An Improved Method to Calculate the Gas Pressure History from Partially Confined Detonations

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Introduction

- Past studies have indicated large conservatism in calculated gas pressures for rooms with large vent areas
- Calculation methods have a number of simplifying assumptions causing conservatism
- Conservatism is especially problematic for existing DoD operations bays with large covered vent areas
  - Existing gas pressure calculations result in very low allowable charge weights in bays

DDESB Project to Improve Gas Pressure Prediction in Explosion Room

- Gather all available gas pressure test data
  - Use data to assess and improve existing methods
- Identify algorithms in existing methods to use as part of improved method
- Develop a test plan to investigate parts of gas pressure prediction that are not well understood or represented by existing data
- Develop final improved fast-running methodology

DDESB Project Tasks

Task	Description
1	Gather all available gas pressure test data into a database
2	Determine best parts of existing fast-running gas pressure models and identify gaps in these “best parts”
3	Assemble best parts from existing models and use test data to develop a new improved gas pressure model for DDESB
4	Write computer program with improved methodology
5	Use research and testing to address gaps in test data and improved methodology
6	Develop final methodology based on research and testing

Overview of Gas Pressure

- Heat/Energy from internal explosion causes overall pressure rise in explosion room (i.e. gas pressure rise)
  - This adds to pressures from shock wave
- Gas pressure decays as pressurized gas in room vents through all openings (i.e. venting)
  - Venting through uncovered openings and openings created by failed walls/roof components
- Gas pressure often causes more structural damage than shock pressure

Physical Processes Causing Gas Pressure

- Heat from internal detonation in confined volume raises overall pressure in explosion room
  - Heat released during detonation process
  - Heat from afterburning of detonation products based on available oxygen in explosion room
- Shock wave helps distributes heat from detonation throughout explosion room
  - Shock wave energy also gradually converted to heat
- Shock wave may help mix detonation products with oxygen for afterburning

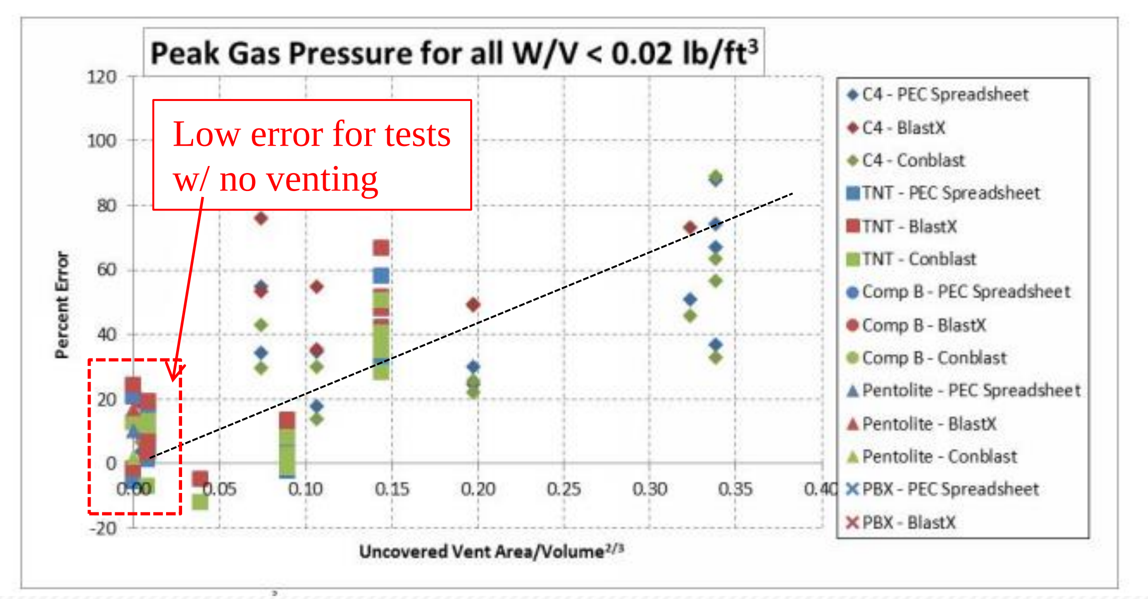
Test Data

- Data on over 150 well documented tests with measured gas pressure have been assembled in spreadsheet
  - All tests have well defined charge weight and geometry
  - This includes over 100 measured pressure histories
- Five test series had multiple pressure gages per test
  - Theoretically gas pressure is constant throughout explosion room
  - Significant variability in gas pressure measured at multiple gages in these tests (COV = 12% on average)

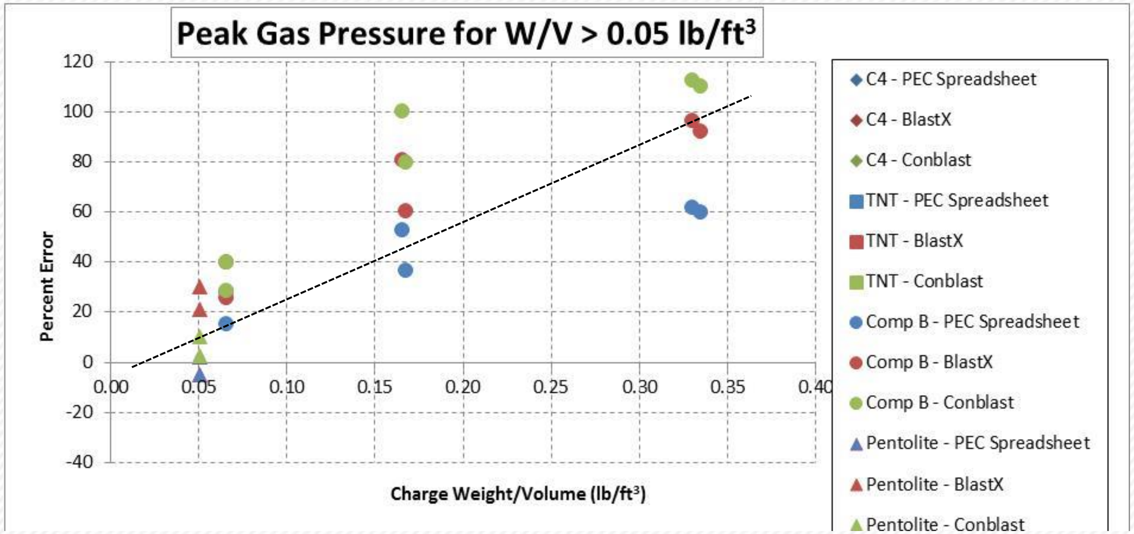
Existing Gas Pressure Methods

- FRANG method (Version 2.0)
  - As incorporated into ConBlast code from EXWC
  - Empirical method to calculate peak gas pressure from UFC 3-340-02
  - Empirical method to calculate gas pressure decay during venting
- BlastX (Version 6.4.2.2)
  - Peak gas pressure from thermochemical equations
  - Gas pressure decay during venting calculated as isentropic flow of ideal gas through a nozzle
- Both methods very conservative compared to gas pressure test data with significant venting

Peak Pressure Error vs. Uncovered Scaled Vent Area



Low error for tests w/ no venting

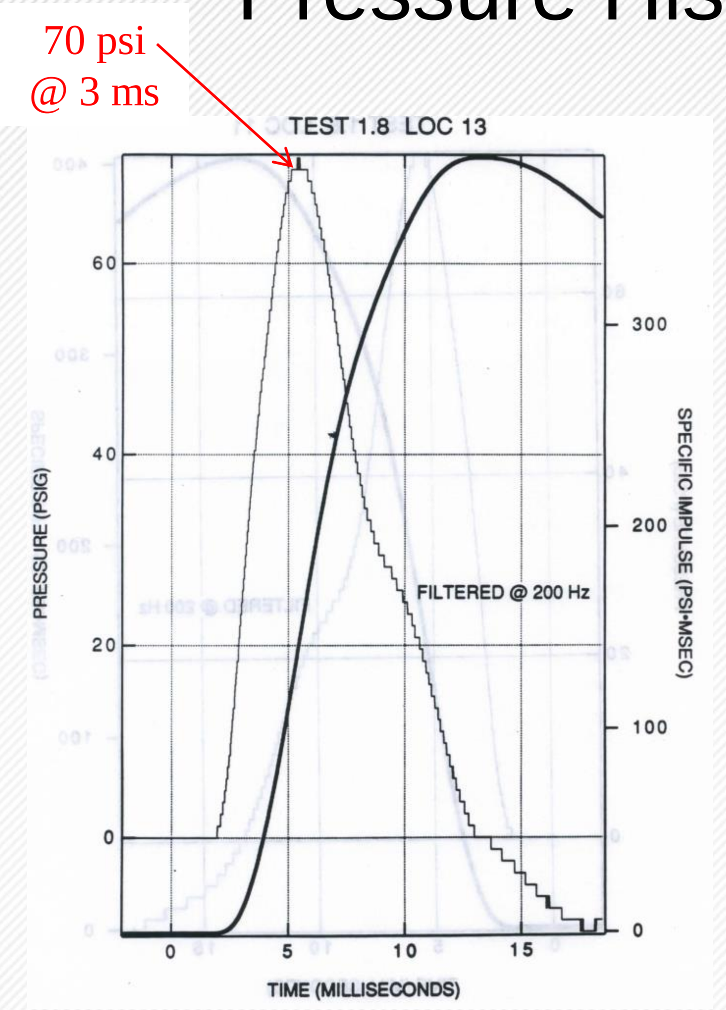


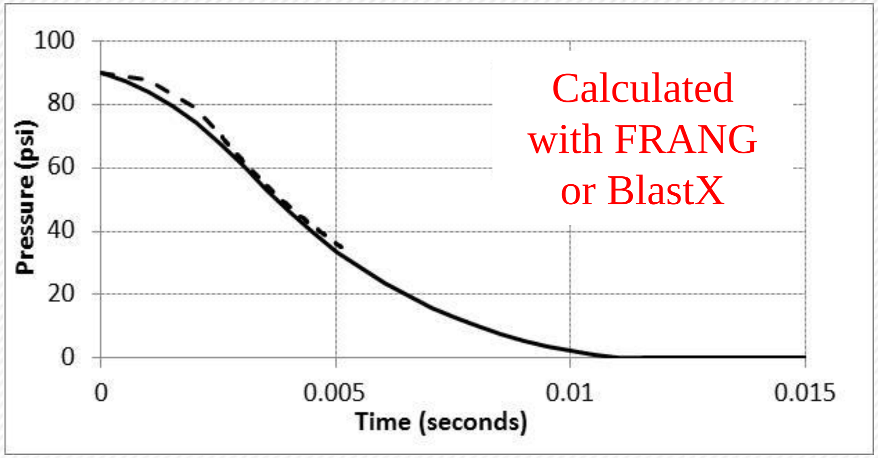
Conservatism in calc. peak gas pressure **increases dramatically with scaled vent area** for small loading densities with complete afterburning,

This indicates **venting of detonation products** is reducing peak gas pressure. Calculation methods do not account for this.

