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

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2025 Internation Explosives Safety Summit and Exposition (IESSE)

January 23, 2026

Improved Gas Pressure Methodology

- ► Gas pressure history must be calculated and added to shock pressure history to determine design blast load from internal detonation
  - Gas pressure loading is often equal or greater than shock pressure loading
- ► In 2020 DDESB funded a large project for gas pressure testing and methodology improvement
  - 2019 study funded by DDESB concluded FRANG significantly overcalculates measured gas pressures for explosion rooms with large vent areas
  - In 2020 gas pressure testing was conducted to provide additional test data for methodology improvement (DDESB tests)

Improved Gas Pressure Methodology

- Fast-running method to calculate gas pressure to replace FRANG code
- Improved method is based in thermodynamics with empirical factors
  - Gas pressure calculated at each time step with ideal gas law
- Improved method is much more accurate than FRANG for tests with large, lightweight vent areas on exterior walls
  - Both methods match test data with very small scaled vent areas well
- Improved method is consistent with the UFC 3-340-02
  - Calculates same fully confined gas pressures as methodology in UFC 3-340-02
  - Analyzes non-TNT charges as TNT except using heats of detonation and combustion from non-TNT explosive

Thermodynamic Equations for Gas Pressure (No Venting)

Mass, Heat of Detonation (H_{det}), and Heat of Afterburning (H_{afb}) for Explosive

Rise Time Equations for Energy from detonation and afterburning, $E_{det}(t)$ and $E_{afb}(t)$

$$\Delta E_{net}(t) = \Delta E_{det}(t) + \Delta E_{afb}(t)$$

Moles of gas (n_g) and Molecular Weight(MW) and composition of products from combustion of equal weight of TNT

Next Δt

Relationship for specific heat (C_v) vs Temp based on C_p curves for each product and relative moles of product ($C_v = C_p - R$)

Temperature (T) Equation with Volume (V) Change

$$T(t) = T(t-1) + \Delta T \quad \text{where } \Delta T = \frac{\Delta E_{net}(t)}{n(t)C_v(T)}$$

$C_v(T)$ = specific heat

Ideal Gas Law to Calculate Gas Pressure (P_g)

$$P_g(t) = \frac{R\, n_g(t) T(t)}{V}$$

R = ideal gas constant

V = volume

Basic Assumptions (No venting)

- Heat of afterburning $H_{afb} = H_{comb} - H_{det}$
  - Available heat energy from afterburning is limited by available oxygen in explosion room
- All explosives modeled as equal weight of TNT to determine molecular products
  - This affects total moles of combusted gas and calculation of specific heat
- Heats of detonation and afterburning dissipate into room volume according to empirical rise time equations to increase gas pressure
  - Heat of detonation is released instantaneously as a point source and dissipates into full volume over rise time
  - Unreacted detonation products distribute within volume and react with oxygen during a longer rise time

Empirical Rise Time Equations

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

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

$E'_{det} = K_{det}(C_w H_{det})$

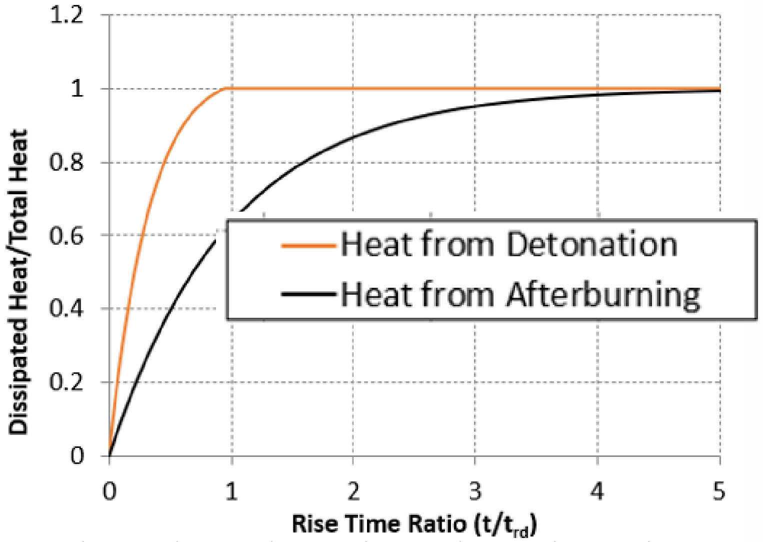
$E'_{afb} = K_{afb}(C_w H_{afb})$

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

$$K_{tr} = \left(\frac{E'_{det}}{E_{amb}}\right)^{\frac{1}{3}} \qquad C_s = \sqrt{\gamma(\gamma - 1)I_{det}}$$

$$I_{det} = \frac{(E_{amb} + E'_{det})}{(M_{air} + M_c)} \qquad E_{amb} = \frac{V_o P_o}{\gamma - 1}$$

$L_{max} = V^{1/3}$



- **Empirical constants**
  - Detonation energy rise time (t_{rd}) is a function of volume, charge weight, and explosive type
  - Afterburning energy rise time (t_{ra}) based on t_{rd} and E'_{afb} relative to E'_{det}
  - Detonation exponent K_{gd} = 2 (controls shape of rise time curve)
  - Afterburning exponent K_{ga} = 1.5 (slightly flatter curve than for detonation energy)
    - This causes $E_{afb}(t_{ra}) = 0.78\, E'_{afb}$
  - $E_{det}(t)$ and $E_{afb}(t)$ are portions of E'_{det} and E'_{afb} that are "converted" into energy dissipated into the overall volume to cause temperature change

Fully Confined Peak Pressure for Non-TNT Explosives

- **Use UFC method to calculate peak gas pressure**
- **Calculate peak pressure with improved methodology**

$$W_{E_g} = \frac{\phi\left[H^c_{EXP} - H^d_{EXP}\right] + H^d_{EXP}}{\phi\left[H^c_{TNT} - H^d_{TNT}\right] + H^d_{TNT}} W_{EXP}$$

Charge Type	Volume (ft³)	Charge Weight (lb)	W/V (lb/ft³)	K_{cw} (ϕ)	H_d (kJ/kg)	H_c (kJ/kg)	TNT Charge Weight (lb)	W_{Eg}/V (lb/ft³)	UFC Pressure (psi)	Calculated Peak Pressure (psi)	Calc/UFC
TNT					4476	14535					
C4	1000	6.93	0.0069	1	5410	10502	5.00	0.0050	56	56.8	1.01
C4	1000	81.65	0.0816	0.23	5410	10502	79.14	0.0791	318	313.4	0.99
C4	1000	206.83	0.2068	0	5410	10502	250.00	0.2500	651	643.3	0.99
PETN	1000	7.94	0.0079	1	6542	9152	5.00	0.0050	56	56.5	1.01
PETN	1000	77.72	0.0777	0.26	6542	9152	79.14	0.0791	318	324	1.02
PETN	1000	171.23	0.1712	0	6542	9152	250.27	0.2503	651	632.3	0.97

