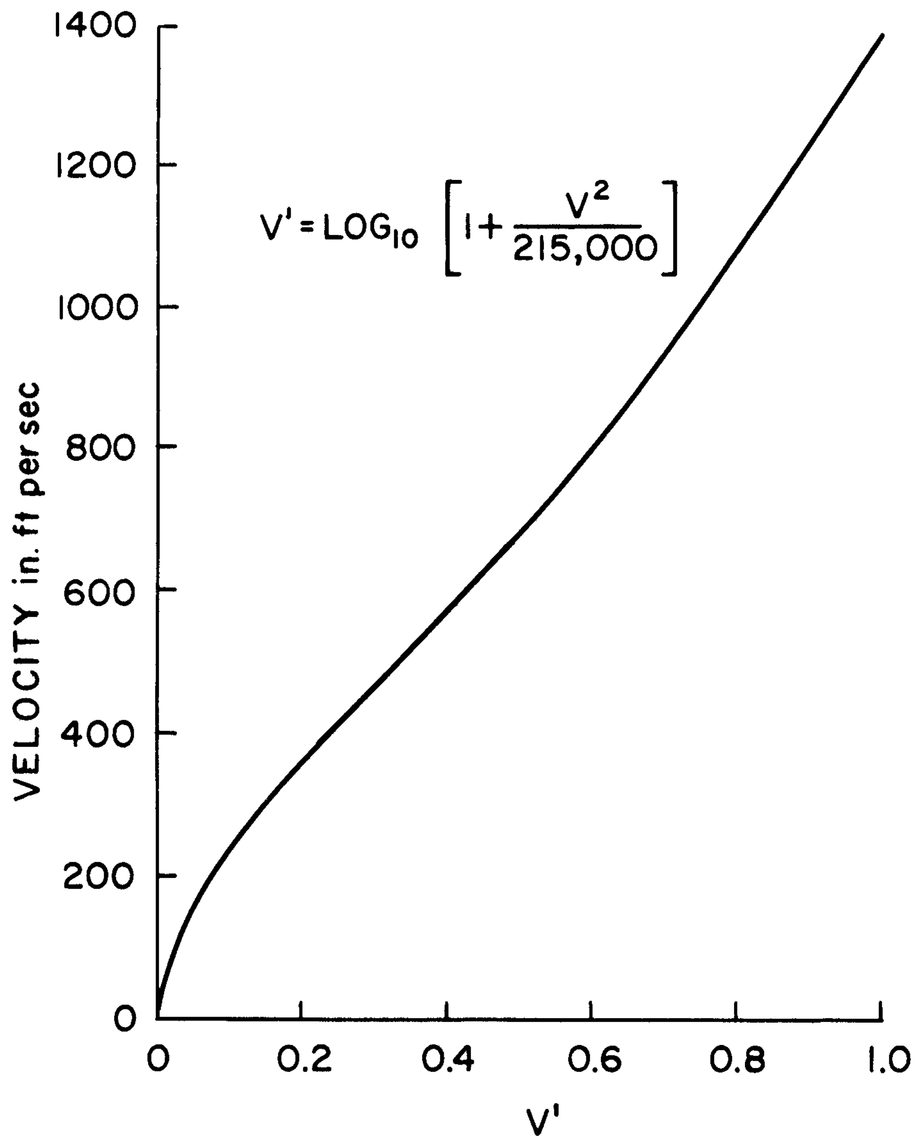


FIG. 4 VELOCITY FACTOR (V') FOR IMPACT PENETRATION

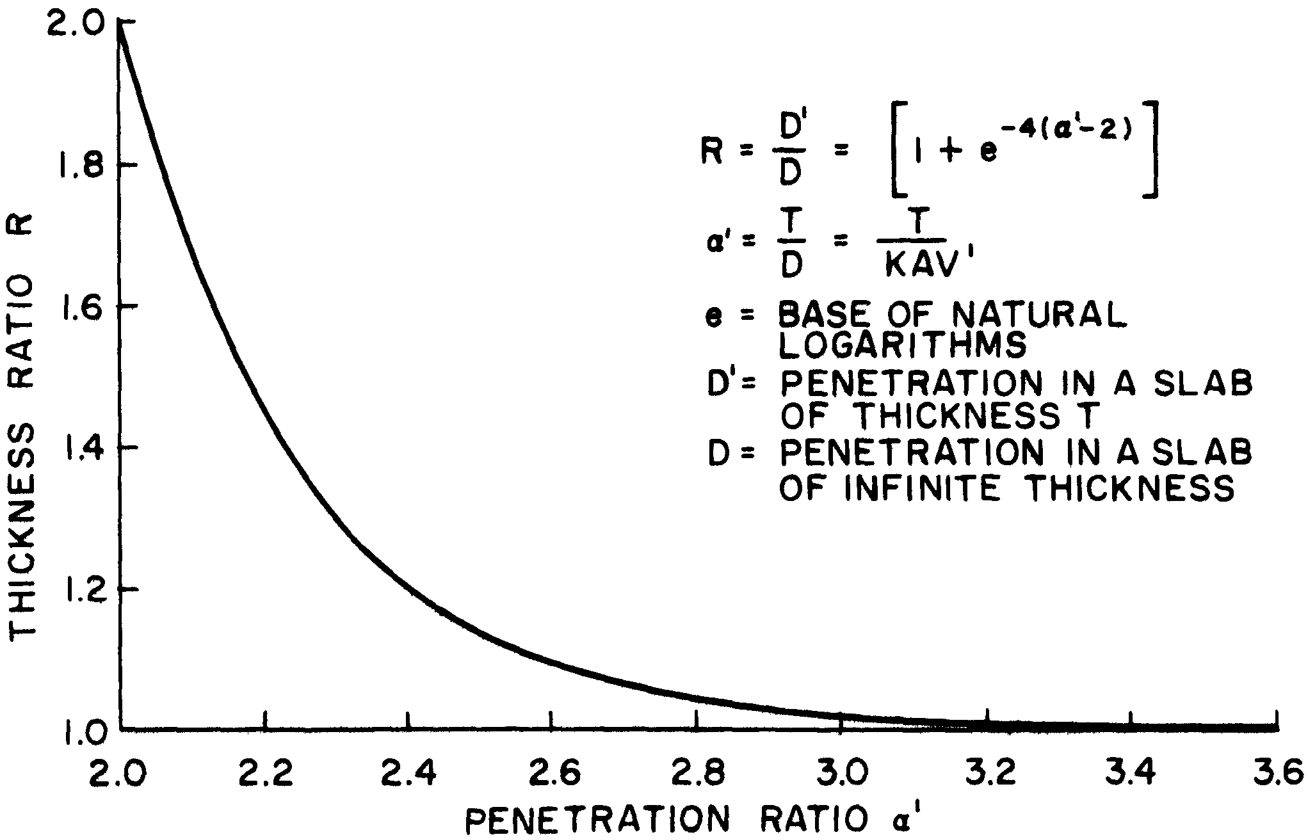


FIG. 5 RELATION OF RELATIVE SLAB THICKNESS TO PENETRATION

3.5 Use of Blast Mats

Woven mats of steel cable or manila rope are commonly used during blasting operations in connection with construction work to prevent rocks from being thrown outside of the blasting area. They have also been used as barricades for hazardous pressure vessels to stop missiles.