<u>Large W/V tests do not have any afterburning so no such trend</u>.

Typical Comparison of Calculated Gas Pressure Histories (¼ Scale Test)





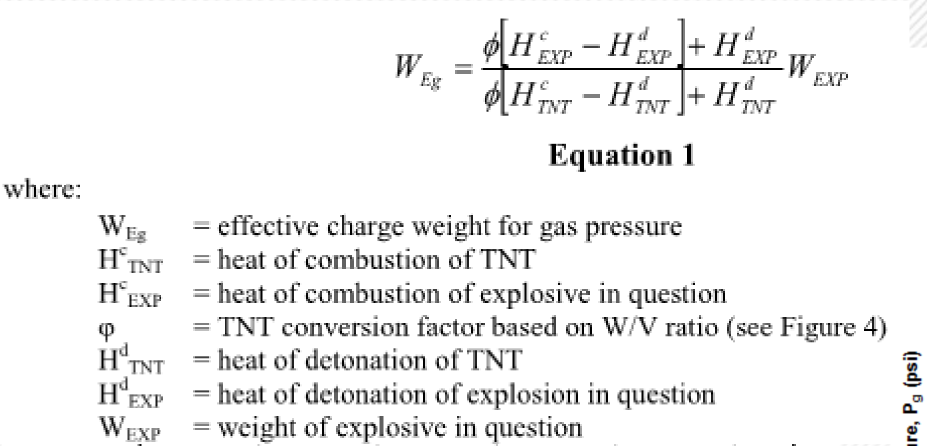
Improved Methodology

- Calculated gas pressure rises gradually to maximum value over a rise time
  - Maximum value is less than peak gas pressure assuming full confinement if venting during rise time
- Calculated effects of mass loss and energy loss due to venting during rise time reduce maximum gas pressure
- Movement of vent panels causes calculated increase in room volume
  - This reduces gas pressure in explosion room
  - Room volume reverts to original volume with no change in density after vent panel moves far enough from explosion room
- Empirical equation for discharge coefficient of venting gas

Maximum Gas Pressure in Improved Methodology

- Peak gas pressure calculated assuming full confinement per UFC 3-340-02
  - Same as current FRANG code
- Empircal equation for gas pressure rise time history
  - This equation used to add peak calculated gas pressure into explosion room during rise time
- Equations for effect of room volume change and mass loss on gas pressure as vent panels blown outwards
  - Theoretically based equations that reduce peak gas pressure
- Equation for energy loss from venting during rise time
  - Empirical equation that reduces peak gas pressure

Peak Gas Pressure for Full Confinement



$$W_{Eg} = \frac{\phi\left[H^{c}_{EXP} - H^{d}_{EXP}\right] + H^{d}_{EXP}}{\phi\left[H^{c}_{TNT} - H^{d}_{TNT}\right] + H^{d}_{TNT}} W_{EXP}$$

Equation 1

where:

W_{Eg} = effective charge weight for gas pressure
H^{c}_{TNT} = heat of combustion of TNT
H^{c}_{EXP} = heat of combustion of explosive in question
φ = TNT conversion factor based on W/V ratio (see Figure 4)
H^{d}_{TNT} = heat of detonation of TNT
H^{d}_{EXP} = heat of detonation of explosion in question
W_{EXP} = weight of explosive in question

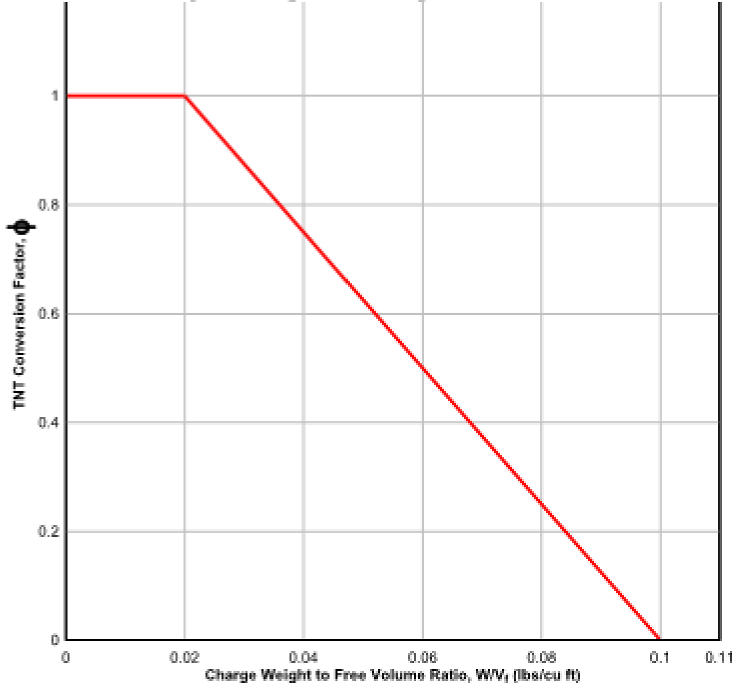
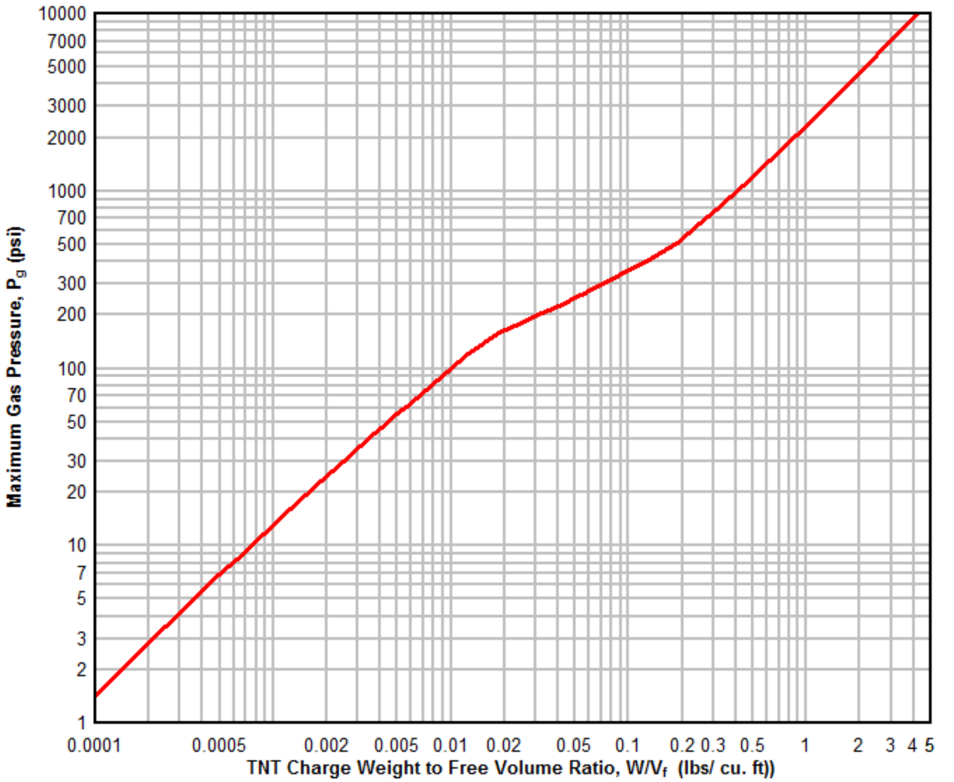


Figure 4. TNT Conversion Factor from UFC 3-340-02

Figure 2-152 Peak gas pressure produced by a TNT detonation in a partially contained chamber



Gas Pressure Rise Time Calculation for Improved Method

$$t_r = K_r \frac{L_{max}}{C_s}$$

$$P_g(t) = P_{max} e^{-\left(\frac{K_a t}{t_r}\right)} \left(1 - \frac{t}{t_r}\right)$$

