Improved Method to Calculate Gas Pressure Histories from Confined Detonations with Venting

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Abstract

The UFC 3-340-02 has a simplified method to the calculate the gas or quasistatic pressure history from an internal detonation in a room with venting that has been programmed into the FRANG code. However, comparisons to measured gas pressures from previous test series and an investigation of an accidental detonation indicate that gas pressure histories calculated with FRANG can be quite conservative, especially when the explosion room has large areas of lightweight vent panels.

This observed conservatism was the catalyst for a recent effort funded by the Department of Defense (DoD) Explosive Safety Board (DDESB) to develop an improved fast-running method to calculate the gas pressure history in a detonation room with venting. This included a large testing program where gas pressure histories were measured in test rooms with lightweight vent panels covering one or two full surfaces of the room. The Improved Methodology that was developed is a time-stepping method that uses the ideal gas law to calculate the gas pressure at each time-step. It is based on thermodynamic principles and test data. The methodology uses an empirical approach to calculate the rate of heat dissipation causing temperature increase in the explosion room and accounts for the beneficial effects of mass flow out of the room and room volume expansion when the user inputs vent panels in the exterior surfaces of the explosion room. An empirical approach is also used to account for increased vent area from breakup of vent panels caused by close-in shock pressure loading.

This paper discusses the Improved Methodology and shows comparisons between calculated and measured gas pressure histories. It also shows comparisons between gas pressures calculated with the Improved Methodology and FRANG.

Introduction

UFC 3-340-02 [1] has a simplified fast-running method to calculate the gas, or quasistatic pressure in the explosion room from a detonation that is based primarily on an empirical approach [2]. This method is programmed into the FRANG computer program [3]. Comparisons of gas pressures measured in previous testing programs to gas pressures calculated using fast running methods in the FRANG and BlastX codes [4] show that these existing fast-running methods can be very conservative for detonations in rooms with significant vent areas. It was noted that the existing test data with measured gas pressure included very limited data from test rooms with lower loading densities (i.e., ratios of charge weight to volume) less than 0.02 lb/ft^3 and large exterior wall areas covered with lightweight vent panels (i.e., at least one full surface of the room). This is significant because these cases with limited test data represent many DoD operating bays. Also, an analysis of an accidental explosion by Zehrt and Bogosian [5] concluded that the gas pressure calculated with FRANG most probably accounted for a large overcalculation of predicted damage to the walls of the detonation room compared to the observed damage.

Starting in 2019, the DoD Explosives Safety Board (DDESB) sponsored work to develop an improved fast-running methodology to calculate the gas pressure in the explosion room from a detonation [6]. This included an extensive testing program (DDESB tests) [7] to measure gas pressures from internal detonations that focused on test rooms with low loading densities and large areas of lightweight vent panels. The Improved Methodology was developed and validated based in large part on this test data [6]. Only an overview of the development and validation is presented in this paper. A detailed explanation is provided elsewhere [6].

Methodology

The Improved Methodology calculates the gas pressure in the detonation room at each time step using the ideal gas law [6]. The temperature rise and the moles of product gases released into the room volume are used to calculate the gas pressure in the explosion room at each time step. The method uses basic thermodynamic and thermochemical relationships to calculate the temperature rise caused by heat released by the detonation and afterburning of reactive product gases.

An important assumption of the methodology is that the heat from both the detonation and from afterburning each dissipate into the room volume to cause temperature increase over separate “rise times” based on scaled empirical relationships. The failure and outward movement of lightweight vent panels from initial shock pressure loading and subsequent mass flow of pressurized gas out of the room volume can begin during these rise times, reducing the peak gas pressure that would otherwise occur in a fully confined volume.

This contrasts with the assumption in current fast-running methods to calculate gas pressure that the heat from detonation and afterburning based on available oxygen in the explosion room cause a near immediate rise in gas pressure to a peak pressure equal, or nearly equal, to that occurring in a fully confined volume. This gas pressure is then reduced by the flow of pressurized gas out of the room volume to the atmosphere through available vent areas. In cases with large areas of lightweight vent panels equal to one or more surfaces of the room, the reduction in the peak calculated gas pressure using the improved method compared to current fast-running methods is very significant, which also causes a corresponding reduction in the calculated impulse.

An overall flowchart for the Improved Methodology without venting (i.e., for full confinement) is shown in Figure 1 (see the Appendix). Equations in this flowchart iare discussed first, followed by equations in the methodology that account for venting.

The heat energies from detonation and afterburning dissipate into the volume of the explosion room to cause temperature change as a function of time per the empirical equations in (1. These equations have a form similar to that proposed by Hager et al.[8] to calculate a rise time for the gas pressure from a detonation, except with an additional term and with different values for constants. $E_{AfbVent}$ in (1 is the heat contained within unburnt product gases that are vented before they can dissipate into the explosion room volume. The factors t_{ra} and t_{rd} in (1 are calculated as shown in (2. The term t_{rd} is the rise time for dissipation of heat energy from the detonation into the room volume, whereas t_{ra} is a factor in the exponential term that affects that rise time for dissipation of heat energy from afterburning into the volume. The values E'_{det} and E'_{afb} in (1 are the total heats released by the detonation and afterburning, respectively, equal to the charge weight multiplied by the heats of detonation and afterburning. For larger ratios of charge weight to room volume, E'_{afb} is modified based on the available oxygen in the explosion room. A more detailed discussion is provided elsewhere [6].

$$E_{\text{det}}(t) = E'_{det}\left[1 - e^{-t\left(\frac{K_{gd}}{t_{rd}}\right)}\left(1 - \frac{t}{t_{rd}}\right)\right]$$

$$E_{\text{afb}}(t) = \left(E'_{\text{afb}} - E_{AfbVent}(t)\right)\left[1 - e^{-t\left(\frac{K_{ga}}{t_{ra}}\right)}\right] \tag{1}$$

Where:

$E_{det}(t)$ = energy released by detonation dissipated into full confined volume at time t

$E_{afb}(t)$ = energy from afterburning dissipated into full confined volume at time t

E'_{det} = total energy released by detonation based on heat of detonation for explosive of interest and charge weight

E'_{afb} = total energy from afterburning in a confined volume based on heat of combustion for explosive of interest, charge weight, and available oxygen in the explosion room

K_{gd} = empirical factor for dissipation of detonation energy = 2

K_{ga} = empirical factor for dissipation of afterburning energy = 1.5

t_{rd} = rise time for full dissipation of E'_{det} (see (2)

t_{ra} = rise time constant for dissipation of E'_{afb} (see (2)