Unfortunately, there are no rational methods for quantitatively estimating the effectiveness of blast mats known to the author.

However, one organization with considerable experience in their use for protection of pressure vessels reports that blast mats made of 3/8 - 1/2" steel cable should stop missiles of not more than 1 lb in size provided the mats are separated from the pressure vessel by at least 3 feet and are flexibly supported (such as by ropes) to permit them to deform readily and thereby absorb energy.

3.6 Analysis of Complex Structures

a. Grids. The results of a series of low velocity perforation tests on steel plates reinforced by lattice-work are reported in reference 8.1.17.

b. Dynamic Analysis. Williamson and Alvy (reference 8.1.7) present a dynamic method of analysis for missile penetration similar to that of Newmark (reference 8.2.4) for blast loadings. In this method of analysis, an equivalent static load is obtained which is then used to evaluate the strength of the barricade. The method requires an evaluation of the natural period of vibration of the barricade and its ductility ratio (the ratio of elastic deflection to the deflection at failure) and knowledge of the missile size and velocity. Curves are presented to aid in the computations.

c. General Methods of Analysis. Available analytical techniques for evaluation of impact are given or reviewed by Goldsmith in references 8.1.15 and 8.1.19 and may be of use in certain cases. However, as Goldsmith states in the conclusion of reference 8.1.19, the available theoretical tools cannot handle most of the collisions encountered in actual practice.

3.7 Use of Lining and Packing Materials

Some test cells constructed in the past have been lined with an inch or two of wood, whose purpose is to absorb energy from impacting fragments, thus providing some protection to the primary barricade and reducing ricochet effects.

It seems reasonable to expect that such linings would have such beneficial effects. However, no method is known to the author for quantitatively evaluating this effectiveness.

If the space between the pressure vessel and the barricade can be completely filled with a cushioning material (such as sand or plaster of Paris) impact loadings can be avoided completely and the barricade can be designed primarily on the basis of blast loadings alone.

3.8 Perforation of Transparent Barricades

Viewing ports, windows, and other transparent barricades or portions of barricades present special problems since operating personnel are likely to be located near to them. Also, most transparent materials from which viewing ports are made are relatively brittle - so it is difficult to predict their behavior under concentrated impact loading such as is produced by missiles.

As a result, where missile hazards are unusually severe it is recommended that alternate methods of viewing be provided, such as periscopes, mirrors, and closed circuit television.

Some recommended thicknesses of laminated bullet resisting glass are presented in Table 2 (from reference 8.3.c.4). These thicknesses are given in terms of the kinetic energy of the missile.

No similar data could be located by the author for transparent plastic viewing ports. In general, however, it is believed (from the test results reported in reference 8.3.c.3) that slightly greater thicknesses of Plexiglas and similar acrylics are required to produce equivalent protection.

The properties of the polycarbonate resins (high impact strength and elongation) are such that they should provide relatively good missile resistance. No data suitable for design purposes could, however, be located by the author.

The use of glass for viewing ports which has been neither laminated nor tempered to prevent shattering under impact is, of course, to be avoided in all cases due to the sharp fragments which are formed on fracture. (Glass used for shielding purposes is thus normally unsuitable for use in barricades.)

TABLE 2. MINIMUM REQUIRED THICKNESSES OF LAMINATED BULLET RESISTING GLASS TO PREVENT PENETRATION BY MISSILES

Missile Kinetic Energy ft-lbs	Required Thickness of Bullet Resisting Glass
490	1 3/16
804	1 9/16
2400	2

3.9 Sample Calculations

a. Steel Plate Barricade. Consider a long cylindrical tube with an inside diameter, d, of 2" and a wall thickness, t, of 0.1" which ruptures due to fatigue while containing saturated water at 600°F.

The wall material is carbon steel having a density of 0.234 lbs/cu in (490 lbs/cu ft).

The ratio of inside diameter to wall thickness is

$$d/t = \frac{2.0}{0.1} = 20$$

From Figure 2, the initial velocity of the missile produced is about 1010 ft/sec.

We shall assume that the tube splits longitudinally and opens flat. Thus, the lengthwise dimension of the missile is the circumference of the tube or

$$L = \pi d = \pi(2) = 6.28 \text{ inches}$$

Let us construct the barricade of ASTM A-7 carbon steel plate having a specified minimum tensile strength of 60,000 psi.

From equation (14), the thickness of plate which will barely retain this missile is given by

$$T = -.0118W + \sqrt{1.38 \times 10^{-4}W^2 + 0.0706\ \rho tLV_p^2/U}$$

From Section 3.3.b, the "equivalent diameter" of the missile is

$$D = 2t = (2)(0.1) = 0.2 \text{ inches}$$

Then, from equation (12)a, let us assume an effective window opening of

$$W = 8D = (8)(0.2) = 1.6 \text{ inches}$$

This is smaller than: (a) any likely spacing of supports, or (b) the opening size given by equation (12)b with any reasonable barricade thickness, or (c) the length, L, per equation (12)c. Thus, the value of 1.6 inches from (12)a will be used. Then, putting in numbers

$$T = -0.0118(1.6) + \sqrt{1.38 \times 10^{-4}(1.6)^2 + \frac{(0.0706)(0.284)(0.1)(6.28)(1010)^2}{60,000}}$$

$$= 0.445 \text{ inches}$$

or rounding off, say, 1/2 inch.

In some cases, a greater thickness may be desirable to provide a greater factor of safety. In this case, however, greater thicknesses are not considered necessary due to the following conservative factors which entered into the calculations:

(1) The tube was assumed to open up flat and to strike the barricade both with its velocity normal to the barricade and with the plane of the missile normal to the barricade at the instant of contact. Both of these conditions are rather unlikely.

(2) The tube was assumed to open out completely flat so that its characteristics on impact would be similar to those of a cylindrical rod. Actually there would probably be some

residual curvature which would lower the buckling characteristics of the missile and thus reduce its penetrating ability.

b. Reinforced Concrete Barricade. Determine the adequacy of a one foot thick slab of normal reinforced concrete to stop the missile of 3.9.a.

From 3.4 the penetration distance will be

$$D' = KAV'R$$

From Table 1, for "normal" reinforced concrete

$$K = 4.76 \times 10^{-3} \ \ ft^3/lb$$

The sectional mass is

$$\begin{aligned} A &= \rho b \\ &= (0.284 \ lb/in^3)(6.28 \ in)(144 \ in^2/ft^2) \\ &= 256 \ lb/ft^2 \end{aligned}$$

The velocity factor is, from Figure 4

$$V' = 0.75$$

The penetration ratio is, from Figure 5

$$\begin{aligned} a' &= \frac{T}{KAV'} \\ &= \frac{1}{(4.76 \times 10^{-3}) \ (256) \ (0.75)} = \frac{1}{0.914} \\ &= 1.10 \end{aligned}$$

The thickness ratio is off scale to the left on Figure 5, thus indicating that the penetration depth is greater than the thickness of the slab.

