DESIGN FOR INTERNAL QUASI-STATIC PRESSURES FROM PARTIALLY CONFINED EXPLOSIONS

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ABSTRACT

In the early 1980's, results from a series of tests in a partially confined enclosure were used to develop a prediction model for internal gas pressure. The test variables were Charge Weight, W; vent area, A, and frangible panel weight, w. The gas pressure time history was measured in each test. A semi-empirical prediction model for predicting scaled gas pressure impulse, $i_g/W^{1/3}$ was developed using the Peak Gas Pressure, P_g , and a decay rate based on the instantaneous gas pressure, $P_g(t)$, and vent area $A_v(t)$, and the constant scaled parameters: maximum vent area $A_V/V^{2/3}$, W/V ratio, frangible panel weight $w/W^{1/3}$, and shock impulse on the frangible panel, $i_r/W^{1/3}$. A computer program was written to predict the total quasi-static gas pressure impulse. The program is now named *FRANG* and is referenced by the tri-service design manual "Structures to Resist the Effects of Accidental Explosions" (Navy NAVFAC P-397, Army TM5-1300, and Air Force AFM 88-22). The work was presented in at the 21st DDESB Seminar: "Effect of Frangible Panels on Internal Gas Pressures" by J.E.Tancreto and E.S. Helseth. *FRANG* is widely used to calculate the internal gas pressure loads on confinement structures.

The design pressure time loading function that results from the recommendation of the original paper is based on the conservative assumption that the gas pressure rise-time is zero [$P_g(t = 0) = P_g$ (for $A_v = 0$)]. Test and accident data indicate that the current design procedures for containment structures result in very conservative designs. This is due to a combination of safety factors, including those introduced by *FRANG*. In this study, the assumptions used in obtaining the gas pressure design loading function are reviewed. Additional data (from tests and analyses) are used to propose a revised application of *FRANG* results. The impact of those changes on design and predicted structural response is shown.

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INTRODUTION

Prediction Model Development

In the early 1980's, The Naval Civil Engineering Laboratory (now the Naval Facilities Engineering Service Center), conducted a series of tests at TERA, New Mexico Tech, Socorro NM (now the Energetic Materials Research and Testing Center, EMRTC) on partially vented containment structures (see the Reference (1) Test Plan). The intent was to develop a semi-empirical prediction model for the internal gas pressures that develop in a containment structure. The effects of partial venting (variable vent area and variable frangible panel weight) were included in the tests. The test data in Reference (2) were used to develop the semi-empirical prediction model. The resulting prediction model was presented at the 21st DDESB Seminar (Reference (3)). The computer code, now called *FRANG* (Reference (4)), is widely used to calculate the internal gas pressure loads on confinement structures. *FRANG* and *SHOCK* (Reference (5)), which calculates the internal shock loads, are used by the tri-service manual for design of structures for accidental explosions (Reference (6)) to calculate the internal overpressure environment from a confined explosion.

As discussed in this paper, the test variables were limited. However, because of a lack of other test data, the original model has been used by analysts and designers to calculate gas pressure loads for conditions that exceed the test limits. Some of the assumptions that were used to develop the gas pressure prediction model may not be applicable when design factors exceed limits of the tested parameters. Those assumptions include: instantaneous gas pressure rise time to the peak quasi-static pressure, P_g, that would occur in a completely enclosed structure; and venting around the edges of a uniformly displacing frangible panel (as occurred in the tests which used steel sheet metal panels) vs. venting through a brittle frangible panel that breaks and disperses when initially loaded by the shock loads.

Application

Detonations inside a structure produce shock loads and internal gas pressure loads (from the confinement of the gaseous products of the chemical explosion) on the interior surfaces. The long duration gas pressure loads usually control the design of a structure that must contain the effects of a detonation, and significantly increase the debris throw distance from unhardened structures. Structures containing explosives are commonly designed with frangible panels that quickly fail and vent gases to reduce their effect.

The prediction of the gas pressure loading on a containment structure is very important, since it usually controls the structural design and greatly increases the debris hazard from an overloaded structure.

PROBLEM

Experience has shown that the predicted response of structures to internal detonation loads is conservative. Because of normal design factors of safety, a structure will normally not reach the design response in a test or accident. This can be attributed to factors of safety in the design loads and in the methods for predicting response. The response of structures to internal loads, however, seems to be excessively conservative; especially when the vent areas are large (for scaled vent areas, $A/V^{2/3}$, > 1, where A is the vent area and V is the structure Volume). The experience of the Army COE, Huntsville (see Appendix A and Reference (7)) resulted in the DDESB requesting that NFESC review and re-evaluate the gas pressure prediction model, *FRANG*.

SCOPE

This paper reviews the basis for the prediction methods in *FRANG*, compares *FRANG* predictions with test data, compares *FRANG* and test data with "*hydrocode"* (AUTODYNE) predictions, recommends improvements that will significantly affect load and structural response predictions when the vent area is large ($A/V^{2/3}$ is greater than 1), recommends an interim prediction method, and proposes a study and certification tests to improve *FRANG* and the design gas pressure loading function.

