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Experiments in Support of Pressure Enhanced Penetration with Shaped Charge Perforators

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ABSTRACT

Computational analysis demonstrated that the penetration of a shaped charge could be substantially enhanced by imploding the liner in a high pressure light gas atmosphere. The gas pressure helps confine the jet on the axis of penetration in the latter stages of formation. A light gas, such as helium or hydrogen, is required in order to keep the gas density low enough so as not to inhibit liner collapse. These results have now been confirmed by experiment. Identical 5-foot long guns, each containing 37 perforators at a shot density of 12 SPF, were inserted in two API Section 1 concrete targets, poured on the same day and cured for the same period. One of the guns was fired with interior ambient (0.1 MPa) air pressure and the other with helium at 13.8 MPa (2,000 psia). The average penetration from the 37 perforations with the helium system increased 40.3% over that obtained with the conventional system.

INTRODUCTION

Modern shaped charges are widely used for both military and commercial applications. Although the main operation is remarkably similar in both applications, there are at least two significant differences in the devices actually employed. The first is cost. Military applications generally demand much higher performance and, in particular, high reproducibility. This, in turn, requires the liner to be forged and precision machined. The main commercial use is in oil or gas well completion, in which the jet from the shaped charge is employed to create a flow path from the reservoir to the wellbore. In this application, a large number of perforators is inserted into the wellbore by a device termed a carrier or gun. Although there are three basic types of guns, perhaps the most common is the casing gun or hollow steel carrier, which can be run into the well on a wireline or conveyed by tubing. The charges are contained in the gun or carrier, protected from impact and from the well fluids, and are arranged so that they face radially outward from the vertical axis of the carrier. In these devices, the liners are pressed using powder metal technology and are at least 2 orders of magnitude less expensive than those used in typical missile warheads.

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The second factor that distinguishes commercial shaped charges from those used in weapons is standoff, i.e., the distance from the liner base to the target (usually measured in charge diameters). The penetrating effectiveness of a shaped charge jet is markedly enhanced by standoff. The reason for this is quite simple. Shaped charge jets normally are formed with a high axial velocity gradient, the tip moving at speeds of 6-10 km/s. The standoff distance allows the jet to stretch or elongate before encountering the target and, to first order, the depth of penetration is directly proportional to the length of the penetrator. There is an optimum standoff. If the distance to the target is too great, the penetration can be much less than if there were no standoff. This occurs because the jet can only stretch so much before breaking; once broken the particles are easily deflected by small perturbations and no longer produce a coherent, unidirectional penetrator. At optimal standoff, typically 6-8 charge diameters (CD), the penetration can be enhanced by 50% or more relative to that achieved with zero standoff. Commercial perforators, however, are rarely able to operate at more than 1 CD because they must fit inside the casing gun which, in turn, must fit inside the casing.

In an earlier computational study [1] we showed that the penetration of a shaped charge jet might be enhanced by at least 25% by imploding the liner in a high-pressure light-gas atmosphere. The calculations indicated that the gas pressure helped confine the jet on the axis of penetration in the latter stages of formation. A light gas, such as helium or hydrogen, is required in order to keep the gas density low enough so as not to inhibit liner collapse.

In this report, we present the results of experiments designed to provide validation of the predicted behavior. Two sets of experiments were performed. The first set employed high resolution radiography to derive time-resolved records which could be directly compared with the calculations.

The second set of experiments was designed to obtain statistical performance data against standard concrete targets with and without pressure enhancement. These experiments employed 2 five-foot guns, each of which contained 37 perforators spaced at 1-inch intervals; a 1-foot spacer region was maintained at each end of the guns. One gun had an ambient air atmosphere and the other contained high-pressure helium. The guns were fired into identical API RP43 Section 1 concrete targets that were poured on the same day from the same batch of concrete. After the shots, the targets were sectioned and the mean penetration and standard deviation were obtained. We present the results with comparison to the hydrocode predictions. Additional experiments were carried out with smaller perforators at a lower shot density and these resulted are discussed as well.

PERFORATOR CHARACTERIZATION

Figure 1 depicts the perforator on which most of the results are based, an OMNI conical shaped charge, manufactured by the Jet Research Center. The outer base diameter of the steel tamper is 46 mm. The explosive charge weighs 22.7 g and consists of 98.5-99% RDX, with the remainder being a wax binder. The liner consists of a mixture of tungsten (45.20% by weight), tin (11.05%), copper (43.19%), and graphite (0.53%) powders, together with a trace amount of lubricating oil. According to mixture theory, the density of the fully compacted liner should be 11.19 g/cm^3. Measurement of the actual density, using the method of Archimedes, yielded a value of 10.15 g/cm^3 [2], so that an initial gas porosity of 0.0929 was inferred.

