Blast Load Prediction for Deflagration of Low Explosives in Confined Concrete Structures

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Motivation

- **According to ACI 370R-14,** when design of concrete structures involving containment of internal explosion effects, both shock waves and gas pressures should be considered. For high explosives (HE) detonations, the empirical relationships in **UFC 3-340-02** are used. Logically, the TNT equivalencies for low explosives (LE) (e.g., propellants and pyrotechnics) are used in some cases to predict the internal gas pressure-time histories, as mentioned in Section 5.2.2 of ACI 370R-14.

- The confined burns of LE in a confined concrete structure without venting generates deflagration (instead of detonation) so that the gas pressures can last tens of minutes. Thus, **dynamic design for HE is not applicable for LE.**

- The confined burns of LE in a confined concrete structure without venting involve complex convective combustion processes where chemical / combustion and aerodynamic experts should play an important role in predicting gas pressures.

- **TNT equivalencies do not work for LE.**

Table of Contents

Hazard Classification

Hazard Class	Material
Class 1	Explosives
Class 2	Gases
Class 3	Flammable liquids
Class 4	Flammable solids
Class 5	Oxidizing substances and organic peroxides
Class 6	Toxic and infectious substances
Class 7	Radioactive materials
Class 8	Corrosive substances
Class 9	Miscellaneous dangerous substances and articles

Hazard Classification (cont.)

Hazard Division	Hazard Type
1.1	Mass explosion
1.2.x	Non-mass explosion, fragment producing
1.3	Mass fire, minor blast or fragment
1.4	Moderate fire, no significant blast or fragment
1.5	Explosive substance, very insensitive (with mass explosion hazard)
1.6	Explosive article, extremely insensitive (no mass explosion hazard)

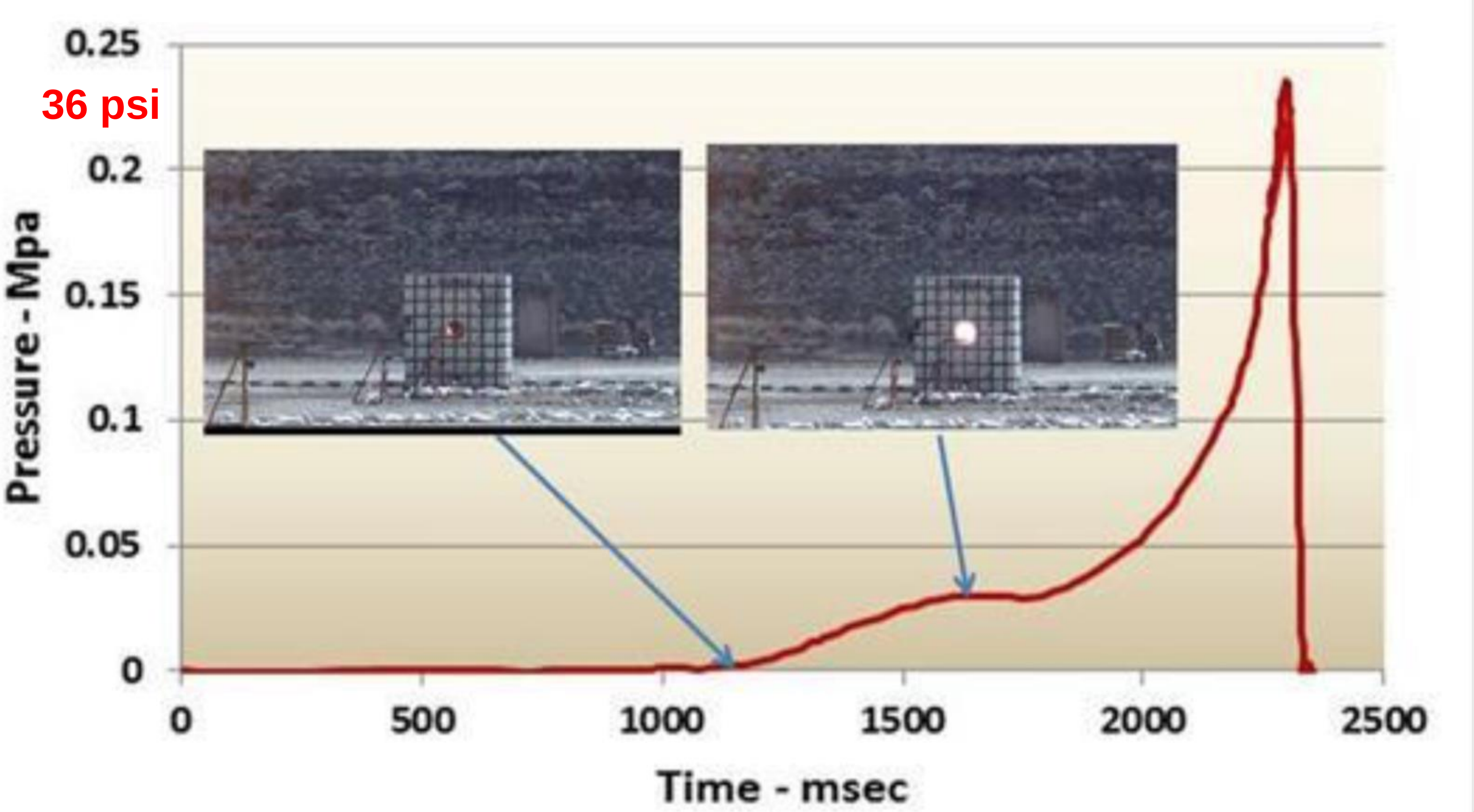
Low Explosives (LE) (HD 1.3)

- Fire (thermal) stimulus is the primary cause in 75% explosives-related accidents from 1900 – 2012.

- HD 1.3 substances and items account for approximately 11% by weight in the U.S. Navy inventory (2010).