Because of budget and time limits this is a preliminary study to identify potential improvements and to recommend a plan to develop and introduce them into *FRANG*.

TESTING

The testing conducted at TERA in the early 1980's is detailed in the Reference (1) test plan and the Reference (2) data report. The test program and results are summarized in the following sections.

Test Setup

The tests used a single test structure with variable roof vent openings and frangible panel weights. Figure 1 shows the test setup. Table 1 shows the conditions for each test. The inside dimensions of the test structure were 7.5 ft x 7.5 ft in plan, and 8 ft. in height. The C4 explosive charge was always centered in the structure. Pressure gauges were located in gauge mounts in the sidewall at ½ height and at ¾ height. Piezoelectric gauges were used to measure shock pressures. Mechanically filtered piezoelectric and piezoresistive gauges were used to measure the long duration gas pressure loads.

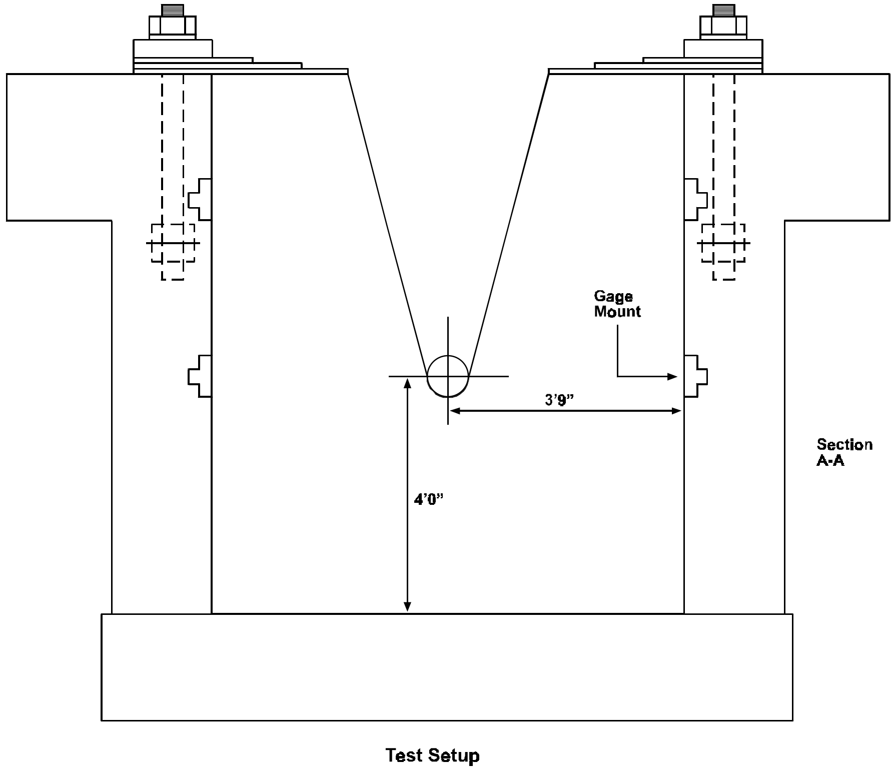

Figure 1. Test Setup

Test Parameters

The test conditions are shown in Table 1. Variables included the explosive weight, W (lb.), the vent area, A (sf), and the frangible panel weight, w (psf). The structure had a constant volume in all tests (450 sf). Therefore, the important charge density parameter, W/V (psf), only varied as the explosive weight varied. The frangible panel was designed to retain its shape, to displace uniformly, and to vent only through the gap created between the panel and the test structure as it accelerated under shock and gas pressure loads. No brittle panels were used that would have allowed venting through the panel. The nominal parameter ranges were:

Explosive weight:	$2 \leq W(\text{lb.}) \leq 27$
Charge Density (psf):	$0.04 \leq W/V \leq 0.06$
Scaled Vent Area :	$0.1 \leq A/V^{2/3} \leq 1$
Scaled Panel Weight (psf/lb$^{1/3}$):	$0 \leq w/W^{1/3} \leq 40$

The key limitations in the test data are a maximum scaled vent area of 1; only three W/V ratios (one test at W/V = 0.06 psf, with the other tests at W/V = 0.0044 & 0.0178); only one tested volume; relatively small scale tests; and a limited number of tests (24).