A Grüneisen equation of state for the fully compacted powder was derived by D. A. Young of our Laboratory; the resultant parameters were: c_0 = 3.79 km/s, s = 1.592, γ_0 = 1.8, and b = 0.5. Here, c_0 is the bulk sound speed, s is the slope of the shock Hugoniot (in shock velocity-particle velocity space), γ_0 is the initial

Grüneisen parameter, and b is the first order volume correction to γ_0.

All simulations described in this report were performed with the CALE hydrocode, developed at LLNL by R. Tipton [3]. The pore compaction treatment in this code follows closely the standard p-α formulation initially devised by Carroll and Holt [4]. In our model, we prescribed a Hugoniot elastic limit of 50 MPa, with complete pore crushup occurring at 161 MPa. No independent measurements were made of the liner strength so that, in effect, the strength model constituted a degree of freedom available to help fit the penetration data. We found that employing the standard Steinberg-Guinan ductile failure model available in CALE, with parameters mainly derived for copper, resulted in excellent agreement between predicted and measured performance.

Figure 2 shows radiographs of the imploding liner at 3 times: 7, 14, and 21 μs. The 3 images on the right are simulated radiographs, based only on the density field; the calculated liner outlines are overlaid on the experimental images, shown on the left hand side of the figure and it is observed that there is very good agreement.

To validate the liner model further, we simulated an experiment performed by Vigil [2], in which the perforator was fired against a 6061-T6 aluminum alloy target; this alloy was chosen for the simulation because its material properties have been accurately measured and are well known. Figure 3 shows the calculated penetration as a function of time, together with a snapshot crossection at 10 ms. The

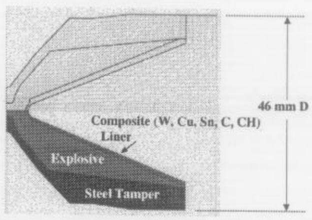

Figure 1: **Cross section of OMNI shaped charge perforator**

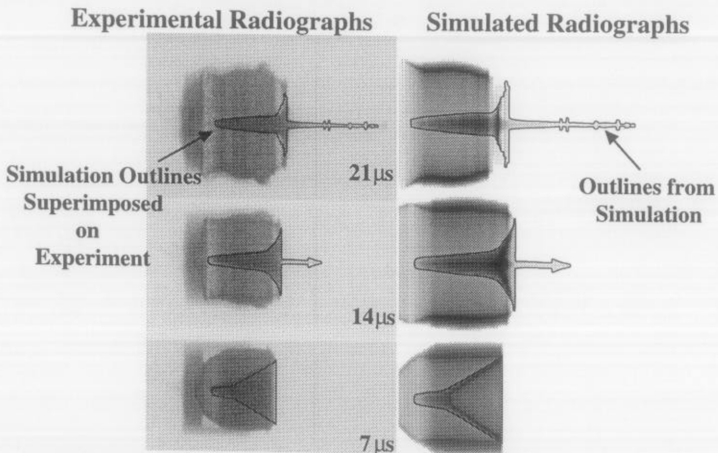

Figure 2: **A comparison of experimental and simulated radiographic images of the OMNI liner implosion.**

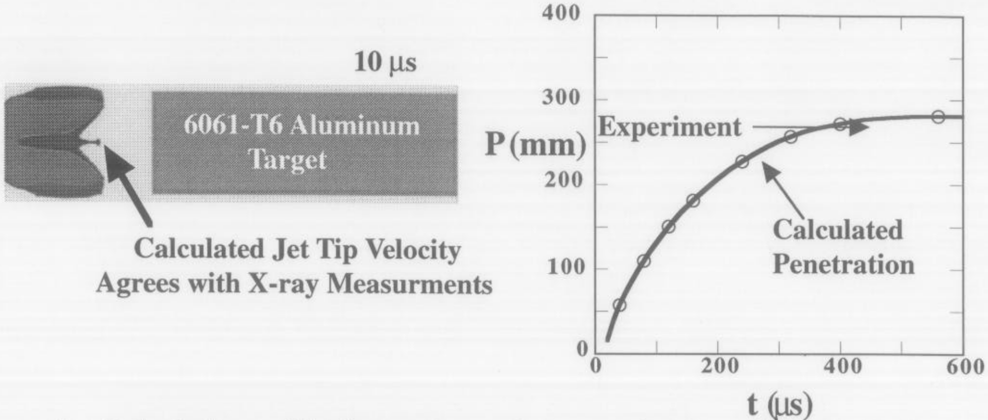

Figure 3: **Calculations of jet formation and penetration in a 6061-T6 Al alloy target are in good agreement with measurements [2].**