$E_{AfbVent}(t)$ = energy of detonation products vented from volume through vent areas that would otherwise contribute to afterburning = 0 for full confinement

t = time between zero and rise time for dissipation of each energy type (t_{rd} or t_{ra})

$$t_{rd} = K_{tr}\frac{L_{max}}{C_s} \qquad t_{ra} = t_{rd}\left(\frac{0.25E'_{afb} + E'_{det}}{E'_{det}}\right)$$

$$K_{tr} = \left(\frac{E'_{det}}{E_{amb}}\right)^{\frac{1}{3}} \qquad C_s = \sqrt{\gamma(\gamma-1)I_{det}} \qquad I_{det} = \frac{(E_{amb} + E'_{det})}{(M_{air} + M_c)} \qquad E_{amb} = \frac{V_o P_o}{\gamma - 1} \tag{2}$$

Where:

t_{rd} = rise time for full dissipation of E'_{det}

t_{ra} = rise time coefficient for full dissipation of E'_{afb}

L_{max} = maximum dimension of explosion room

C_s = average shock velocity in confined volume

γ = ratio of specific heats for air (1.4)

I_{det} = energy from detonation of explosive per unit mass in confined volume

E_{amb} = energy of air in explosion room at ambient conditions (prior to detonation)

E'_{det} = total energy released by detonation

E'_{afb} = total energy from afterburning in available oxygen of explosion room

M_{air} = mass of air in explosion room at ambient conditions (prior to detonation)

M_c = mass of explosive charge

P_o = ambient pressure in explosion roo

Figure 2 shows ratios of dissipated heat into the room volume to cause a temperature change compared to total heats from detonation and afterburning in a fully confined volume (i.e., no venting) based on (1 and (2. The figure is for a case where the room volume has sufficient oxygen for full afterburning of TNT explosive. Note that time is scaled vs. t_{rd} so that the dissipated heat ratio for the detonation heat energy must equal 1.0 at a scaled time of 1.0. The calculated heat from the detonation dissipates at a high initial rate that slows as the dissipated heat ratio nears 1.0. The same observation is true, although to a lesser extent, for the dissipated heat ratio from afterburning.

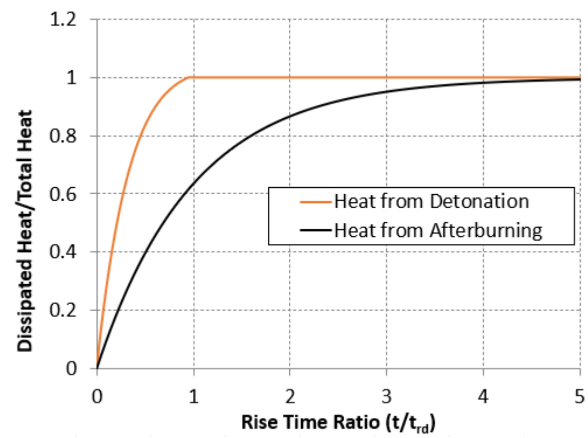


Figure 2. Ratio of Dissipated Heat to Total Heat from Detonation and Afterburning of TNT into a Confined Volume vs Scaled Time

The temperature in the explosion room is calculated at each time step with (3 based on the net energy increase during the time step (i.e., energy dissipated into the volume from the detonation and afterburning per (1 minus heat loss in vented gas), the moles of gas in the room, and the specific heat at constant volume of the gas in the room at the time step. At time-steps where failed vent panels have moved away from the explosion room to increase the "effective" room volume, as discussed later, the temperature reduction caused by this adiabatic volume increase is also included in (3. The moles of gas in (3 are conservatively based at time zero on the product gases from detonation and the maximum possible afterburning given the ratio of charge weight to room volume and then decrease with time based on venting (rather than increasing with time similar to the dissipated heat).

The specific heat in (3 is a weighted average value, based on the mole ratios of the gases in the explosion room and the specific heats calculated for each gas species at the current temperature. The relationships between specific heat and temperature for each gas species are based on curves from Cooper [9]. This approach to determine temperature in the explosion room at each time-step is based on a similar approach from Edri et al. [10]. This part of the methodology is simplified for non-TNT explosives into an "equivalent TNT" approach by calculating the product gases from an equal weight of TNT rather than the actual product gases from the wide array of all possible non-TNT explosives. This simplification is consistent with the general approach in Chapter 2 of UFC 3-340-02 of using an equivalent TNT weight to calculate gas pressure. (3 also has several less important parameters that are explained elsewhere [6].

$$T(t) = T(t-1)\left(\frac{V_{eff}(t-1)}{V_{eff}(t)}\right)^{\gamma(t)-1} + \Delta T$$

$$\text{where } \Delta T = \frac{\Delta E_{net}(t)}{n(t)C_v(T)}$$

$$\Delta E_{net}(t) = \Delta E_{det}(t)K_{LF}(t) + \Delta E_{afb}(t) - \Delta E_{loss}(t-1) \quad (3)$$

where:

- $T(t)$ = average absolute temperature in confined volume
- $V_{eff}(t)$ =effective confined volume accounting for any volume increase in the confined volume caused by vent panel movement = initial volume (V_o) for full confinement (i.e., no venting or vent panels)
- $\Delta E_{net}(t)$ = net energy change in confined volume during time-step
- $\Delta E_{det}(t)$ = detonation energy dissipated into volume during time-step
- $\Delta E_{afb}(t)$ = afterburning energy dissipated into volume during time-step = 0 if scaled vent area
- $\Delta E_{loss}(t-1)$= heat loss from venting during previous time-step = 0 for full confinement
- $n(t)$ = moles of gas in confined volume
- $C_v(T)$ = specific heat at constant volume for confined volume based on temperature at previous time step
- $\gamma(t)$ = specific heat at time t, which is a function of T(t)
- $K_{LF}(t)$ = energy loss factor for uncovered vent areas with high loading density = 1.0 for full confinement

Figure 3 and Figure 4 (see Appendix) show that gas pressure histories measured in fully confined volumes match histories calculated with the Improved Methodology well over the rise times for the gas pressures [6]. These comparisons help to validate (1, (2, and (3, which calculate the dissipation of heat from detonation and afterburning into the full volume of the explosion room and corresponding temperature rise, as well as the use of the ideal gas law to calculate the gas pressure in the time-stepping method. Additional measured gas pressure histories in fully confined tests would be very helpful to validate these equations over a larger range of parameters.

Appendix Figure 5 shows a flowchart of the Improved Methodology for the more general case of calculating the gas pressure history from a confined volume with venting, including venting through user defined exterior surface areas covered with panels that are failed at a very early time by shock pressure loads (i.e., "vent panels"). The methodology for a confined explosion from Appendix Figure 1 is shown in Appendix Figure 5 within a red rectangle where additional terms caused by venting are highlighted in yellow. The mass of gas flow through available vent areas is calculated at each time step using the equation for isentropic gas flow through a nozzle, accounting for choked flow when applicable.