Table 1. Test Parameters

Test	W (lb)	A (sf)	w (psf)	W/V (psf)	$A/V^{2/3}$	$w/W^{1/3}$ ($psf/lb^{1/3}$)
A	2	56.25	0	0.0044	0.96	0.0
1	2	56.25	2.6	0.0044	0.96	2.1
2	2	56.25	6.35	0.0044	0.96	5.0
3	2	56.25	15.5	0.0044	0.96	12.3
4	2	56.25	52	0.0044	0.96	41.3
5	8	56.25	8.92	0.0178	0.96	4.5
7	2	28.125	0	0.0044	0.48	0.0
8	2	19	0	0.0044	0.32	0.0
9	2	11.6	0	0.0044	0.20	0.0
10	2	6.25	0	0.0044	0.11	0.0
10-2	2	6.25	0	0.0044	0.11	0.0
11	2	28.125	6.35	0.0044	0.48	5.0
12	2	28.125	15.5	0.0044	0.48	12.3
13	2	28.125	52	0.0044	0.48	41.3
14	8	28.125	0	0.0178	0.48	0.0
15	8	28.125	8.92	0.0178	0.48	4.5
16	8	28.125	83	0.0178	0.48	41.5
17	2	11.6	15.5	0.0044	0.20	12.3
18	2	11.6	52	0.0044	0.20	41.3
19	8	11.6	0	0.0178	0.20	0.0
20	8	11.6	83	0.0178	0.20	41.5
23	2	56.25	0	0.0044	0.96	0.0
24	8	56.25	0	0.0178	0.96	0.0
25	27	56.25	0	0.0600	0.96	0.0

Test Results

Gauge data and test results are provided in Reference (2). A summary of the measured peak gas pressures and impulses is provided in Table 2. Gas pressure environment values, P_g, i_g, and t_g, are the average from two gas pressure gage readings.

Peak Gas Pressure. The peak gas pressure, P_g, was determined from the test data by extrapolating a best fit line for P_g (t) to time = 0 (time of detonation). This was assumed to approximate the peak gas pressure that would occur in a completely confined internal detonation. The explosive weight shown in Table 2, W_{TNT}, is the TNT equivalent weight determined as shown in Reference (2) and following the procedure detailed in Reference

(6) for TNT gas pressure equivalency (as a function of W/V, and heats of detonation and combustion).

Gas Pressure Impulse. The gas pressure impulse was determined by integrating the P_g (t) data for the duration of the gas pressure.

Gas Pressure Duration. The gas pressure duration was determined from the best fit approximation of P_g (t).

Table 2. Test Results[1] Summary

Test	W_{TNT} (lb)	P_g (psi)	i_g (psi-ms)	t_g (ms)
A	1.4	28	162	8
1	1.4	23	229	14
2	1.4	24	344	19
3	1.4	31	556	24
4	1.4	30	753	35
5	1.4	105	828	16
7	1.4	25	197	16
8	1.4	25	317	28
9	1.4	29	535	38
10	1.4	28	1045	71
10-2	1.4	32	1170	77
11	1.4	35	435	22
12	1.4	35	630	28
13	1.4	36	873	38
14	5.6	88	711	20
15	5.6	105	1135	23
16	5.6	110	2148	34
17	1.4	35	841	46
18	1.4	35	1179	52
19	5.6	95	1939	52
20	5.6	118	2748	47
23	1.4	27	144	8
24	5.6	95	339	9
25	22.14	215	734	11

[1] P_g, i_g, & t_g are average of readings from two gauges

FRANG

Methodology

FRANG is a semi-empirical numerical analysis program for predicting internal gas pressure from confined explosions. It includes the effects of explosive weight, W, structure volume, V, vent area, A, and frangible panel weight, w. Development of the program is detailed in Reference (3).

Important assumptions include:

(a) The peak gas pressure, P_g, for a completely confined explosion is assumed to be developed instantaneously at the time of the detonation. The effect of the chemistry of the explosive is accounted for with the gas pressure TNT equivalency calculated as detailed in Reference (6).

(b) The decay of the gas pressure at time, t, is the measured decay rate (from tests in References (1) and (2)) as a function of the time-dependent values: $P_g(t)$, and $A(t)/V^{2/3}$, and the constant parameters: W/V, and $w/W^{1/3}$.

(c) The shock loads, calculated from *SHOCK*, are applied as an impulse at time = 0. This establishes the initial velocity of the frangible panel.

Design Gas Pressure Loads

Typical design internal pressure loads are shown in Figure 2. The peak shock pressure, P_r, and shock impulse, i_r, are calculated from the program *SHOCK* or from figures, based on *SHOCK*, in Reference (6). An equivalent triangular load, with $t_r = 2i_r/P_r$ is allowed for calculation of response. Because the actual duration is much longer, this short duration triangular impulse load is conservative for determining response.

FRANG output, P_g and i_g, are used to define an equivalent triangular load function with $t_g = 2i_g/P_g$. The two equivalent triangular load functions are overlapped [$P_r(t)$ is not added to $P_g(t)$]. This is equivalent to delaying the start of the gas pressure until time t_b. However, at t_b the rise time to P_b is instantaneous.