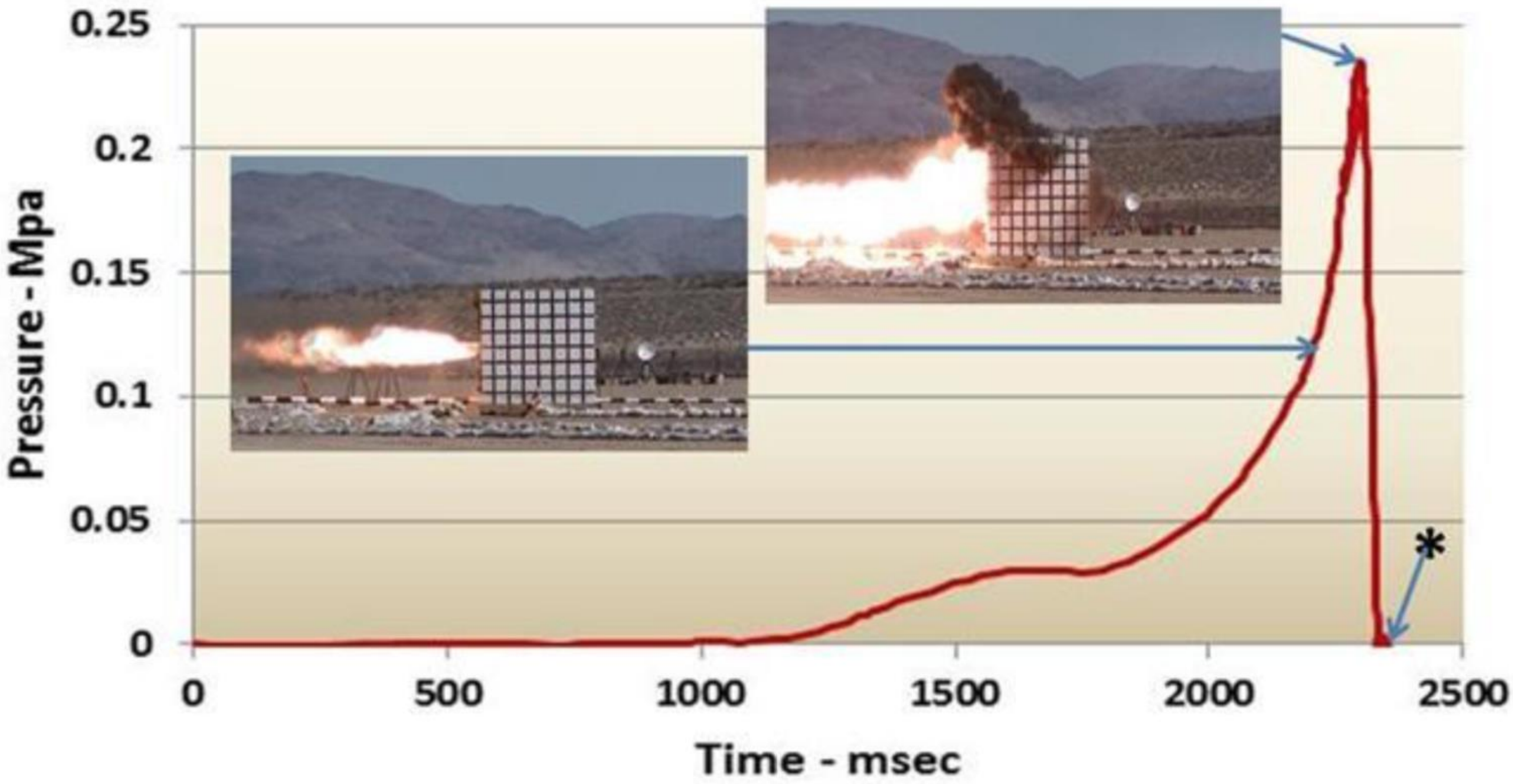
- The burning of LE (HD 1.3) substances and items is different from the detonation of HE (HD 1.1).

Internal Pressure – Time History (Concrete Structure)



Internal Pressure – Time History (Concrete Structure) (cont.)

36 psi



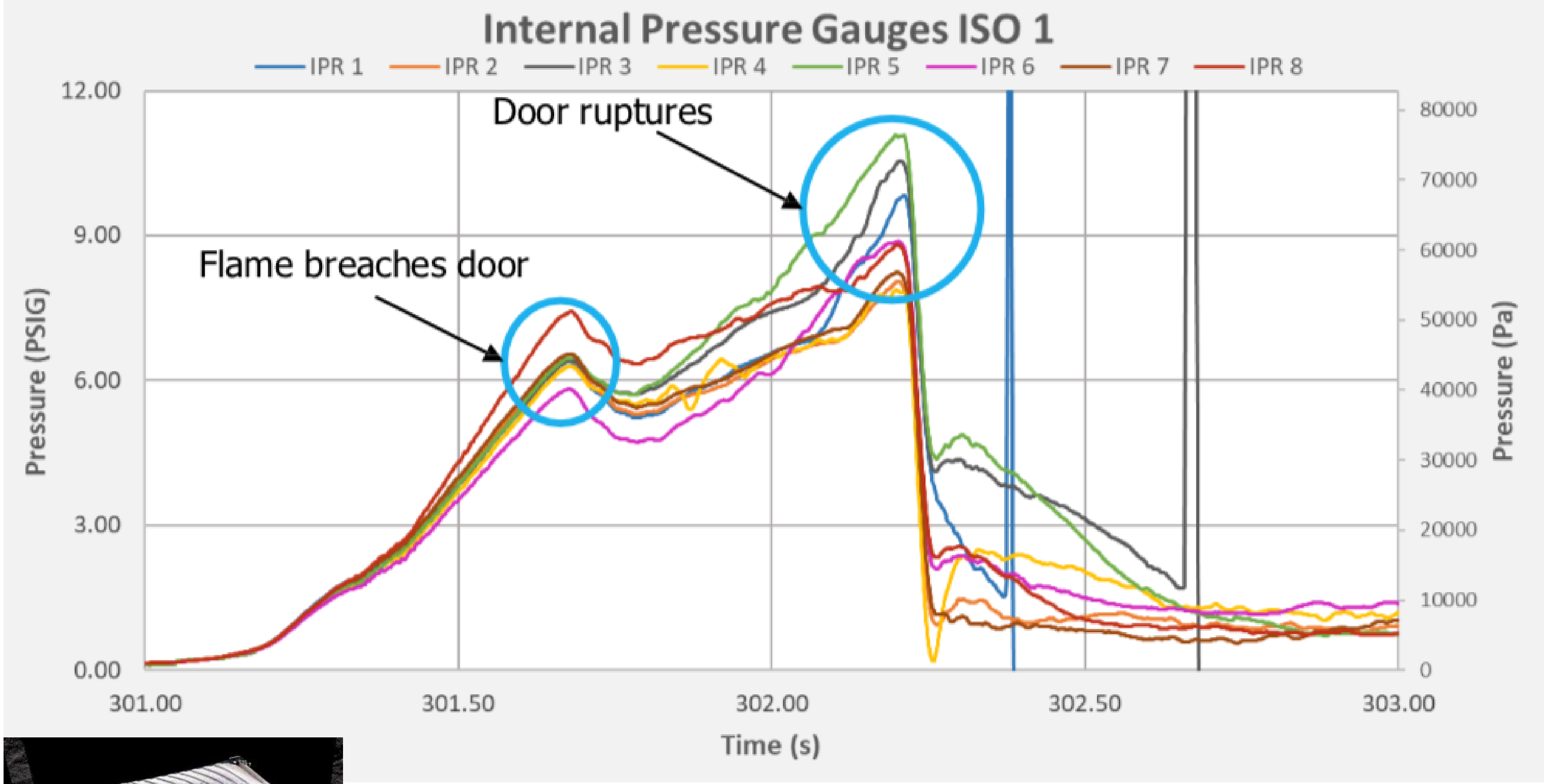
Internal Pressure – Time History (Steel ISO Container)

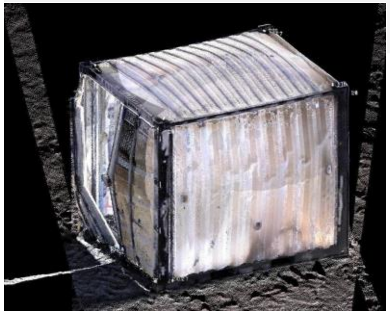
- Burn down (27 s post initiation)

