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Heinz Reichenbach, Peter Neuwald, Allen L. Kuhl

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WAVEFORMS MEASURED IN CONFINED THERMOBARIC EXPLOSIONS

Heinz Reichenbach[1], Peter Neuwald† & Allen L. Kuhl[2]
[1]Ernst Mach Institut, Eckerstraße 4, 79104 Freiburg, Germany
[2]Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551 USA

ABSTRACT

Experiments with 1.5-g Shock-Dispersed-Fuel (SDF) charges have been conducted in six different chambers. Both flake Aluminum and TNT were used as the fuel. Static pressure gauges on the chamber wall were the main diagnostic. Waveforms for explosions in air were significantly larger than those in nitrogen—thereby demonstrating a strong thermobaric (combustion) effect. This effect increases as the confinement volume decreases and the mixture richness approaches 1.

INTRODUCTION

Described here are experiments of confined thermobaric explosions performed at a laboratory scale. A shock-dispersed-fuel (SDF) charge concept was employed. This concept was first described at the *34th ICT Conference on Energetic Materials*, where we used (SDF) charges to experimentally study gas-dynamic effects of distributed energy release in confined explosions [1]. We have continued to study various aspects of such SDF explosions [2]-[12]. At the *36th Conference* [6], we described the effect that chamber volume (for a fixed geometry) and geometry (for a fixed volume) have on the completeness of fuel consumed [7,8]. At the *37th ICT Conference* [9], we presented high-speed visualizations of the turbulent mixing and combustion in SDF explosions. More recently [11], we described experiments where the SDF charges were distributed along the centerline of a tunnel, and explored how the charge ignition sequence influenced the blast wave at the far end of the tunnel. Blast wave impulses for distributed SDF charges were shown to be significantly larger than for a concentrated SDF charge of the same mass. In these previous studies, we focused on the enhancement of the peak quasi-static pressure as the main indicator of thermobaric effects [12]. In this paper we focus on pressure waveforms measured in SDF explosions.

The loci of thermodynamic states encountered during SDF explosions were presented at the *34th* and *37th ICT Conference* [13, 14], and a generalized Quadratic Model will be

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presented at this Conference [15]. A combustion locus in Thermodynamic State Space has also been found [16]. We have developed multi-phase Models of SDF explosions [17], and used them to simulate Aluminum combustion in explosions [18]. In addition, in this Conference we will report on parametric studies of numerical simulations of SDF explosions [19], made with a simpler (analytic) Equation of State (EOS) that is more computationally efficient than the tabular EOS developed in [17].

EXPERIMENTS

Experiments were conducted in cylindrical bomb calorimeters (Fig. 1) and calorimetric tunnels (Fig. 2). The SDF charge construction is shown in Fig. 3. It begins with a 0.5-g spherical PETN booster (initial density of 1 g/cc). The booster is surrounded by fuel. For the composite charge, the fuel consists of 1.0-g spherical shell of TNT (initial density of 1.0 g/cc). For the Al-SDF charge, the booster is surrounded by a thin paper cylinder, and the void space is filled with 1.0-g of flake Aluminum (initial bulk density of 0.63 g/cc). SEM photographs of the Al powder indicates a flake-like structure of characteristic dimension 100 microns and a thickness of 1 micron. The booster is detonated by an exploding bridge wire located at the center of the charge. Detonation of the booster created an expanding fuel cloud of explosion products gases and hot aluminum particles (or TNT detonation products gases). When this fuel mixed with air, it formed a turbulent combustion cloud that consumed the aluminum (or TNT products), and liberated 31 kJ/g (or 14.5 kJ/g for TNT) of energy in addition to the energy of the booster that created the explosion. Explosions in a nitrogen atmosphere (which suppresses combustion) allow one to confirm the heat of detonation of the charge, while explosions in an air atmosphere allow one to study the dynamics of afterburning and combustion in a confined explosion.

The SDF charge was placed at the center of the chamber. The main diagnostic consisted of 8 piezo-electric pressure gages (Kistler 603B). For the cylindrical calorimeters they were located at 5 and 7.5 cm radii on the lid of the vessel; for calorimetric tunnels they were located on the side-wall and end-wall of the tunnel. To protect against heat transfer effects from the hot combustion products gases, the gauges were thermally insulated with a 0.1mm thick layer of silicon rubber. To check the influence of heating on the pressure, a pressure gage based on a different measurement principle (a piezo-resistive gage that is less sensitive to heat transfer effects) was employed.