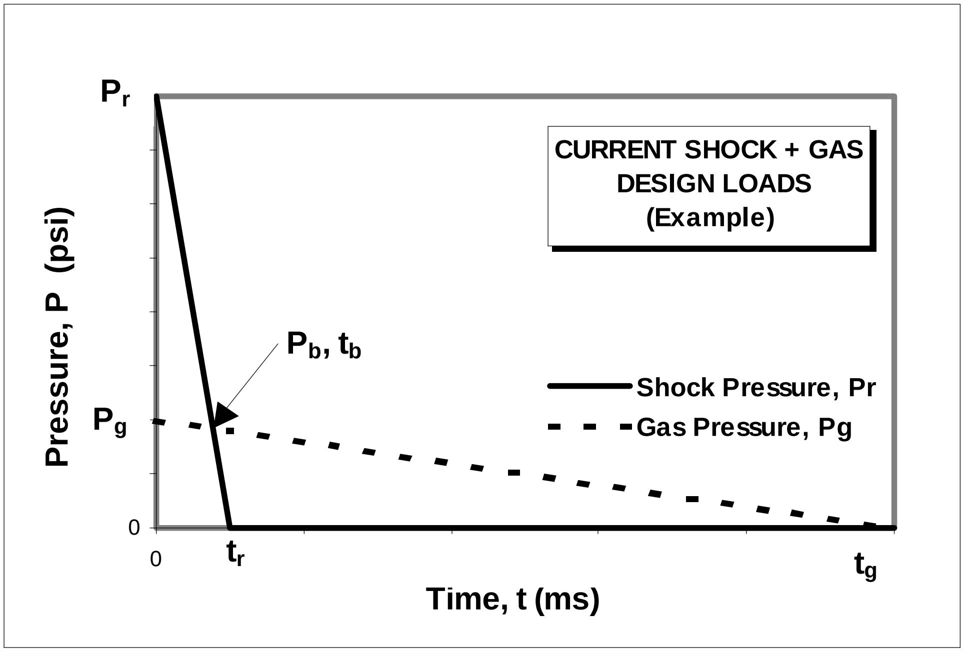

Figure 2. Current Design Internal Pressure Loads (Ref. (6))

FRANG VS. TEST DATA

For this study, *FRANG* was compared to pressure gauge data from Tests 9, 17, 18, 19 & 20 (see Tables 1 and 2 for the test conditions). Typical comparisons of *FRANG* results for $P_g(t)$ with gauge data are shown in Appendix B. The *FRANG* results match the test data very well overall. *FRANG*, however, does not account for the gas pressure rise time. The dashed lines in the plots in Appendix B approximate the gas pressure time history in the pressure gauge data. (Note that although the gas pressure gauges were relatively low frequency, were calibrated to measure the peak gas pressures, and were mechanically filtered, the effect of the direct and reflected shock pressures (although filtered) still overlays the gas pressure data).

For the conditions studied, the actual rise time was in the range of 10 to 15 ms. Also, the peak quasi-static gas pressure in a completely confined condition, Pg, was never developed. Neglecting the rise time, as is now done, does not unreasonably increase the gas impulse for the tested conditions. However, as the scaled vent area increases and the gas pressure duration decreases, the conservatism will increase.

It is also important to note that the shape of the gas pressure function can also have a significant effect on structural response. Therefore, the conservative affects of an instantaneous rise time (vs. the better fit of a ramp loading from zero gas pressure to the peak gas pressure), are as important to the response of the structure as the total impulse.

AUTODYNE VS. TEST DATA AND *FRANG*

Since the scope of this study did not support additional testing, the "*hydrocode*" *AUTODYNE* (*A/D*) was evaluated for its accuracy in predicting $P_g(t)$ and for its application to problems outside the parameter range of the test data used to develop *FRANG*. *A/D* results for Tests 9, 17,18, 19, & 20 were compared to test data. Excellent correlation was found, as long as the effects of combustion were included (necessary when W/V < about 0.10). *A/D* does not calculate the effects of combustion. Therefore, the additional combustion energy must be introduced into the *A/D* model to obtain accurate P_g. When this was done, *A/D* accurately predicted the $P_g(t)$ time-history.

See Fig. 3 for typical results (Test 9) of *A/D* vs. *FRANG*. The *A/D* results include gas and shock pressure. *A/D* results in Figure 3 are shown with and without venting. The *A/D* model with no venting produces a quasi-static pressure time history that reaches an equilibrium P_g of about 45 psi. *FRANG* predicts about 35 psi. The Test 9 *A/D* model (with venting) closely matches the test data (see Appendix B for Test 9 results). The *A/D* results are also compared to *FRANG* output (the uniformly decaying curve from P_g = 35 at t = 0, to P_g = 0 at t = 53) in Figure 3. As was typical for the other comparisons of *A/D* and *FRANG*, *A/D* accurately predicted the test data results and predicted rise times of 10 to 15 ms to a peak gas pressure that was below the confined peak gas pressure, P_g.