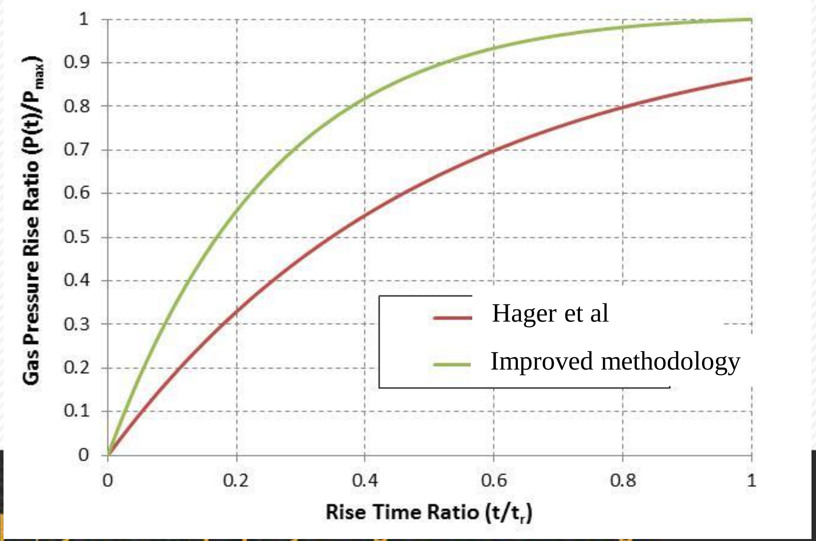
Based on very similar equations by Hager et al (2006)

where:

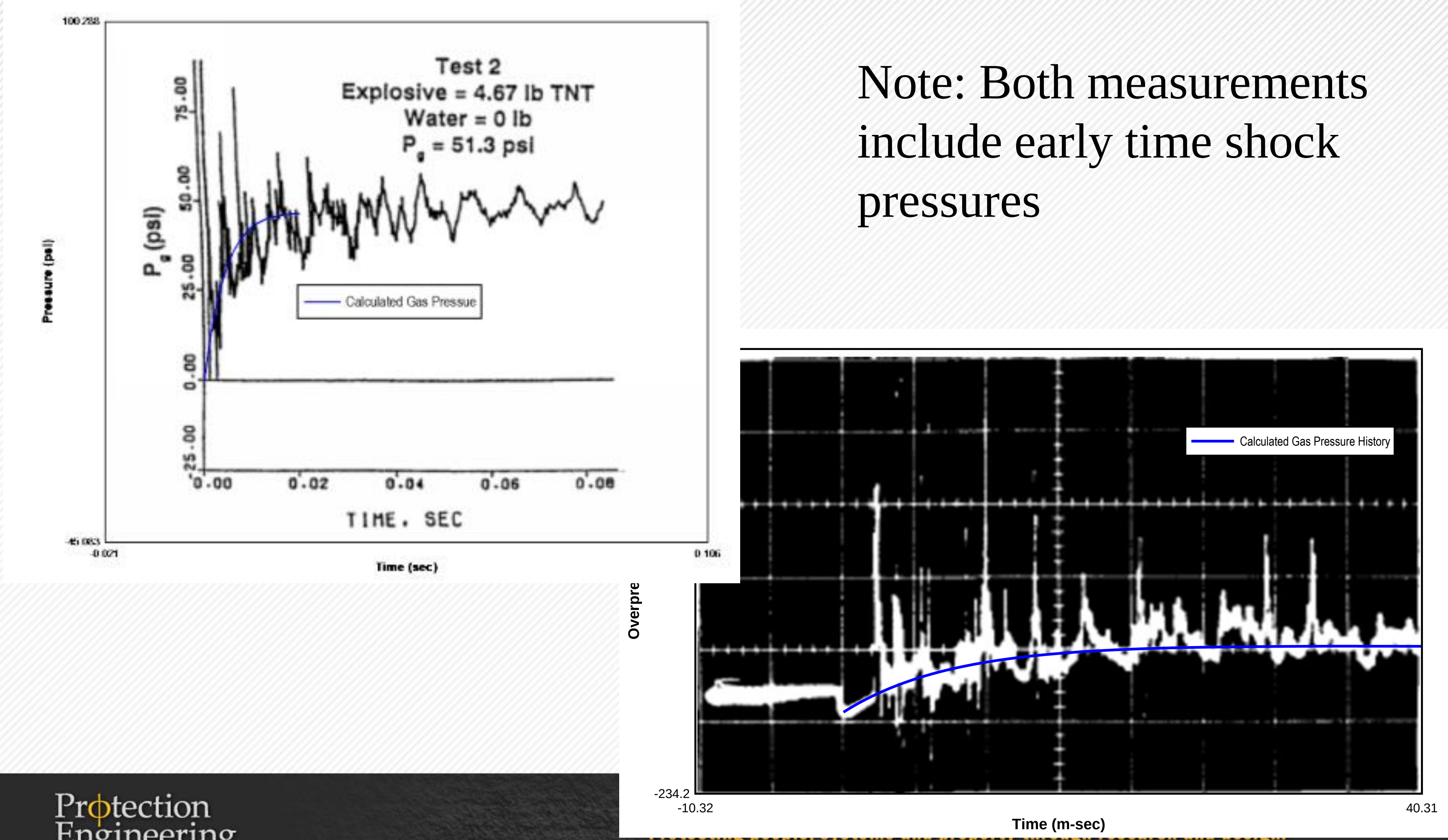
t_r = maximum gas pressure rise time (i.e. in a fully confined volume)
L_{max} = maximum dimension of the confined volume
C_s = average shock velocity in confined volume
K_r = empirical factor for rise time

where:

$P_g(t)$ = gas pressure during rise time (when $t \leq t_r$)
P_{max} = maximum gas pressure at end of rise time
t_r = gas pressure rise time in a fully confined volume
K_a = empirical factor for rise time history
t = time for $t \leq t_r$

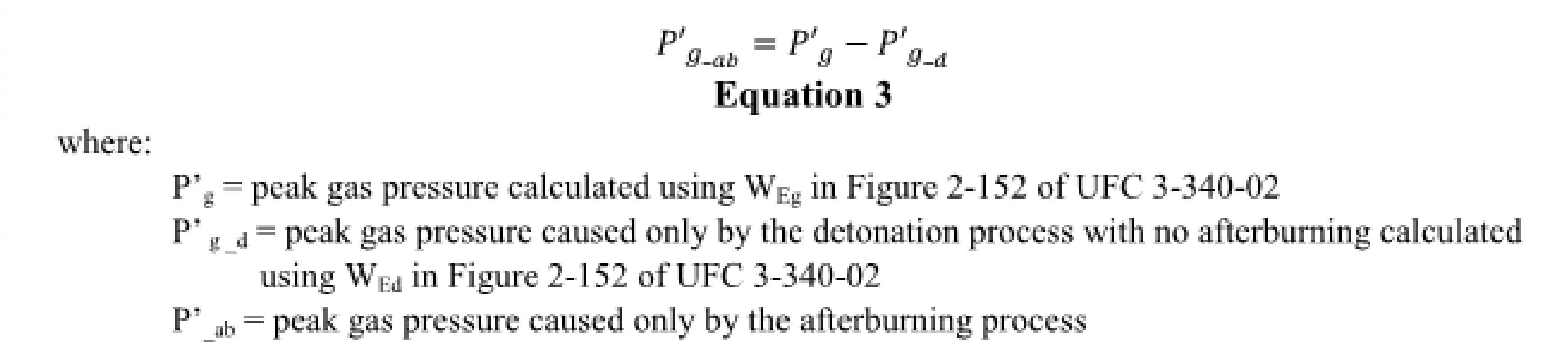


Gas Pressure Rise History with Improved Method vs. Measured in Fully Confined Tests



Note: Both measurements include early time shock pressures

Calculate Peak Gas Pressures Caused by Detonation and Afterburning



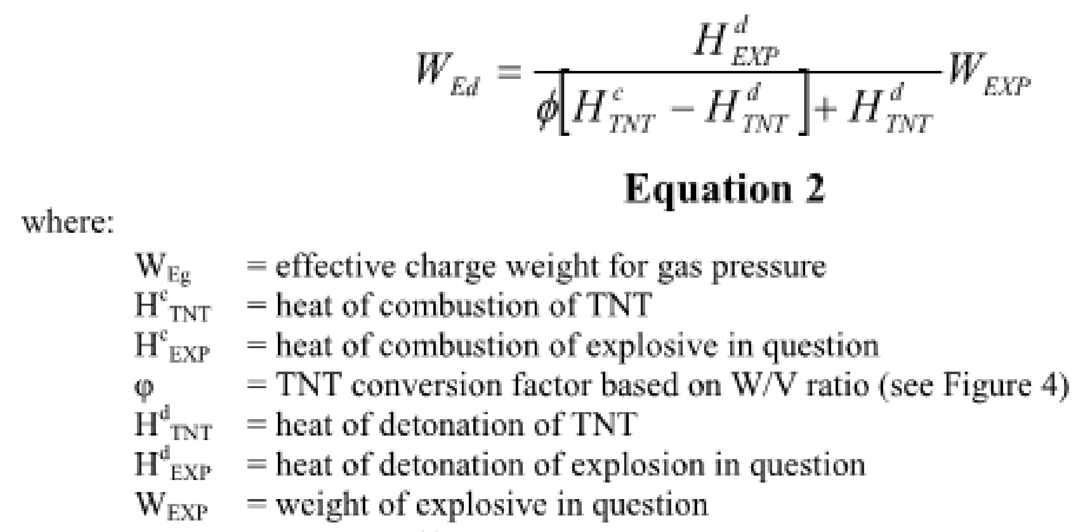
$$P'_{g\text{-}ab} = P'_{g} - P'_{g\text{-}d}$$

Equation 3

where:

P'_{g} = peak gas pressure calculated using W_{Eg} in Figure 2-152 of UFC 3-340-02
P'_{g_d} = peak gas pressure caused only by the detonation process with no afterburning calculated using W_{Ed} in Figure 2-152 of UFC 3-340-02
$P'_{\_ab}$ = peak gas pressure caused only by the afterburning process

Use W_{ed} with the volume in Figure 2-152 of UFC, to calculate P'_{g_d}.