- Flare up (39 s post initiation)

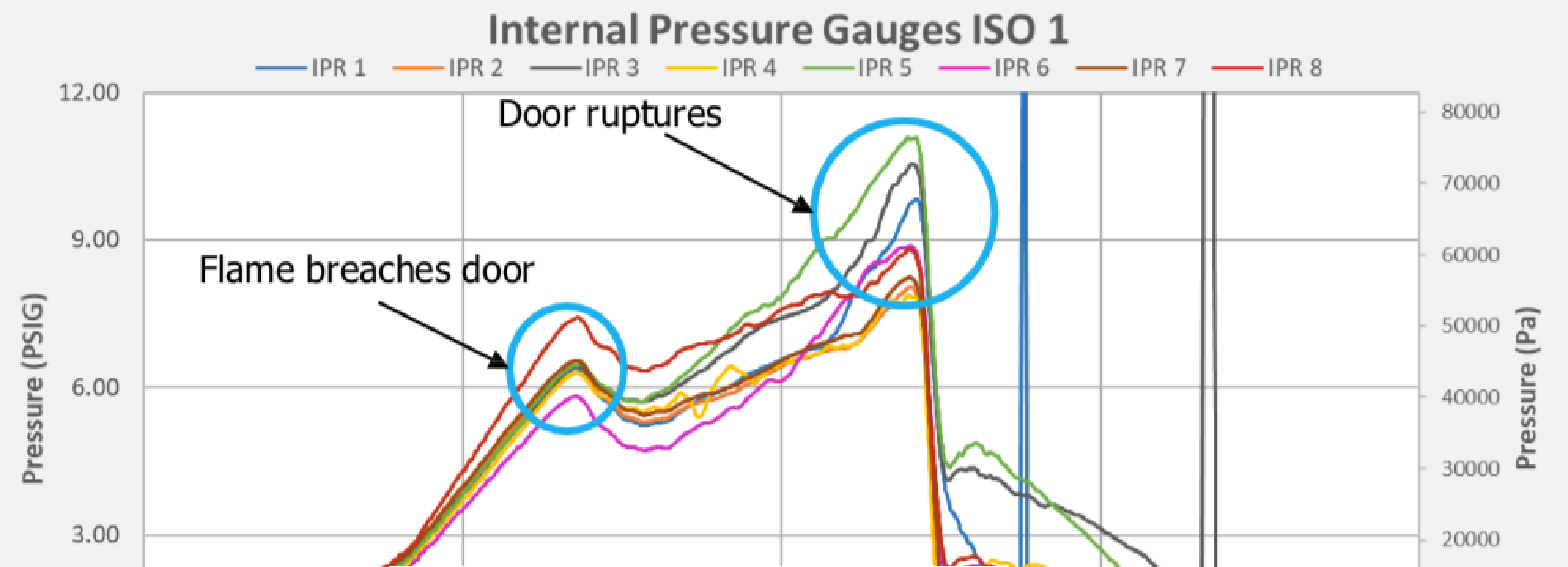
- Large 2nd jet plume (55 s post initiation)

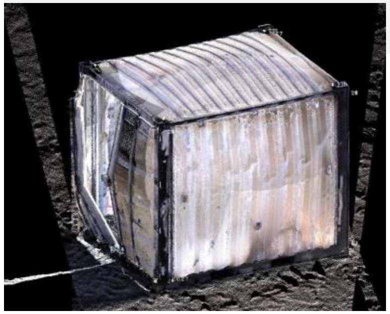
Internal Pressure – Time History (Steel ISO Container) (cont.)





Internal Pressure – Time History (Steel ISO Container) (cont.)