Temperature Equations

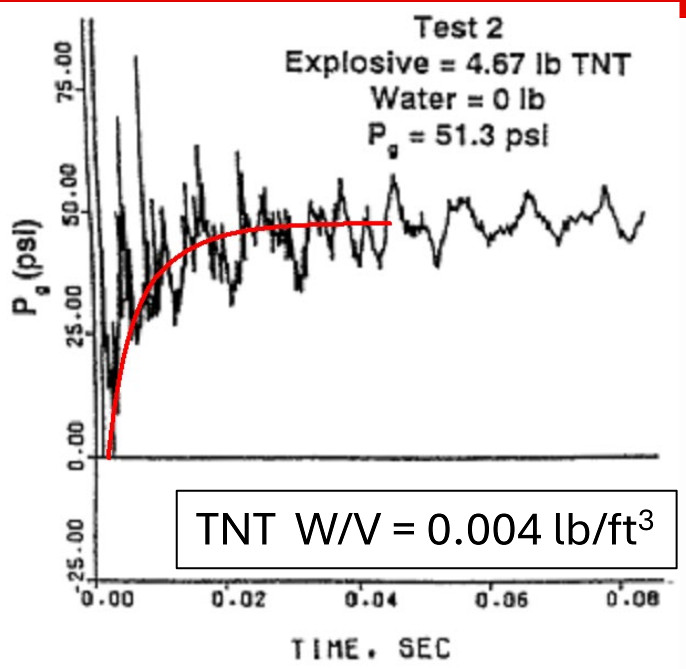
- Temperature is increased at each time step by net energy per unit mass $\frac{\Delta E_{net}(t)}{m(t)}$ added to system and specific heat at constant volume, $C_v(T)$,
  - **Net delta energy (**$\Delta E_{net}(t)$) is from: 1) heat gain from detonation and afterburning based on their rise time curves, 2) heat lost from vented gas, during time step
  - **The specific heat** ($C_v(T)$, is based gas species mole ratios and temperature at previous time step
- Also, the temperature is reduced due to the adiabatic volume increase caused by vent panel displacement at the previous time step (γ = ratio of specific heats)

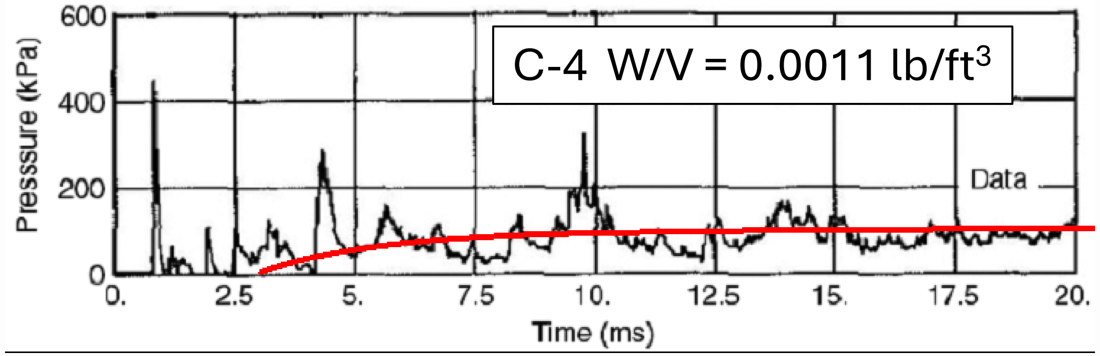
$$T(t) = T(t-1)\left(\frac{V(t-1)}{V(t)}\right)^{\gamma-1} + \frac{\Delta E_{net}(t)}{m(t)C_v(T)}$$

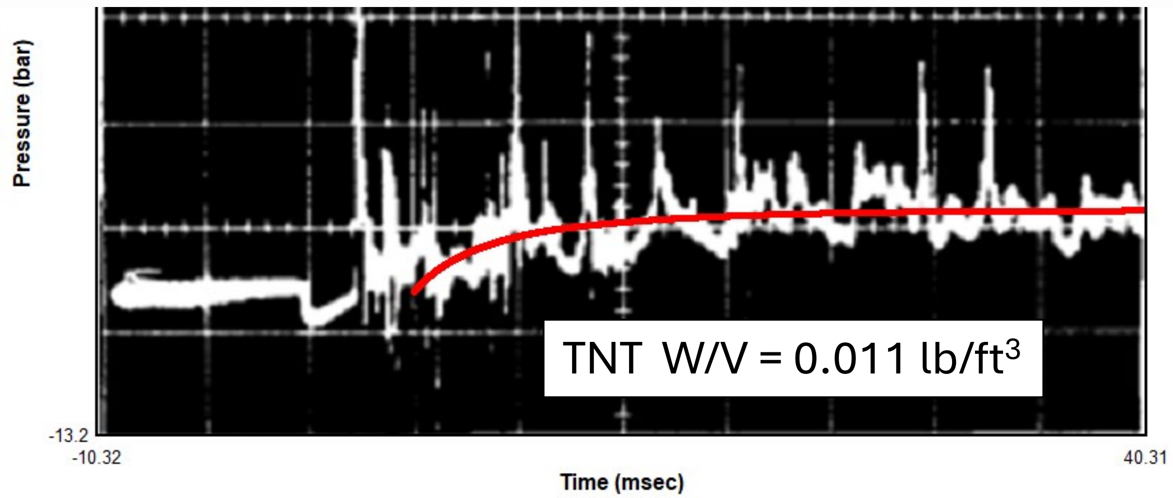
$$\Delta E_{loss}(t) = \frac{\Delta M_{loss}(t)}{MW} C_v(T)T(t)$$