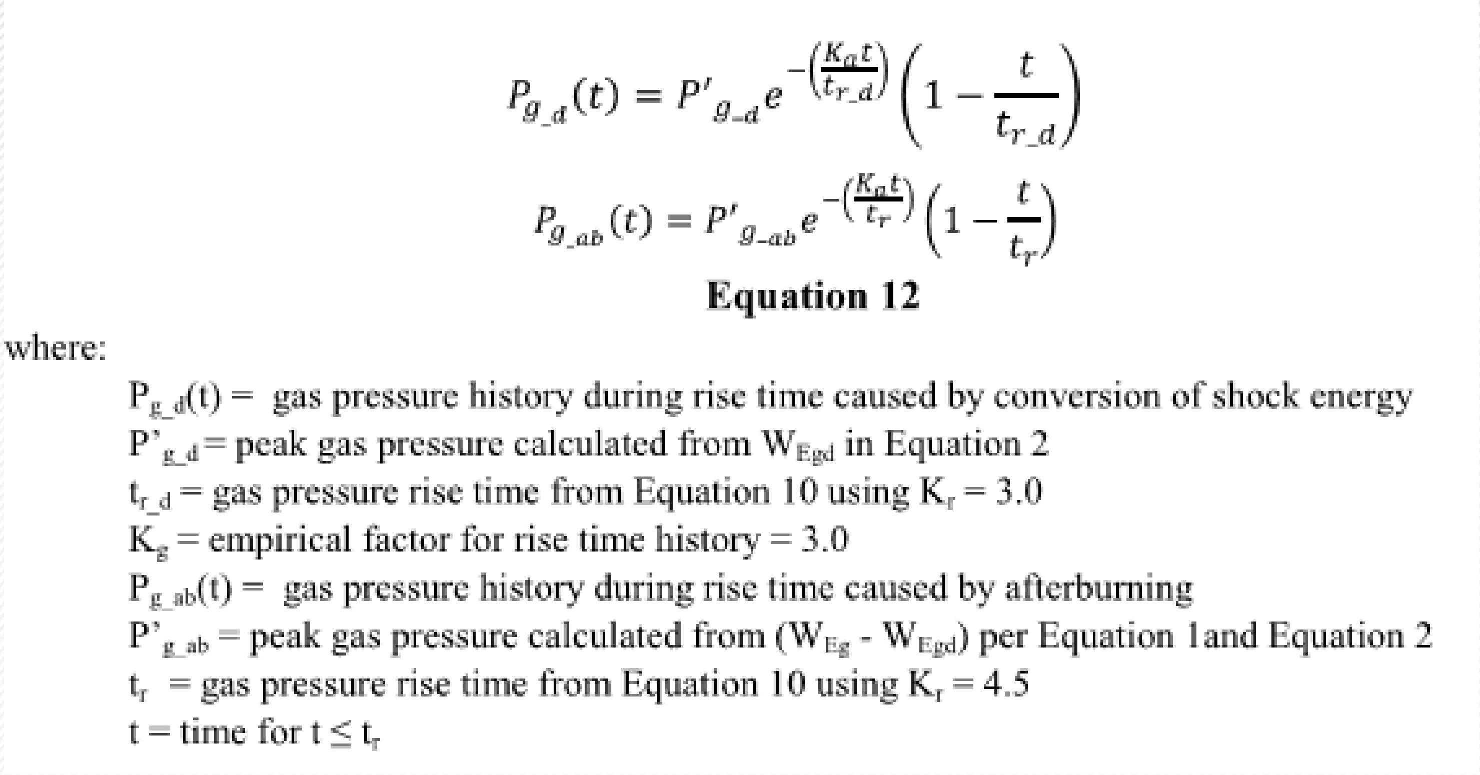
$$W_{Ed} = \frac{H^{d}_{EXP}}{\phi\left[H^{c}_{TNT} - H^{d}_{TNT}\right] + H^{d}_{TNT}} W_{EXP}$$

Equation 2

where:

W_{Eg} = effective charge weight for gas pressure
H^{c}_{TNT} = heat of combustion of TNT
H^{c}_{EXP} = heat of combustion of explosive in question
φ = TNT conversion factor based on W/V ratio (see Figure 4)
H^{d}_{TNT} = heat of detonation of TNT
H^{d}_{EXP} = heat of detonation of explosion in question
W_{EXP} = weight of explosive in question

Equations for Rise Time of Gas Pressure from Each Energy Source



$$P_{g\_d}(t) = P'_{g\_d}\, e^{-\left(\frac{K_g t}{t_{r\_d}}\right)}\left(1 - \frac{t}{t_{r\_d}}\right)$$

$$P_{g\_ab}(t) = P'_{g\_ab}\, e^{-\left(\frac{K_g t}{t_r}\right)}\left(1 - \frac{t}{t_r}\right)$$

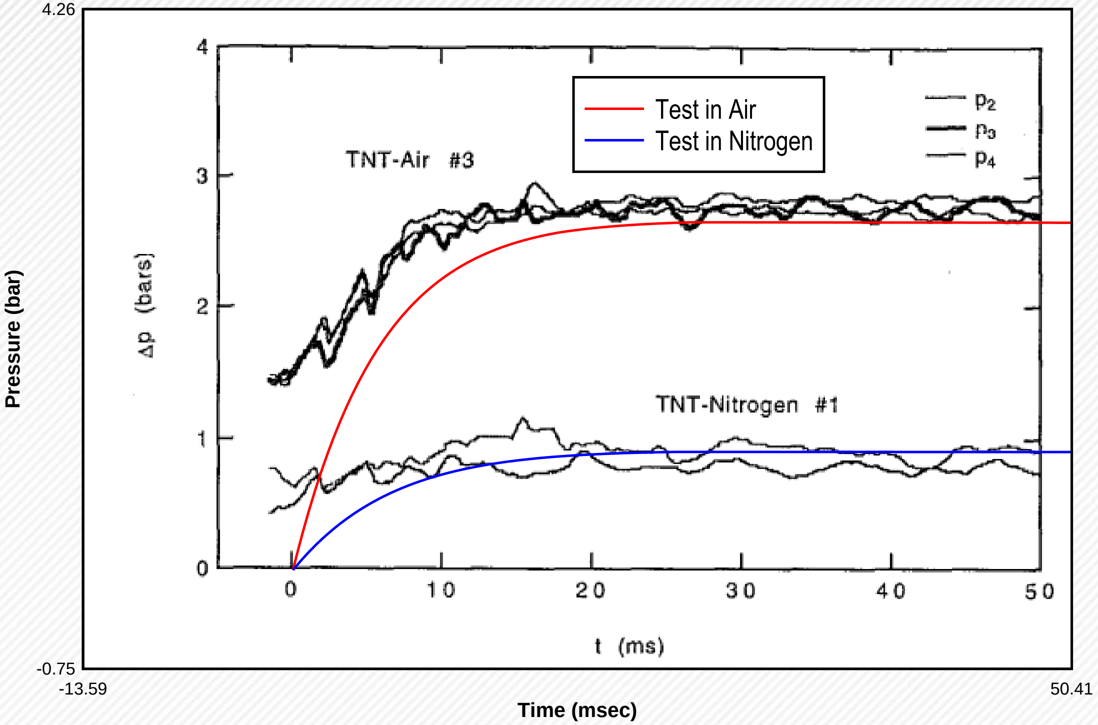
Equation 12

where:

$P_{g\_d}(t)$ = gas pressure history during rise time caused by conversion of shock energy
P'_{g_d} = peak gas pressure calculated from W_{Egd} in Equation 2
t_{r_d} = gas pressure rise time from Equation 10 using $K_r = 3.0$
K_g = empirical factor for rise time history = 3.0
$P_{g\_ab}(t)$ = gas pressure history during rise time caused by afterburning
P'_{g_ab} = peak gas pressure calculated from (W_{Eg} - W_{Egd}) per Equation 1and Equation 2
t_r = gas pressure rise time from Equation 10 using $K_r = 4.5$
t = time for $t \leq t_r$

