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# A HYDROCODE-DESIGNED WELL PERFORATOR WITH EXCEPTIONAL PERFORMANCE

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The objective of the well perforator improvement effort was to increase the jet energy and penetration as much as possible while maintaining the same outer dimensions of the perforator body and limiting the explosive mass to 39 gm. The strategy was to replace the conical liner with a bell-shaped one of variable thickness, similar to ones that have shown significant gains in performance in prior studies. The outcome was an improved design that produced a jet with 10% more kinetic energy than before, with much of the increase at the back of the jet, where it was most effective in increasing the penetration depth. The penetration into the concrete target increased by 28% relative to the baseline.

The hydrodynamic computer program AUTODYN 2D™* and its thin-shell jetting option and the analytical penetration analysis program JEPETA™† were used to evaluate the baseline design and candidate alternative designs.

## INTRODUCTION

Perforators, shaped charges for penetrating well casings and hydrocarbon-bearing rocks (Figure 1) must be low in cost yet effective to be marketable. The most critical component of the perforator is the liner, which is often fabricated by the low-cost process of pressing from a metal powder. For rocks of low porosity, the best perforations are ones that are as deep as possible.

Performance is characterized by testing against an American Petroleum Institute target (specifically, API RP-43 [API, 1991], Section 1) in which a thick layer of concrete simulates the hydrocarbon-bearing rock (Figure 2). The perforator's jet must penetrate the wall of a steel carrier, a fluid layer, and a steel wellbore casing before entering the concrete. An effective jet is one that creates a smooth, well-rounded hole through the casing as well as a deep, uniform hole in the concrete.

This paper reports the results of an effort to improve the penetration performance of a 2.11-inch diameter perforator with a steel body, loaded with 39 gm of HMX explosive. Figure 3 is a pair of conceptual diagrams of the baseline and the improved perforators. Features of the baseline and improved designs follow:

*AUTODYN 2D is a trade mark of Century Dynamics Inc.
†JEPETA is a trade mark of Shock Transients, Inc.

| | *Baseline* | *Improved* |
|---|---|---|
| *Liner Diameter* | 1.60 in (4.06 cm) | 1.73 in (4.39 cm) |
| *Liner Shape* | Conical | Bell |
| *Thickness Profile* | Linear (Tapered) | Variable (Arbitrary) |

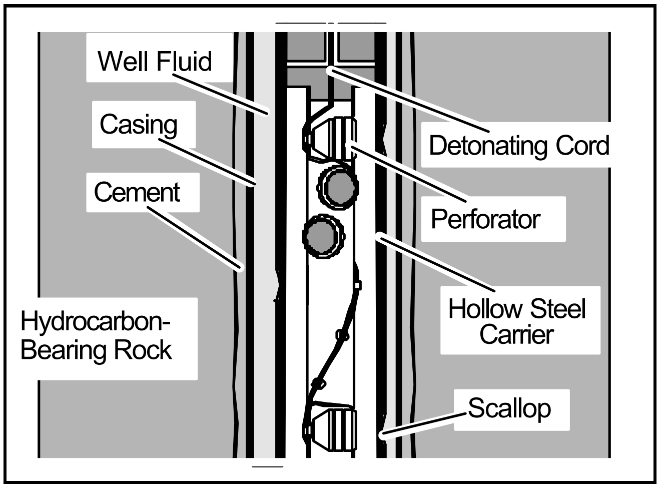


**Figure 1.** Section of a jet gun prior to firing. After a well is drilled, a steel casing is lowered into place and cement is pumped into the annulus between the casing and the rock. The jet gun is then lowered to the appropriate depth and fired to connect the hydrocarbon-bearing rock to the wellbore. The jet gun has a steel wall (hollow carrier) with thin, scalloped areas through which the perforators fire. Perforators are sequentially initiated with a detonating cord. Thick steel charge cases minimize charge-to-charge interference. In the diagram above, the gun is vertical, and perforators are oriented along vertical planes separated by an angle of 60º. After firing the jet gun, the hydrocarbon-bearing rock has many channels or perforations through which gas and/or oil flows into the wellbore.