To barely stop the missile, then, the slab must have a thickness of

$$\begin{aligned} T_M &= 2(KAV') \\ &= (2)(1.10) = 2.20 \ ft \end{aligned}$$

Let us try a thickness of 3.0 ft. Then

$$a' = \frac{3.0}{1.10} = 2.73$$

From Figure 5, the thickness ratio is

$$R = 1.06$$

The depth of penetration in this slab will then be

$$D' = (0.914)\ (1.06) = 0.97 \text{ ft}$$

The slab thickness of 3.0 ft is more than 1-1/2 times this depth, so no anti-scabbing plate is needed.

4. BLAST RESISTANCE OF BARRICADES

4.1 Conditions Requiring Evaluation

Blast effects will be produced whenever high pressure fluids are suddenly released to atmosphere. These effects are often (perhaps usually) more destructive than the effects of missiles - which act over much smaller areas. It is thus felt that blast effects should be evaluated unless experience has shown that for credible modes of failure, blast effects will be negligible.

4.2 Physiological Effects of Blast

This report is concerned primarily with evaluation of structural effects and the structural adequacy of barricades. It is felt that a barricade which is structurally adequate to resist blast and which provides line of sight protection for personnel will normally also provide adequate physiological protection.

However, when determining the need for a blast barricade or for evaluating possible effects on personnel who might be inside a barricade at the wrong time, some consideration of physiological effects may be of interest.

Table 3 (adapted from Glasstone, reference 8.3.a.12) gives values for the peak overpressures at which various physiological effects are anticipated. These values were obtained largely in connection with the

TABLE 3. PHYSIOLOGICAL EFFECTS OF BLAST PRESSURES

Peak Overpressure psi	Physiological Effect
1	Knock Personnel Over
5	Threshold for Eardrum Rupture
15	Threshold of Lung Damage
35	Threshold for Fatalities
65	Fatalities 99% Probable

effects of atomic weapons - which are characterized by unusually long period blast waves. With the shorter period blast waves which are expected from pressure vessel explosions, these values are felt to be conservative.

In order for this table to have any predictive value, it is necessary, of course, to obtain an estimate of peak overpressure in a given incident.

Rigorous calculations of blast wave pressures can be very complex (see references 8.2.3, 8.2.5, and 8.2.18). However, it is believed that a rough estimate for the purposes described above may be obtained by multiplying the static pressures obtained by the methods of 4.3.a by a factor of 6. (This factor was obtained by comparing predicted static pressures from 4.3.a with those obtained by Porzel in reference 8.2.3.)

In addition to physiological effects resulting from pressure load, effects may also be produced by the high temperatures which frequently accompany blasts, such as by scalding by steam. Protection should be provided against such hazards when present.

4.3 Effective Static Pressure

a. Static Analysis. The effective static overpressure for structural evaluation purposes may be estimated from the following expression (adapted from Loving, reference 8.2.9):

$$P = 5.75 \frac{V_p}{V_c} E_v \qquad (16)$$

where P = Effective static overpressure - psig
V_p = Volume of pressure vessel - cu in
V_c = Volume of chamber into which fluid is released on explosion of pressure vessel - cu ft
E_v = Energy released due to expansion of fluid or chemical reaction (if present) per unit volume of pressure vessel - Btu/cu in

This expression may be rearranged in the form

$$\frac{P}{V_p/V_c} = 5.75\ E_v$$

which is given by Figure 6 for saturated water as a function of water temperature and pressure.

For nonreacting fluids, the available energy E_v should be obtained by determining the amount of energy released by isentropic expansion of the fluid from rupture conditions to one atmosphere.

For reactions of certain explosive compounds, see reference 8.2.9.

The above expressions were obtained for chambers having a maximum dimension no greater than twice the minimum dimension. Thus, for long, narrow chambers (such as pipes) an effective volume should be used for V_c equal to the volume of a space having its maximum dimension twice that of the minimum dimension of the chamber.

The pressure is used by conventional static structural techniques to determine barricade adequacy.

b. Dynamic Analysis. Examples of calculations in which transient pressures during pressure vessel incidents were calculated are given by references 8.2.2, 8.2.3, 8.2.5, 8.2.18, 8.3.a.1, and 8.3.a.6.

Newmark, in reference 8.2.4, gives a method for evaluating the effects of blast loading in terms of an equivalent static pressure. This method requires an evaluation of the natural frequency of vibration of the structure, its ratio of elastic deflection to deflection at failure, and a knowledge of the duration and magnitude of the blast loading.

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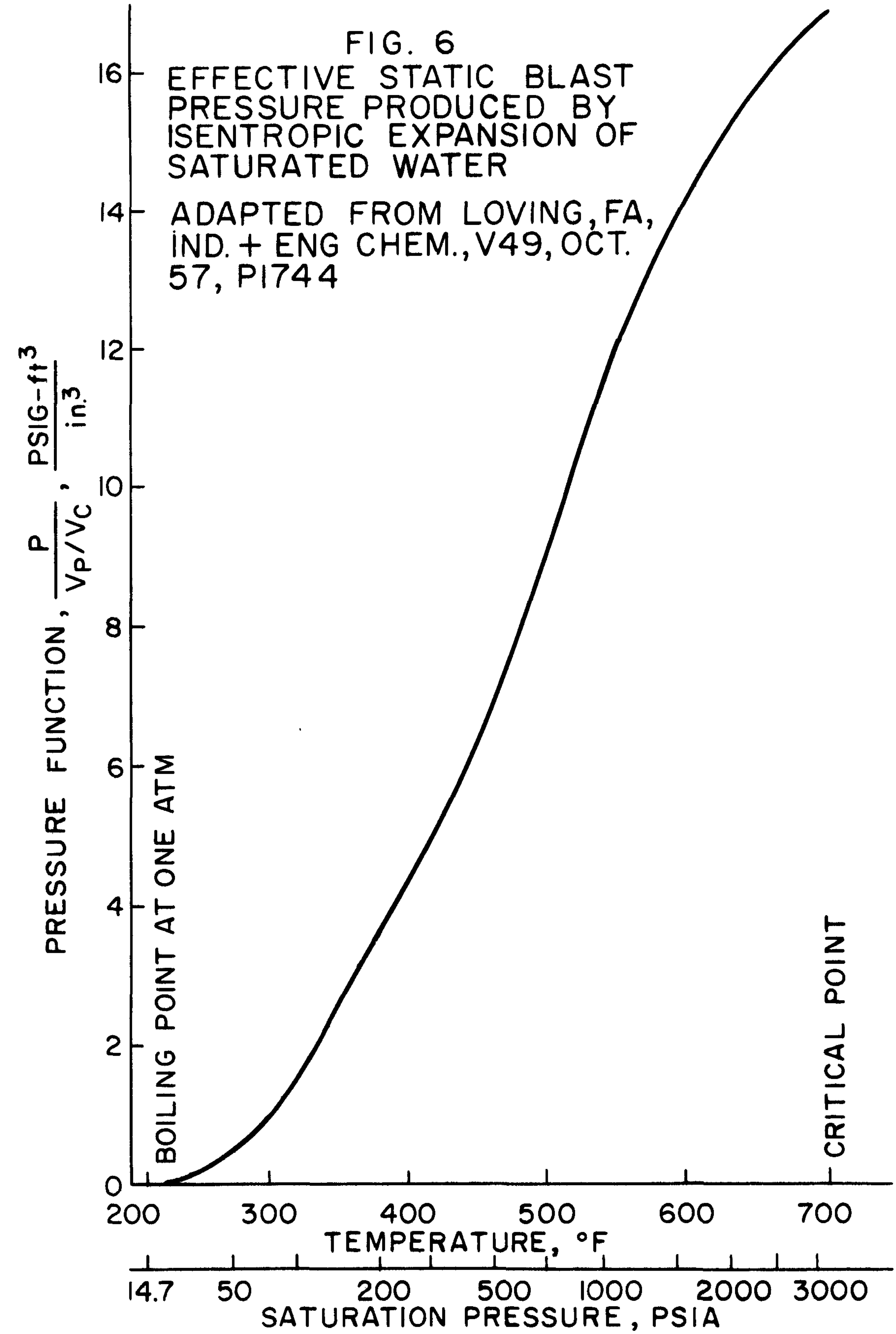
FIG. 6
EFFECTIVE STATIC BLAST PRESSURE PRODUCED BY ISENTROPIC EXPANSION OF SATURATED WATER
ADAPTED FROM LOVING, FA, IND. + ENG CHEM., V49, OCT. 57, P1744
PRESSURE FUNCTION, P / VP/VC , PSIG-ft3 / in.3
0
2
4
6
8
10
12
14
16
BOILING POINT AT ONE ATM
CRITICAL POINT
200
300
400
500
600
700
TEMPERATURE, °F
14.7
50
200
500
1000
2000
3000
SATURATION PRESSURE, PSIA