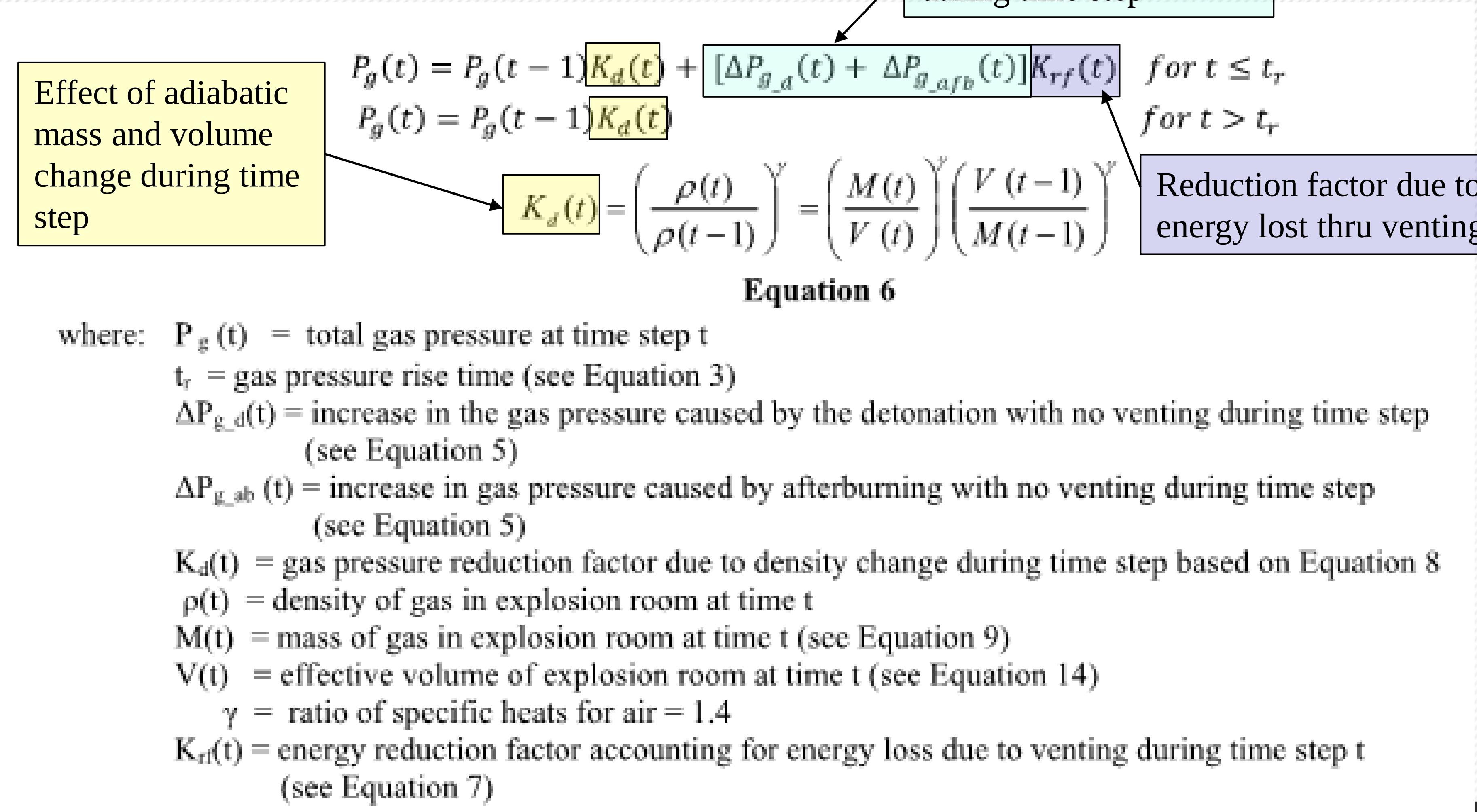
Use same form of rise time equation for both pressure rise time histories with slightly different rise time coefficient. Based on very limited data, the pressure rise from detonation energy is a little faster than when combined with afterburning.

Calculated Gas Pressure Rise History from Detonation vs. Fully Confined Test in Nitrogen



Note: Plots show moving average of measured pressure over 7.5 ms duration

General Equation for Gas Pressure History



Effect of adiabatic mass and volume change during time step

Increase in gas pressure during time step

Reduction factor due to energy lost thru venting

$$P_g(t) = P_g(t-1)\boxed{K_d(t)} + \boxed{[\Delta P_{g\_d}(t) + \Delta P_{g\_afb}(t)]}\boxed{K_{rf}(t)} \qquad for\ t \le t_r$$

$$P_g(t) = P_g(t-1)\boxed{K_d(t)} \qquad for\ t > t_r$$

$$\boxed{K_d(t)} = \left(\frac{\rho(t)}{\rho(t-1)}\right)^{\gamma} = \left(\frac{M(t)}{V(t)}\right)^{\gamma}\left(\frac{V(t-1)}{M(t-1)}\right)^{\gamma}$$

Equation 6

where: $P_g(t)$ = total gas pressure at time step t

t_r = gas pressure rise time (see Equation 3)

$\Delta P_{g\_d}(t)$ = increase in the gas pressure caused by the detonation with no venting during time step (see Equation 5)

$\Delta P_{g\_ab}(t)$ = increase in gas pressure caused by afterburning with no venting during time step (see Equation 5)

$K_d(t)$ = gas pressure reduction factor due to density change during time step based on Equation 8

$\rho(t)$ = density of gas in explosion room at time t

$M(t)$ = mass of gas in explosion room at time t (see Equation 9)

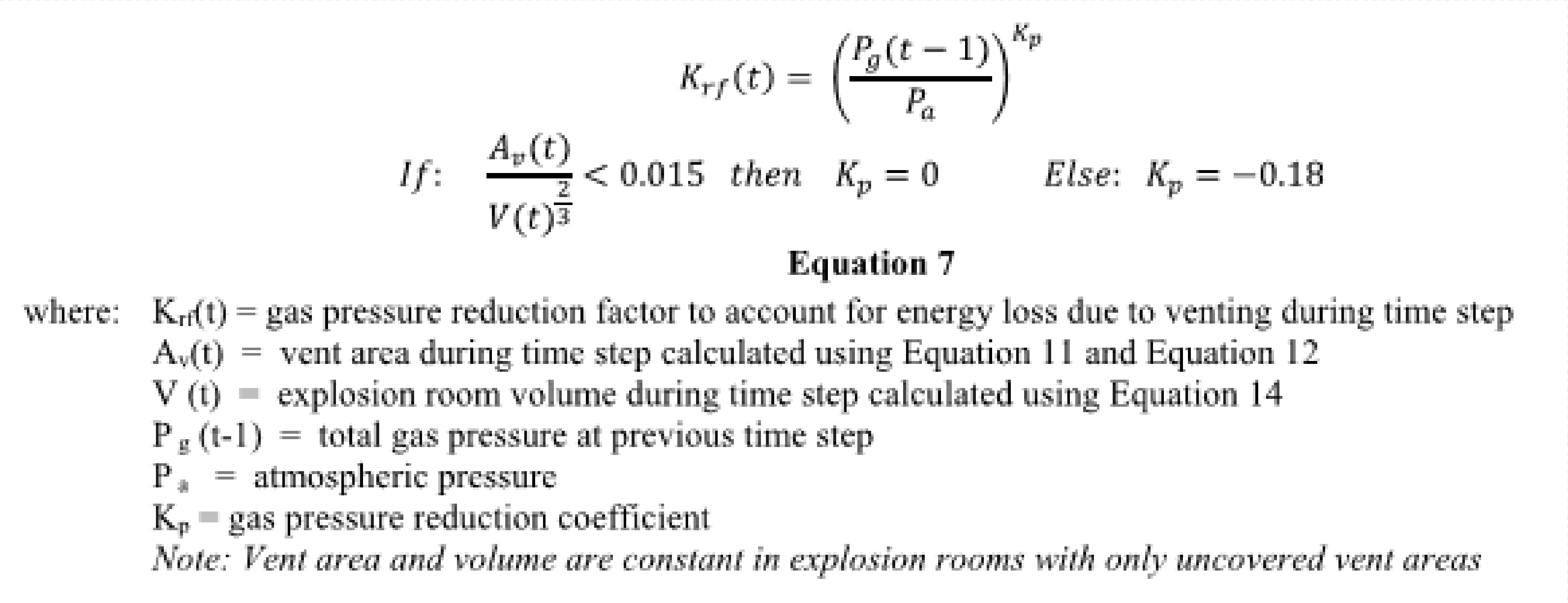
$V(t)$ = effective volume of explosion room at time t (see Equation 14)

γ = ratio of specific heats for air = 1.4

$K_{rf}(t)$ = energy reduction factor accounting for energy loss due to venting during time step t (see Equation 7)

Empirical Equation for Energy Loss Due to Venting During Rise Time

$K_{rf}(t)$ approaches 1.0 (i.e. no reduction) as the gas pressure approaches atmospheric pressure or the vent area is very small.



$$K_{rf}(t) = \left(\frac{P_g(t-1)}{P_a}\right)^{K_p}$$

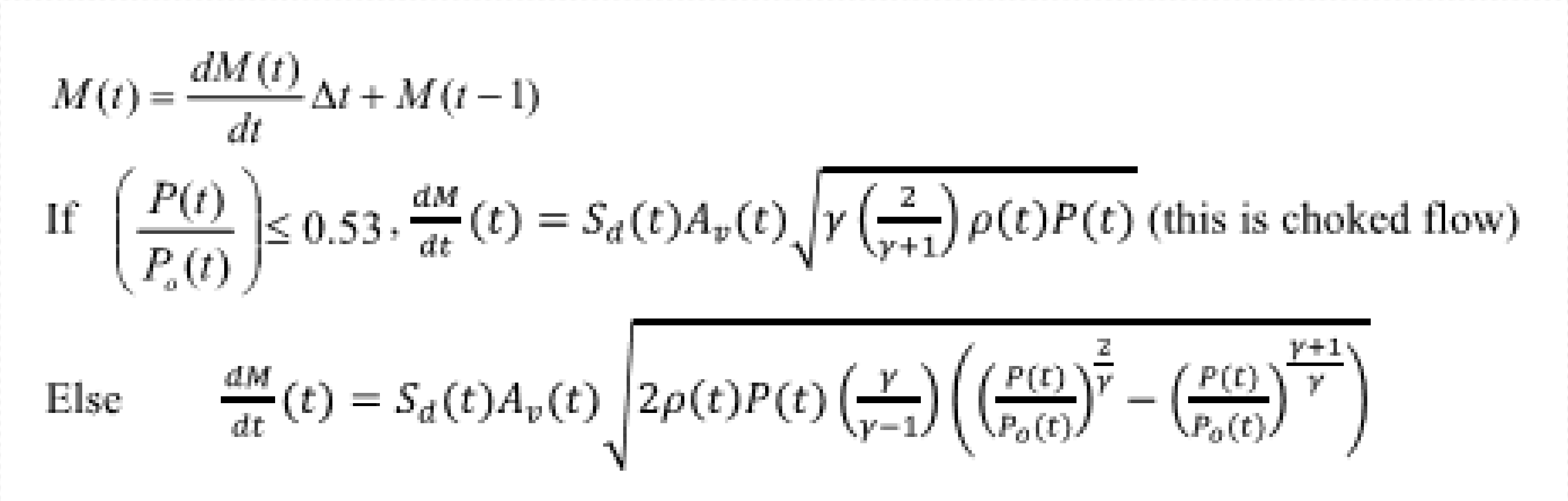
$$If: \quad \frac{A_v(t)}{V(t)^{\frac{2}{3}}} < 0.015 \quad then \quad K_p = 0 \qquad Else: \quad K_p = -0.18$$

Equation 7

where: $K_{rf}(t)$ = gas pressure reduction factor to account for energy loss due to venting during time step
$A_v(t)$ = vent area during time step calculated using Equation 11 and Equation 12
$V(t)$ = explosion room volume during time step calculated using Equation 14
$P_g(t-1)$ = total gas pressure at previous time step
P_a = atmospheric pressure
K_p = gas pressure reduction coefficient
Note: Vent area and volume are constant in explosion rooms with only uncovered vent areas

Mass Loss During Venting

Theoretical equation for isentropic flow through a nozzle is used.