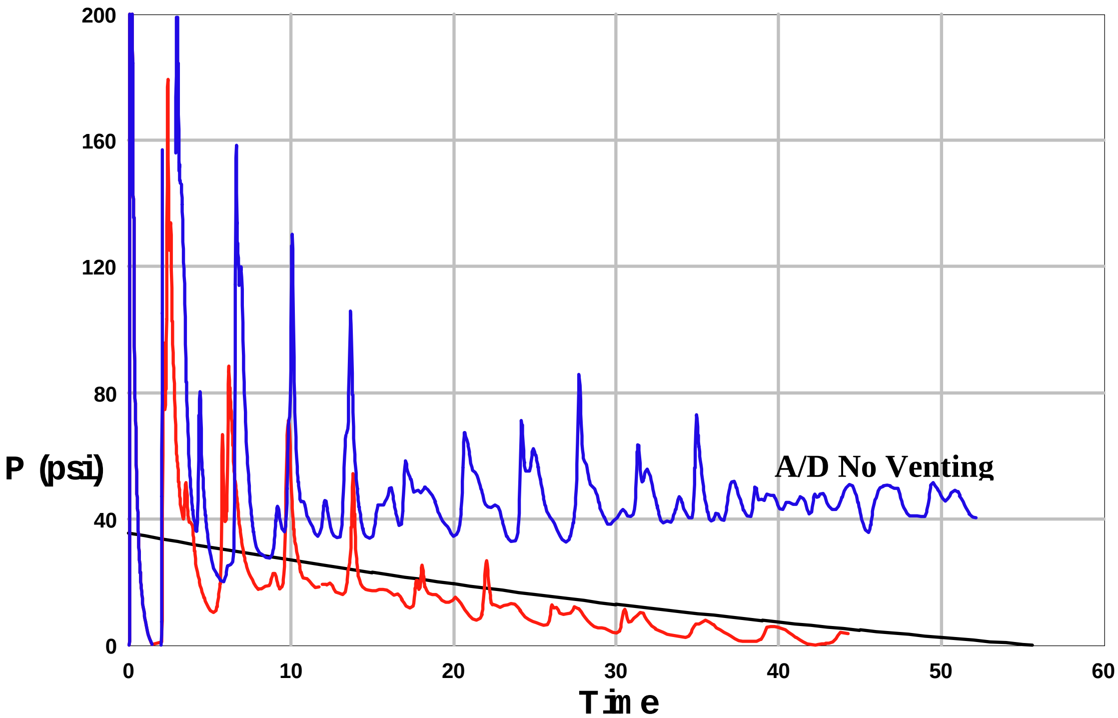

Figure 3. $P_g(t)$: AUTODYNE (*A/D*) and *FRANG* (W = 2 lb., W/V = 0.0044, $A/V^{2/3}$ = 0.20, Test #9)

FINDINGS

Design of structures for internal shock and gas pressure loads is conservative. The design process (reference (6) for blast hardened structures) which includes conservative predictions of both loads and response, are expected to produce reasonably conservative designs. However, experience with containment structures indicates that their design may be excessively conservative.

The conservatism of the gas pressure loads is especially important when $A/^{V2/3} > 1$. At the time *FRANG* was developed, there was not enough information to include the initial rise time of the gas pressure function in the prediction model; data was only available for $A/^{V2/3} < 1$; and no data was (or is) available for brittle frangible panels that break-up during response. For many problems (with large vent areas and short gas pressure durations), the effect of the rise time in reducing the design peak gas pressure and impulse and in changing the shape of the loading function is critical in obtaining reasonable structural response predictions. This study has shown that, if combustion is properly included, *AUTODYNE* may be used to predict the $P_g(t)$ time history. This would allow development of a relationship for the gas pressure rise time, t_b, for use in constructing the gas pressure loading function shown in Figure 4.

RECOMMENDATIONS

A *"hydrocode"*, such as *AUTODYNE*, should be used to develop a relationship for the gas pressure rise time, t_b:

$$t_b = f(W, W/V, A/V^{2.3}, \text{and } w/W^{1/3})$$

Certification tests would be required to validate the relationship for t_b. The calculation of P_g, i_g, t_g, P_r, i_r, and t_r, from *FRANG* and *SHOCK* would be unchanged. However, with a relationship for t_b, the design loads shown in Figure 4 would be used to calculate structural response. The equivalent triangular gas pressure loading in Figure 4 intersects the peak fully confined quasi-static gas pressure P_g at $t = 0$ and,

$$P_b = P_g (1 - t_b/t_g)$$

Until this work is completed, <u>validated</u> "hydrocodes" may be used to determine the gas pressure history for conditions outside the limits of the parameters used to develop *FRANG* and to determine a rise time for use in the load function shown in Figure 4.