The vent area for pressurized gas flow out of the explosion room created by failed vent panels is calculated in two ways. First, a perimeter vent area is calculated at each time-step equal to the user defined perimeter of each "group" of adjacent vent panels that are input together as a collective large vent panel multiplied by the outward movement of the panel away from the explosion room accounting for any recessed depth of the panel relative to the surrounding walls and roof. The vent panel has an initial calculated velocity based on the user defined impulse from the internal applied shock pressure. The velocity is increased at each time step based on the calculated gas pressure and areal panel mass assuming the panel is a rigid plate. This perimeter vent area is calculated in the same manner as in the FRANG code. The outward distance of the panel movement away from the explosion room causing the perimeter vent area to equal the input area of the panels is designated as H_{crit} in the methodology.

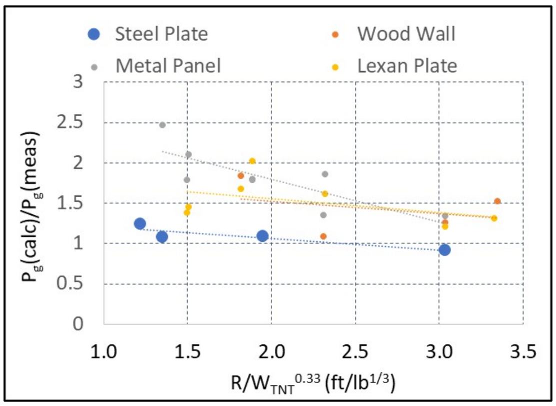
Secondly, additional vent area is calculated through pieces of lightweight vent panels that are fragmented by the applied shock pressure. This vent area increases as the panels move away from the explosion room relative to H_{crit} using an empirical relationship based primarily on the scaled standoff distance between the explosive charge and center of the vent panel. Vent panels are considered fragmented in the methodology if they have an areal weight less than 6 psf and the explosive is at a scaled standoff distance less than 3 $ft/lb^{1/3}$. This additional vent area often exceeds the perimeter vent area for cases where the vent panel is considered fragmented.

The methodology also accounts for an increase in the explosion room volume as failed vent panels move away from the explosion room. The effect of the volume expansion on the gas pressure is not straightforward since the vent panels gradually become more "disengaged" from the explosion room as they move further away. The Improved Methodology increases the room volume as vent panels move away from the explosion room, where the additional volume from each incremental panel movement has less effect on the gas pressure, until the vent panel is considered "separated" from the room volume. This occurs when the time step when the total calculated vent area associated with the panel movement is equal to the area of a panel. The explosion room volume reverts to a volume that does not include any expansion based on the vent panel movement at this time step in a manner that does not affect the density of gas or temperature in the explosion room.

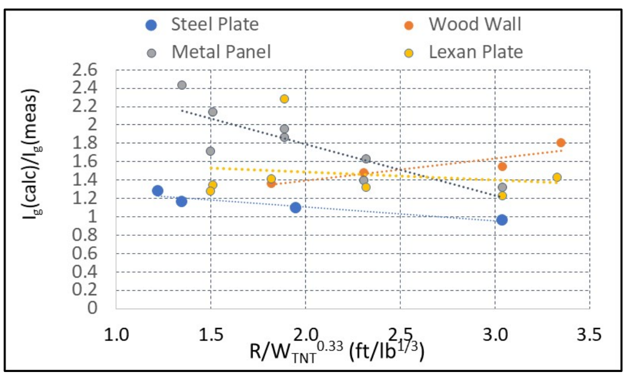
The gradual reduction in the effect of the extra volume created by vent panel movement is accounted for with an empirical factor. It was noted that internal blast gages very near vent panels in gas pressure tests sponsored by DDESB [7] measured less gas impulse than the average impulse measured at all the other gages further from the vent panels [6]. Figure 6 (see Appendix) shows that the blast gage nearest the vent panel in this test program had a gas impulse approximately 75% of the average impulses measured at the other gages further away from the vent panel in the same test, on average over the applicable tests. This observation was used to develop an empirical parameter $K_{rp}(t)$, which is calculated in Equation 4 (see Appendix).

K_{rp} reduces the gas pressure within the additional volume created by vent panel movement compared to the calculated gas pressure in the main volume of the explosion room, where the reduced gas pressure is used to calcuate venting of gas out the open vent area associated with the vent panel at each time step. K_{rp} also reduces the incremental volume from vent panel movement that is included at the time-step in the "effective" volume used in the ideal gas law to calculate the gas pressure in the explosion room. Thus, K_{rp} acts in the methodology to limit the reduction in the calculated gas pressure caused by vent panel movement away from the explosion room. As shown in Appendix Equation 4, $K_{rp}(t)$, reduces gradually from 1.0 to 0.5 (with an average value of 0.75) as a vent panel moves further from the explosion room relative to H_{crit} that was defined previously.

As stated previously, the DDESB funded a large test program where gas pressures from internal detonations were measured in one-half scale test rooms with vent panels on one or two surfaces of the room [7]. The testing also included fully confined test rooms where the gas pressure histories shown in Appendix Figure 4 were measured. Figure 7 shows ratios of peak gas pressure and impulse calculated with the Improved Methodology to measured values in these tests with three types of lightweight vent panels covering one surface and the test room and all tests with heavy steel vent panels (i.e., 0.25-inch thick) covering one or two full surfaces. These tests had loading densities varying from 0.003 lb/ft^3 to 0.022 lb/ft^3. The plots in Figure 7 show that the gas pressure is calculated conservatively for almost all cases. It is calculated significantly more conservatively for the tests with lightweight vent panels, which were fractured by the shock wave (i.e., become debris), compared to tests with steel plate vent panels that did not fracture. Similar comparisons plots to Figure 7 for tests from the DDESB test series where two full surfacs of the test rooms were covered with lightweight panels show much more conservatism for the Improved Methodology than that in Figure 7 [6]. Much lower magnitude gas pressure was measured in these tests compared to tests with lightweight panels only over one surface that was sometimes difficult to discern with the measuring system that was used. The maximum velocities of the vent panels from the DDESB tests were also calculated with the Improved Methodology and they were within 5% of the measured velocities, on the average [6].



a) Ratios of Calculated to Measured Peak Gas Pressure



b) Ratios of Calculated to Measured Gas Pressure Impulse

Figure 7. Ratios of Calculated to Measured Peak Gas Pressure and Impulse for Internal Detonation Tests Primarily with Large Vent Panel Over One Surface

Figure 8 shows ratios of total calculated impulse (i.e., from the shock pressure plus gas pressure) to total measured impulse for the same DDESB tests with lightweight vent panels on one surface as Figure 7. The total measured impulse is the average impulse measured on all gages of the test room in the confined tests. The total calculated impulse is the average impulse from the shock pressure calculated on the gages in the backwall of the test rooms (which were always very near the average impulse of the gages in the floor of the test structure) with the SHOCK V2 code [17] plus the impulse of the gas pressure history calculated for each test using the Improved Methodology. The average value of the ratio of calculated to measured total impulse in Figure 8 is 1.04. From this perspective, the calculated gas impulse is less conservative than shown in Figure 7b, in part due to a small amount of non-conservatism in the calculated shock impulses [6].