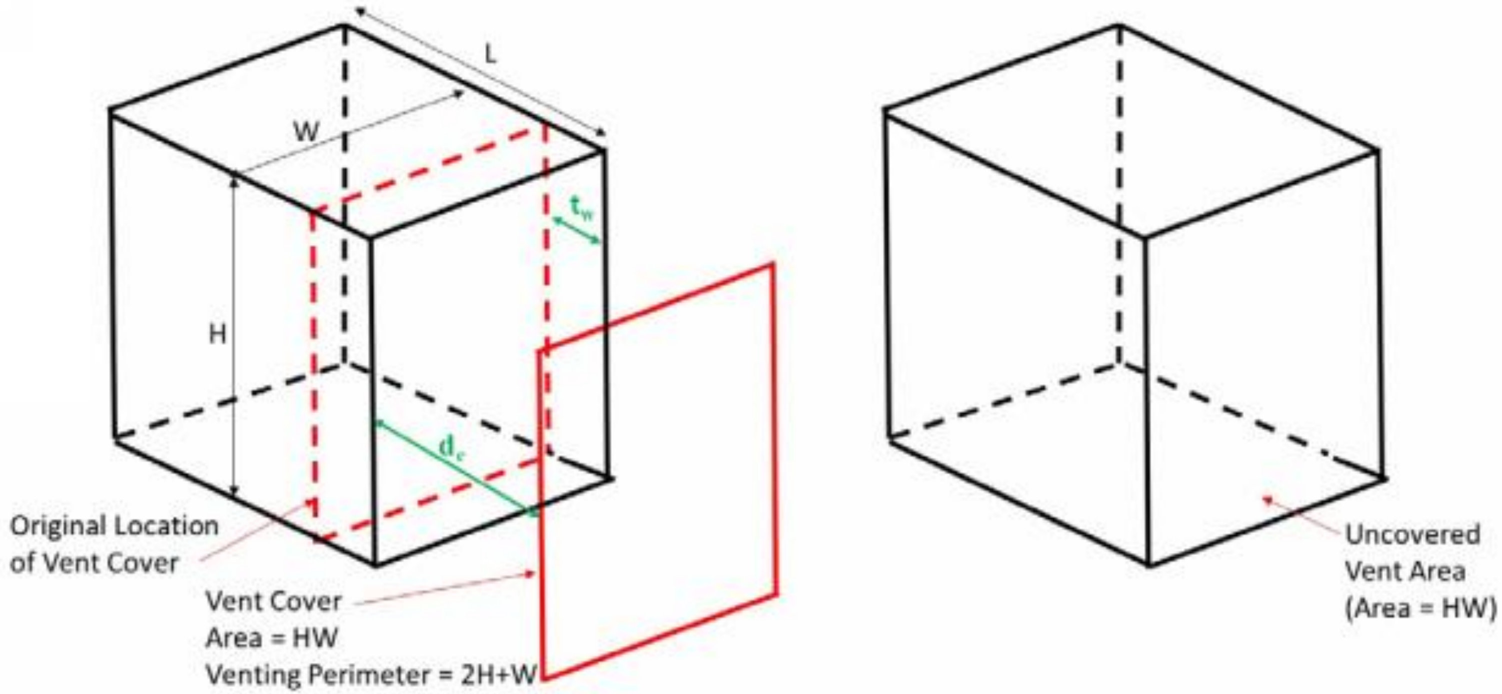
$$M(t) = \frac{dM(t)}{dt}\Delta t + M(t-1)$$

If $\left(\frac{P(t)}{P_o(t)}\right) \leq 0.53$, $\frac{dM}{dt}(t) = S_d(t)A_v(t)\sqrt{\gamma\left(\frac{2}{\gamma+1}\right)\rho(t)P(t)}$ (this is choked flow)

Else $\frac{dM}{dt}(t) = S_d(t)A_v(t)\sqrt{2\rho(t)P(t)\left(\frac{\gamma}{\gamma-1}\right)\left(\left(\frac{P(t)}{P_o(t)}\right)^{\frac{2}{\gamma}} - \left(\frac{P(t)}{P_o(t)}\right)^{\frac{\gamma+1}{\gamma}}\right)}$

dM/dt = mass flow rate out of vent area $A_v(t)$. This is a function of the gas pressure P(t), atmospheric pressure, P_o, the ratio of specific heats, γ, and empirical discharge coefficient, $S_d(t)$.

Room Volume Change from Outward Movement of Vent Panel



$V(t) = (HW)L + (HW)d_c$
$d_c = HW/(2H+W)$

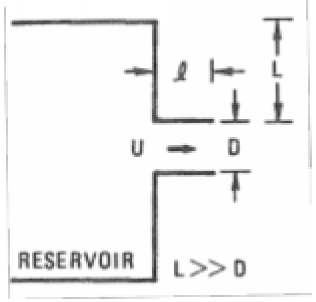
a) Explosion room including volume out to vent cover at time t when $d(t) = d_c$

$V(t+1) = (HW)L$
$M(t+1) = M(t) - \rho(t)^*(HW)d_c$

b) Explosion room at time t+1 when $d(t) > d_c$

Note: V(t) = room volume at time t, M(t)= mass of gas in room at time t, ρ(t)=density of gas in room at time t
t+1 is the next time step

Empirical Equation for Discharge Coefficient $S_d(t)$



ℓ/D	S_d
0	0.61
2–3	0.61–0.82
>3	0.82

Static (non-blast)

Discharge Coefficient, S_d (from Blevins, 2003)

Venting around Vent Panel Perimeter

$$S_d(t) = 0.61$$

For uncovered vent areas:

$$if \left(\frac{W_{Eg}}{V(t)}\right) < 0.02\ \frac{lb}{ft^3} \qquad S_d(t) = 0.8\left(\frac{A_{uc}}{V(t)^{\frac{2}{3}}}\right) + 0.61 \leq 1.0$$

$$Else \qquad S_d(t) = 0.76\,\frac{W_{Eg}}{V(t)} + 0.74 \leq 1.0$$

Equation 12

where:

$S_d(t)$ = discharge coefficient for Equation 11Equation 11

A_{uc} = uncovered vent area

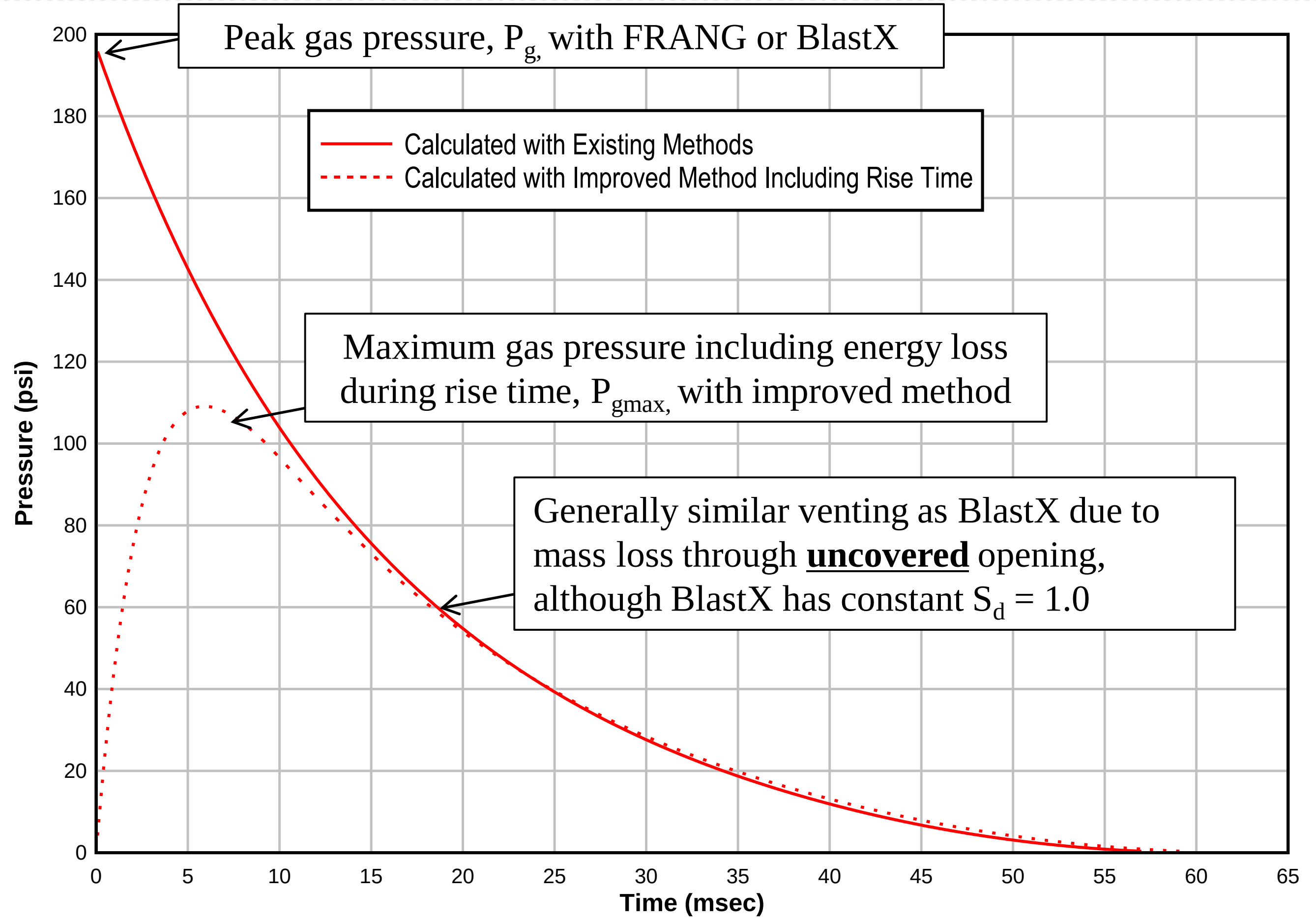
$V(t)$ = confined volume during time step calculated using Equation 10