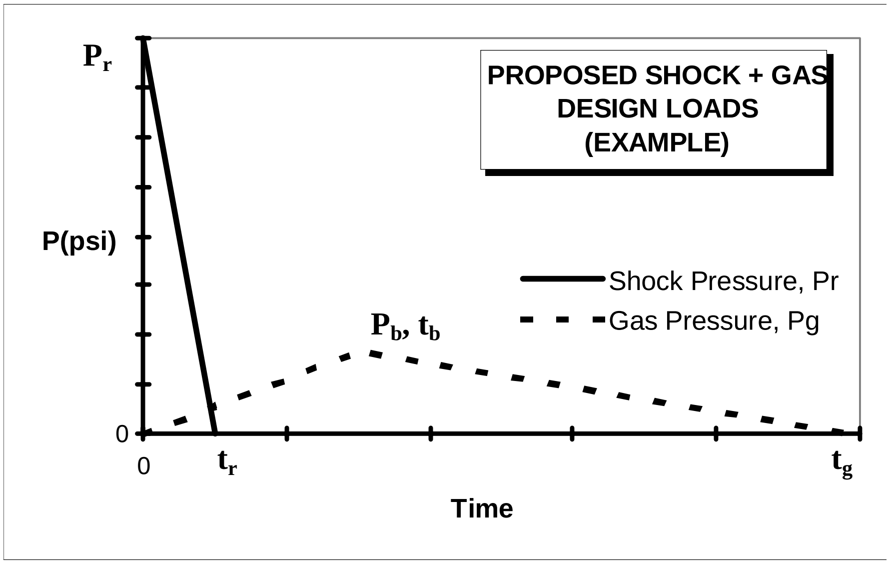

Figure 4. Proposed Design Internal Pressure Loads

REFERENCES

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3. "Effect of Frangible Panels on Internal Gas Pressures" Proceedings of the 21st DDESB Seminar, August 1982. by Tancreto, J.E. and Helseth, E., Naval Civil Engineering Laboratory, Port Hueneme, CA.

4. "*FRANG* Users Manual", Naval Civil Engineering Laboratory, Port Hueneme, CA, Jan 1988.

5. "*SHOCK* Users Manual", Naval Civil Engineering Laboratory, Port Hueneme, CA, May 1989.

6. "Structures to Resist the Effects of Accidental Explosions", Army TM 5-1300, Navy NAVFAC P-397, and Air Force AFR 99-22, November 1990.

7. "Assessment of Analytical Methods Used to Predict the Structural Response of 12" Concrete Substantial Dividing Walls to Blast Loading", Proceedings of 28th DDESB Seminar, August 1998, by David Begosian, Karagozian & Case Structural Engineers, Glendale, CA and William H. Zehrt, Jr., U.S. Army Engineering & Support Center, Huntsville, AL

APPENDIX A:

DESIGN AND ACCIDENT EXPERIENCE

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In recent years, much time and effort have been expended on the evaluation of explosive limits for 12-inch concrete substantial dividing walls (SDWs). Large numbers of these walls exist throughout the munitions production, operations, maintenance, and storage infrastructure. SDWs are used to subdivide explosives for quantity-distance definition and to provide operational shields for personnel. Current Army and Air Force safety regulations assume that 12-inch concrete SDWs will protect personnel from the detonation of up to 15 pounds of Hazard Class 1.1 explosives.

In the DoD Ammunition and Explosives Safety Standards, DoD 6055.9-STD, Army Technical Manual 5-1300 (NAVFAC P-397, AFR 88-22) is referenced for the design of suitable barriers (such as dividing walls) to provide the required protection from blast effects. Using TM 5-1300, explosive limits for 12-inch concrete SDWs protecting personnel in an adjacent acceptor bay are typically less than 2 pounds net explosive weight (NEW).

In an attempt to resolve the discrepancy between regulatory and analytical explosive limits, the U. S. Army Industrial Operations Command (IOC), Safety Division tasked the U. S. Army Engineering and Support Center, Huntsville (CEHNC), in FY 96 and FY 97, to evaluate the blast resistance of 12-inch concrete SDWs. These taskings were follow-on work to previous studies of 12-inch concrete SDWs funded by the Department of Defense Explosives Safety Board (DDESB) and the U. S. Army Technical Center for Explosives Safety (USATCES).

Under the DDESB and USATCES studies, the CEHNC evaluated the 425 pound NEW non-propagation limit for 12-inch concrete SDWs. In FY 94, Karagozian & Case Consulting Engineers (K&C), Glendale, CA, performed 14 advanced finite element analyses of typical 12-inch concrete SDWs under blast loading. Using a modified version of the DYNA3D computer code, K&C first validated wall models against data from two explosive tests. After successfully validating the code, K&C then analyzed the response of two typical 12-inch SDWs to the detonation of bare charges ranging in NEW from 50 to 425 lb.

Under the IOC tasking, the CEHNC first evaluated potential sites for explosive testing. In FY 96, the CEHNC identified two buildings at Sunflower Army Ammunition Plant for the tests. Both buildings contained numerous 12-inch concrete SDWs, and both were slated for demolition. At the time, it was anticipated that funding would be provided for tests in one of the buildings. Follow-on DYNA3D analyses of typical SDWs also were planned which would use the explosive test results for validation. Unfortunately, due to budget constraints, the IOC could fund only the DYNA3D analyses; the planned FY 97 explosive tests were canceled.