RESULTS

Figure 4 presents a comparison of waveforms measured in the explosion of a 1.5-g composite TNT charge (0.5-g booster + 1.0-g TNT) in different chambers. The red curves denote experiments with an air atmosphere, while the blue curves correspond to experiments with a nitrogen atmosphere. In calorimeters *A* and *B*, and tunnel *F*, the thermobaric effect (i.e. enhancement in pressure due to afterburning of TNT detonation products with air) is most pronounced.

Figure 5 presents a comparison of waveforms measured in the explosion of a 1.5-g Al-SDF charge (0.5-g booster + 1.0-g Al flake) in different chambers. The red curves denote experiments with an air atmosphere, while the blue curves correspond to experiments with a nitrogen atmosphere. Thermobaric effects (i.e., the enhancement in pressure due to combustion of Al with air) is quite evident in all cases, but is most dramatic in calorimeter A and tunnel F.

Figure 6 compares the waveforms measured in 1.5-g Al-SDF explosions in air with those measured in 1.5-g TNT-SDF explosions. Although the waveforms are similar, the Al-SDF charge produces somewhat more impulse, especially in chambers A, B and C. This highlights the counter-balancing effects in thermobaric explosions: while Al-air combustion produces much higher temperatures than TNT-air (4,100 K versus 2,900 K, respectively), it produces fewer moles of gas, and pressure is the proportional to their product. Nevertheless, both Aluminum and TNT SDF charges produce significant enhancement (thermobaric effect) over the non-combustion cases (blue curves in Figs. 4 and 5).

Experiments were also conducted in a 15.75 m^3 cylindrical tank [20]. In one series, 0.8-kg cylindrical TNT charges were used. In another series, 0.8-kg Aluminized cylindrical charges (80% TNT + 20% Al powder with $\bar{d} = 15\mu m$) were used. Pressure records on the wall of the tank are shown in Fig. 7. Late-time pressures in air were considerably larger for tests in the air atmosphere—illustrating the afterburning effect for TNT explosions at the 1-kg scale. There was very good repeatability in the pressure records from test to test. Gauge records from 3 TNT tests in air overlay each other, as do records from 3 tests with aluminized charges; similar repeatability was found for tests in nitrogen. This means that the pressure records are controlled by the shock/acoustic waves reverberating within the chamber. The aluminized charges had 20% more combustion energy (Heat of Combustion with air) than the TNT charges. But the pressure records from the aluminized charges overlay those from TNT

charges (for both atmospheres). This suggests that the Aluminum reacted with the TNT detonation products and not with the air. Thus the charge design (along with the Aluminum particle size distribution), is the key element in maximizing the thermobaric effect.

CONCLUSIONS

Experiments from 1.5-g SDF charges have been conducted in six different chambers. Pressure waveforms for explosions in air were significantly larger than those in nitrogen for all six chambers—thereby demonstrating a strong thermobaric effect in this test series. This was true for both Aluminum and TNT-SDF charges. This effect was stronger in chamber A and tunnel F, corresponding to smaller chamber volumes where the mixture richness approaches 1.

The charge design is very important. If one uses the SDF charge design, the Aluminum reacts with the air, while if one distributes the Aluminum in the explosive, it reacts with the detonation products gases. The SDF charge design maximizes the thermobaric effect. Additional studies are needed to pin down the effects of particle size distribution and to explore scaling effects in thermobaric explosions.

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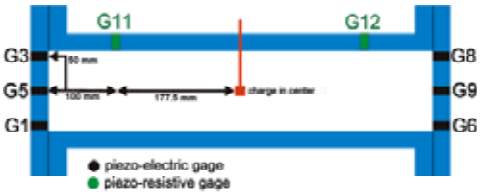
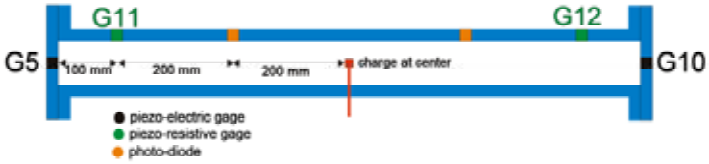
Figure 1. Cylindrical bomb calorimeters: case A (*V*=6.6 liters: *L*=21 cm, *D*=20 cm, *L/D*=1.05), case B (*V*=21.2 liters: *L*=30 cm, *D*=30 cm, *L/D*=1.00) and case C (*V*=40.5 liters: *L*=37.9 cm, *D*=36.9 cm, *L/D*=1.03).