KS-57568

Methods for the design of specially constructed masonry walls to resist blast loading are given by McKee and Monk in references 8.2.6, 8.2.7, and 8.2.15.

4.4 Blast Energy Absorption by Deformation

Methods which may be used for the evaluation of blast resistance of cylindrical containment structures in terms of their energy absorption abilities are given by Wise in references 8.2.8 and 8.2.14.

The use of crushable materials such as wood and celotex is discussed by Porzel (references 8.2.5 and 8.2.12), Hanna and Ewing (reference 8.2.20), Monson (reference 8.3.a.7) and Zaker and his associates at Armour Research Foundation (now IITRI) (reference 8.2.19 and subsequent periodic reports). As yet, however, no simple, generally applicable design techniques are known.

Absorption of blast energy from steam and water pipes ruptured under water is discussed by Luken and Leeman (reference 8.2.21).

4.5 Sample Calculation

Let us determine the adequacy for blast resistance of the barricade selected in 3.9.a. A 1/2 inch steel plate was selected as adequate for missile resistance.

We will assume that the barricade is in the form of a nominal 10 inch diameter Schedule 60 pipe having a nominal wall thickness of 1/2 inch, the same length as the pressure vessel, and constructed of ASTM-SA-106B material.

From Figure 6, the blast pressure function developed by rupture of the pressure vessel containing 600° water is

$$\frac{P}{V_p/V_c} = 14.1 \quad \frac{\text{psig - ft}^3}{\text{in}^3}$$

The volume of the chamber will be

$$V_c = \frac{\pi}{4} D^2 L$$

where D = Inside diameter of barricade - ft
L = Length of barricade - ft (taken as unit length or 1 ft)

The inside diameter of 10-inch Schedule 60 pipe is 9.75 inches. Thus

$$V_c = \frac{\pi}{4} \left(\frac{9.75}{12}\right)^2 (1) = 0.518 \text{ ft}^3$$

Similarly, the inside volume of the exploding pipe is

$$V_p = \frac{\pi}{4} d^2 L$$

$$= \frac{\pi}{4} (2)^2 (12)$$

$$= 37.7 \text{ in}^3$$

Then the effective static pressure produced is

$$P = (14.1) \frac{V_p}{V_c} = (14.1) \left(\frac{37.7}{0.518}\right) = 1025 \text{ psig}$$

From paragraph UG-27 of Section VIII of the ASME Boiler Code, the thickness required to withstand this pressure is given by

$$t = \frac{PR}{SE-0.6P}$$

where S = Maximum stress allowable by Code (equals 15,000 psi for this material)
E = Joint efficiency (equals 1 for seamless pipe)
R = Inside radius - inches

Putting in these values we obtain

$$t = \frac{(1025)(4.875)}{(15,000)(1) - (0.6)(1025)}$$

$$= 0.348 \text{ in}$$

This is less than the 1/2 inch required for missile resistance. Thus the blast resistance is satisfactory.

4.6 Evaluation of Barricades by Test

The ASME Boiler Code provides standard overload proof tests by means of which pressure vessels having geometries whose adequacy cannot be reliably evaluated by analysis can be shown to be adequate.

Unfortunately, similar proof tests for barricades are likely to be prohibitively expensive and should be considered only when no other means for evaluation exist.

A program to develop and evaluate scaling laws for tests of model barricades using explosive charges is described in references 8.2.10, 8.2.16, 8.2.17, 8.2.22, and 8.2.23. The application of these laws to tests of a 1/4 scale model of a nuclear reactor barricade is described in references 8.2.13 and 8.2.17.

The design of a laboratory cell and tests of a full scale mockup of the cell using up to 50 lb charges of TNT are described in references 8.3.b.11 and 8.3.b.12.

Tests conducted on a full scale portable barricade are described in reference 8.3.b.13.

4.7 Blast Resistance of Transparent Barricades

Circular glass viewing ports with manufacturer's static pressure ratings may be purchased in sizes up to 17 inch diameter (reference 8.3.c.1 and 8.3.c.5). These are considered generally preferable to "homemade" designs due to the difficulties of providing edge supports which develop the full strength of the glass.

If, however, a special design is desired, the following equation may be used for estimating the required thickness (from Shand, reference 8.3.c.2) of solid glass or plastic ports

$$t = d\sqrt{\frac{K_1 P}{\sigma}} \quad \text{inches} \qquad (17)$$

where
- d = Diameter of circular port or smaller dimension (width) of rectangular port - inches
- P = Effective static pressure due to blast - psi
- σ = Allowable working stress of port material - psi
- K_1 = Stress factor. For circular ports K_1 = 0.3025. For rectangular ports K_1 is a function of the ratio of length to width and is given by Table 4.

Recommended working stresses are 1500 psi for tempered glass and 1100 psi for Plexiglas G.