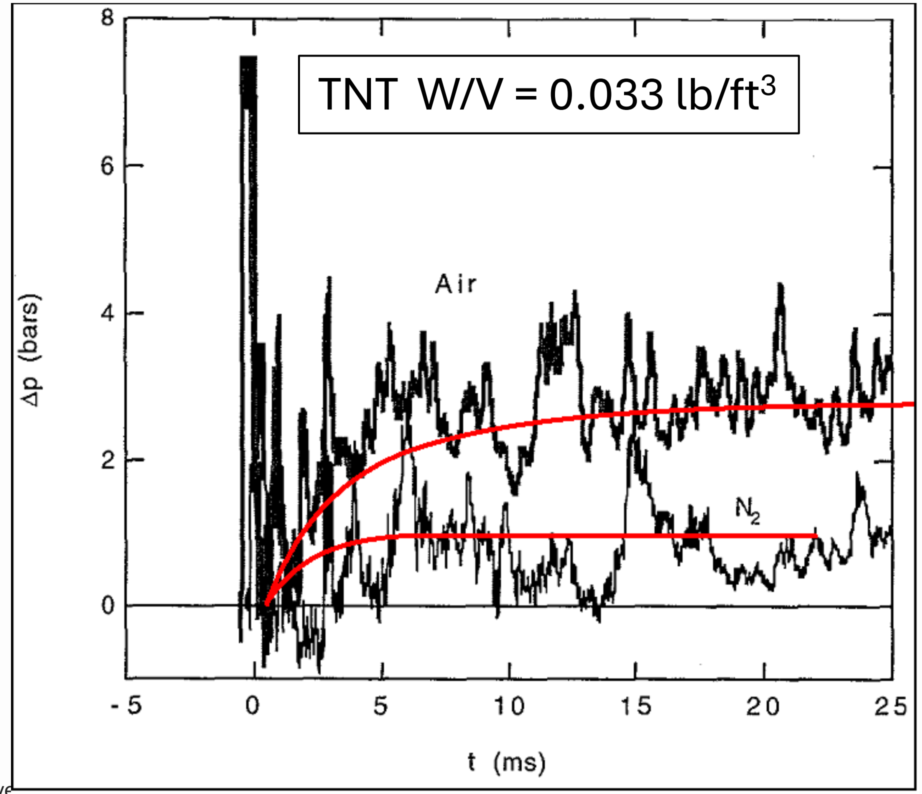
$$\Delta E_{net}(t) = \Delta E_{det}(t) + \Delta E_{afb}(t) - \Delta E_{loss}(t-1)$$