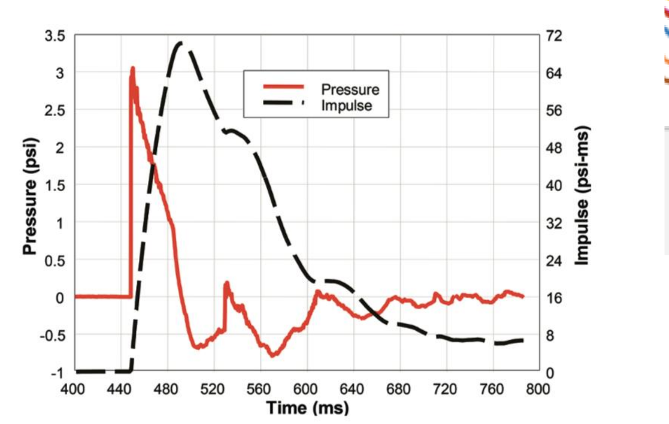
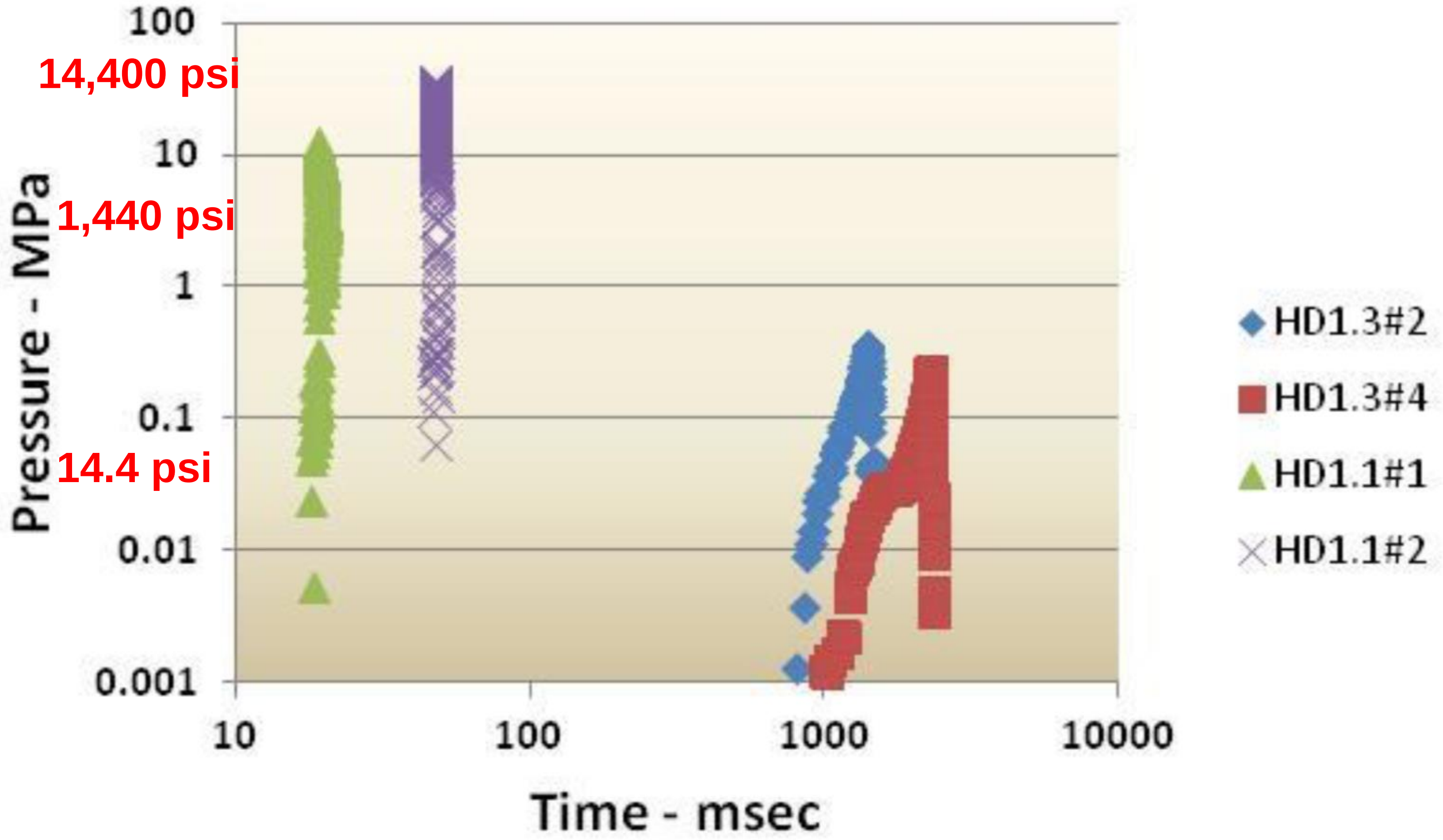
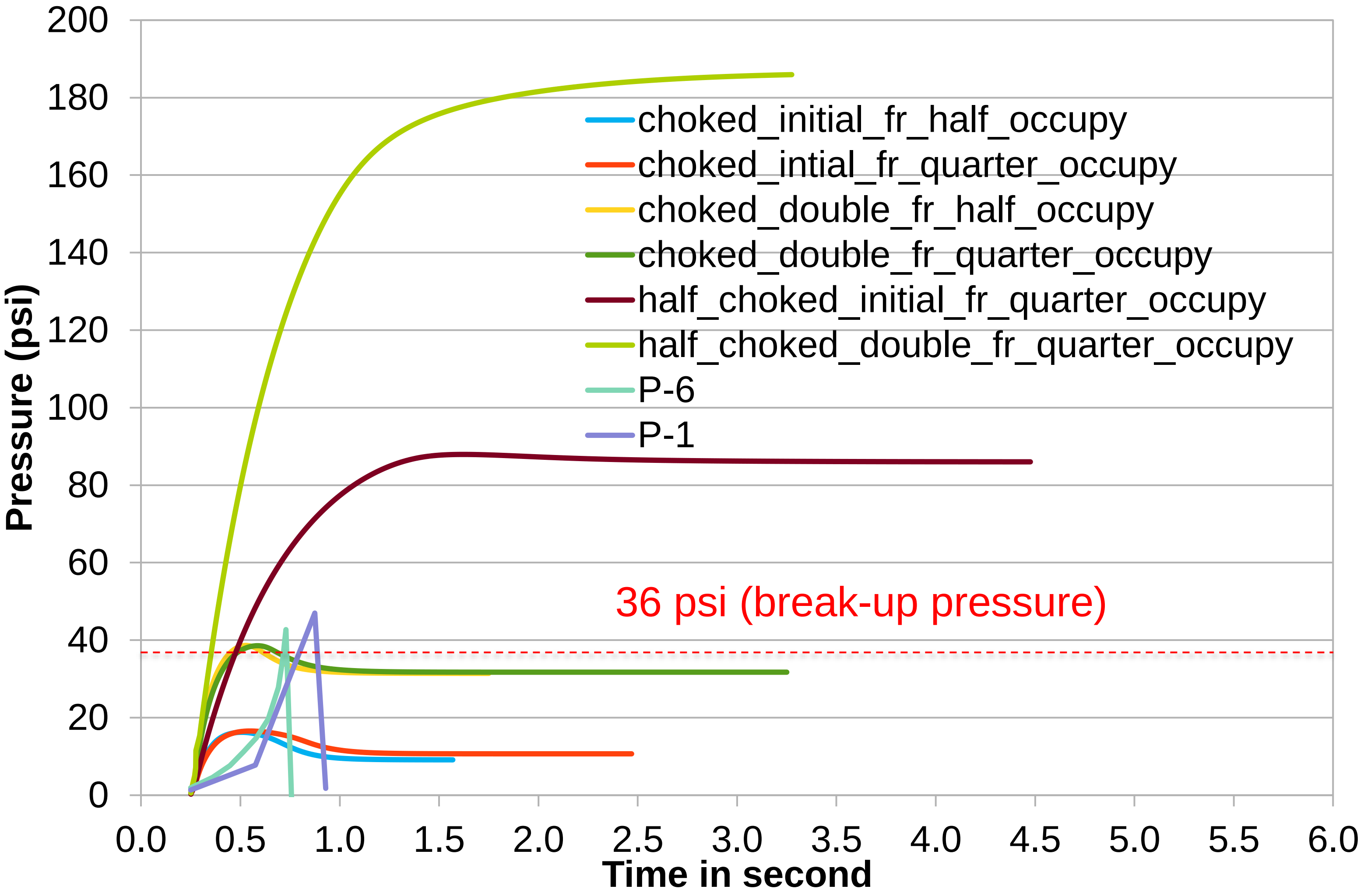


Fig. 5.1.1—Pressure transducer trace from high explosive detonation (UFC 3-340-02). (Note: 1 psi = 6.895 kPa.)

HD 1.3 Deflagration vs. HD 1.1 Detonation



Computer Modeling of Internal Pressure (Concrete Structure)



Fast Running Model (Ideal Gas Law) without venting

When W (in kg) HD 1.3 burning in a confined structure (V in m^3) without venting

$$\mathbf{P_{internal}\ V / T_v = 1\ atm.\ (W\ G) / 273K}$$

where internal temperature T_v = 500K or 227 ℃ or 440 ℉
for concrete structures
1,600K or 1,327 ℃ or 2420 ℉
for steel ISO containers

G (Average Grain Mole) = 39 moles of Gas per kilogram (STP)
G (M1 propellant)= 45 moles of Gas per kilogram (STP)

Fast Running Model (Ideal Gas Law) without venting (cont.)

$P_{internal}$ (in atm.) = W/V (39 moles) (0.0224 m^3/mole) (500K/273K) = $1.61D_{atm}$

where D_{atm} = Loading Density = W / V in kg/m^3.