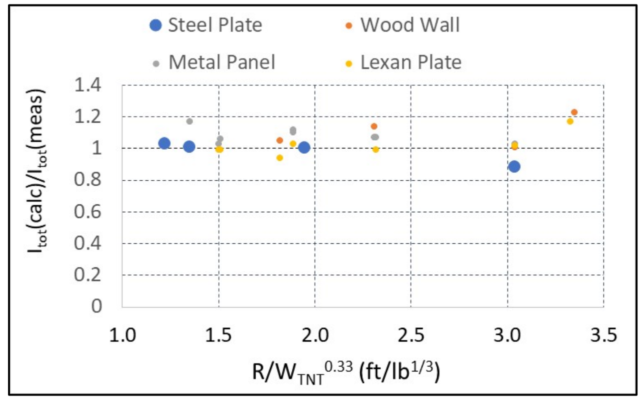
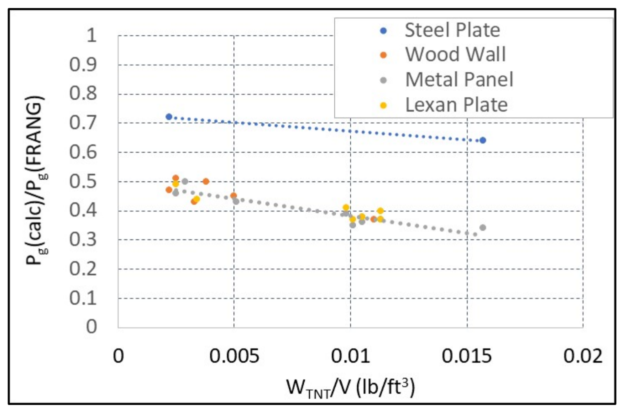
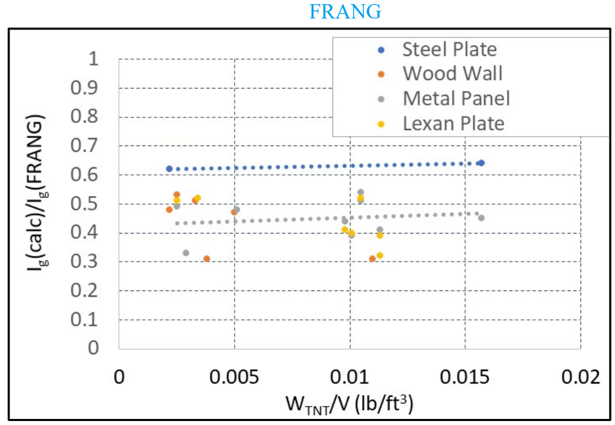


Figure 8. Ratios of Calculated to Measured Total Impulse for Internal Detonation Tests Primarily with Large Vent Panel Over One Surface

Figure 9 shows a comparison of peak gas pressure and impulse calculated with the Improved Method and with the FRANG code for the tests in Figure 7. These comparisons show that the FRANG code is conservative by approximately a factor of two compared to the Improved Method for the tests with lightweight vent panels on one surface of the test structure. A slightly larger level of conservatism is shown by similar plots for the internal detonation tests where two surfaces were covered with lightweight vent panels [6].The Improved Methodology compares more closely to FRANG in Figure 9 for the tests with the heavier steel vent panels that have slower outward movement and are not fractured by the applied shock pressures. Both methods calculate similar gas pressure for fully confined explosion rooms.



a) Ratios of Calculated Peak Gas Pressure with Improved Method and FRANG



b) Ratios of Calculated Gas Pressure Impulse with Improved Method and FRANG

Figure 9. Ratios of Peak Gas Pressure and Impulse Calculated with Improved Method to FRANG Code for Internal Detonation Tests with Large Vent Panel Covering One Surface

Comparisons were also made between gas pressure calculated with the Improved Methodology and measured gas pressure in several previous test programs. These testing programs primarily used special "quasistatic pressure" gages for measuring gas pressure. Figure 10 shows the comparisons for one of these additional test programs, the MTC (Missile Test Cell) test series by NCEL [15]. These tests had loading densities varying from 0.004 lb/ft^3 to 0.037 lb/ft^3 and heavy vent panels with areal weights from 30 lb/ft^2 to 134 lb/ft^2 that covered less than one surface of the test room.

Figure 11 shows a typical gas pressure history from the MTC tests compared to the gas pressure calculated for this test with the Improved Methodology. The short duration, early time pressure spikes in Figure 11 are typical of gas pressure histories measured with the quasistatic pressure gages, indicating that these pressure histories include some early time contribution from applied shock pressure. The dashed red line in Figure 11 shows an example of how peak measured gas pressures were estimated from the measured gas pressure histories for these tests in order to determine peak gas pressure ratios in Figure 10. The impulse ratios in Figure 10 are based on the full measured gas impulses in the tests including impulse from early time high frequency pressure pulses (i.e., shock pressure pulses). Comparisons of the peak gas pressure and impulse calculated with the Improved Methodology to those measured in the TERA test programs by NCEL [18] are similar to Figure 10 except they show more conservatism in the calculated gas pressure histories [6].

