Effects of scale on internal blast measurements

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Abstract. This paper presents a comparative study between large and small-scale internal blast experiments with the goal of using the small-scale analog for energetic performance evaluation. In the small-scale experiment, highly confined explosive samples <0.5 g were subjected to the output from a PETN detonator while enclosed in a 3-liter chamber. Large-scale tests up to 23 kg were unconfined and released in a chamber with a factor of 60,000 increase in volume. The comparative metric in these experiments is peak quasi-static overpressure, with the explosive sample expressed as sample energy/chamber volume, which normalizes measured pressures across scale. Small-scale measured pressures were always lower than the large-scale measurements, because of heat-loss to the high confinement inherent in the small-scale apparatus. This heat-loss can be quantified and used to correct the small-scale pressure measurements. In some cases the heat-loss was large enough to quench reaction of lower energy samples. These results suggest that small-scale internal blast tests do correlate with their large-scale counterparts, provided that heat-loss to confinement can be measured, and that less reactive or lower energy samples are not quenched by heat-loss.

1. Introduction

Internal blast refers to gas pressure generated by an explosive within a confined space usually enclosing air or other atmospheres. This pressure is largely due to heating the existing air, and to a much lesser extent, to the gas actually generated by the explosive [1]. Explosive energy release in confined space has been studied using detonation chambers as barometric calorimeters: internal blast peak pressure correlates with energy released [2]. At NSWC IHEODTD large charges up to 23 kg are tested in our 180-m^3 bombproof, while ½-g charges can be tested in a 3-liter chamber.

Small-scale tests are often simpler and less expensive than large scale, and thus are preferred for screening explosive formulations, especially when new materials are not readily available. Blast explosives typically comprise high levels of fuels and reactive materials to enhance or control the release of energy, and may be insensitive and slow-reacting, with performance that may not scale well to small size tests. High confinement of a small sample can compensate for low sensitivity, but at the expense of heat loss to the confinement, resulting in reduced blast pressure.

2. Objective

This work focuses on the total energy released by internal blast explosives, determined by the metric of peak quasi-static pressure. The difference between calculated and measured pressure reflects the performance of a blast explosive and can be used to quantify overall efficiency or extent of reaction of an ingredient, provided there is no systemic energy loss in the measurement. The objective therefore is to compare the efficiency of measurement between large and small-scale internal blast tests, and determine whether the small-scale test can provide the same measure as the large-scale counterpart.

3. Experiments

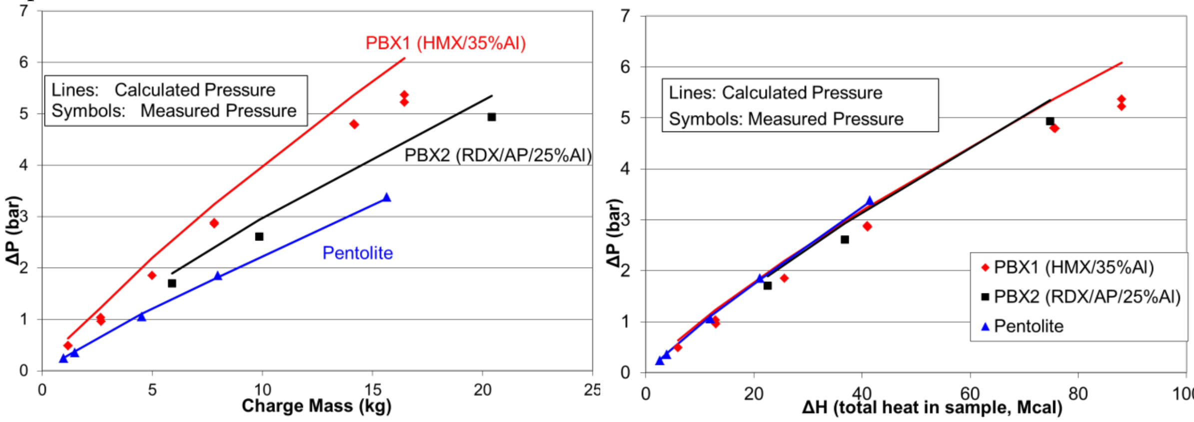
Large-scale tests were conducted on unconfined charges in the NSWC IHEODTD 23-kg bombproof. The rectangular chamber is 6 m x 6 m x 5 m high, with 180 m^3 volume. Small-scale tests were conducted on highly-confined half-gram samples in a 3-liter chamber (a factor of 60,000 reduction in volume) illustrated in figure 3. The explosives tested are listed in table 1.