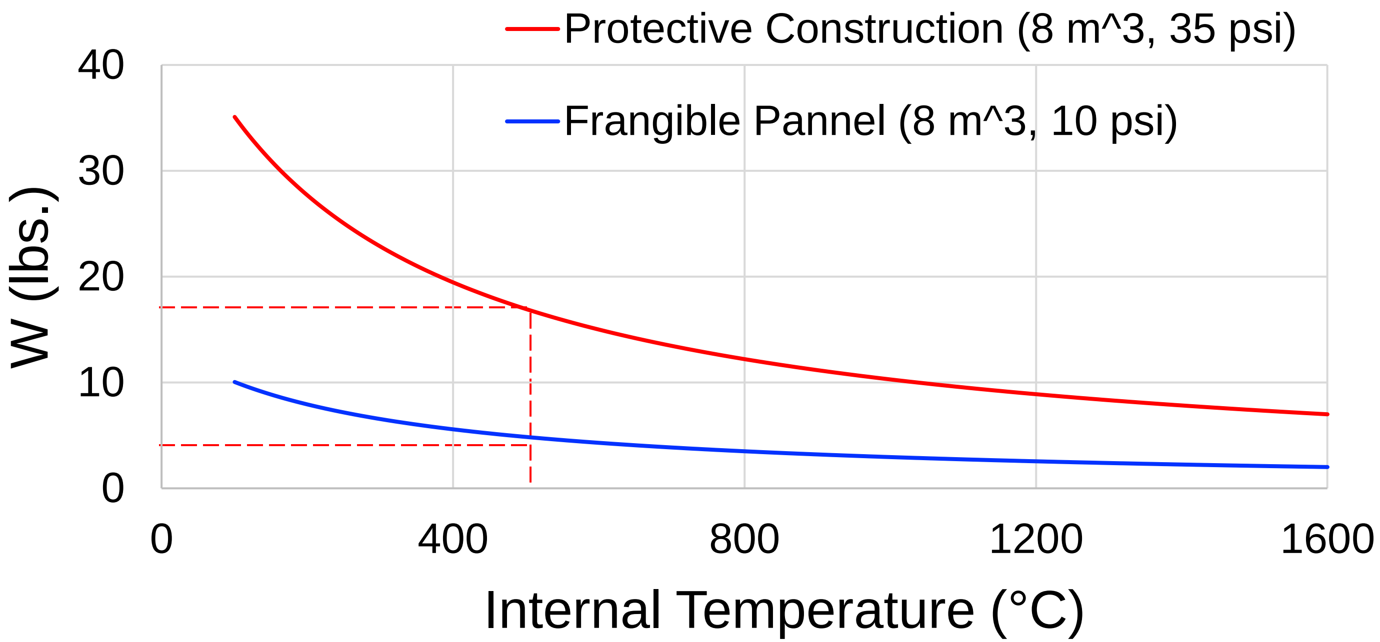
For the break-up (rupture) pressure of a concrete structure, $P_{rupture}$ (e.g. 36 psi for concrete structures)

$P_{rupture}$ (psi) / 14.7 (psi / atm) = 1.61 D_{atm} (internal temperature = 500K)

$P_{rupture}$ (psi) = 24 D_{atm} (internal temperature = 500K) = 24 W / V

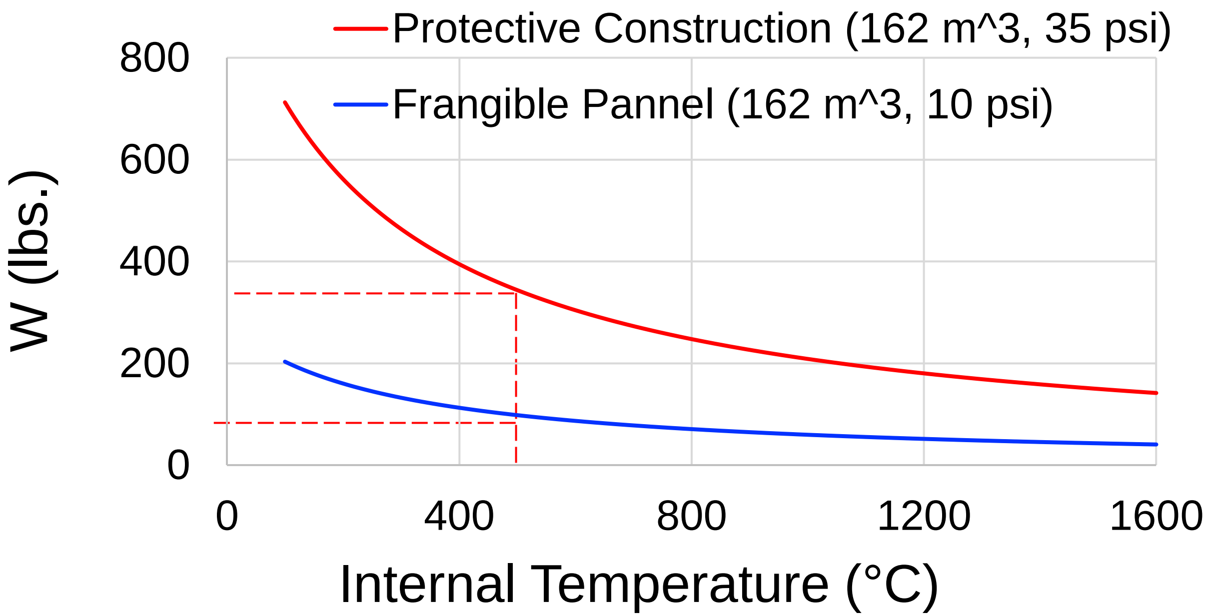
W (max. in kg) = $P_{rupture}$ (psi) V (m^3) / 24 = 0.04 $P_{rupture}$ (psi) V (m^3)

Example (2m x 2m x 2m – 8m^3 Concrete Structure)



If M1 propellant W < 17 lbs. (5 lbs.), no rupture occurs when the internal temperature is less than 500 ℃ or 773K or 932 ℉ and the container's strength is 35 psi (10 psi)

Example (50 ft. x 14 ft. x 8 ft. Earth Covered Magazine, ECM)



If M1 propellant W < 350 lbs. (100 lbs.), no rupture occurs when the internal temperature is less than 500 ℃ or 773K or 932 ℉ and the container's strength is 35 psi (10 psi)

Fast Running Model (Ideal Gas Law) with venting

The gas exit velocity v_{exit} at the venting opens (A_{vent} in m^2)

For un-choked flow, $v_{exit} = \sqrt{\frac{T_v R}{M_w}\frac{2\gamma}{\gamma-1}\left[1-\left(\frac{P_{outside}}{P_{internal}}\right)^{\frac{\gamma-1}{\gamma}}\right]}$