Calculated Rise Time vs. Measured Fully Confined Gas Pressure Tests

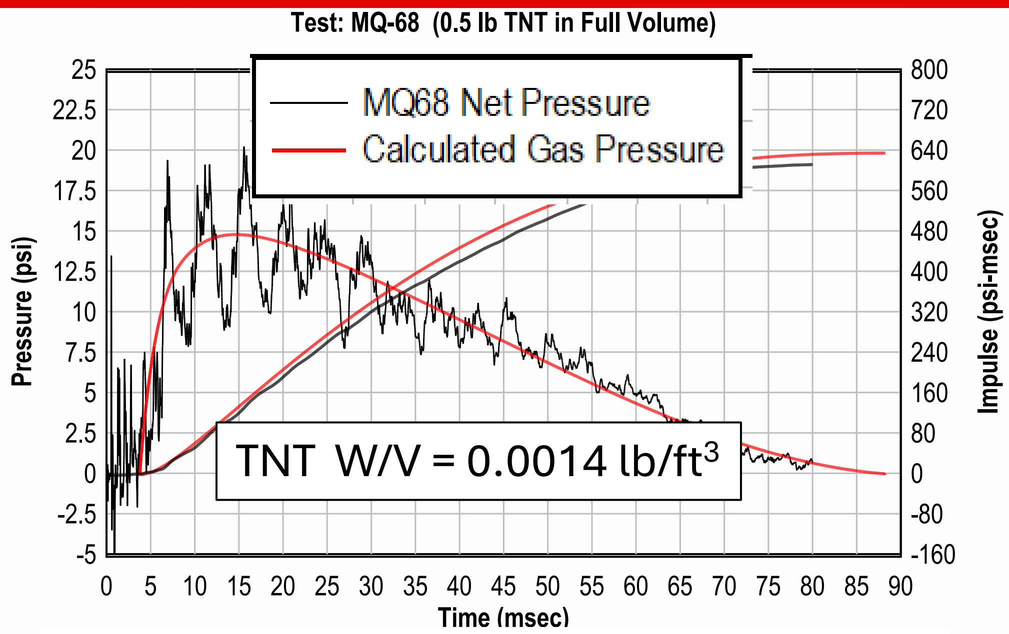


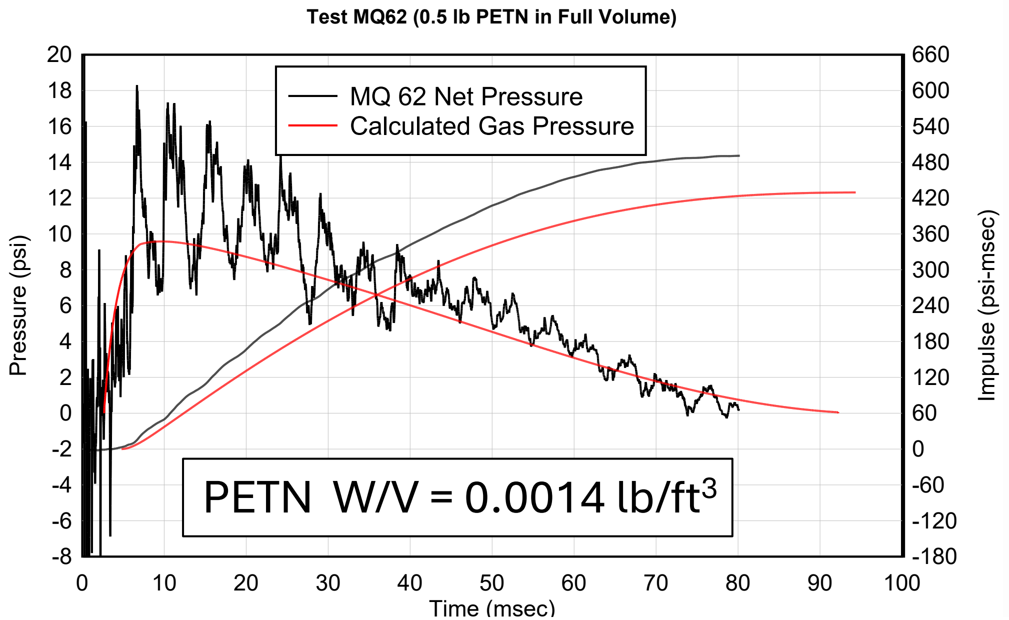


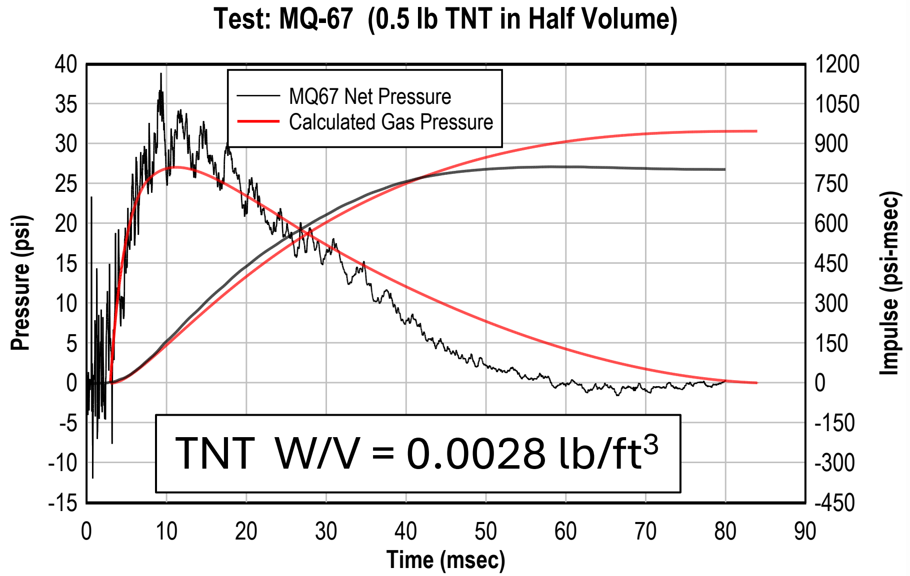


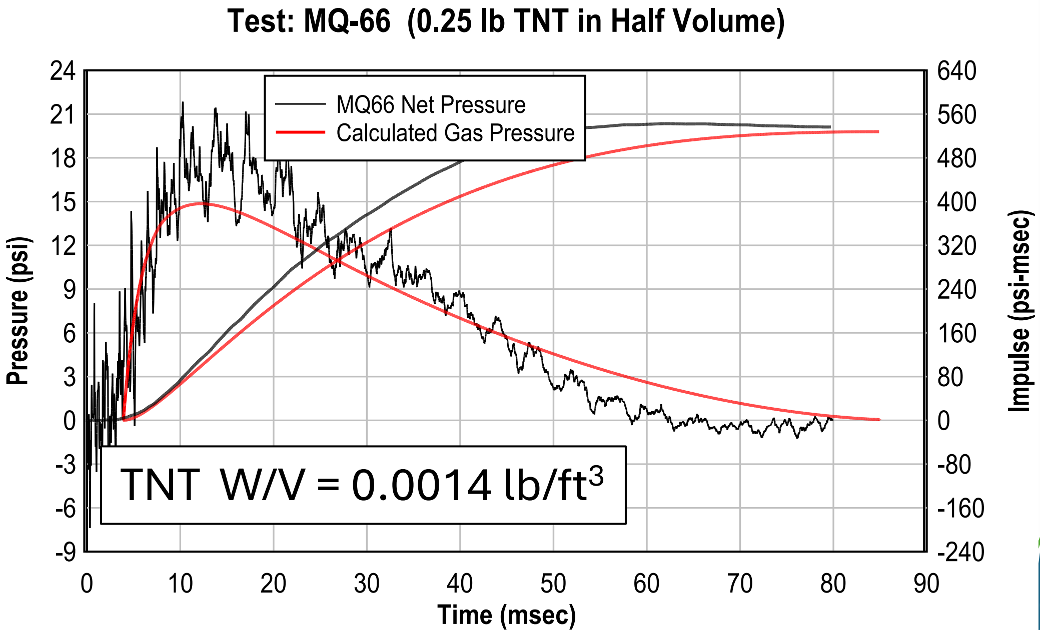


Calculated Rise Time vs. Measured for Confined Gas Pressure Tests (DDESB Tests)









Equations for Venting Through Failing Panel

Mass, Heat of Detonation (H_{det}), and Heat of Afterburning (H_{afb}) for Explosive

Rise Time Equations for Energy from detonation and afterburning, $E_{det}(t)$ and $E_{afb}(t)$

Energy Equation (E)

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

Moles of gas (n_g) and Molecular Weight(MW) and composition of products from combustion of equal weight of TNT

Next Δt

Relationship for specific heat (C_v) vs Temp based on C_p curves for each product and relative moles of product ($C_v = C_p - R$)

Temperature (T) Equation with Volume (V) Change

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

$C_v(T)$ = specific heat

Ideal Gas Law to Calculate Gas Pressure (P)

$$P_g(t) = \frac{R\, n_g(t)T(t)}{V_{eff}(t)}$$

Reduced Gas Pressure (P_{gr}) in Extended

$$P_{gr} = (P_g - P_{air})K_{rp} + P_{air} \qquad K_{rp} = \left(1 - \frac{0.5H(t-1)}{H_{crit}}\right)$$

Vent Displacement, d(t) and H(t)

$$d(t) = \iint \frac{(P_{gr} - P_a)}{m_{vp}} - m_{vp}g' - P_{drag}$$

$$H(t) = d(t) - t_w$$

Vent Area (A_v) Equation

$$A_v(t) = A_{vper} + A_{vdf}(t) \qquad A_{vdf}(t) = d(t)\sqrt{A_{vp}K_{df}}$$

Volume (V) Equation

$$V_{eff}(t) = V_o + t_w A_c + K_{rp}(t)H(t)A_c$$

Isentropic Flow Equation (Choked or unchoked)

$$\Delta M_{loss} = f\left[\frac{P_{gr}}{P_{air}}, \rho(t), A_v(t), C_d\right]$$

Vented Combustion Products

$$\Delta E_{AfbVent}(t) = \frac{\Delta M_{loss}(t)}{M(t)}\left(E'_{afb} - E_{afb}(t) - E_{AfbVent}(t-1)\right)$$

Vented Energy Loss

$$\Delta E_{loss} = \frac{\Delta M_{loss}}{MW} C_v(T)T(t)$$

Update mass M(t) and moles of gas m(t)

$$M(t) = M(t-1) - \Delta M_{loss}(t)$$

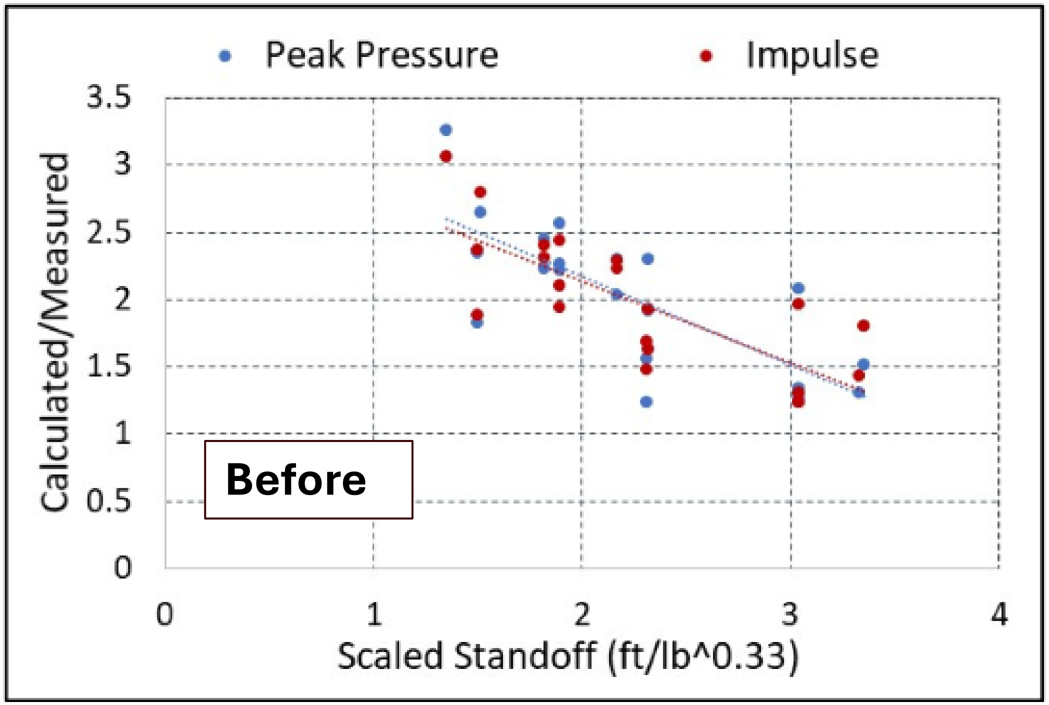
$$m(t) = m(t-1) - \frac{\Delta M_{loss}(t)}{MW}\frac{m_g}{m_{prod}}$$