Tunnel D (*V*=6.3 liters: *L*=55.5 cm, *D*=12 cm, *L/D* =4.65)



Tunnel E (*V*=6.3 liters, *L* =100 cm, *x*=*y*=8 cm, *L/D*=12.5)



Tunnel F (*V*=3.98 liters: *L*=38.6 cm, *x*=*y*=10.1 cm, *L/D*=3.86)

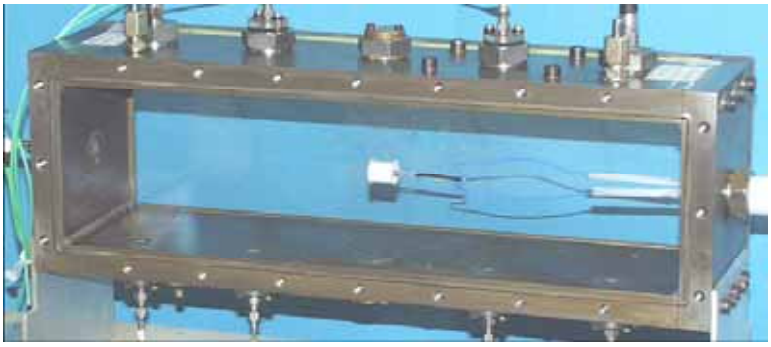


Figure 2. Calorimetric tunnels D, E and F.