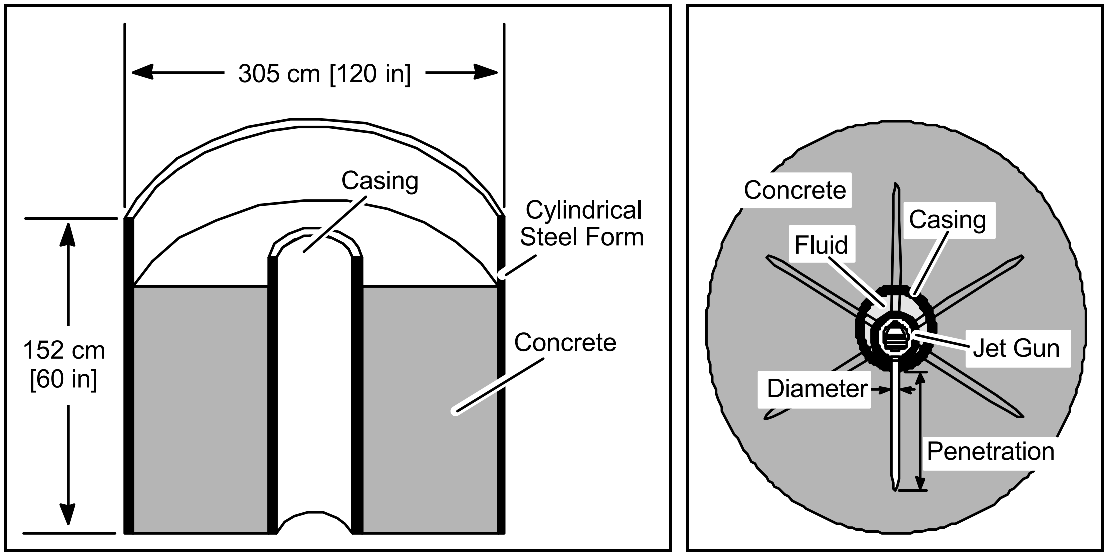


**Figure 2.** Perspective cutaway of the API RP 43, Section 1 target [API, 1991] and top view of the target showing the eccentric placement of the jet gun within the casing. For this work, the jet gun's outer diameter was 11.43 cm (4.50 inches) in diameter, and the casing's outer diameter was 17.78 cm (7.00 inches).

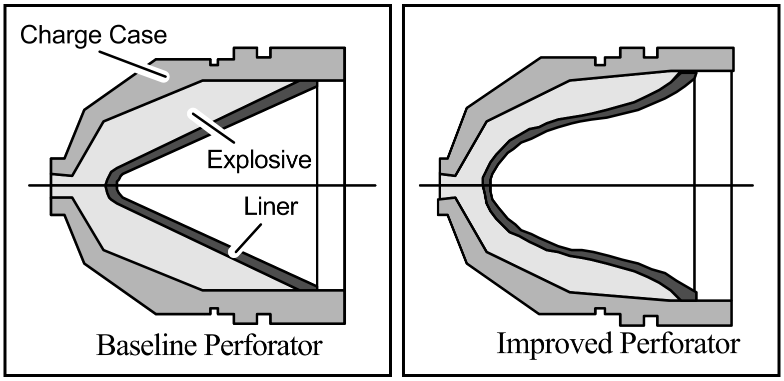


**Figure 3.** *Conceptual* diagrams of perforators; the actual liner shapes are proprietary. The baseline perforator has a conical liner of linear thickness variation, and the improved perforator has a bell-shaped liner of a slightly larger diameter, with a variable thickness. The improved liner's surface area is greater than that of the baseline, and points along the improved liner travel further than points along the baseline liner. All of these factors contribute to an improved jet that is more energetic than the baseline, and one that creates a deeper and wider perforation in concrete.