Prior to initiation of the DYNA3D analyses by K&C, the CEHNC performed an extensive literature search of accident reports in the DDESB and USATCES libraries. Through this effort, the CEHNC identified two explosive accidents for code validation. In the first accident, approximately 8 pounds NEW detonated. Due to poor venting, the most severely damaged SDW suffered significant damage, but it remained standing. In the second accident, approximately 16 pounds NEW detonated. In this accident, the cubicle was well vented and the 12-inch concrete SDWs suffered only minor damage. Unfortunately, for both cases, the DYNA3D models predicted complete destruction of the walls. For personnel protection (2 degree support rotation per Army TM 5-1300), the DYNA3D model for each wall estimated the explosive limit at less than 2 pounds NEW.

As noted in the final K&C report, the DYNA3D models appear to significantly overstate the response of 12-inch concrete SDWs to blast loading. As a result, the models yield a very conservative, general explosive limit of less than 2 pounds NEW for typical 12 inch SDWs supported on 2 sides (floor and rear wall). The DDESB and USATCES accident data do not support this limit. The most likely sources of this disparity are the assumption that no additional support is provided by the frangible wall and/or roof in acceptor cubicles and the very conservative gas pressure loading applied to the SDWs. Gas pressure loading curves were calculated in accordance with Army TM 5-1300 using the *FRANG* computer code. Assumptions made by *FRANG* include: an instantaneous rise time to peak gas pressures; the monolithic motion of frangible panel(s); and the use of a constant gas pressure loading which is placed on the entire wall surface at any given time. As a result of these assumptions, a SDW's response depends primarily on the peak gas pressure placed upon it. Unless the wall's ultimate resistance approaches this peak pressure, it will fail.

Due to the continued disparity between analytically predicted and actual wall responses, the CEHNC performed an additional review of the DDESB and USATCES accident data. The review concentrated on 20 accidents involving low charge weights and 12-inch concrete SDWs or similar construction. Major conclusions were:

(1) The lowest charge weight at which a 12-inch concrete SDW suffered significant damage from a single explosive detonation was approximately 8 pounds NEW. Consequently, as long as a cubicle contains at least one lightweight vent surface (wall or roof), an interim explosive limit of 6 pounds NEW appears reasonable for these walls. Explosive testing and additional analysis (including validation of the *FRANG* code) are strongly recommended to validate this limit.

(2) The damage to 12-inch concrete SDWs is significantly enhanced in slowly venting cubicles. These cubicles typically use "heavy" vent surfaces, such as tile walls or

tongue-in-groove wood roofing systems; vent into a corridor; and/or have vent surfaces which must travel some distance before clearing the 12-inch concrete side walls.

(3) The likelihood of personnel injury does not depend solely on the response of the SDW(s). The injury potential in areas near a blast cubicle is significantly enhanced when: the cubicles are in a horse-stall type arrangement; the cubicles share a common roof; the roof over adjacent areas is particularly light (such as transite); the blast cubicle vents into a corridor or another cubicle; and/or the adjacent areas include glass windows. In these situations, a site specific analysis should be performed to assess the protection afforded personnel. In lieu of an analysis, the application of a K24 separation distance will likely provide a reasonable margin of safety.

APPENDIX B:

$P_g(t)$: *FRANG* VS. TEST DATA

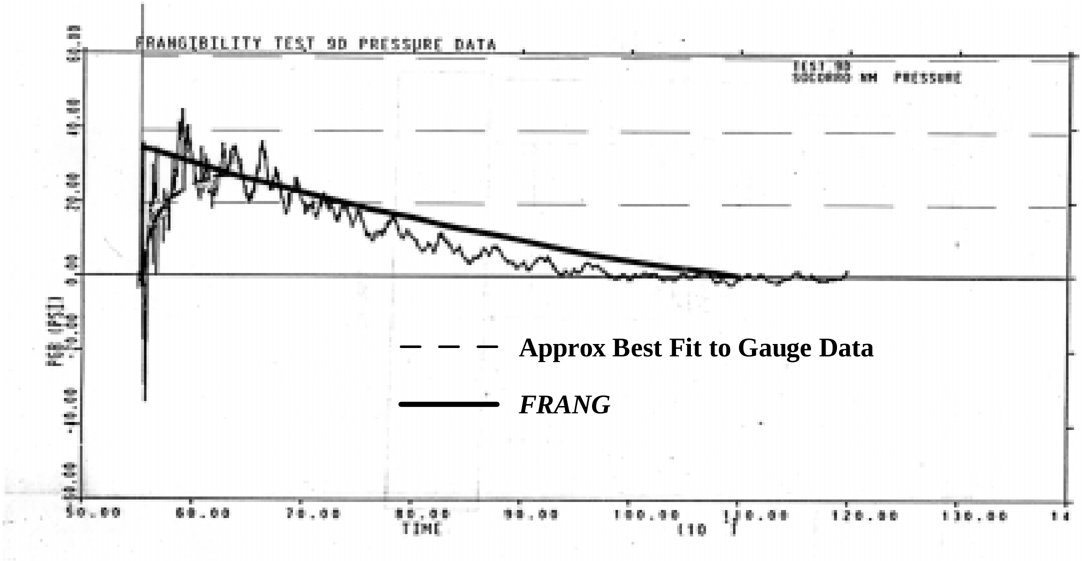

Figure B-1. Test 9: Gas Pressure Gauge Data vs. *FRANG* Results
$W/V = 0.0044$, $A/V^{2/3} = 0.20$, $w/W^{1/3} = 0$