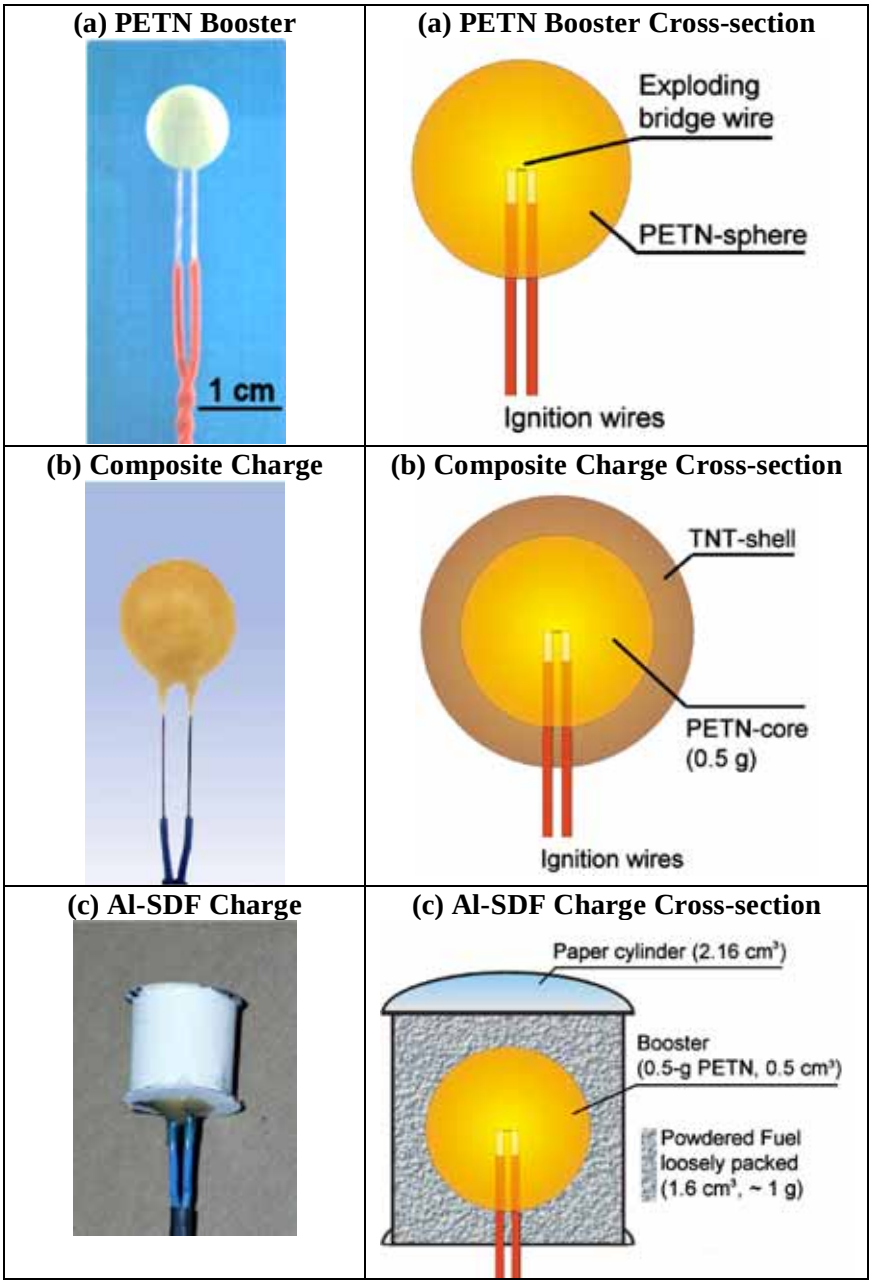


Figure 3. Charge construction: (a) 0.5-g PETN booster charge; (b) composite charge (0.5-g PETN booster + 1-g TNT shell); (c) Al-SDF charge (0.5-g PETN booster + 1-g Aluminum).