TEST RESULTS

The baseline and improved perforators were tested against the API target of Figure 2 and against the "quality control" (QC) target of Figure 4. Results were as follows:

| | *Target* | *Baseline* | *Improved* |
|---|---|---|---|
| *Entry Hole Diameter* | API | 0.46 in (1.17 cm) | 0.37 in (0.94 cm) |
| | QC | 0.54 in (1.37 cm) | 0.35 in (0.89 cm) |
| *Total Target Penetration* | API | 37.61 in (96 cm) | 48.13 in (122 cm) |
| | QC | 41.24 in (105 cm) | 49.43 in (126 cm) |
| *Diameter Hole at Bottom* | QC | 0.05 in (0.13 cm) | 0.20 in (0.51 cm) |

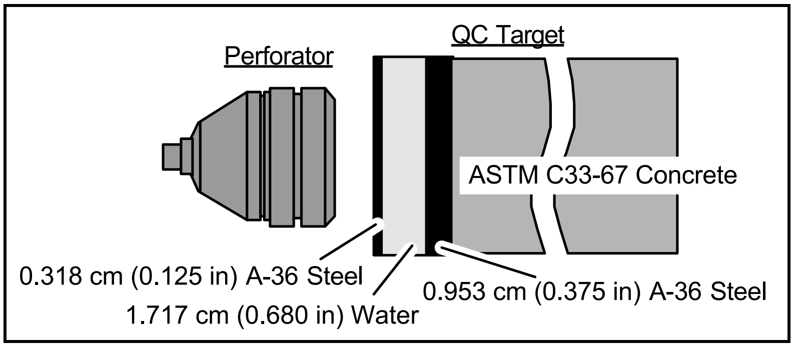


**Figure 4.** Perforator and cross-section of quality-control (QC) target; the QC target simulates the API RP 43 Section 1 target in preliminary testing. A single perforator is fired (vertically) through a target consisting of flat steel plates representing the gun wall and casing, enclosing water and backed up by stacked, four-inch diameter cylinders of cast concrete. The air gap between the perforator and the target was 1.575 cm (0.620 in) thick.

Perforations created by the baseline design tapered to a small diameter. Those created by the improved design were deeper and did not taper to a small diameter. The latter are more effective in bringing hydrocarbons (gas or oil) to the wellbore. The improved design has been named the Owen-STI NTX SDP™*. The "STI" in the name recognizes the contribution of Shock Transients, Inc., to the design; "NTX" stands for "New Technology, X Series;" and "SDP" stands for "super-deep penetrator."

THEORY

The improved perforator was designed to maximize its efficiency: the liner absorbed a greater amount of the explosive's energy than did the liner for the conventional, baseline perforator. Figure 5 is a plot of velocities as functions of time for several points along a liner. The plot illustrates the difference between the velocity histories for baseline and the improved perforators. Further details of the design process can be found in [Davison and Arvidsson, 1985] and [Davison and Nordell, 1992].

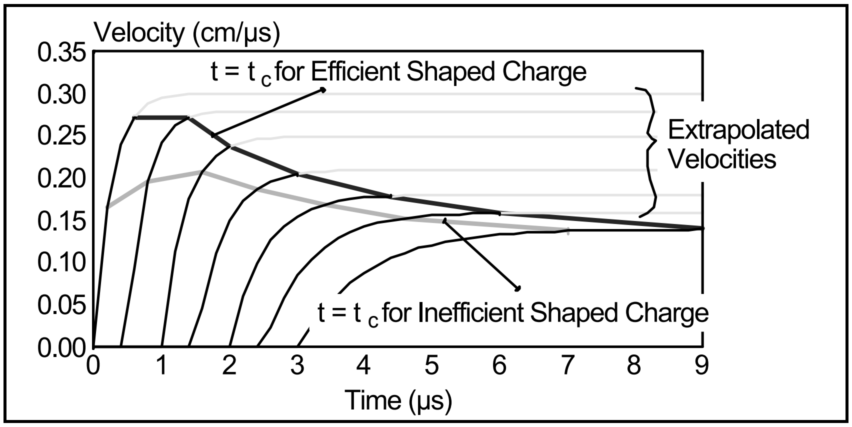


**Figure 5.** Velocity as a function of time for several points along a shaped charge liner. $t_c$, the collapse time, is the time at which the liner reaches the axis of symmetry, giving up its kinetic energy to the jet and slug. The kinetic energy of a jet element is proportional to that of the associated liner element at the moment of collapse, and the kinetic energy of a liner element is proportional to the square of its velocity. For an inefficient shaped charge the liner reaches the axis of symmetry while the velocity curve is steep. For an efficient shaped charge the liner reaches the axis of symmetry when the velocity curve has begun to level off. Shaped charges with bell-shaped liners are more efficient than those with conical or trumpet-shaped liners. The liner surface area is greater, and points along the liner are further from the axis of symmetry, allowing more time for the explosive to act on it.