Equations for Venting at Each Time Step

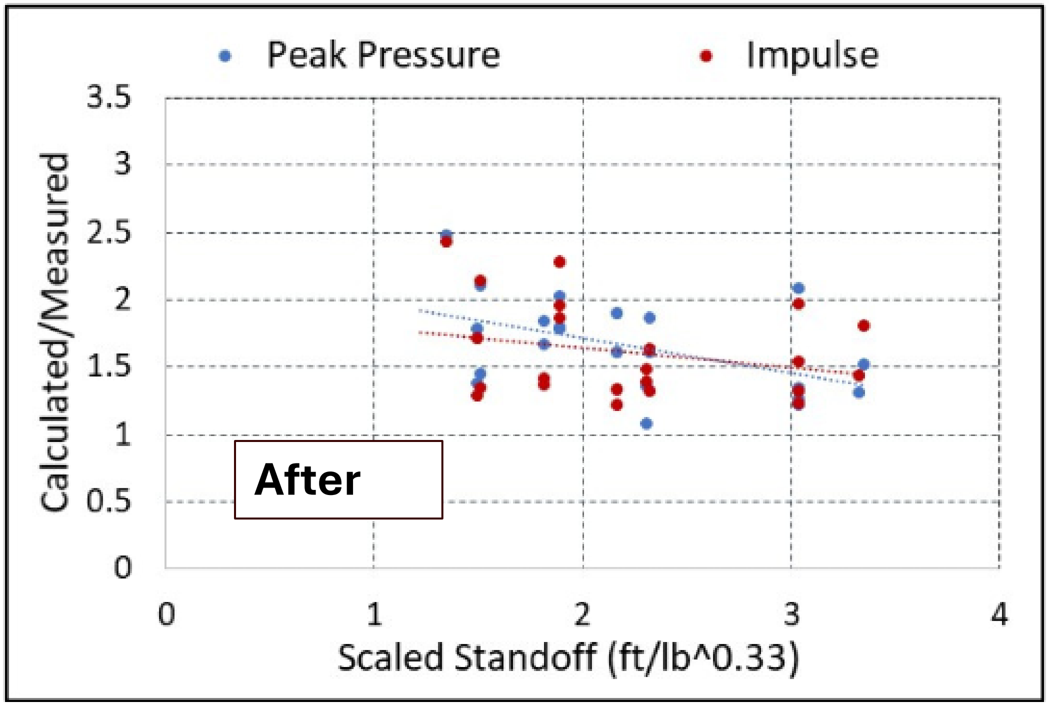
- Mass of pressurized gas outflow through vent area at each time step calculated with isentropic flow equation through a nozzle
  - Relates mass outflow to pressure and gas density in the volume and the flow area (vent area)
  - Empirical discharge coefficient of 0.6 accounts for turbulence at nozzle reducing flowrate
- Calculated vent area around/through vent panels
  - Perimeter vent area created by vent panel movement away from explosion room
  - Additional vent area calculated through “fractured” panels that increases with vent panel movement away from explosion room
  - Panels are considered fractured to varying extent if center of panels at close-in standoff < 3 $ft/lb^{1/3}$ to charge and panel mass per unit area < 6 psf

Method to Calculate Additional Vent Area

- Empirical method for additional vent area through fractured vent panel was developed to improve calculated/measured gas pressure
  - Improved method was developed initially without vent area through panels



a) Before Vent Area Through Damaged Vent Panel



b) After Vent Area Through Damaged Vent Panel

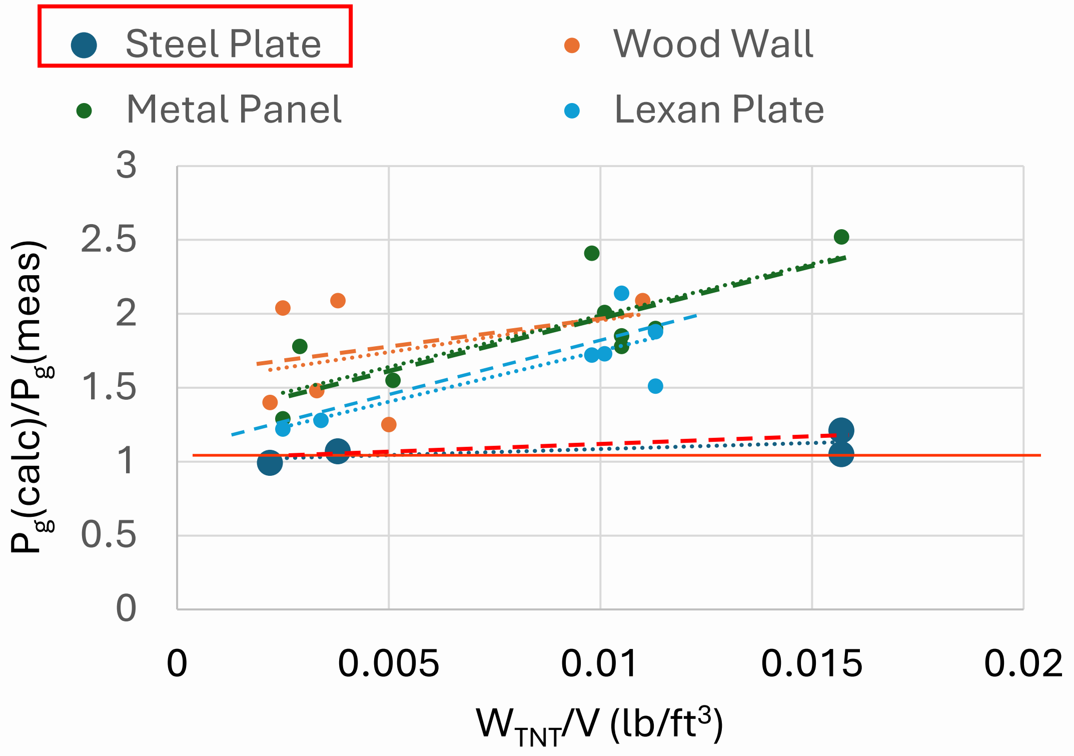
Additional Complexities for Modeling Venting