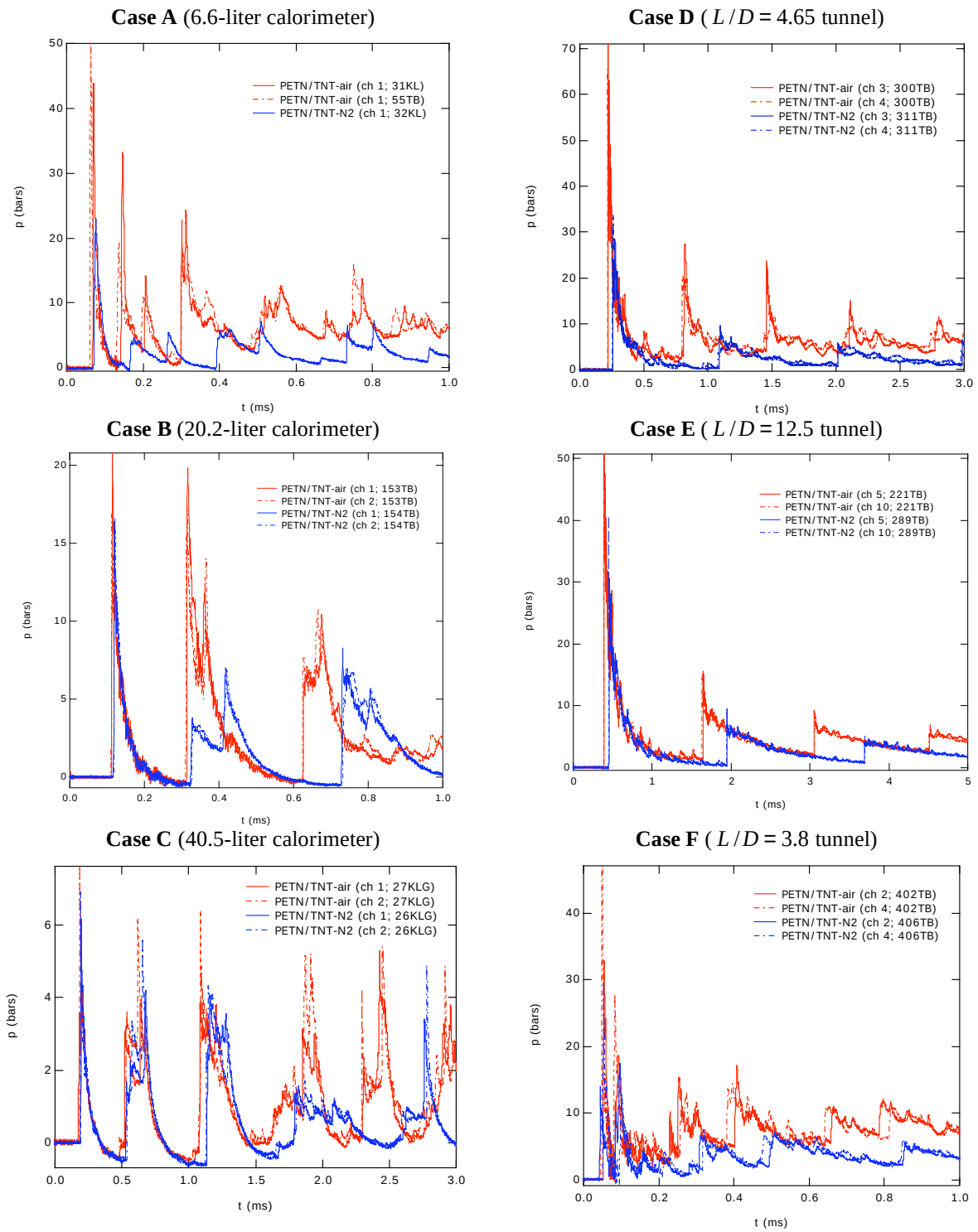


Figure 4. Comparison of pressure waveforms created by the explosion of a 1.5-g TNT-SDF charge in air (red curves) and nitrogen (blue curves) in different chambers. Pressure enhancement (red curves versus blue curves) is a consequence of afterburning of the explosion products gases with air.