Table 1. Explosives List.

PBX1 (HMX, HTPB binder, 35% aluminum)
PBX2 (RDX, HTPB binder, AP, 25% aluminum)
Pentolite (91% TMD in large-scale test, 90% TMD in small-scale test)
TNT (85-90% TMD)
HMX (60% TMD)
HMX/aluminum, 80/20 (70% TMD)
PETN detonator

3.1. Large-Scale Tests

Bombproof tests were conducted on the two PBXs and on Pentolite. Calculated and measured peak quasi-static internal blast pressures (ΔP) [1] are shown in figure 1. Lines show calculated theoretical pressures (Cheetah [3]), and symbols show measured values. figure 1(a) shows a typical internal blast plot of pressure vs. charge mass, with different explosives separated vertically by differences in their heats of combustion. Pentolite measurements are close to theoretical values (~98%), while the aluminized PBX measurements are significantly below theoretical, which is typical for aluminized explosives.



(a) (b)

Figure 1. Large-Scale Tests. **(**a) ΔP vs. Charge Mass. (b) ΔP vs ΔH.

By plotting ΔP vs. ΔH, the heat content rather than charge mass (figure 1(b)), the three curves nearly coincide[2], and all data may be compared to a single theoretical curve. ΔH, heat of combustion

[1] ΔP is the quasi-equilibrium pressure reached after the explosive energy has equilibrated with the existing air (millisecond time scale), before any gas vents from the enclosed space. This pressure may thus be calculated by an equilibrium thermochemical code such as Cheetah. Also see reference [1].

[2] Small differences between the theoretical curves are due to differences in the amounts of gas and solid products produced by the explosives. See reference [1].

times sample mass, is the total available energy from the explosive for a test in air.

3.2. Small-Scale Tests

The Small-Scale Internal Blast Test (SSBT), illustrated in figure 2, was originally developed to measure shock reactivity of small samples often well below critical diameter [4]. Very high confinement maintains pressure and temperature from a detonator, allowing the small sample time to react. The reaction products then vent from the high confinement into the enclosing small chamber, reach equilibrium in a couple of milliseconds, and are recorded as internal blast pressure [5].

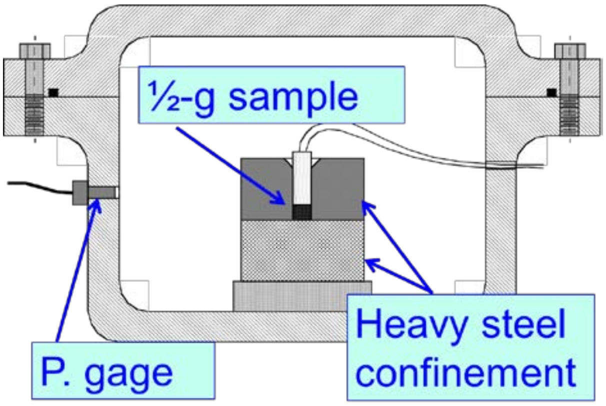


Figure 2. Small-Scale Internal Blast Test (SSBT) Apparatus.

Results from small-scale tests are plotted in figure 3. Cheetah-calculated peak quasi-static pressures for seven different explosives are shown as X-symbols, and are fitted by the dashed line. All other symbols show measured values. All of the measured pressures are significantly lower than the theoretical values.