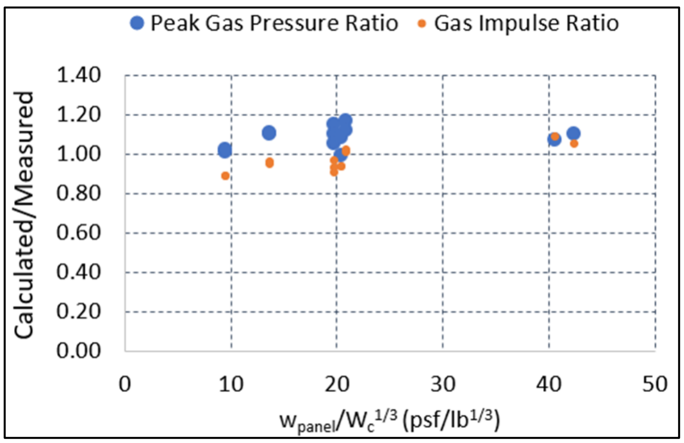


Figure 10. Calculated Peak Gas Pressure and Impulse Compared to Measured Values in MTC Tests with Covered Vent Areas

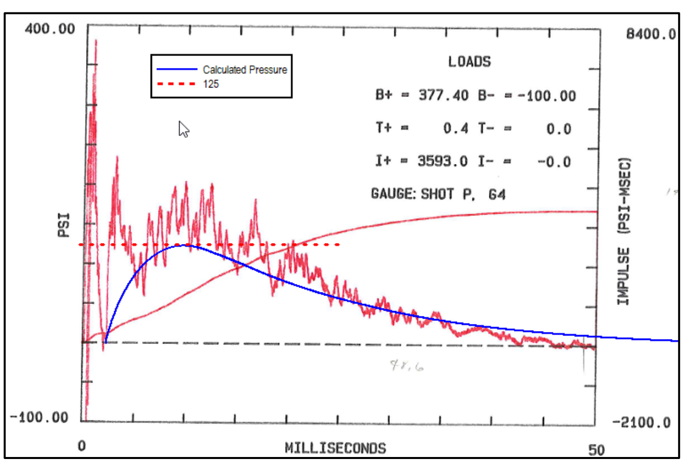


Figure 11. Comparison of Calculated Gas Pressure History to Measured Pressure History for MTC Test 11

Figure 12 shows comparisons between peak gas pressure and impulse calculated with the Improved Methodology and measured gas pressure in several previous test programs with uncovered vent areas [6]. Most of these tests had relatively small vent areas where the scaled vent areas (i.e., vent area divided confined volume to the 2/3 power) was less than 0.2. The measured quasistatic pressure histories in these tests included early time contrbutions from high frequency shock pressure pulses similar to that shown in Figure 11. In total, gas pressures calculated with the Improved Methodology were compared to measured gas pressure histories from approximately 100 tests [6].

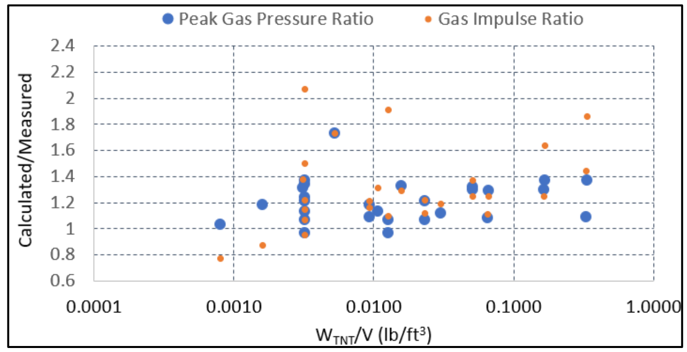


Figure 12. Calculated Peak Gas Pressure and Impulse Compared to Measured Values in Test Series with Uncovered Vent Areas

Some of the DDESB tests had a heavy steel plate one "rigid" side of the test structure used for the DDESB tests that deflected elastically from the applied blast pressure in these tests [7]. The maximum deflection history of the steel plates were meausred in these tests. The steel plate was attached to the test structure with gusseted steel angles that caused fixed supports along three sides. The dynamic responses of the steel plates in these tests were calculated with single-degree-of-freedom (SDOF) [17] analyses using; 1) the input average of the measured blast loads on the opposite face of the cubic test structure and, 2) using an input blast load equal to the shock pressure plus gas pressure histories calculated for each applicable test with the SHOCK V2 program [16] and the Improved Methodology, respectively. The total calculated gas pressure history consisted of the right triangular shock pressure history followed by the calculated gas pressure history. The opposite face of the test structure that had blast gages in the DDESB tests was symmetric to the deflecting steel plate with respect to the charge location and other surfaces of the test structure in these tests and was therefore assumed to have equal blast loading as the plate.

Table 1 shows; 1) the maximum measured deflections of the steel plates in each applicable test, 2) the maximum plate deflections calculated with SDOF analyses using the measured blast loads, and 3). the maximum plate deflections calculated with the same SDOF models using the calculated blast loads [6]. All the tests in Table 1 had one lightweight vent panel covering either the front side or the roof of the test structure. The responding steel plate was also on either the front wall or roof of the test structure, whichever surface did not have the vent panel.

The last two columns of Table 1 show ratios of the calculated to measured maximum steel plate deflections where the calculated deflections use the measured blast load and the calculated blast load. The average ratios in these two columns are 1.02 and 0.98, respectively indicating close agreement between calculated and measured maximum deflections. Also, the maximum plate deflections determined from the calculated blast loads for the confined/vented tests are just as accurate, on the average, as the maximum plate deflections determined from the measured blast loads. This helps to confirm the accuracy of the Improved Methodology.

Finally, the Improved Methodology calculates an estimated "arrival time" for the gas pressure in the explosion room, equal to the lag time between a detonation and when the gas pressure begins to rise from zero pressure in the explosion room. The empirical equation developed for the scaled arrival time is shown in (4. This equation was derived from the measured times between charge detonation and when the initial rise in gas pressure occurred in the measured gas pressure histories from the internal detonation tests sponsored by DDESB [6]. An improved method was used to measure the gas pressure in these tests compared to the use of quasistatic pressure gages in similar previous test programs that avoided most of the early time contribution of shock pressure shown in Figure 11. Figure 13 also shows the type of high explosive used for each test where the arrival time was measured.

$$\frac{t_a}{{E'_{det}}^{1/3}} = 5.22\left(\frac{V_o}{E'_{det}}\right)^{0.513} \quad (4)$$

Where:
t_a = arrival time of gas pressure at walls and roof of confined volumes (msec)
E'_{det} = total heat energy released by detonation of explosive charge (KJ)
V_o = initial confined volume (m^3)

It is expected that the arrival time of the gas pressure at the far end of a very long room, such as a hallway, from an explosion at the opposite end of the room could exceed the value that is calculated with (4 since the dimensions of the explosion room in the internal detonation tests sponsored by DDESB had a maximum aspect ratio of 1.3.