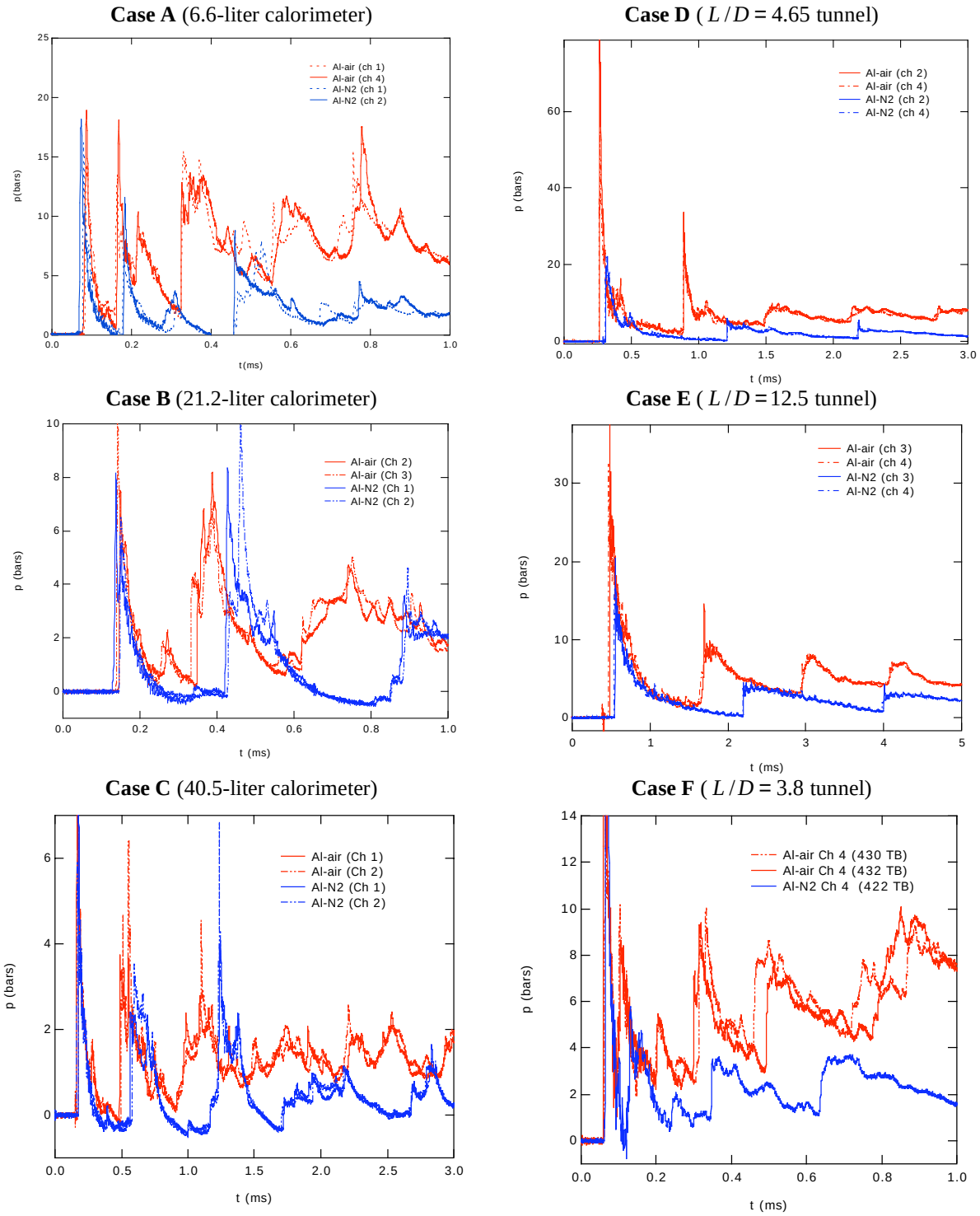


Figure 5. Comparison of pressure waveforms created by the explosion of a 1.5-g Al-SDF charge in air (red curves) and nitrogen (blue curves) in different chambers. Pressure enhancement (red curves versus blue curves) is a result of Al-air combustion.

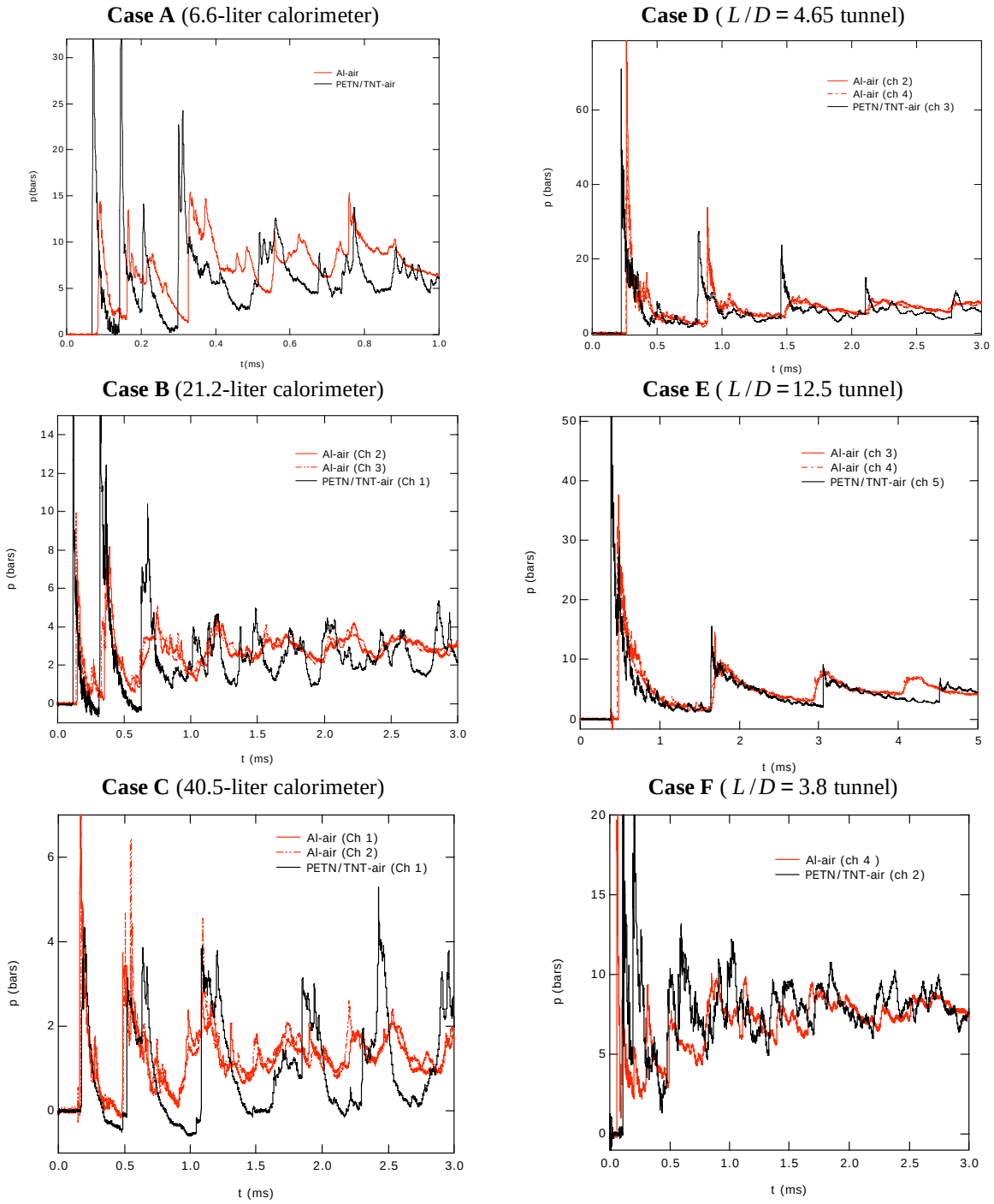
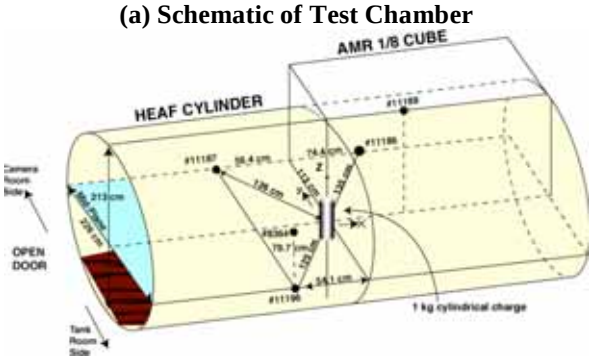
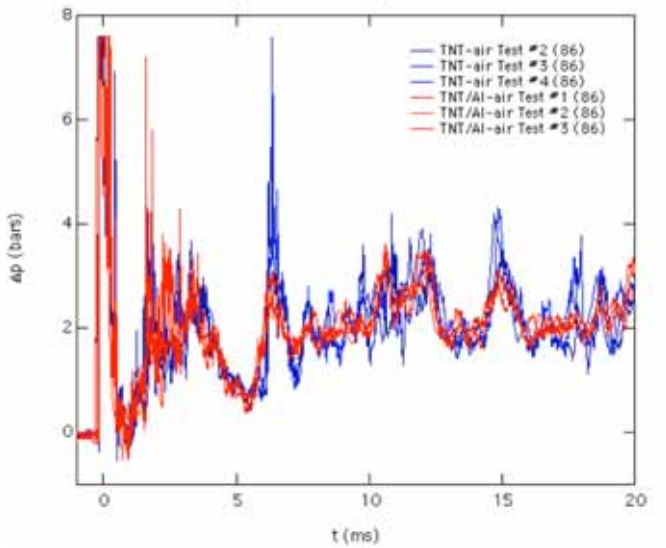