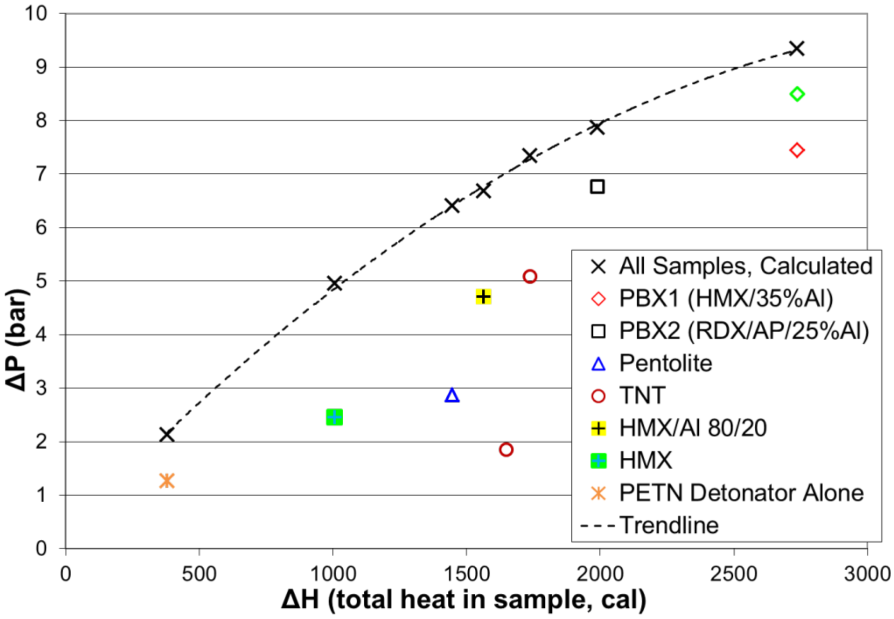


Figure 3. Small-Scale Tests, ΔP vs. ΔH.

3.3. Scalable Parameter ΔH/V

Sample heat content ΔH varies by four orders of magnitude between large- and small-scale tests, plotted separately in figures 1 and 3, making it difficult to directly compare results. By using the blast-scalable parameter of energy per unit volume, ΔH/V, all tests are reduced to a single scale.

Figure 4 plots ΔP vs. ΔH/V for all samples, large and small, on a single chart. The lines are Cheetah-calculated values; the solid lines are for the large-scale tests, and the dashed line is for the small-scale tests and is a fit of the X symbols calculated for all of the small-scale tests (SSBT). All other symbols show measured values: solid symbols are from large-scale tests, and open symbols (and + and *) are from small-scale tests. The large-scale measurements are much closer to their theoretical values than are the small-scale measurements.