W_{Eg} = equivalent TNT charge weight to calculate peak gas pressure per UFC 3-340-02

$d(t)$ = displacement of vent cover at time t calculated with Equation 9

d_c = critical displacement of vent cover when venting type changes to uncovered venting

Typical Comparison of Calculated Gas Pressure Histories

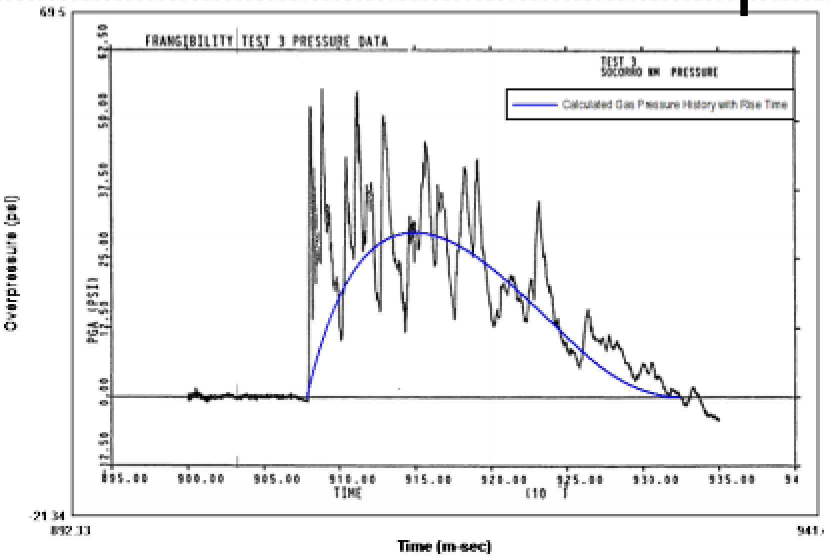


Peak gas pressure, $P_{g,}$ with FRANG or BlastX

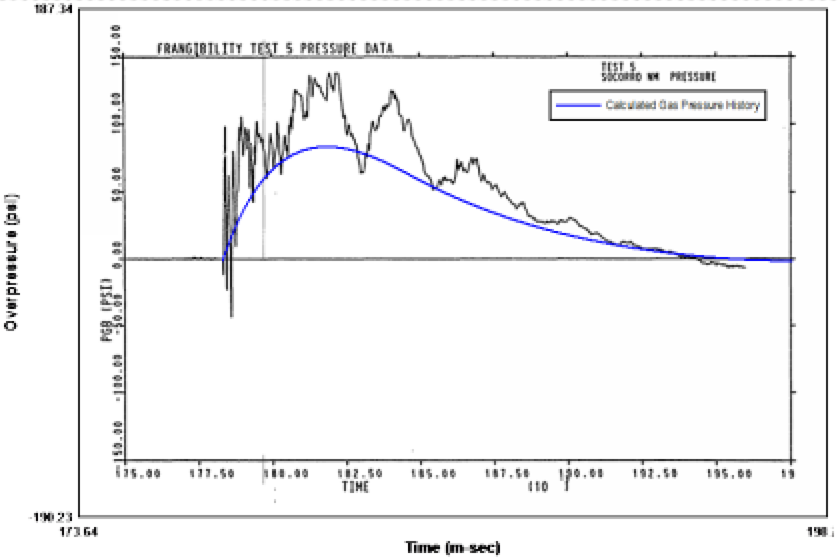
Maximum gas pressure including energy loss during rise time, $P_{gmax,}$ with improved method

Generally similar venting as BlastX due to mass loss through **uncovered** opening, although BlastX has constant $S_d = 1.0$

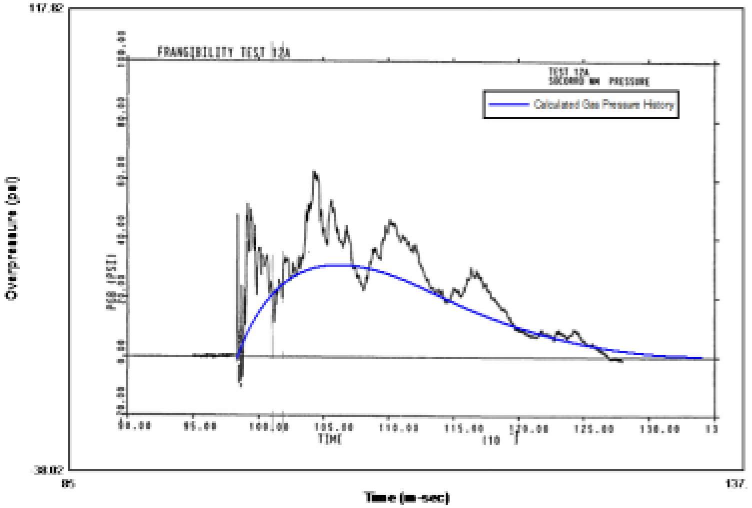
Comparisons of Gas Pressure Histories Calculated with Improved Method vs. Data