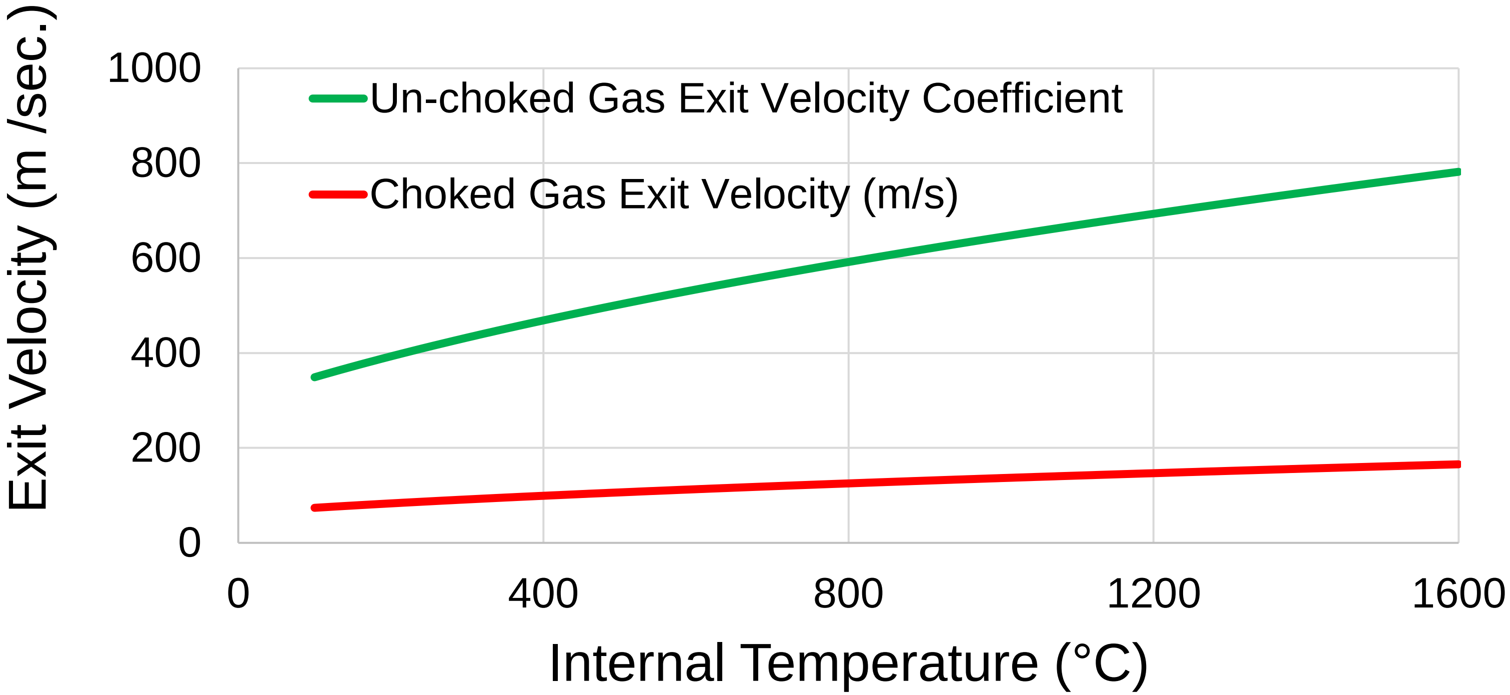
For choked flow, $v_{exit} = \sqrt{\frac{T_v R}{M_w}\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$

v_{exit} = 106 m / sec. (constant) when Tv = 500 ℃

For nitrocellulose based propellants, the ratio of specific heats γ = 1.26, R = 8.3144621 Joules/(mole K), a typical molecular weight M_w = 247 g/mole

For un-choked flow, $v_{exit} = 1{,}113\sqrt{1-\left(\frac{P_{outside}}{P_{internal}}\right)^{0.2063}}$ (m / sec.)

Fast Running Model (Ideal Gas Law) with venting (cont.)



For the un-choked gas exit velocity, only gas exit velocity coefficient is plotted herein. The choked gas exit velocity increases from 74 to 166 m/ sec. when Tv increases from 100 to 1,600 ℃. (e.g., Tv = 500 ℃, a constant of 106 m /sec.)

Pressurization in Confined HD 1.3 Burning with Venting

The gas exit volume V_{gas} during Δt seconds at the venting A_{vent} in m^2

(Tv = 500 °C)

For un-choked flow, $V_{gas} = C_D(A_{vent})\ 502\ \sqrt{1 - \left(\frac{P_{outside}}{P_{internal}}\right)^{0.2063}}\ (\Delta t)$

For choked flow, $V_{gas} = C_D(A_{vent})\ 106(\Delta t) = 68\ (A_{vent})(\Delta t)\ (\mathrm{m}^3)$

where C_D = discharge coefficient (typically 0.64).

$P_{internal}$ (atm.) = $((WG)T_v / 273K - V_{gas}) / V$

$\Delta P_{internal}$ (atm.) = $(\dot{m}(\Delta t)(39\ \text{moles})\ (0.0224\ m^3/\text{mole})\ (773/273) - V_{gas}) / V$

$\Delta P_{internal}$ (atm.) = $(2.47\ \dot{m}(\Delta t) - V_{gas}) / V$ (Tv = 500 °C)

where $\dot{m}(\Delta t)$ is the total mass (in kg.) burning during Δt seconds.

Un-Choked Flow Pressurization (Tv = 500 ℃)

For un-choked flow, $V_{gas} = C_D(A_{vent})\ 502\sqrt{1-\left(\frac{P_{outside}}{P_{internal}}\right)^{0.2063}}\ (\Delta t)$

Let $p_{out/in} = \frac{P_{outside}}{P_{internal}}$, $V_{gas} = 321(A_{vent})\sqrt{1-(p_{out/in})^{0.2063}}(\Delta t)$

$\Delta P_{internal}$ (atm.) $= (2.47\ \dot{m}(\Delta t) - V_{gas})/V$

$= (2.47\ \dot{m}/V - 321\ (\frac{A_{vent}}{V})\sqrt{1-(p_{out/in})^{0.2063}})(\Delta t)$

When $2.47\ \dot{m} - 321\sqrt{1-(p_{out/in})^{0.2063}}(A_{vent}) \le 0$, $P_{internal}$ will not increase.

Thus, A_{vent} (in m²) $\ge 0.0077\dot{m}$ (kg / sec.) / $\sqrt{1-(p_{out/in})^{0.2063}}$

Un-Choked Flow Pressurization (Tv = 500 ℃) (cont.)

By definition of the choked flow, $p_{out/in} \leq \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} = 0.553$

$V_{gas} = 321 \ (A_{vent})\sqrt{1-(0.553)^{0.2063}}(\Delta t) = 109 \ (A_{vent})(\Delta t)$

$P_{internal} = (2.47 \ \dot{m}(\Delta t) - V_{gas}) / V$

$= (2.47 \ \dot{m} - 109 \ (A_{vent}))(\Delta t) / V$

When $2.47 \ \dot{m} - 109A_{vent} \leq 0$, $P_{internal}$ will not increase.

Thus, A_{vent} (in m^2) $\geq$ $0.022\dot{m}$ (kg / sec.) (Tv = 500 °C)

When $p_{outside}$ = 1 atm. $P_{internal} \leq$ 1.81 atm. = 26.6 psi.

Choked Flow Pressurization (Tv = 500 ℃)

For choked flow, $V_{gas} = C_D(A_{vent})\ 106\ (\Delta t) = 68\ (A_{vent})(\Delta t)\ (\mathrm{m}^3)$

$\Delta P_{internal}$ (atm.) $= (2.47\ \dot{m}(\Delta t) - V_{gas})/V = (2.47\ \dot{m} - 68\ A_{vent})\ (\Delta t)/V$

When $2.47\dot{m} - 68\ A_{vent} \le 0$, $P_{internal}$ will no longer increase.