TABLE 4. STRESS FACTORS FOR RECTANGULAR VIEWING PORTS
(Shand, ref. 8.3.c.2)

Length/Width Ratio	Stress Factor K_1
1	0.29
1.5	0.48
2	0.61
2.5	0.67
3	0.71
4	0.74
Over 5	0.75

4.8 Effectiveness of Venting for Blast Protection

Laboratory test cells are normally constructed with one wall either open or of lightweight construction to act as an explosion vent. Such vents are of considerable value for minimizing the effects of relatively slow explosions such as occur if the test cell is filled with a hydrocarbon or combustible dust mixture and ignition occurs (see reference 8.2.11).

When pressure vessels explode, however, the resultant blast wave is projected outwards from the vessel at the velocity of sound. Thus portions of the surroundings which are acted upon by one portion of the blast wave will be relatively unaffected by what is happening elsewhere to the blast wave. As a result, little reliance can be placed on the beneficial effects of venting for the types of explosions considered here.

This lack of effectiveness of venting has been demonstrated when pressure vessels have exploded out of doors (under "ideal" venting conditions) with extensive blast damage resulting.

5. DESIGN OF LABORATORY TEST CELLS

Laboratory test cells consist, in general, of three reinforced walls constructed of concrete or similar materials and a fourth wall of lightweight blowout construction pointed in a safe direction. The designs of a number of such test cells are described in references 8.3.b.1 through 8.3.b.12 and 8.3.b.14 and 8.3.b.15.

6. ADDITIVE MISSILE AND BLAST EFFECTS

Usually a barricade will have a considerably greater margin of strength for blast resistance than for missile resistance. Thus exposure of the barricade to blast effects will not affect its subsequent resistance to missiles. (Blast waves usually travel faster than the missiles and thus act upon the barricade first.)

If, however, the blast and missile resistance of a barricade are about equal, the blast effects could conceivably cause weakening or dislodgement of the barricade so that barricade failure subsequently occurs due to missile impact - where such failure would not be expected for either of the effects acting singly. Thus the possibility of additive effects should be considered when the required thicknesses for blast and missile resistance are about the same.

7. ACKNOWLEDGMENT

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8. REFERENCES

8.1 References Dealing Largely with Missile Effects

1. P. E. Duwez, D. S. Wood, and D. S. Clark, "Preliminary Report of Deflection and Perforation of Plates at Impact Velocity up to 150 Ft per Sec," OSRD-1402, 1943.

2. R. W. Gurney, "Initial Velocities of Fragments From Bombs, Shells, and Gernades," BRL Report 405, September 14, 1943, 11 pp.

3. N. P. White (Editor), "Effects of Impact and Explosion," Office of Scientific Research and Development Report, STR-2-1, 1946, pp. 393-400 (Confidential).

4. T. E. Sterne, "A Note on the Initial Velocities of Fragments From Warheads," BRL Report 648, September 2, 1947.

5. A. Amirikian, "Design of Protective Structures (A New Concept of Structural Behavior)," Bureau of Yards and Docks, NP-3726, August, 1950.

6. J. S. Rinehart and J. Pearson, "The Behavior of Metals Under Impulsive Loads," American Society for Metals, 1954, 256 pp.

7. R. A. Williamson and R. R. Alvy, "Impact Effects of Fragments Striking Structural Elements," NP-6515, 1957.

8. H. F. VanKessel, "Hazards and Missile Survey of Nuclear Reactor Vapor Containment for SM-2," APAE-45, 1958, 171 pp.

9. N. R. Zabel, "Containment of Fragments From a Runaway Reactor," Stanford Research Institute Report SRI-1, April 2, 1958.

10. N. R. Zabel, "Containment of Fragments From a Runaway Reactor," Stanford Research Institute Report SRIA-2, October 1, 1958.

11. G. B. Huber, et al, "Containment of Fragments From a Runaway Reactor," Stanford Research Institute Report SRIA-17, October 30, 1959 and SRIA-36, October 31, 1960.

12. S. S. Rosen, ed., "Hazards Summary Report for the Army Package Power Reactor SM-1," Task XVII, APAE-2 (Rev. 1), May, 1960, 260 pp.

13. H. F. VanKessel and M. J. Celantano, "Vapor Container Concepts Study for SM-2," APAE-63 (AD-238033), May 16, 1960, 64 pp.

14. D. E. Davenport, "Penetration of Reactor Containment Shells," Nuclear Safety, Vol. 2, December, 1960, pp. 31-37.

15. W. Goldsmith, Impact, Edward Arnold Ltd., London, 1960.

16. D. E. Davenport, G. B. Huber, and N. R. Zabel, "Containment of Fragments From Runaway Nuclear Reactors - A Review of Model Studies Carried out at Stanford Research Institute," Progress in Nuclear Energy, Series IV, Item 4, pp. 484-503, 1961.

17. "Study on Hull Structure Around Reactor of Nuclear Ship," Nuclear Powered Ship Research Association of Japan, NP-12553, December 16, 1961 (in Japanese but with abstract, figures, tables and equations in English).

18. R. W. White and N. B. Botsford, "Containment of Fragments from a Runaway Reactor," Tech. Report No. 6, SRIA-113, September 15, 1963, 33 pp.

19. W. Goldsmith, "Impact: The Collision of Solids," Applied Mechanics Review, Vol. 16, No. 11, November, 1963, pp. 855-866.

20. N. B. Botsford, D. D. Keough, and R. W. White, "Containment of Fragments From a Runaway Reactor," Technical Report No. 5, SRIA-43, December 2, 1963.

8.2 References Dealing Largely with Blast Effects

1. R. Flohr and A. Kush, "Tests on Enclosed Steel Barricades," Picatinny Arsenal Report AD-44883, January 5, 1954, 30 pp.

2. P. F. Pasqua, "Pressures in the HRT Shield Resulting From Rupture of Reactor," ORNL-CF-54-9-30, September 3, 1954.

3. E. F. Lype and F. B. Porzel, "Shock Hydrodynamics of an Exploding Steam Pressure Vessel," APAE-Memo-136, November 25, 1955

4. N. M. Newmark, "An Engineering Approach to Blast Resistant Design," Trans. ASCE, Vol. 121, p. 45, 1956.

5. F. B. Porzel, "Design Evaluation of Boiling Experimental Reactor in Regard to Internal Explosions," ANL-5651 and ARF No. D-090, June, 1956.

6. K. E. McKee, "Dynamic Characteristics of Structural Clay Masonry Walls, Phase Report III, High Explosive Test Program," ARF No. K-576, July, 1956.

7. K. E. McKee, "Dynamic Characteristics of Structural Clay Masonry Walls, Phase Report IV, Blast Resistant Design," ARF-K-576, October, 1956.

8. W. R. Wise, Jr., "Calculation of the Energy Absorption Potential for the Blast Shield of the Argonne National Laboratory Nuclear Reactor EBR-II," Navord Report 4470, February 2, 1957.

9. F. A. Loving, "Barricading Hazardous Reactions," Industrial and Engineering Chemistry, Vol. 49, No. 10, October, 1957, pp. 1744-1746.

10. R. J. Larson and W. Olson, "Measurement of Air Blast Effects from Simulated Nuclear Reactor Core Excusions," BRLM Report-1102, AEC No. WASH-747, September, 1957.