The following is a summary of the shaped charge design approach: (1) Compute the perforator jetting with the definitive AUTODYN 2D program; (2) Compute the hole shape using the analytical penetration theory; (3) Derive liners that give jets of maximum energy and holes of maximum size; (4) Test the most promising designs; and (5) Iterate to converge on the "best" design(s).

Usage of AUTODYN 2D in shaped charge calculations is described in [Birnbaum and Cowler, 1989]. The liner is characterized as a jetting thin shell coupled to a fully two-dimensional representation of the explosive. The jet is modeled in accordance to the theory described in [Pugh et al., 1952].

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*Owen-STI NTX SDP is a trade mark of Owen Oil Tools, Inc.

The JEPETA program takes the jet produced by the jetting thin shell model in AUTODYN 2D and computes its effect on a target. JEPETA includes the influence of target strength and jet breakup. It starts with the equations of [Eichelberger, 1956] and [Birkhoff et al., 1948] and continues with those of [Allen, 1977].

For JEPETA, the incremental penetration $\Delta p$ is $\Delta p = \Delta L_j / \nu\gamma$, where $\Delta L_j$ is the length of the jet increment including air spaces, $\nu$ is the ratio of $\Delta L_j$ to the length of the solid particles in the jet increment, and $\gamma = \sqrt{\rho_t / \rho_j}$ for respective target and jet densities $\rho_t$ and $\rho_j$. The incremental hole volume $\Delta V$ is proportional to the incremental jet kinetic energy; the ratio of energy to volume, $E_S$, is the target's specific energy. The jet's incremental kinetic energy depends on its incremental length, diameter, and velocity. The hole radius is $r_h = \sqrt{\Delta V / \pi \Delta p}$.

Some *focusing* (diameter reduction) of a powdered metal jet occurs when it passes through concrete and rocks such as sandstone and limestone [Aseltine, 1985]. In addition to focusing, rocks (and, to a lesser degree, concrete) also *disturb* jets, because of asymmetries and constrictions, reducing their effectiveness. When rocks contain hydrocarbons in their pores, the disturbance decreases, suggesting that *crushing* of the rock is a factor in the disturbance. Finally, jets are *disrupted* by reflections of shocks off target boundaries such as those of the QC configuration shown in Figure 4.

Of the four effects (focusing, disturbance, crushing, and disruption) observed and described by Aseltine, the first, focusing, causes the jet to be more effective than otherwise by concentrating the particles on the axis of symmetry. It remains dense and continuous, and it can be modeled as such in JEPETA.

The other three effects result from asymmetries or non-uniformities and are not modeled by the JEPETA computer program, which considers targets to be uniform and infinite in diameter. Consequently, JEPETA over-predicts penetration when these effects occur.

## AUTODYN 2D ANALYSIS

The liners for the baseline and improved perforators were pressed from powdered metal, primarily tungsten and copper. The average density for the baseline liner was determined from the weight in air and in water to be 11.04 gm/cm³. Liners were sectioned axially into thirds, and densities for each third were measured. As indicated in Figure 6, a curve was fit through the data. The curve was used for making adjustments to thicknesses in the AUTODYN 2D analysis of the baseline so that the liner mass distribution would be correct. The adjustment was made in reverse to obtain the correct thicknesses for fabrication of the improved design.

Figure 7 is a set of velocity curves for the baseline and a set for the improved design. The following table lists features of the two jets:

| *Jet Feature* | *Baseline* | *Improved* |
|---|---|---|
| *Tip/Tail Velocity (cm/µs)* | 0.703/0.101 | 0.695/0.118 |
| *Mass (gm)* | 10.8 | 11.9 |
| *Kinetic Energy (kJ)* | 62.4 | 68.8 |

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