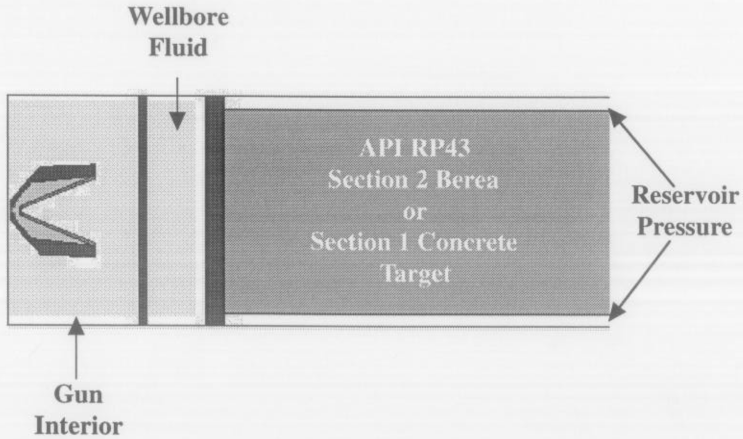

Figure 4: **Setup for concrete penetration studies. Gas pressure was independently variable in each of the 3 regions shown.**

calculated jet tip velocity at this time was 6.4 km/s, the same value measured from the radiographs in the experiment. The final penetration was 265 mm, again in excellent agreement with the interpolated curve derived from the measurements (the calculation was performed at a standoff of 22.1 mm; the experiments were performed at standoffs of 6.35, 152.4, and 482.6 mm). The standoff position chosen for the calculations was the same as the position of the first target plate employed in the concrete penetration experiments, described below.

CONCRETE PENETRATION CALCULATIONS

Figure 4 illustrates the setup for the concrete penetration studies, which was chosen to replicate, as far as possible, the standard API RP43 Section 1/2 targets. For the simulations, the outer boundary of the computational box was assumed rigid. The first steel target plate is supposed to simulate the gun wall and the second steel target plate butted up against the concrete is supposed to simulate the casing. The pressure inside the gun, P_1 (normally assumed to be ambient air pressure), the wellbore fluid pressure, P_2 , and the reservoir pressure, P_3, can each be varied independently. The concrete constitutive model employed is consistent with the specification for API RP43 Section 1 targets and fits reasonably well the shock Hugoniot data reported for this material by Furnish [5]. The initial gas porosity was assumed to be 0.18, corresponding to a density of 2.15 g/cm^3. The unconfined compressive strength was taken as 51.7 MPa (7,260 psi), and the strength increased with pressure up to a maximum of 160 MPa at a pressure of 1 GPa.

Figure 5 and 6 show the results when the pressure P_1 is varied from 0.1 to 30 MPa (14.5 to 4,350 psia). The reservoir and wellbore pressure were assumed equal and set to 10 MPa. Figure 5 shows that the penetration decreases monotonically with increasing gun pressure, but the decrease is insignificant for pressures below 10 MPa. For higher P_1, penetration decreases dramatically. Figure 6 shows that, at 30 MPa, the liner collapse is inhibited by the formation of a high-pressure air bubble and even the steel casing is not completely perforated.

If a light gas such as helium or hydrogen is substituted for the air, the density can be reduced by an order of magnitude for the same initial pressure. Figure 7 illustrates the penetration obtained with helium; in these calculations, the reservoir and wellbore pressures were increased from 10 to 34.5 MPa (5,000 psia), which has the effect of increasing the strength of the concrete. The calculations show that the maximum penetration, with helium, occurs when P_1 is between 1,500 and 5,000 psia. Although the final penetration has not been attained in the plots in Fig. 7, the penetration at 1,500 psia is at least 25% greater than obtained when the liner is surrounded by ambient air pressure.