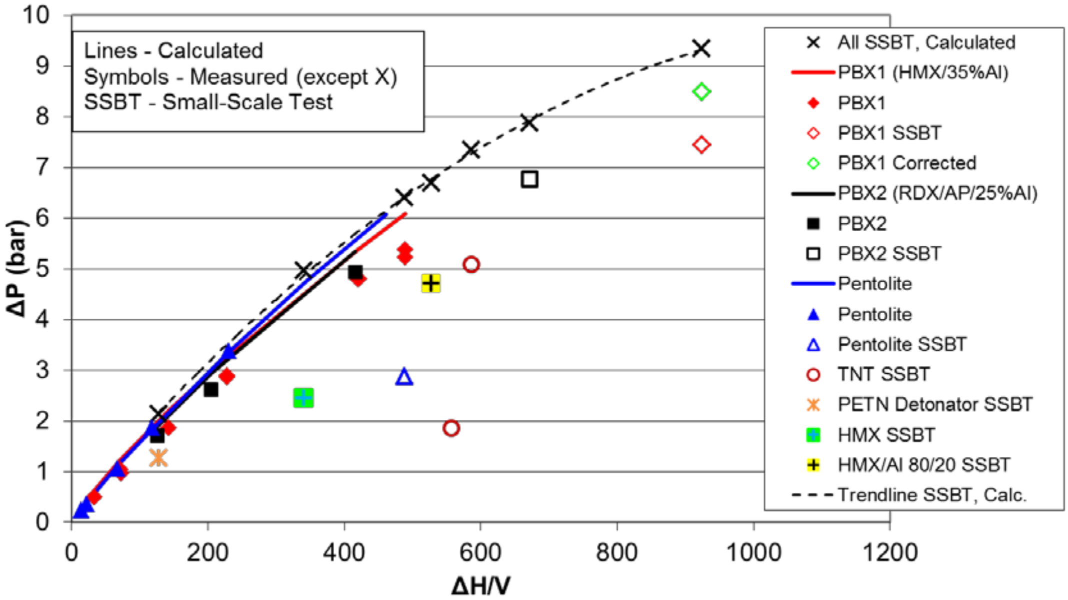


Figure 4. All Tests, ΔP vs. ΔH/V.

4. Discussion

Measured pressures in large-scale tests on Pentolite account for 98% of theoretical energy, while the two aluminized PBXs release only 85 and 90% of their energy on average for the two large-scale series. If the missing energy is attributed to incomplete reaction of aluminum, then one may estimate the extent of aluminum reaction to be 61% and 81% for the PBX1 and PBX2 series, respectively. The performance of enhanced blast explosives depends on the reaction of high-energy fuels, and the determination of the extent of reaction by barometric calorimetry depends on accounting for all available energy. Since the large-scale Pentolite test accounted for essentially all of the available energy, there are no systemic energy losses in the large-scale test.

The small-scale test uses high confinement to overcome critical diameter effects, but at the cost of a large energy loss to the steel confinement. Correcting for this energy loss brings the small-scale PBX1 measurement in line with the large-scale measurements, as shown by the single corrected point identified in the legend for figure 4. The correction was determined by embedding thermocouples within the confinement blocks and measuring the heat rise in each block [6]. The lost heat is deposited in the blocks very quickly, through shock-heating and thermal conduction from hot product gases, until the gases escape the confinement long before the peak pressure is recorded at about 2 milliseconds. The heat equilibrates in the blocks over a few seconds, after which the peak temperatures are recorded.

4.1. Shock-Energy Loss

The shock-heating component of the heat lost to the confinement may be roughly estimated by considering available energy to be partitioned into shock and expansion energy [7]. For an ideal detonation in a rigid, closed sample confinement, the "shock energy" may be qualitatively considered as:

$$\int_{Vcj}^{Vo} PV - 1/2u^2$$

where the integral gives the work done by the product gases expanding isentropically from the C-J volume to V_0, the original volume of the explosive, about where the pressure of the product gases may be considered equal to the shock pressure in the confinement. The second term is the kinetic energy of detonation. The Cheetah thermochemical code [3] was used to evaluate this integral, usually reported as E(R) for the first C-J adiabat expansion point of a default "Standard Run" in Cheetah. By this simplistic treatment the shock-heating component of PBX1 amounted to only 7% of the lost heat. This suggests that heat-loss occurs primarily by conduction to the confining steel blocks.

4.2. Incomplete Reaction

Some lower-energy high-fuel samples may lose enough heat to inhibit the late-time fuel-air reactions. This apparently happened to one of the small-scale TNT tests in figure 5, with a measured pressure of 1.8 bar compared to the calculated pressure of 7 bar. After this test the chamber was coated with black soot, not present after the second, slightly larger, TNT sample was tested. The Pentolite small-scale test may have been similarly affected. Neuwald [2] suggested that cooling due to expansion of the product gas and unburned fuel cloud could inhibit fuel afterburning, especially for larger expansions. Expansion cooling, although limited in the small chamber used in the current work, would add to the cooling from heat-loss to confinement. But again, this may only affect samples with low initial energy or less-reactive fuel.

5. Conclusions

Small-scale internal blast pressure measurements were correlated with large-scale measurements. A pressure correction was made for the heat-loss to the heavy confinement in the small-scale apparatus, making it possible to obtain an accurate large-scale explosive energy release from a small-scale internal blast explosive test. Lower energy or lower reactivity samples may not be suitable for very small-scale tests, if heat-loss to the heavy confinement is great enough to quench reaction.

References

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