11. I. Hartmann and J. Nagy, "Venting Dust Explosions," Industrial and Engineering Chemistry, Vol. 49, No. 10, October, 1957, pp. 1734-1740.

12. F. B. Porzel, "Some Hydrodynamic Problems in Reactor Containment," Paper P-434, Proceedings of 2nd UN International Conference on Peaceful Uses of Atomic Energy, Vol. 11, 1958, pp. 85-91.

13. W. E. Baker, "Scale Model Test for Evaluating Outer Containment Structures for Nuclear Reactors," Paper P-1028, Proceedings of 2nd UN International Conference on Peaceful Uses of Atomic Energy, Vol. 11, 1958, pp. 79-84.

14. W. R. Wise, Jr., "An Investigation of Strain-Energy Absorption Potential as the Criterion for Determining Optimum Reactor-Vessel Containment Design," Navord Report 5748, June 30, 1958, 139 pp.

15. C. B. Monk, Jr., "Resistance of Structural Clay Masonry to Dynamic Forces," Research Report No. 7, Structural Clay Products Research Foundation, Geneva, Ill., November, 1958.

16. W. E. Baker, W. O. Ewing, Jr., and J. W. Hanna, "Laws for Large Elastic Response and Permanent Deformation of Model Structures Subjected to Blast Loading," BRL Report No. 1060, December, 1958.

17. J. W. Hanna, W. O. Ewing, Jr., and W. E. Baker, "The Elastic Response to Internal Blast Loading of Models of Outer Containment Structures for Nuclear Reactors," BRL Report No. 1067, February, 1959.

18. I. I. Glass, "Analysis of Boiler Room Pressures Following Potential Rupture of the Main Coolant Line in the Nuclear Power Demonstration (NPD-2) Plant," Report No. 169/79, AECL-1930, February, 1960, 24pp. plus 7 Appendices.

19. T. A. Zaker (Editor), "Studies of Reactor Containment," Armour Research Foundation Summary Reports 1, 2, and 3, ARF-4132-12, ARF-4132-13, and ARF-4132-4, 1961 and subsequent related periodic reports by Illinois Institute of Technology Research Institute.

20. J. W. Hanna and W. O. Ewing, Jr., "Effectiveness of Lining Materials in Increasing the Blast Resistance of a Simulated Outer Containment Vessel for a Nuclear Reactor," BRLM Report, No. 1341, April, 1961.

21. R. C. Luken and C. A. Leeman, "Vapor Suppression Test Program Report," BAW-1258, August, 1962, 89 pp.

22. W. E. Baker, "The Elastic Response of Thin Spherical Shells to Internal Blast from Eccentrically Placed Explosive Charges," BRL-Memo-Report 1520, November, 1963.

23. J. W. Hanna and W. O. Ewing, Jr., "The Plastic Response to Internal Blast Loading of Models of Outer Containment Structures for Nuclear Reactors," BRL-Memo-1530, January, 1964, 30 pp.

8.3 References Concerned with Both Blast and Missile Effects

a. References Dealing with Nuclear Reactor Containment

1. P. M. Wood, "A Study of Possible Blast Effects from HRT Pressure Vessel Rupture," CF-54-12-100, December 14, 1954.

2. P. M. Fye and E. C. Noonan, "Naval Ordnance Laboratory Reactor Safety Program," Navord Report 4286, April, 1956.

3. W. J. Levedahl and R. D. Howerton, "A Method for Computing Pressures, Fragment Velocities, and Core Reactivity During Explosion of a Reactor Pressure Vessel," KAPL-M-WJL-1, August 7, 1956, 32 pp.

4. W. J. Levedahl, "Missiles Produced by S3G Vessel Failure," KAPL-M-WJL-3, October 9, 1956, 23 pp. (Confidential).

5. W. Baker and J. Patterson, "Blast Effects Test of a Quarter-Scale Model of the Air Force Nuclear Engineering Test Reactor," Ballistic Research Laboratory Report 1011, March, 1957, 191 pp.

6. E. M. Fisher and W. R. Wise, Jr., "Containment Study of the Enrico Fermi Fast Breeder Reactor Plant," Navord Report 5747, October 7, 1957.

7. H. O. Monson and M. M. Sluyter, "Containment of EBR-II," Proceedings of UN International Conference on Peaceful Uses of Atomic Energy, Paper P1892, Vol. 11, pp. 124-138, 1958.

8. R. O. Brittan and J. C. Heap, Reactor Containment Paper P437, Proceedings of Second UN International Conference on Peaceful Uses of Atomic Energy, Vol. 11, pp. 66-78, 1958.

9. K. R. Bohannon, Jr. and W. E. Baker, "Simulating Nuclear Blast Effects," Nucleonics, Vol. 16, No. 3, March, 1958, pp. 74-79 (with discussion by F. B. Porzel and R. W. Deuster).

10. R. O. Brittan, "Reactor Containment (Including a Technical Progress Review)," ANL-5948, May, 1959, 261 pp.

11. W. McGuire and G. P. Fisher, "Containment Studies for Atomic Power Plant (Fermi)," Proceedings of the American Society of Civil Engineers, Vol. 86, No. PO3, Paper No. 2508, June, 1960, pp. 27-53.

12. S. Glasstone, ed., "Effects of Nuclear Weapons," U.S. Govt. Printing Office, April, 1962, 730 pp.

13. S. H. Fistedis, A. H. Heineman, M. J. Janicke, "Testing of Containment Capabilities of Reinforced Concrete Shielded Enclosures," ANL-6664, March, 1963, 42 pp.

14. D. W. Mueller and A. P. Furnish, "Prestressed Concrete Spherical Containment Vessel," LA-2901, May 1, 1963, 64 pp.

15. W. R. Wise, et al, "Enrico Fermi Shield - Plug Response to a 1000 lb TNT Accident," Experimental Mechanics, Vol. 3, October, 1963, pp. 245-52.

16. R. J. Smith, ed., "Reactor Containment (Bibliography)," NP-12980, November, 1963, 22 pp.

17. W. B. Cottrell, ed., Reactor Containment Handbook, Chapter 5, "Analytical Techniques," Preliminary Draft under preparation at Oak Ridge National Laboratory, 1964.

b. References Dealing with Laboratory Test Cells

1. A. L. Glassbrook and J. B. Montgomery, "High Pressure Laboratory Design for Safe Operation," Industrial and Engineering Chemistry, Vol. 41, October, 1949, pp. 2368-2373.

2. H. S. Mabley, "Operating High Pressure Equipment," Chemical Engr. News, Vol. 27, No. 52, December 26, 1949, pp. 3860-3861.

3. H. S. Coleman, ed., Laboratory Design, Reinhold, New York, 1951, (Chapter 9, "High Pressure Laboratories" by R. L. Savage, pp. 241-249).

4. R. L. Porter, P. A. Lobo and C. M. Sliepcevich, "Design and Construction of Barricades," Industrial and Engineering Chemistry, Vol. 48, May, 1956, p. 841-846.

5. J. F. Miller, "Unit Type Batch Reaction Cubicles," Industrial and Engineering Chemistry, Vol. 48, May, 1956, p. 846-848.