- "Effective" volume of explosion room increases with vent panel displacement
  - Effective volume is used in ideal gas law at each time step to calculate gas pressure
- A reduction factor, $K_{rp}(t)$, is used to determine reduced gas pressure in expanding delta volume (ΔV) created by vent panel movement
  - $K_{rp}(t)$ is an empirical factor based on lower measured gas pressure nearest the vent panel in 12 tests
  - Reduced gas pressure in ΔV reduces venting through vent area of failed vent panel
- $K_{rp}(t)$ also reduces ΔV added into "effective" volume at each time step
  - $K_{rp}(t)$ =1 initially and then reduces with increasing vent panel displacement
  - $K_{rp}(t)$ only affects ΔV(t) added to volume at each given time step
- Maximum vent area for each vent panel equals area of panel
  - All additional volume from vent panel movement deleted from room volume at time step when this occurs w/ no change in density or temperature in explosion room

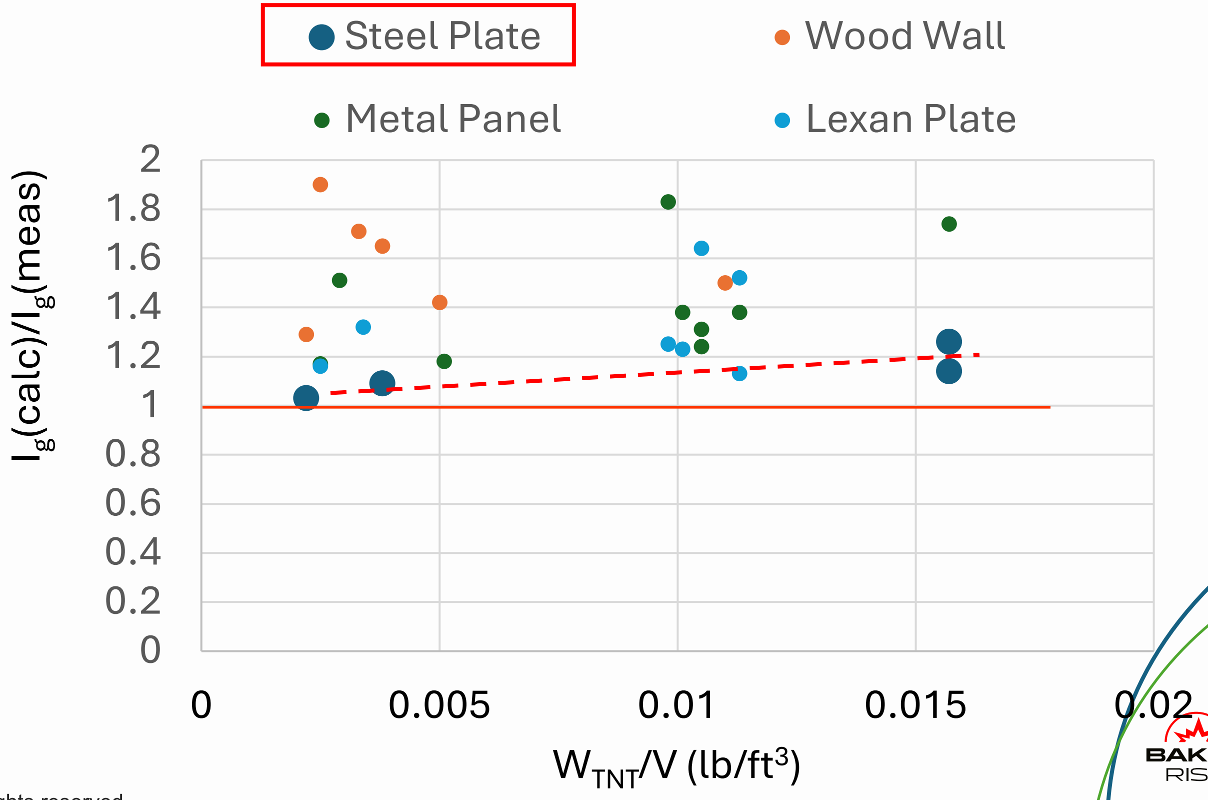
DDESB Tests (Single Vent Surface) – Calc/Meas Gas Pressure

- **Calculated gas pressure conservative compared to curve-fits to net pressure by ratios of 1.0 to 2.0**
  - No evident trend related to vent panel type
  - Peak gas pressure conservatism increases with W/V (and $R/W^{1/3}$) <u>for panels with breakup</u>