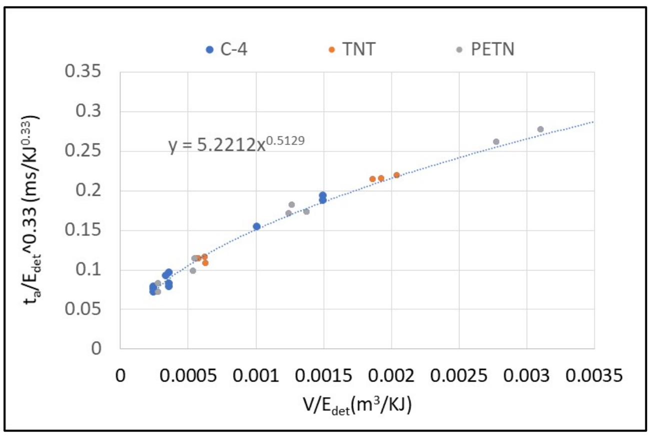


Figure 13. Curve-fit of Scaled Gas Pressure Arrival Time to Scaled Room Volume

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Contact Information

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Appendix

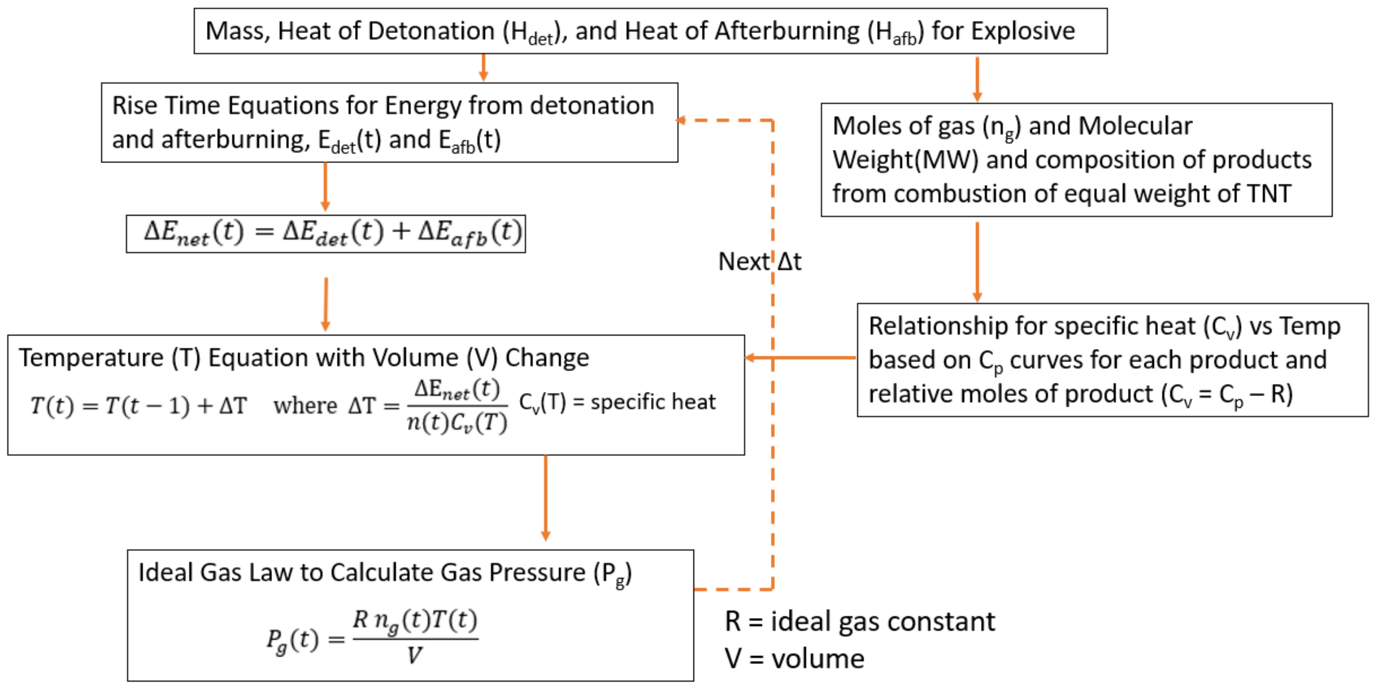
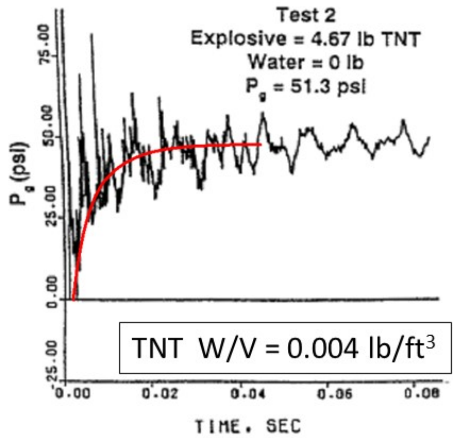
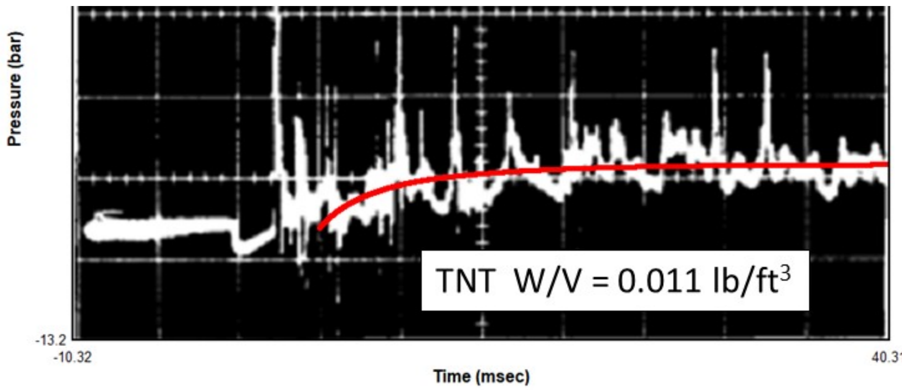


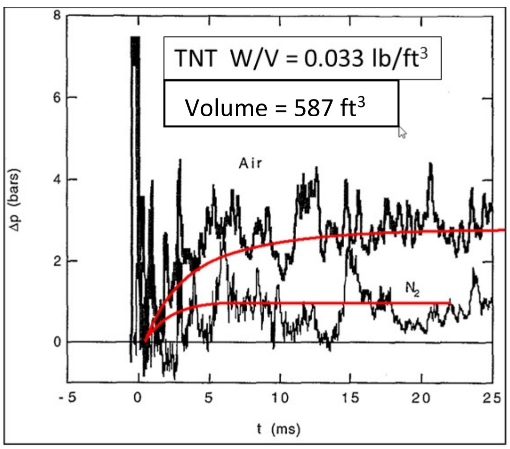
Figure 1. Flowchart for Calculation of Fully Confined Gas Pressure History