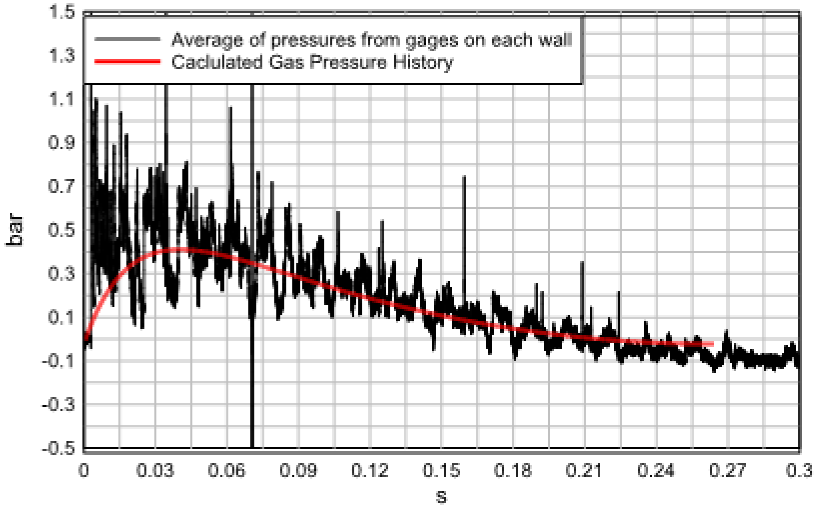
T3 – NCEL TERA Test 3



T3 – NCEL TERA Test 5

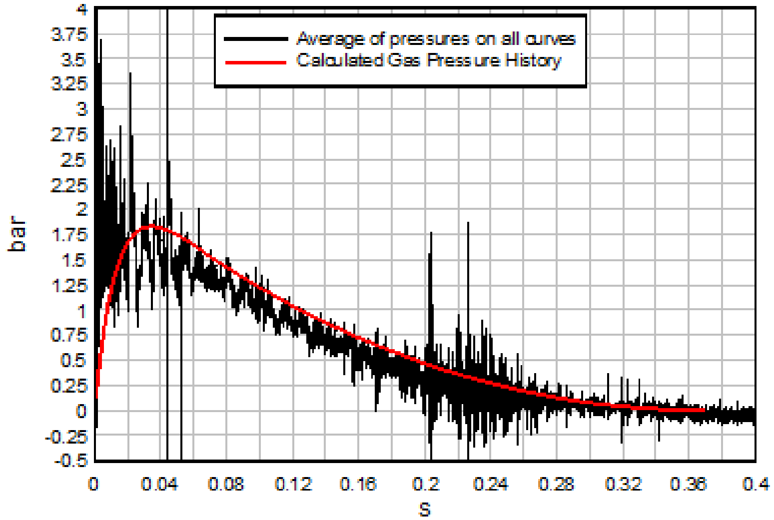


T3 – NCEL TERA Test 12

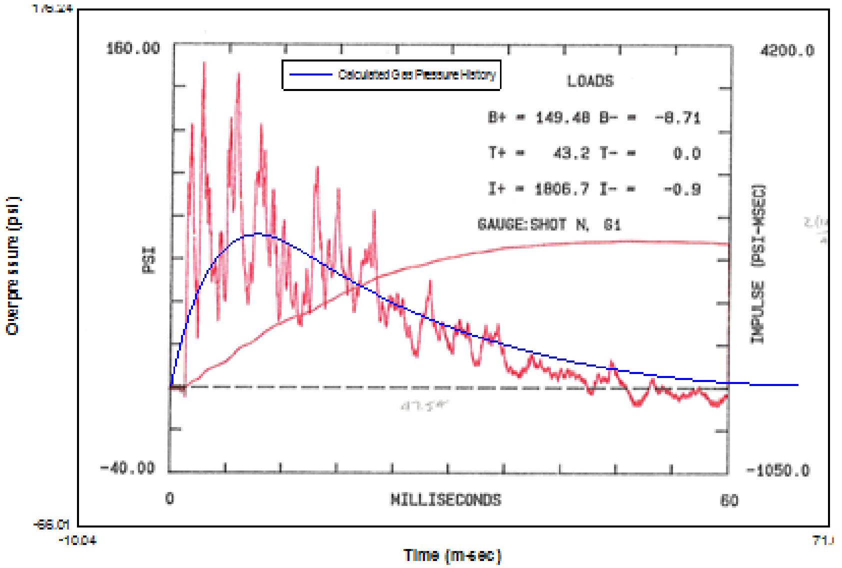


L1 - Ladeburg Test B4E1

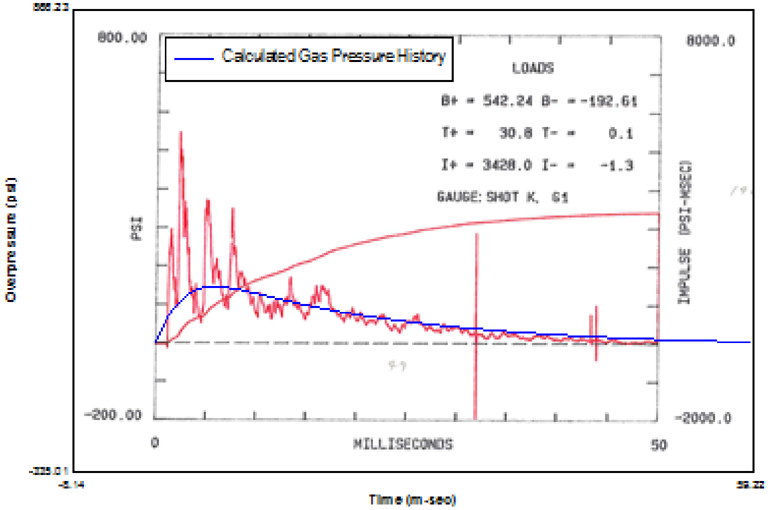
Comparisons of Gas Pressure Histories Calculated with Improved Method vs. Data



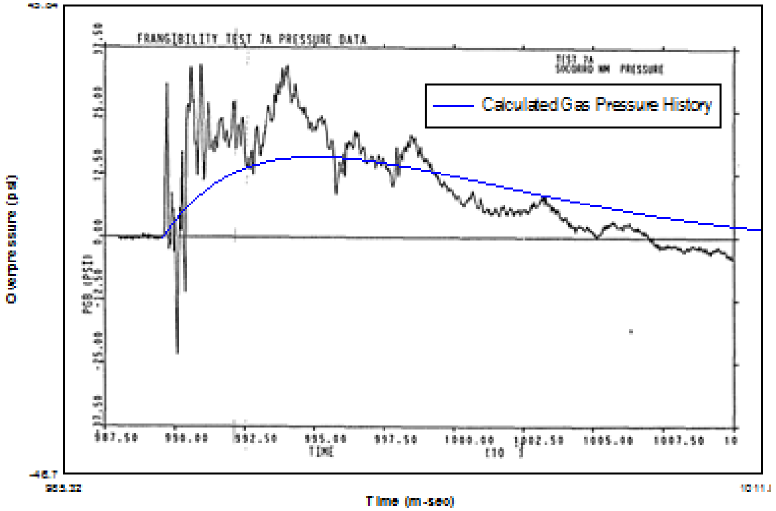
L1 - Ladeburg Test B4E3



M18 - NCEL MTC Test 18



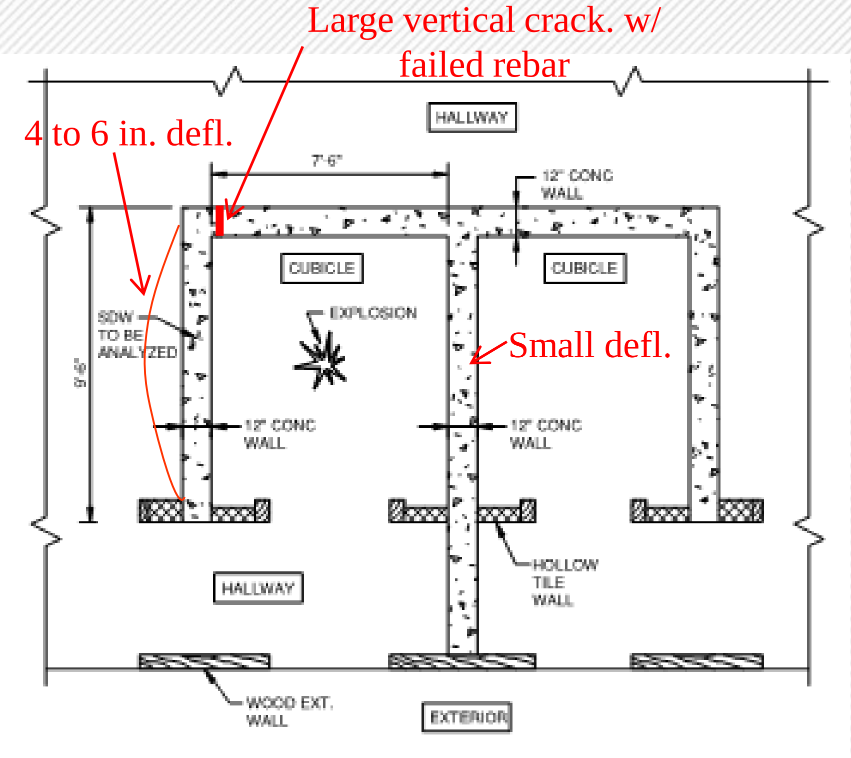
M11 - NCEL MTC Test 11



T7 – NCEL TERA Test 7

Explosion Accident from DDESB

- 8 lb. TNT
- Venting plywood roof and clay tile wall
- Venting through door and failed roof, wall
- 3 ft. high wall parapets above roof
- Heavy damage but no wall failure



Large vertical crack. w/ failed rebar

4 to 6 in. defl.

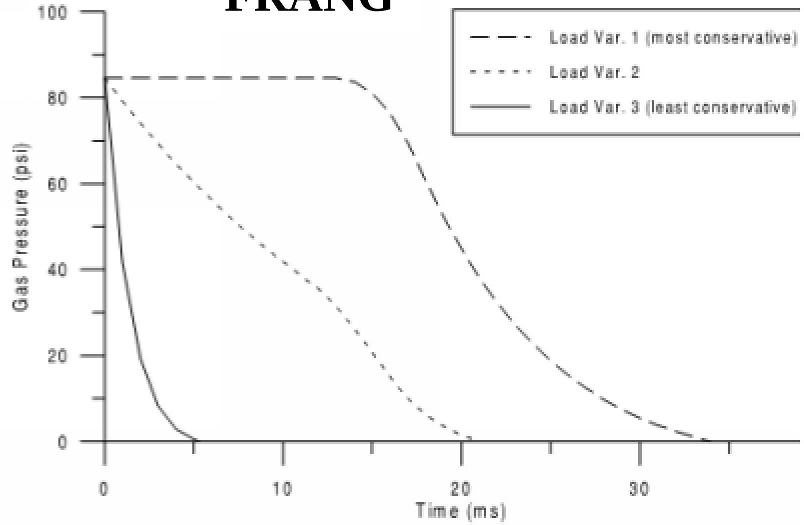
Small defl.

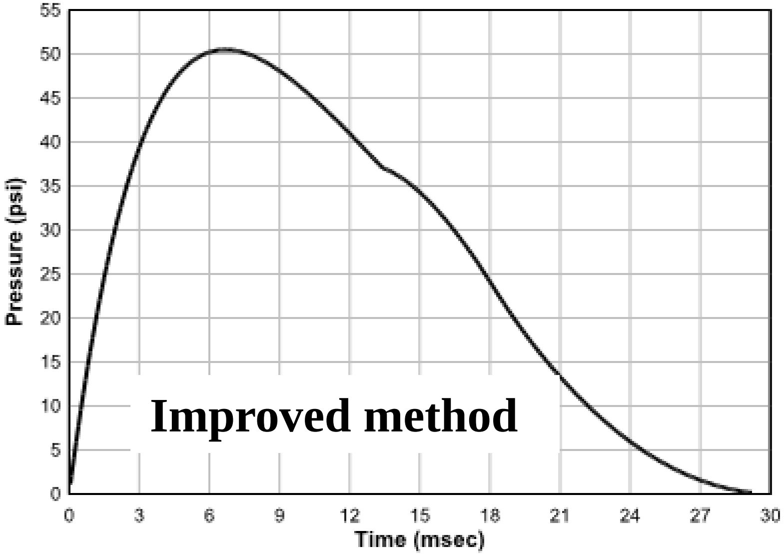
Figure 1. Plan view of cubicle for validation case V-1.

Calculated Results

- Maximum deflection of wall with gas pressure from improved method was 8 inches vs. 70 inches with FRANG
  - Difference is partially due to differing assumptions for boundary conditions of wall

FRANG





Improved method

Protection
Engineering
CONSULTANTS