Peak Gas Pressure

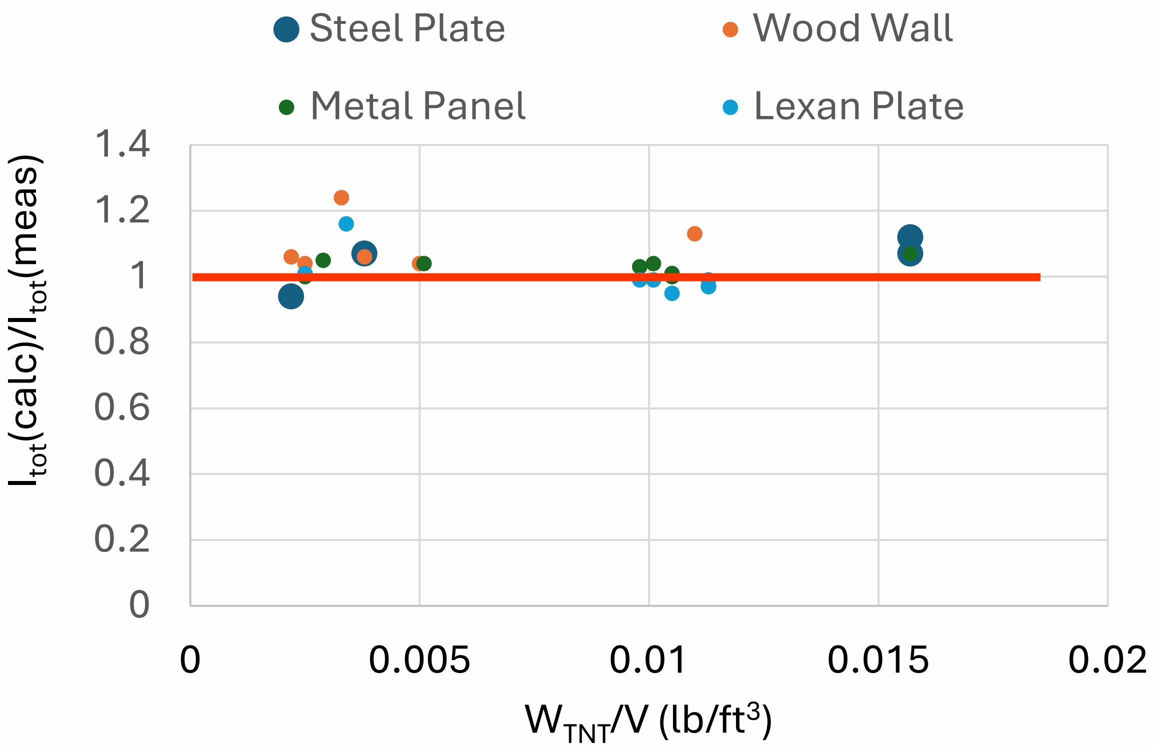


Gas Pressure Impulse



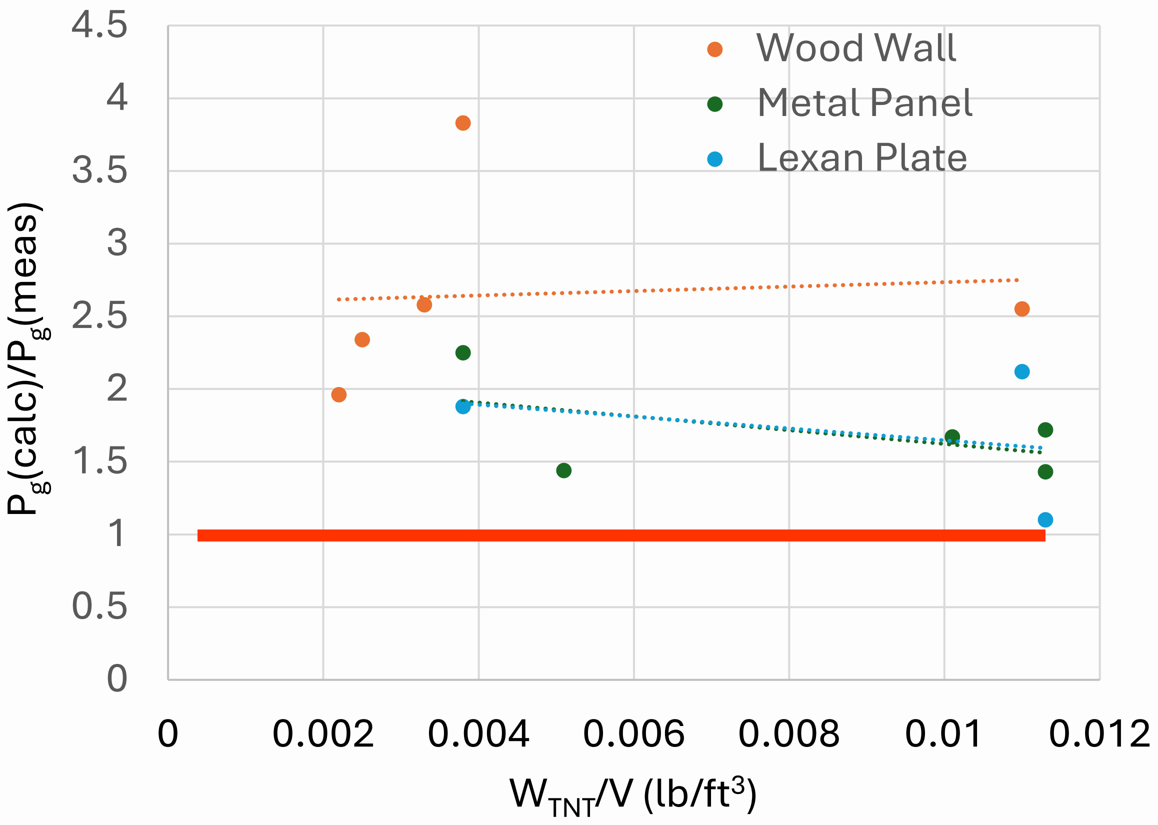
DDESB Tests (Single Vent Panel) – Calc/Meas Total Impulse

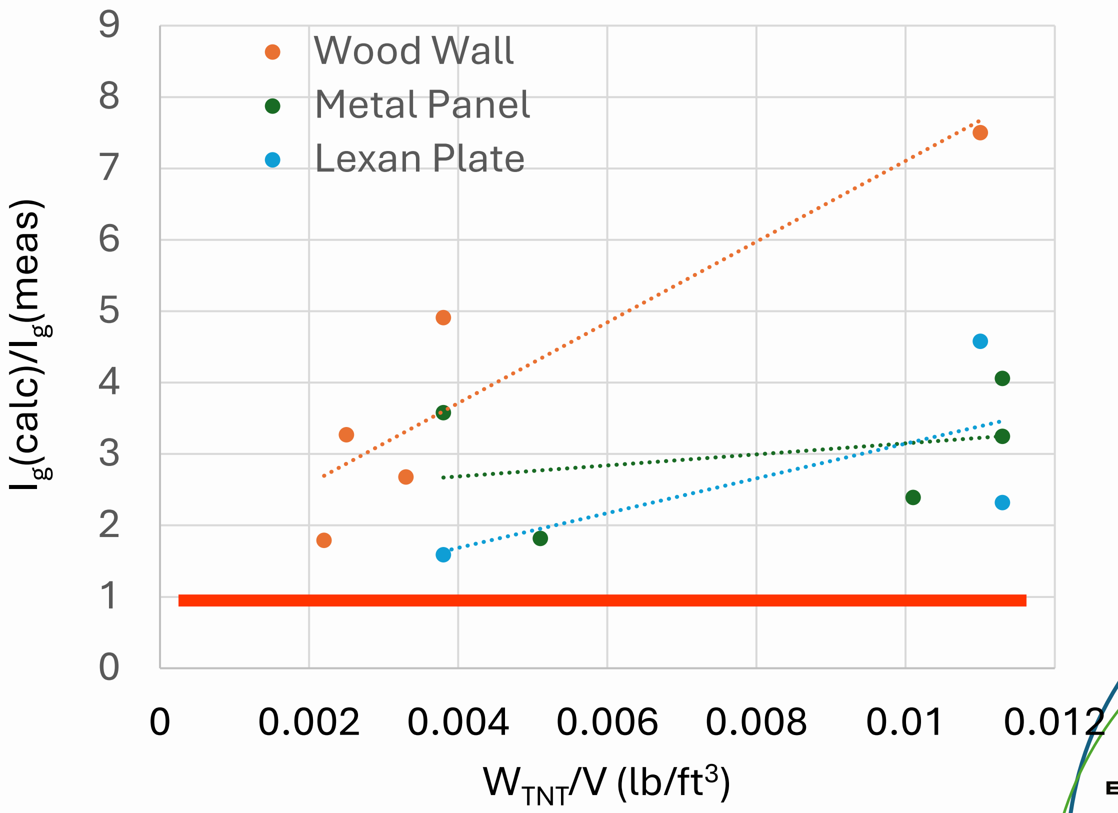
- **Total** measured impulse compared to calculated shock + gas impulse
  - Average **calculated shock pressure at gages** with SHOCK code **+ calculated gas impulse** with Improved Methodology
  - Calculated total impulse is conservative by lesser ratios than gas impulse only