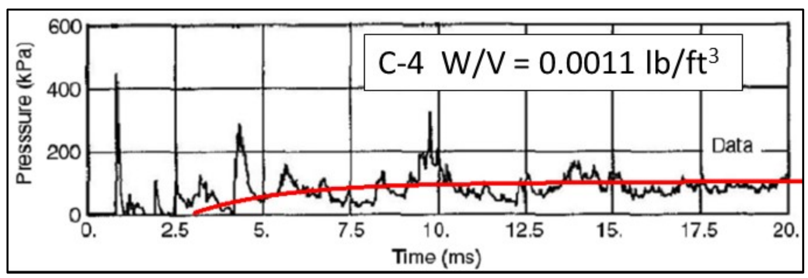
a) Confined explosion room volume = 1150 ft³ [11]



b) Test 18 in test chamber with volume = 995 ft³ [12]



c) Tests in Air (full afterburning) and Nitrogen (no afterburning) [13]



d) Test in steel bunker with volume = 640 ft³ [14]

Figure 3. Calculated Gas Pressure Histories Compared to Fully Confined Internal Detonation Tests

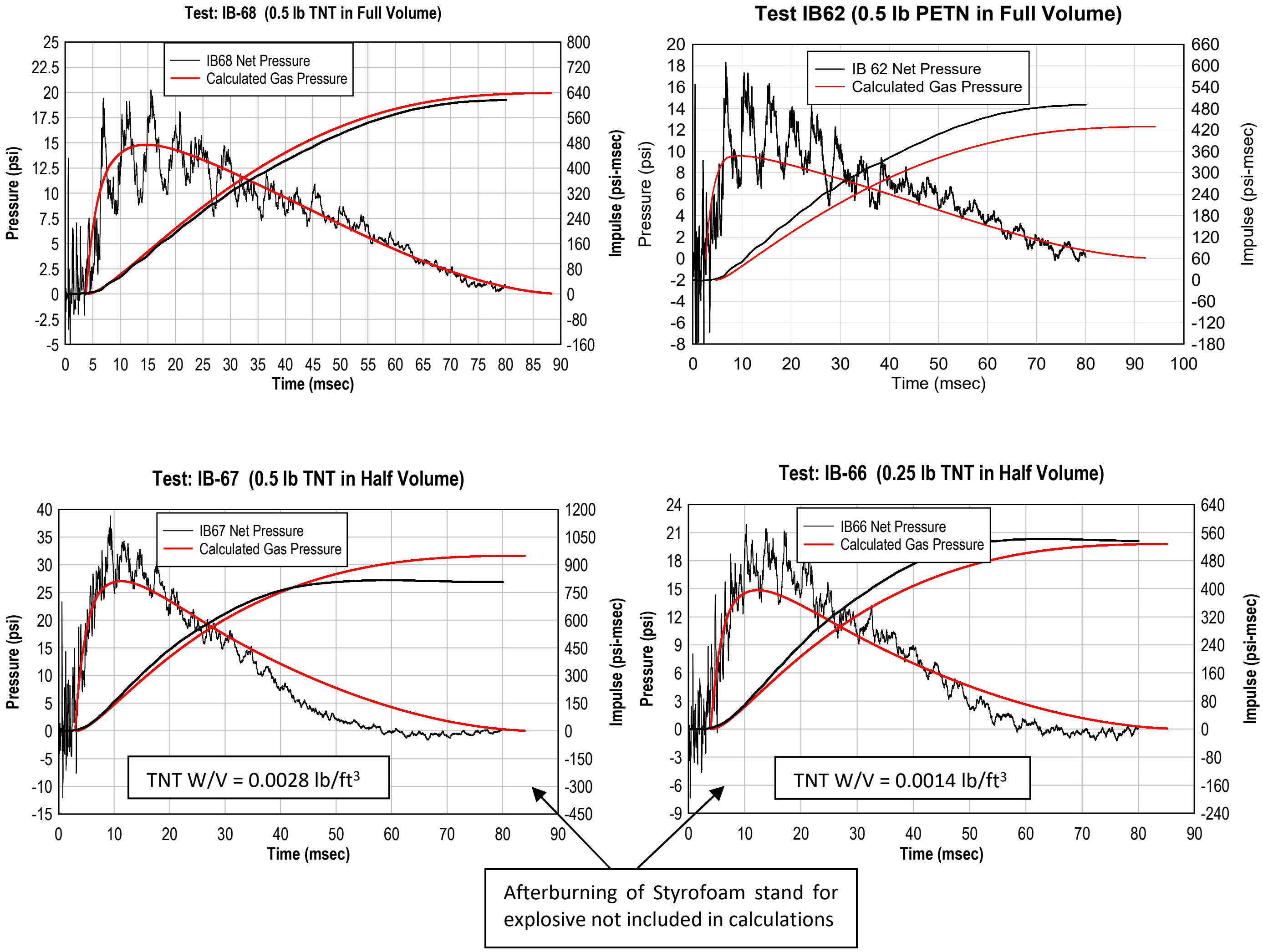


Figure 4. Calculated Gas Pressure Histories Compared to Heavily Confined Internal Detonation Tests in DDESB Test Series