Thus, A_{vent} (in m^2) $\ge 0.036\dot{m}$ (in kg / sec.)

The minimum venting area A_{vent} (in m^2) increases from 0.025 to 0.056 $\dot{m}$ (kg / sec.) when the internal temperature increases from 100 to 1,600 ℃.

Since HD 1.3 burning in a confined concrete structure with venting involves convection and hot gas turbine, $\dot{m}$ varies significantly. The integrated violence models may be used to estimate $\dot{m}$.

Conclusions

- HD 1.3 confined burning in a steel ISO container showed that all of the pressure sensors installed at different locations inside the container recorded the identical pressure-time histories before the container door opened. This indicated that the steel container behaved as a pressurized vessel.

- The internal pressure in a pressurized vessel after stopping the burns lasts much longer than the shock waves and gas pressures after HD 1.1 detonation (minutes or hours vs. milliseconds or seconds). Thus, **the internal pressure caused by HD 1.3 confined burning should be treated as a sustaining load with static approaches instead of dynamic analysis for HD 1.1 detonation in terms of structural design and analysis.**

Conclusions (cont.)

- It is very important to realize that the duration of internal gas pressures due to HD 1.1 detonation is much shorter than those due to HD 1.3 deflagration so that the **TNT equivalences in terms of total energy, impulse, or peak pressure do not work for LE. The energy release rate is a critical parameter.**

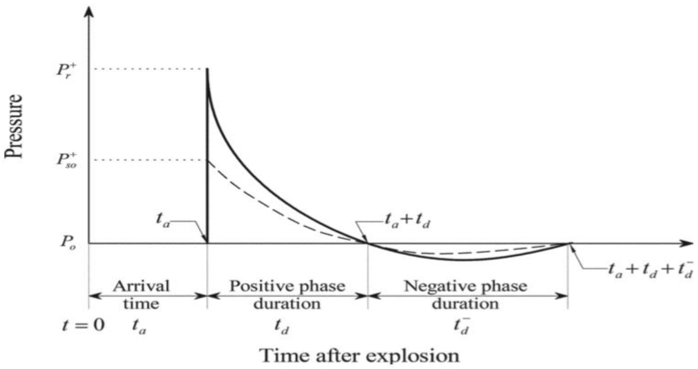
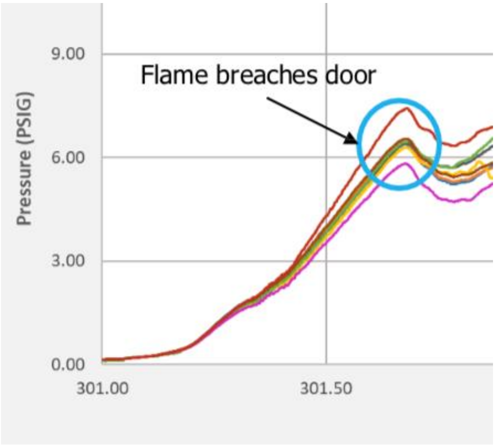
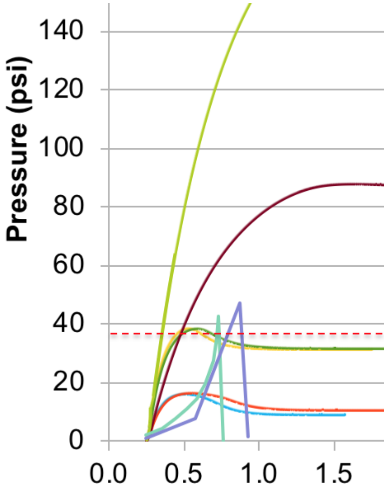


Fig. 5.1.2—Typical side-on pressure-time history for shock loads.





- The required venting area is a function of ṁ. since HD 1.3 burns in a confined container with venting involves convection and hot gas turbine, ṁ varies greatly.

References

Risk Management for Explosives Safety under Uncertainty

Josephine Covino, Ph. D.,
Department of Defense Explosives Safety Board (DDESB)
Alexandria, Virginia, USA

Ming Liu, Ph. D., P.E., F. ASCE (Presenter)
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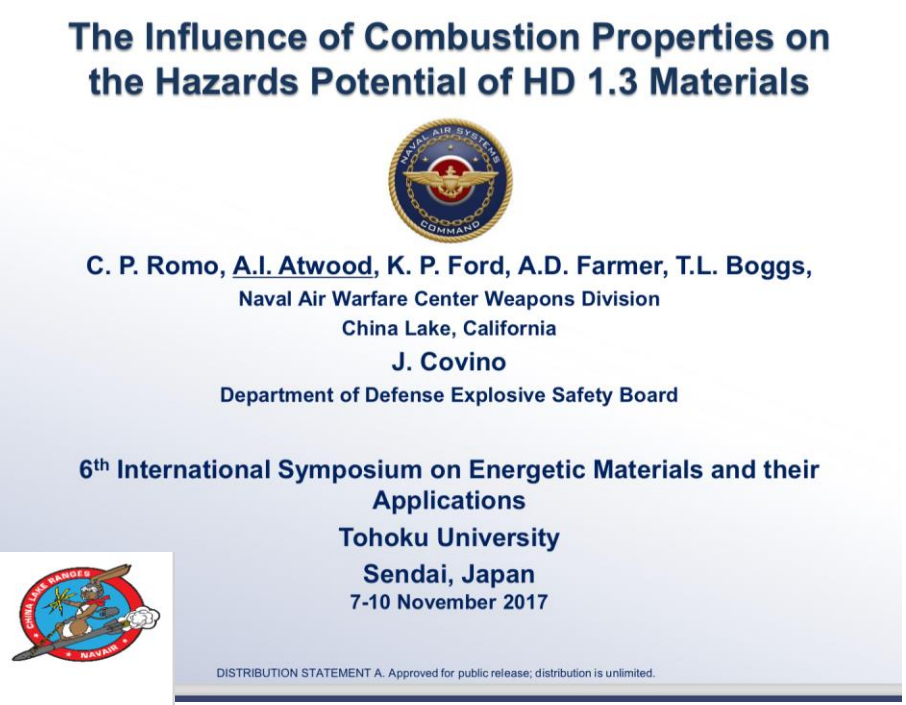
The 3rd International Conference on Structural Safety under Fire & Blast Loading
Brunel University, London, UK
2-4 September 2019



The Influence of Combustion Properties on the Hazards Potential of HD 1.3 Materials

C. P. Romo, A.I. Atwood, K. P. Ford, A.D. Farmer, T.L. Boggs,
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6th International Symposium on Energetic Materials and their Applications
Tohoku University
Sendai, Japan
7-10 November 2017