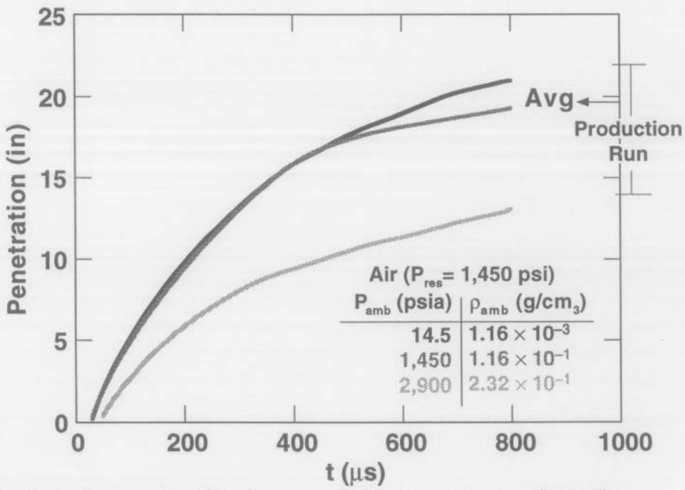

Figure 5: Calculated penetration in concrete target as a function of ambient air pressure.

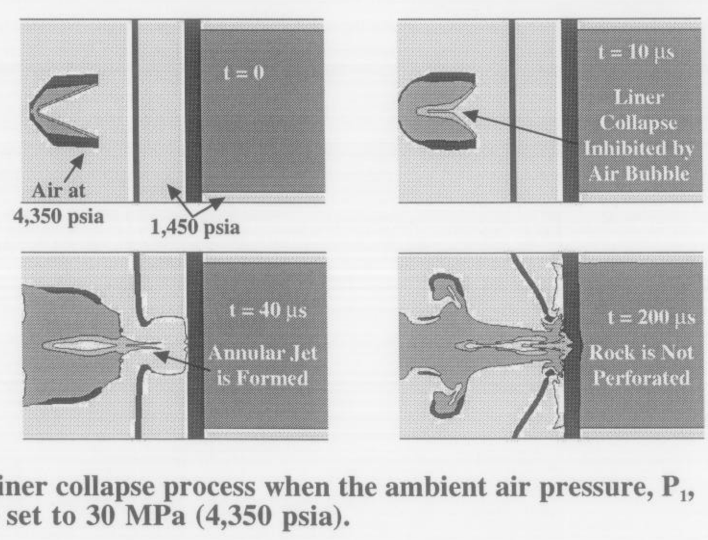

Figure 6: Liner collapse process when the ambient air pressure, P_1, is set to 30 MPa (4,350 psia).

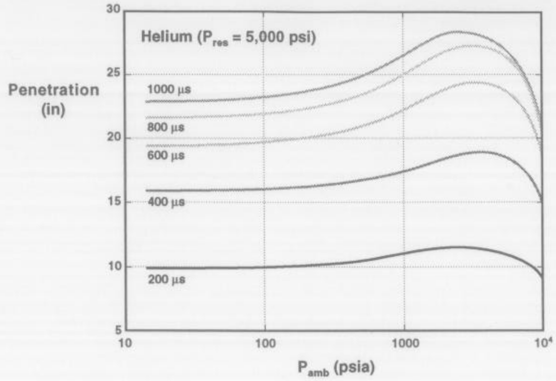

Figure 7: Calculated penetration in concrete target as a function of ambient helium pressure surrounding perforator.

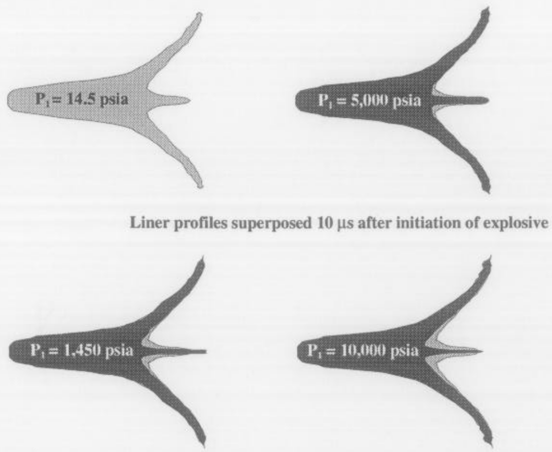

Figure 8: Increasing the helium pressure surrounding the liner produces an increasingly narrow and elongated jet.