Figure 6. Comparison of pressure waveforms measured in thermobaric explosions in different chambers. Red curves denote results from 1.5-g Al-SDF explosions in air, while black curves represent results from 1.5-g TNT-SDF explosions in air.

(a) Schematic of Test Chamber



(b) Air Atmosphere



(c) Nitrogen atmosphere

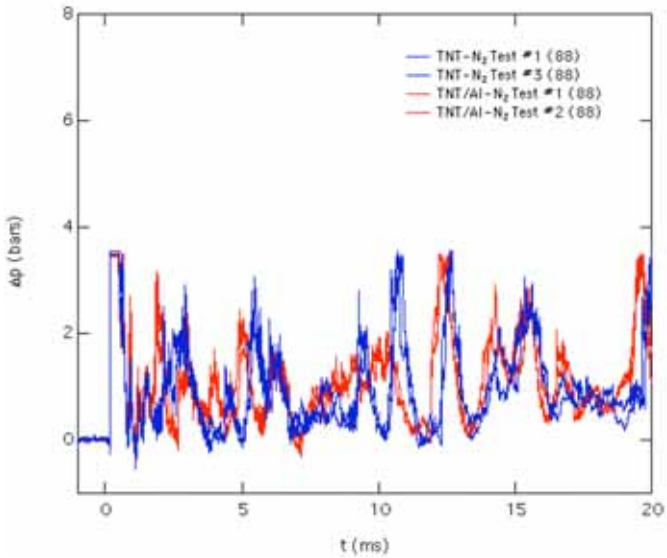


Figure 7. Comparison of pressure records for 0.8-kg TNT charges (blue curves) with 0.8-kg Tritonal (80%TNT, 20%Al) charges (red curves) in the 15.75 m^3 cylindrical tank (a).