DDESB Tests (Two Vent Panels) – Calc/Meas Gas Pressure

- Much more conservatism in methodology compared to measured gas pressure for two vent panels than for one vent panel
- "Measured" gas pressure for these tests was difficult to identify from test data

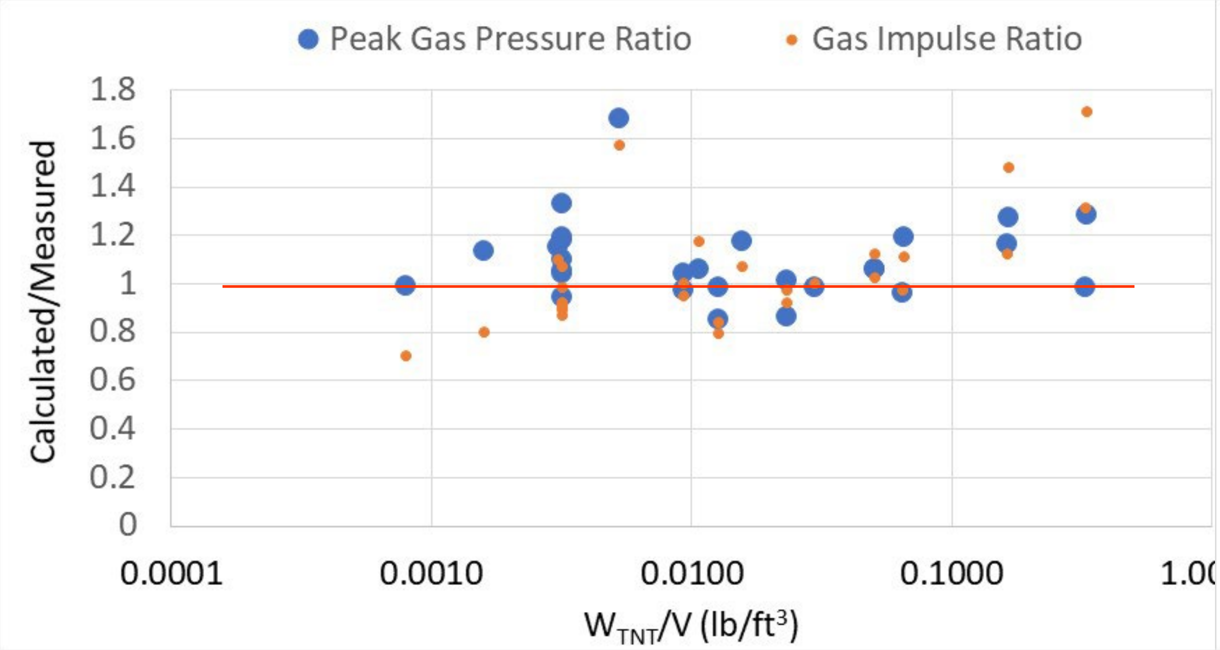




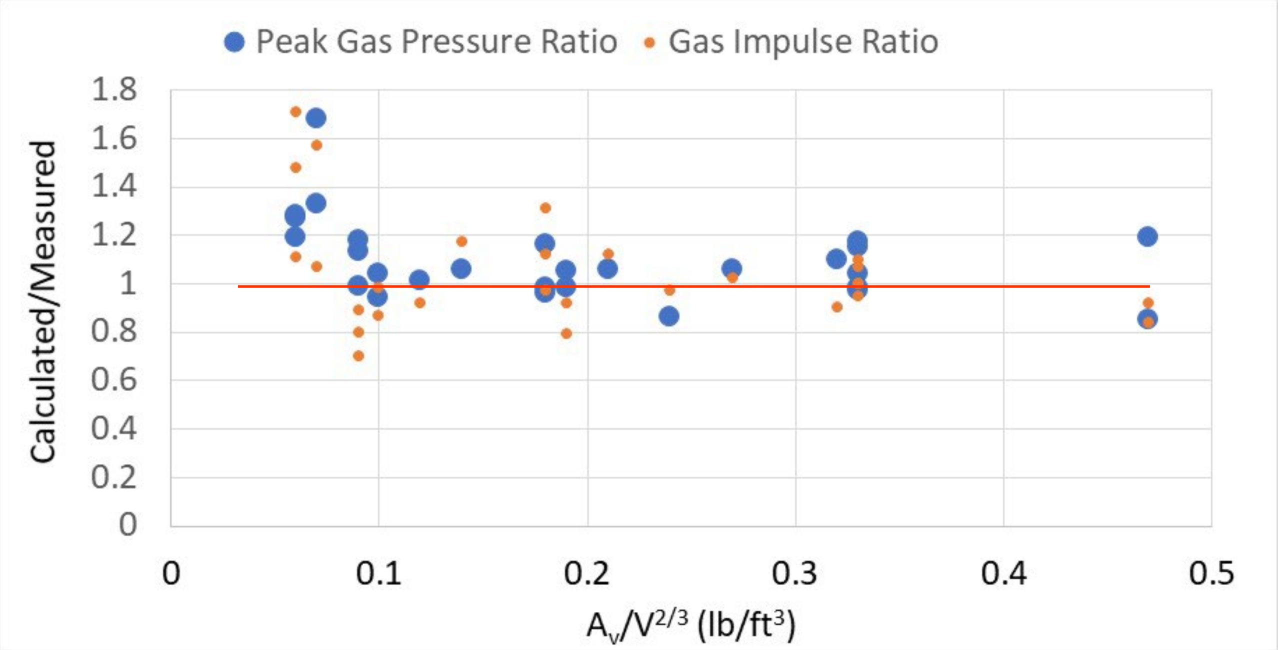
Previous Tests with Uncovered Vent Areas

- Test charge weights include TNT, Pentolite, Comp B, C-4
- Peak gas pressures compare well with some apparent non-conservatism for impulse
  - Measured gas pressure impulse includes some shock pressure based on measured high amplitude, short duration pressure spikes in measured pressure histories

Comparing Calc/Meas vs. Loading Density



Comparing Calc/Meas vs. Scaled Vent Area



Comparison of Improved Method to FRANG

- Improved method calculates 30% to 50% of peak gas pressure and 25% to 40% of impulse compared to FRANG for DDESB tests with one vent panel
  - More reduction with increasing W/V and lower vent panel mass
  - All cases have large covered vent area with $A/V^{2/3} = 1.0$
- The difference is less, but still significant, for case of heavy steel vent panel