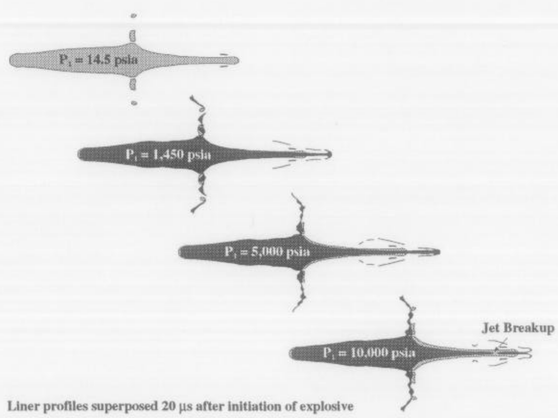

Figure 9: Increasing the helium pressure surrounding the liner stretches the jet and increases penetration depth in the target until jet break up occurs.

Figures 8 and 9 illustrate the physical basis for this increased performance. In both figures, the cross section of just the liner material for the calculations with higher P_1 overlay the liner cross section for P_1 = 0.1 MPa (14.5 psia). Figure 8 shows the situation at 10 μs, when the jet tip velocity has attained its maximum value, prior to perforation of the first plate (gun wall). It is clearly observed that, as the initial helium pressure surrounding the liner is increased, the base of the jet is forced to recede and an increasingly narrow and elongated jet is produced.

Figure 9 depicts the liner profiles at 20 μs. As the initial surrounding pressure increases, the jets are seen to elongate and their cross sections diminish. When P_1 is 69 MPa (10,000 psia), the tip is still slightly ahead of the low-presure case, but the calculation shows evidence of jet breakup beginning to occur. Although there is no explicit constitutive model for breakup in the code, the interface treatment implicitly produces this effect when the cross section gets sufficiently small; gas and jet material are then intermixed, and the local density is concomitantly reduced which, in turn, tends to decrease penetration.

CONCRETE PENETRATION EXPERIMENTS

Two API RP43 Section 1 concrete targets were poured on the same day and cured for the same period. We inserted identical 5-foot long guns in each target. Each gun employed 37 4-5/8" OMNI Deep Penetrating perforators, the design of which was discussed above; shot density was 12 SPF, with 1 foot spacing at either end. One of the guns was operated with interior ambient (0.1 MPa) air pressure and the other with helium at 13.8 MPa (2,000 psia).

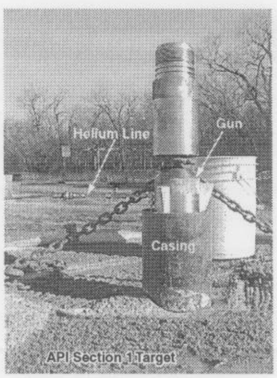

Figure 10: Perforator gun installed in Section 1 concrete target prior to firing.

Figure 11: Concrete target after firing perforator gun. "Picker" has split target in preparation for measurement of penetration made by each perforator.

Figure 10 shows the helium gun prior to firing; the chains attach the gun to the target exterior to prevent it from being transported out of the casing by the explosion products. Figure 11 shows the target after it has been split by the "picker" (a motorized jackhammer) so that each perforation can be carefully measured.

The average penetration from the 37 perforations with the helium system increased 40.3% over that obtained with the conventional system. The standard deviation was 11.3% of the mean penetration when the high-pressure helium was used and 12.9% when ambient air was employed. This actually exceeds the predicted improvement in performance, which assumed an ideal (axisymmetric) perforator. The high-pressure light gas surrounding the jet tends to inhibit instabilities that enable the jet to wander off axis and thus decrease penetration.

Pressure enhanced penetration does not work well, however, with very small perforators. This was confirmed by two additional sets of experiments similar to those described above in which 2" Super-DP perforators (6 g explosive charge) were fired at a shot density of 4 SPF. In this case, the penetration actually decreased by roughly 30% when the conventional guns were replaced by helium systems operated at 1,000 and 2,000 psia. The 2" Super-DP perforators produce a needle-like jet when operated in an ambient air environment. The effect of substituting high-pressure helium for the air further reduces the jet diameter and, although the axisymmetric simulations predicted improved performance, it was difficult to obtain adequate resolution across the jet and there were indications that Kelvin-Helmholtz type instabilities would be operative in the actual (3D) case.

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