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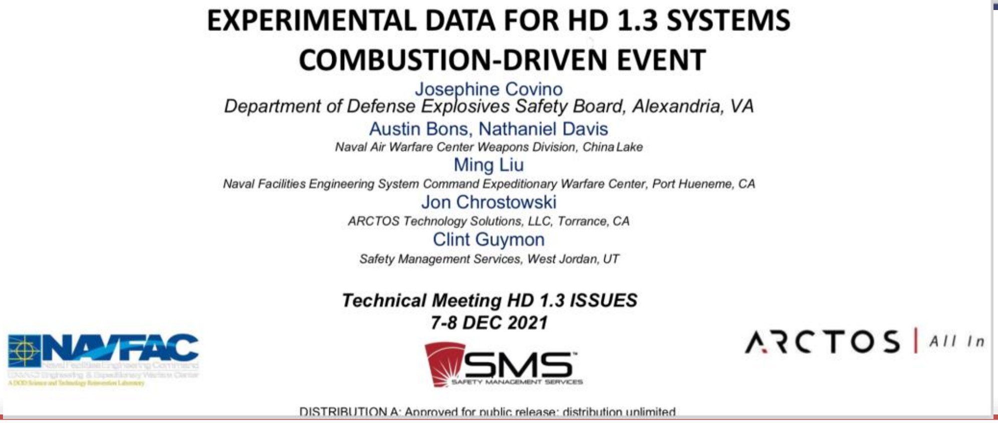

EXPERIMENTAL DATA FOR HD 1.3 SYSTEMS COMBUSTION-DRIVEN EVENT

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Technical Meeting HD 1.3 ISSUES
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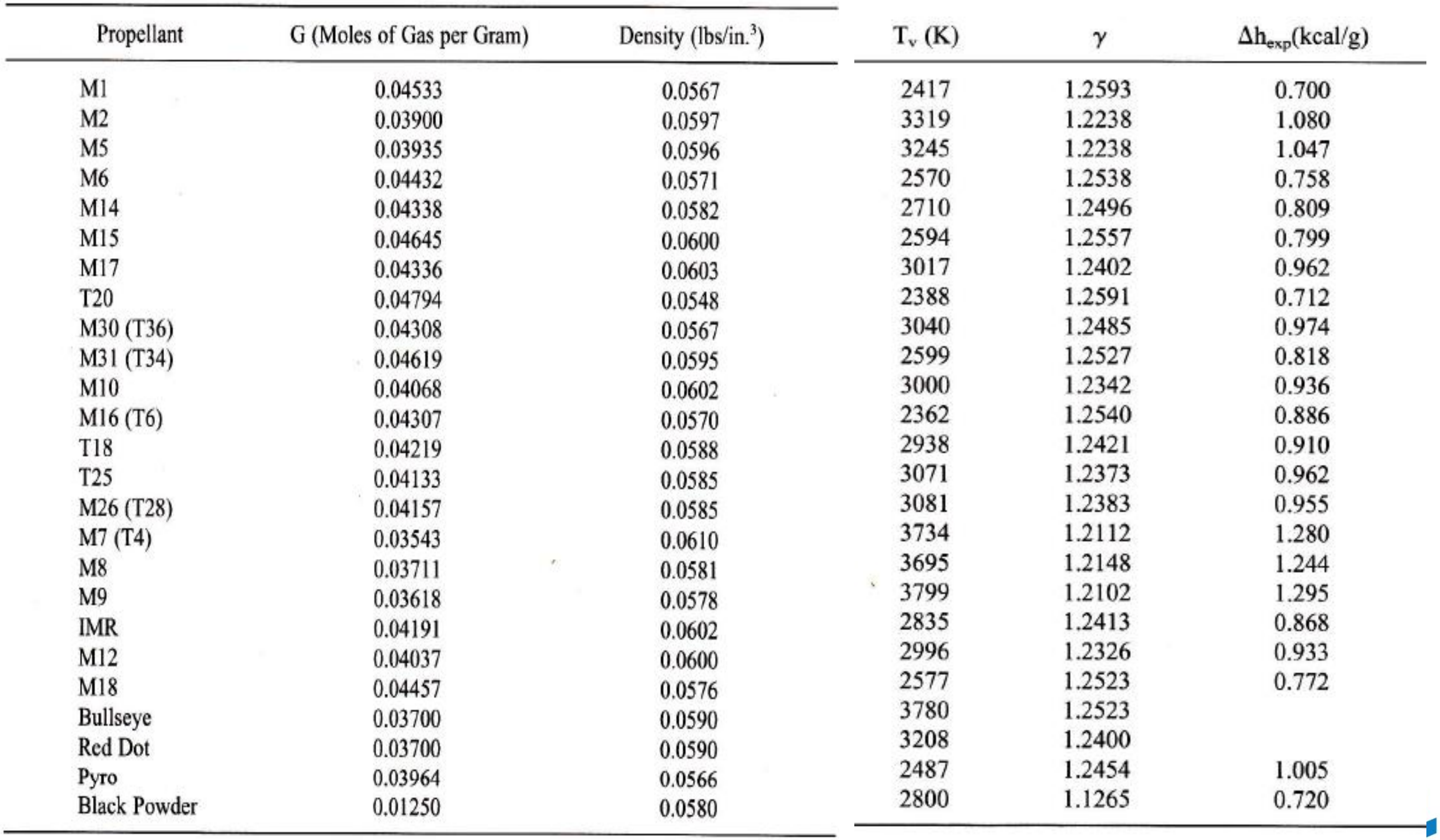

Propellant	G (Moles of Gas per Gram)	Density (lbs/in.^{3})	T_v (K)	γ	Δh_{exp}(kcal/g)
M1	0.04533	0.0567	2417	1.2593	0.700
M2	0.03900	0.0597	3319	1.2238	1.080
M5	0.03935	0.0596	3245	1.2238	1.047
M6	0.04432	0.0571	2570	1.2538	0.758
M14	0.04338	0.0582	2710	1.2496	0.809
M15	0.04645	0.0600	2594	1.2557	0.799
M17	0.04336	0.0603	3017	1.2402	0.962
T20	0.04794	0.0548	2388	1.2591	0.712
M30 (T36)	0.04308	0.0567	3040	1.2485	0.974
M31 (T34)	0.04619	0.0595	2599	1.2527	0.818
M10	0.04068	0.0602	3000	1.2342	0.936
M16 (T6)	0.04307	0.0570	2362	1.2540	0.886
T18	0.04219	0.0588	2938	1.2421	0.910
T25	0.04133	0.0585	3071	1.2373	0.962
M26 (T28)	0.04157	0.0585	3081	1.2383	0.955
M7 (T4)	0.03543	0.0610	3734	1.2112	1.280
M8	0.03711	0.0581	3695	1.2148	1.244
M9	0.03618	0.0578	3799	1.2102	1.295
IMR	0.04191	0.0602	2835	1.2413	0.868
M12	0.04037	0.0600	2996	1.2326	0.933
M18	0.04457	0.0576	2577	1.2523	0.772
Bullseye	0.03700	0.0590	3780	1.2523	
Red Dot	0.03700	0.0590	3208	1.2400	
Pyro	0.03964	0.0566	2487	1.2454	1.005
Black Powder	0.01250	0.0580	2800	1.1265	0.720