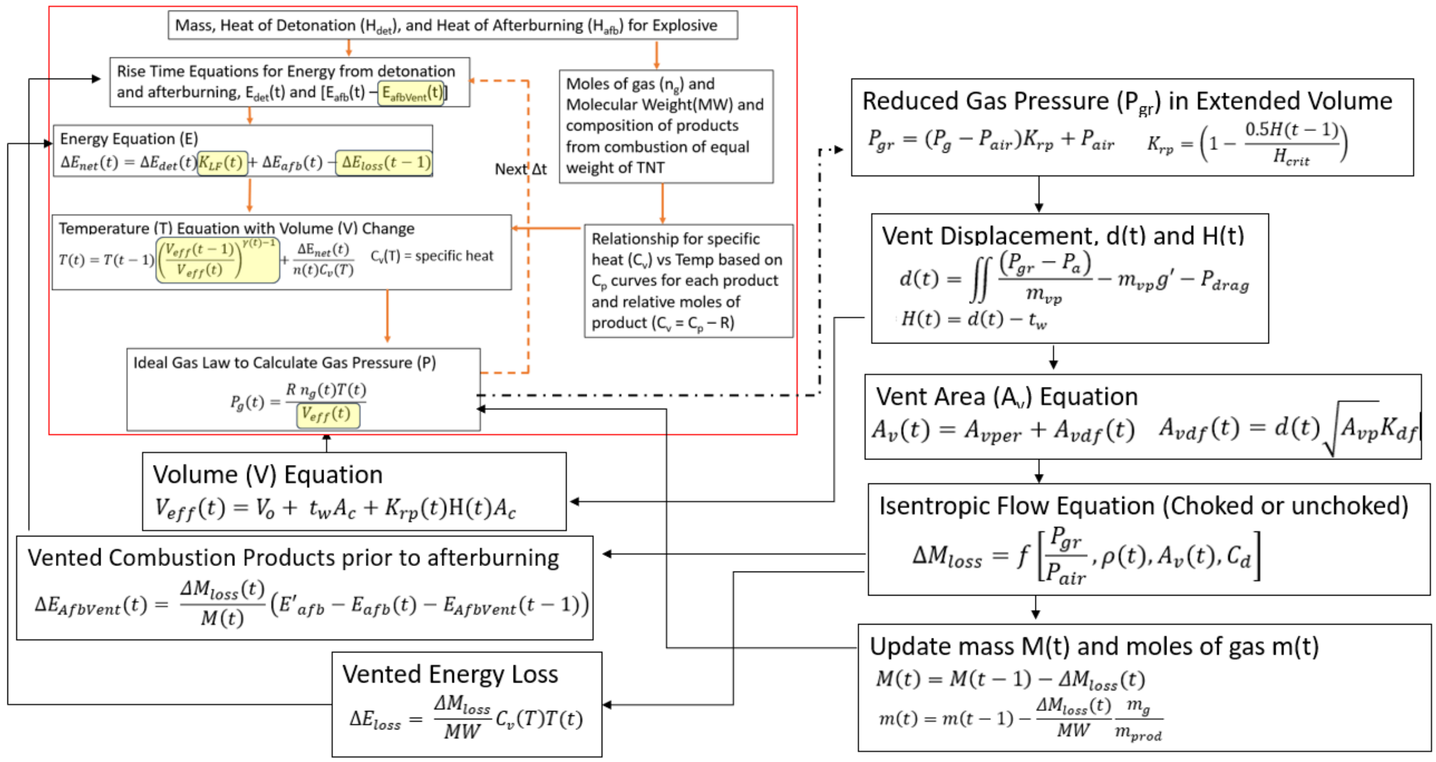
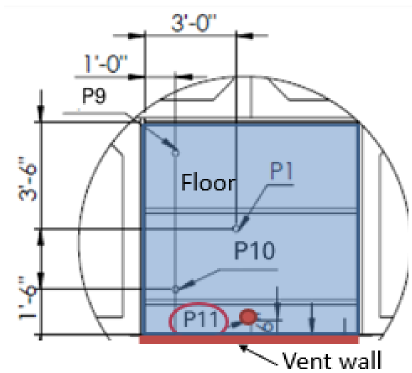


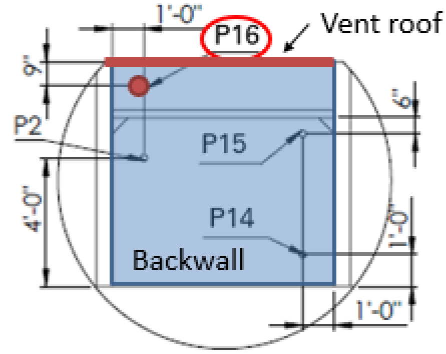
Figure 5. Flowchart for Calculating Gas Pressure for Confined Volume with Venting

Test	Impulse Ratios	
	P11/Avg Floor	P16/Avg Backwall
21	0.77	
23		0.76
24		0.73
26		0.75
27		0.79
35		0.80
36		0.83
44		0.75
45		0.71
48	0.69	
52		0.80
53		0.85

a) Impulse ratios of Gage P11 to average of interior floor gages and Gage P16 to average of interior backwall gages



b) Plan view of floor showing gage P11 and vent wall panel



c) Elevation view of backwall showing gage P16 and vent roof panel

Figure 6. Reduced Gas Impulse at Gages P16 and P11 Near Vent Panels in DDESB Tests

$$\begin{aligned} &For\ 0 < H(t) \le H_{crit} && K_{\mathrm{rp}}(t) = \left(1 - \frac{0.5\mathrm{H}(t)}{H_{crit}}\right) \\ &Else && K_{rp}(t) = 1.0 \end{aligned} \qquad (5)$$

Where:

$K_{rp}(t)$ = pressure reduction factor for vent panel that only applies prior to vent panel “separating” from room volume
H(t) = displacement of vent panel that allows perimeter venting
H_{crit} = critical vent panel displacement causing perimeter vent area to equal vent panel area

Table 1. Comparison of Deflections from Calculated and Measured Blast Loads to Deflections Measured in Steel Plates in DDESB Tests

Test	Test Type[1,2]	Explosive Type	Loading Density W_{TNT}/V^3 (lb/ft^3)	Vent Panel	Maximum Deflection		
					Measured (inch)	Ratio of Calculated/Measured	
						Measured Load	Calculated Load
22	Baseline	C-4	0.0025	N/A	1.8	1.0	1.0
23	Confined/ Vented	C-4	0.0025	Metal Panel	3.0	1.0	1.1
24	Confined/ Vented	C-4	0.0025	Lexan	3.2	1.0	1.0
25	Baseline	C-4	0.0105	N/A	2.1	1.1	1.1
26	Confined/ Vented	C-4	0.0105	Metal Panel	3.6	1.1	1.15
27	Confined/ Vented	C-4	0.0105	Lexan	3.6	1.1	1.2
33	Baseline	TNT	0.0033	N/A	1.6	1.1	0.9
35	Confined/ Vented	TNT	0.0033	Wood Wall	2.4	1.0	1.3
36	Confined/ Vented	TNT	0.0033	Lexan	3.3	0.8	0.95
42	Baseline	TNT	0.01	N/A	2.0	0.8	0.8
44	Confined/ Vented	TNT	0.01	Metal Panel	2.9	0.9	1.0
45	Confined/ Vented	TNT	0.01	Lexan	2.9	1.1	1.0
46	Baseline	PETN	0.0022	N/A	1.0	1.1	0.9
48	Confined/ Vented	PETN	0.0022	Wood Wall	1.6	1.1	0.9
49	Confined/ Vented	PETN	0.0022	Steel Plate	3.0	0.9	0.63
50	Baseline	PETN	0.005	N/A	1.9	0.7	0.8
52	Confined/ Vented	PETN	0.005	Metal Panel	2.4	1.0	1.0
53	Confined/ Vented	PETN	0.005	Wood Wall	2.5	0.9	1.0

Note 1: Baseline tests have one large uncovered surface and therefore only have shock pressure and no gas pressure.
Note 2: Confined/Vented tests have all surfaces covered including one surface with a lightweight vent panel. These tests have combined shock and gas pressure.
Note 3: The ratio of volume to equivalent TNT weight for each test, where equivalent TNT weight was calculated per Equation 2-5 in UFC 3-340-02 [1].