6. C. V. Foster, A. O. Knedler, J. F. Peterson and M. L. Sharrah, "Petrochemical Research Pilot Plant," Industrial and Engineering Chemistry, Vol. 48, May, 1956, p. 849-853.

7. R. W. Kiefer, "Safety at High Pressure," Industrial and Engineering Chemistry, Vol. 49, No. 12, December, 1957, pp. 2017-2018.

8. H. R. Stephens and K. A. Walker, "Safety in Small Scale High Pressure Experiments," Industrial and Engineering Chemistry, Vol. 49, No. 12, December, 1957, pp. 2022-2025.

9. J. C. Bowen and R. L. Jenkins, "Features of an Eight Cubicle Laboratory," Industrial and Engineering Chemistry, Vol. 49, No. 12, December, 1957, pp. 2019-2021.

10. M. A. Rebenstorf, "Designing a High Pressure Laboratory," Industrial and Engineering Chemistry, Vol. 53, No. 2, January, 1961, pp. 40A-42A.

11. H. C. Browne, H. H. Leman and L. C. Weger, "Barricades for High Pressure Research," Industrial and Engineering Chemistry, Vol. 53, No. 10, October, 1961, pp. 52A-58A.

12. J. P. Weber, J. Savitt, J. Krc, Jr., and H. C. Browne, "Detonation Tests Evaluate High Pressure Cells," Industrial and Engineering Chemistry, Vol. 53, No. 11, November, 1961, pp. 128A-133A.

13. R. L. Porter and C. M. Sliepcevich, "A Portable High Pressure Laboratory," Industrial and Engineering Chemistry, Vol. 54, July, 1962, pp. 44-47 (also R. L. Porter, "Movable Barricade-Explosive and Burning Test," Autoclave Engineers' Bulletins T-160 and 160).

14. J. F. Stenberg and E. G. Coffey, "Designing a High Pressure Laboratory," Chemical Engineering, November 26, 1962, pp. 115-118.

15. R. A. Terselic, "Design of Safety Barricades," Safety Engineering, Vol. 129, No. 1, January, 1965, pp. 14-18 and 20-22.

c. Transparent Barricades

1. "Sight Glasses," Bulletin B-61, Pressure Products Company, P.O. Box 424, Charleston, West Virginia, no date.

2. E. B. Shand, Glass Engineering Handbook, McGraw-Hill, 1958, 484 pp.

3. C. E. Green and J. F. Hester, "An Evaluation of Safety Goggles and Safety Shields," Report S-18, Rohm and Haas Company, Redstone Arsenal Research Division, Huntsville, Alabama, September, 1958, 19 pp.

4. "Bullet Resisting Glass," Engineering Data Bulletin, Pittsburgh Plate Glass Company, 1 Gateway Center, Pittsburgh 22, Pa., May, 1960.

5. "Sight Glasses by Corning," Bulletin EB-20, Corning Glass Works, Corning, New York, May 1, 1963.

8.4 References Mentioned Only in Appendices

1. "Power," Vol. 22, August, 1902, pp. 36-7.

2. "Power," Vol. 22, December, 1902, p. 65.

3. "Power," Vol. 32, May 31, 1910, pp. 1000-1002.

4. "Power," Vol. 32, November 15, 1910, pp. 2041-2042.

5. "Power," Vol. 33, February 7, 1911, pp. 241-242.

6. "Power," Vol. 35, April 16, 1912.

7. A. L. Brown and J. B. Smith, "Failure of Spherical Hydrogen Storage Tank," Mechanical Engineering, Vol. 66, 1944, pp. 392-397.

8. Private Communication from J. R. Alexander, General Electric Co., Schenectady, N.Y., December 14, 1964.

9. Private Communication from F. A. Loving, December 12, 1963.

10. A. Kolflat, "Results of 1959 Nuclear Power Plant Containment Tests," SL-1800, March 30, 1960, 35 pp.

APPENDIX A. CHECK OF MISSILE VELOCITY ESTIMATE

The expression given by Equation (5) for the estimation of the velocities of fragments of exploding pressure vessels is an extrapolation from the Gurney equation (Equation 1) - which has been verified by experiment for explosions of high explosives in cylindrical geometries over a wide range of diameters and thicknesses of cylinders.

Its use in the form given by Equation (5) for the much slower and lower pressure explosions characteristic of pressure vessels is, of course, without sound theoretical foundation. Thus an attempt was made to correlate predicted velocities obtained from Equation (5) with some calculated from the distances of travel of fragments of exploded pressure vessels reported in the literature (references 8.4.1 thru 8.4.8).

The literature references give, in general, the distances traveled by fragments of the pressure vessel shells, the pressures at which the explosions occurred, the dimensions of the pressure vessels prior to the explosions and, in the cases of the fire tube boilers studied, usually some indication of the water level at the time of the explosion. All of the explosions studied except one (reference 8.4.7) were fire tube boilers.

It was assumed in predicting the velocities by Equation (5), that the fire tube boilers were filled to the equivalent of fifty per cent of their internal volume with water; the remainder of the space being the normal steam space in the boiler and the space occupied by the fire tubes.

The minimum initial velocities calculated from the range of the fragments were calculated by the method suggested by Wood (reference 8.3.a.1) with an additional correction factor taken from ordnance data to account for air resistance. This method implies that the missile was fired at a forty-five degree angle (or elevation) to the horizontal. Thus the computed velocity is the maximum which could have occurred and may be considerably less than the actual initial velocity.

The results of this comparison are summarized in Figure 7 - in which the minimum velocity computed from the range of the fragments is plotted on the vertical scale, and the velocity predicted by Equation (5) is plotted on the horizontal scale. The dotted line represents an exact correlation. The numbers next to the points refer to reference numbers given in 8.4.

A.2

All of the points fall below the dotted line, thus indicating that Equation (5) gives results which appear to be conservative - which is reassuring.

The scatter in the vertical direction of the predicted velocity may be explained on the basis of the random elevations of the fragments. If this is, in fact, a true explanation then the upper points most accurately represent the true initial velocities. Using these points, the velocities predicted by Equation (5) are high by about forty or fifty per cent of the "true" velocities.

Some caution should, however, be observed before jumping to the conclusion that Equation (5) is, in fact, this conservative - since the apparent conservatism may also be explained by the following factors:

a. A relatively small number of cases of explosions were studied; thus there is a significant probability that none of the fragments came off at close to the forty-five degree elevation required to produce maximum range.

b. In the fire tube boiler explosions studied, considerable kinetic energy may have been absorbed in accelerating the tubes - many of which were thrown considerable distances. No allocation of energy was made to the tubes, however, in estimating the velocities of the fragments. Thus vessels which do not contain comparable internal structures might be expected to produce higher shell fragment velocities.

c. The data for the explosions was of rather poor quality by laboratory standards. Most of it was taken by untrained observers, some of whom were probably biased by personal considerations.

d. All the explosions studied occurred at relatively low pressures; the highest being 100 psig. What sort of correlation would be obtained at higher pressures can only be speculated. It seems reasonable, however, to expect better agreement - since vessels exploded at higher pressure would seem to approach more nearly the conditions occurring during detonation of high explosives.