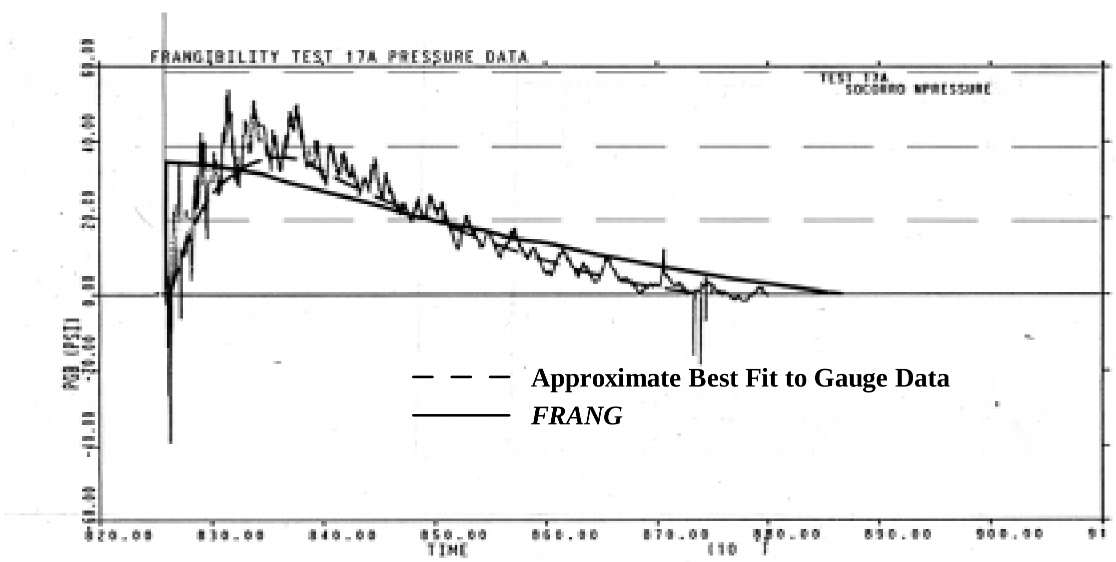

Figure B-2. Test 17: Gas Pressure Gauge Data vs. *FRANG* Results
$W/V = 0.0044$, $A/V^{2/3} = 0.20$, $w/W^{1/3} = 12.3$

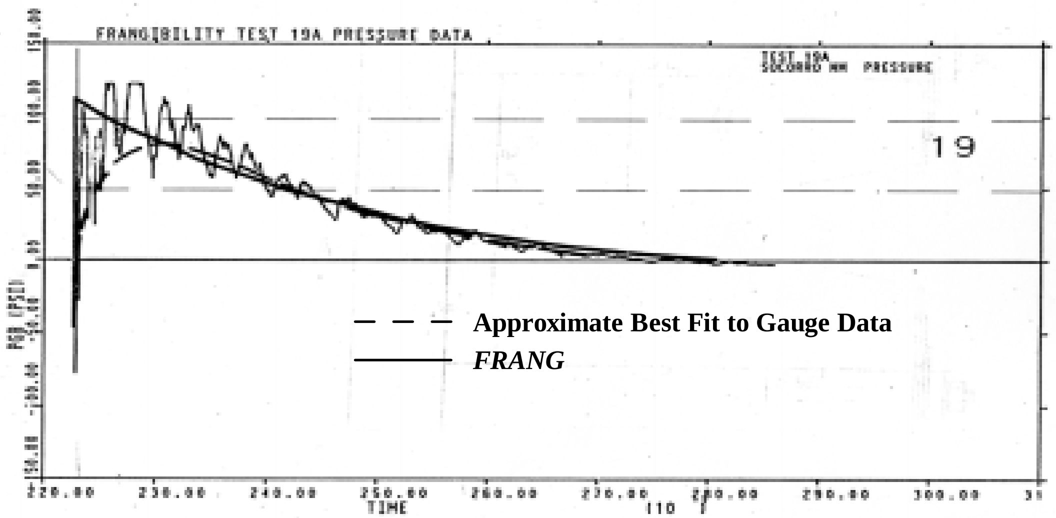

Figure B-3. Test 19: Gas Pressure Gauge Data vs. *FRANG* Results
W/V = 0.0178, $A/V^{2/3}$ = 0.20, $w/W^{1/3}$ = 0