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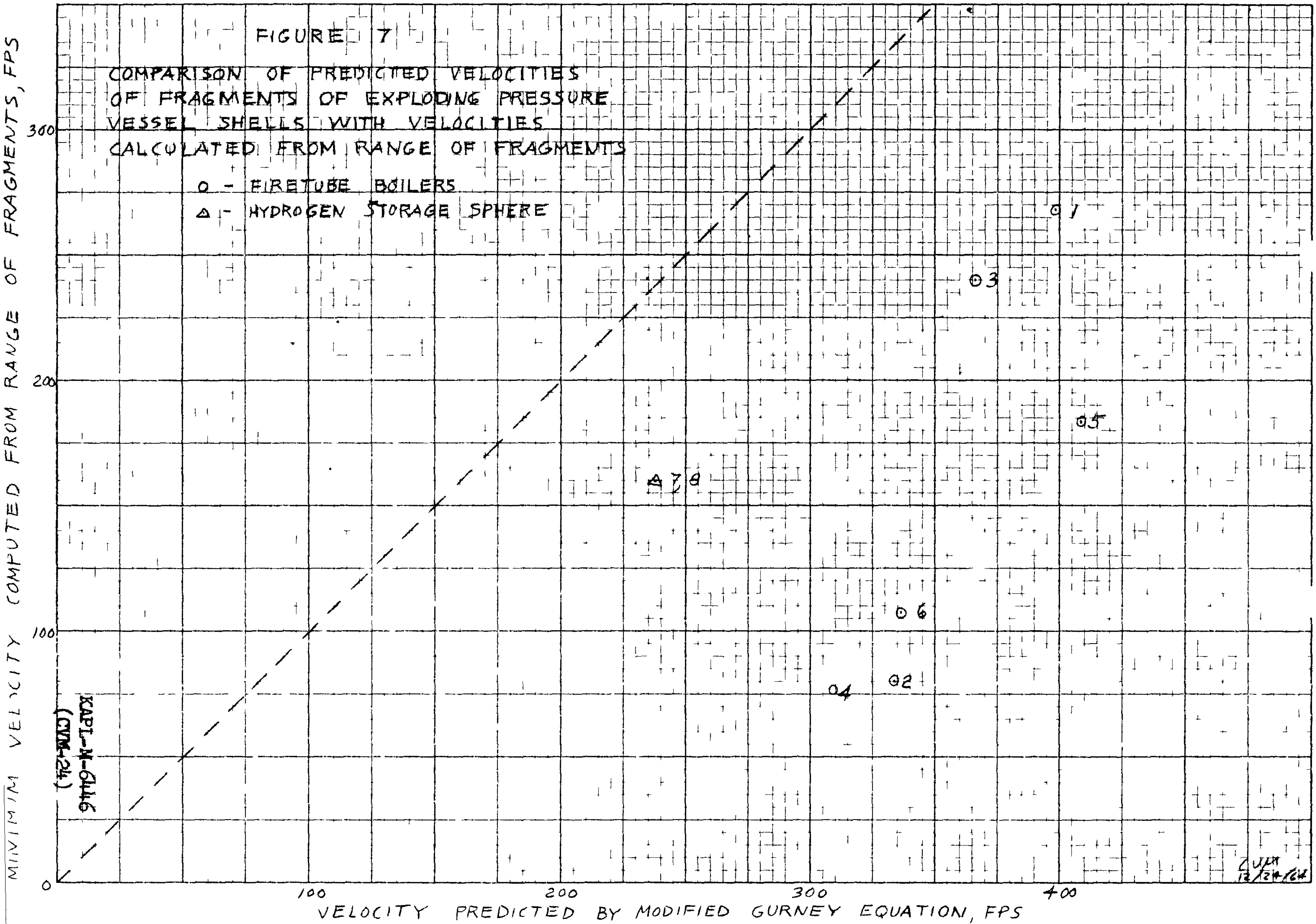

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APPENDIX B. CHECK OF EQUIVALENT STATIC OVER-PRESSURE ESTIMATE

Hanna and Ewing (reference 8.2.23) have reported data for a series of experiments in which charges of 50/50 pentolite were exploded while suspended on the center lines of cylindrical steel pressure vessels of various sizes. The pressure vessels were instrumented with strain gauges whose readings were recorded with high speed instrumentation during the explosions.

From the strain gauge readings, an effective over-pressure during the explosion can be derived. (That is, the static internal pressure which would be required to produce the same strain.) With strains in the elastic range such an over-pressure would seem to be equivalent to the effective static over-pressure discussed in 4.3.a. Such a pressure was calculated for round 221 (reference 8.2.23) - giving a value of 155 psi.

Loving's equation (reference 8.2.9) from which Equation (16) was derived is

$$P = K \frac{W}{V_c} \qquad (18)$$

where P = Over-pressure in lbs per sq inch gauge
W = Weight of material exploded in lbs
V_c = Chamber volume in cubic feet
K = 15,000 for PETN

The value of K given was based on an available energy release of 1450 calories per gram (reference 8.4.9). Loving does not give a value of K for 50/50 pentolite, however, one can be extrapolated from the value of K given for PETN by assuming that K is directly proportional to the available energy release and using the value of 1220 calories per gram reported in reference 8.2.23.

Making this extrapolation, an equivalent static over-pressure of 113 psi is obtained from Equation (18). This value compares reasonably well with the 155 psi derived from the strain gauge data.

A number of experiments have been reported in the literature in which pipes or vessels containing pressurized water have been discharged into larger vessels initially filled with air - following the breaking of rupture discs or the opening of quick opening valves. (for example, references 8.2.19, 8.2.21, and 8.4.10)

B.2

In most of these, either no blast pressures have been measured or very small pressures have been measured. In all cases with which the author is familiar, however, the sizes of the suddenly produced openings have been relatively small compared to the volume of pressurized water. (That is, the area of the opening has been very, very small compared to the area of cross-section of a sphere having a volume equal to the volume of the pressurized water.) Thus the conditions of the experiments have been relatively mild compared to those which apparently occurred during many recorded explosions of pressure vessels - judging from the damage produced and the configurations of the pressure vessel remains.

The most severe (by this standard) tests known to the author are those reported by Kolflat (reference 8.4.10). In these tests a drum, 42 inches in diameter by 23 feet long, filled with various quantities of saturated water at pressures up to 600 psig was discharged through a 12 inch rupture disc into an outer vessel having an inside diameter of 14 feet and a height of 32 feet.

The effective over-pressure predicted by Equation (16) for Kolflat's test number 11 was 328 psi. The first pulse of measured pressure reported by Kolflat was 86 psi. The large difference between the predicted and measured pressures is believed to be due primarily to the relatively small size of the opening - which had an area only 1/12 of the cross-sectional area of the drum. A contributing factor might also have been a lack of adequate speed of response of the pressure measuring and recording equipment which would tend to cause an under estimation of very rapid pressure transients.