Improved Frac Efficiency Using FocusShot™ Perforating
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Introduction
This paper will present a new concept (FocusShot) in perforating gun design tailored specifically for fracturing operations (Sites, US Patent 9,145,763 B1). Current perforating guns shoot jets perpendicular to the gun body (and casing), thus creating holes in the casing and tunnels through the cemented annulus and formation, Figure 1. These perforating tunnels are usually evenly spaced along the axis of the casing and can be phased in many configurations, the most popular being 0°, 0-180° and 60°. FocusShot configures the gun assembly so that shaped charges displaced from center are oriented back to the mid-point of the perforating gun assembly (orientation angle increases as displacement increases), thus converging the explosive energy and the perforating tunnels on a single plane at the center of the perforated interval, Figure 2. With the exception of modifying the charge carrier to hold charges at an angle, the converging FocusShot gun-string uses the same components as a conventional perforating assembly. The converging shot configuration works with most gun sizes, lengths, shot densities and can be run in 0°, 0-180° and 60° phasing. In this paper, we will review the background for horizontal well perforating, review the design and testing of the FocusShot technology and then present field test results that demonstrate the value for Frac optimization.

BACKGROUND
Perforating cemented casings with explosive shaped charges has been employed for decades.

Over the past fifty years, the technology has advanced and developed in response to industry demands for different products to solve reservoir and completion design issues. The concept of explosive shaped charge perforating originated in World War II with the bazooka design.

An explosive shaped charge utilizes powdered explosives compressed behind a metal liner (powdered or solid) into a case, Figure 3. When the shaped charge is detonated, the explosion causes the metal liner to collapse from the center and flow at extremely high velocities perpendicular to the charge case surface. This jet of high velocity metal creates a hole (perforation) in the gun carrier, casing, cement annulus and tunnels into the rock formation. Perforating guns are designed to carry multiple shaped charges configured in variable shot densities and phasing dependent upon the application. The design of the shaped charge will determine the diameter of the entry hole in the casing, depth of penetration into the rock formation and shape of the perforation tunnel.

PERFORATING FOR FRACTURING
Much has been written about perforating for fracturing optimization (Willingham, et al. 1993) including the selection of EHD (Entry Hole Diameter), phasing (azimuthal distribution of charges around the carrier), shot density (perforations per foot) and length of perforated interval (cluster) (van de Ketterij, de Pater 1997). It has been proven that perforation design has a substantial impact on the fracturing efficiency and performance (Behrmann and Nolte 1998). The perforations are the conduit for the fracturing fluid to exit the steel casing and apply pressure to the rock formation. The ideal perforation would have sufficient friction and pressure drop to insure fluid is evenly distributed to each perforation in the cluster/stage, and create the least amount of tortuosity in the fracture path. These ideal perforations would allow the immediate initiation of a single transverse fracture at the Preferred Fracture Plane (PFP) at each perforation cluster within a stage, Figure 4. It is undesirable for multiple fractures to be initiated in the proximity of the perforation interval (cluster), or for axial fracturing to occur (Daneshy 2014). Multiple fractures and/or, axial fracturing can rob energy from the fluid, reduce fracture width, reduce...
the length of the fracture and restrict the placement of proppant into the formation. Restrictions on fluid flow outside of the perforation can result in a screen-out. This was true for vertical wells, but is proving to be even more critical for horizontal well completions. For optimal horizontal well completions, we prefer single transverse fractures initiated at each cluster within the stage, with maximum length, Figure 5.

Previous work (Daneshy 1973, 2009, 2014) demonstrated that the state of stress in a borehole provides a natural tendency for longitudinal (axial) fracture initiation. According to Daneshy, this is a geometrical effect and independent of in-situ stress orientation. If longitudinal fractures are not perpendicular to the minimum horizontal stress, they need higher initial pressure to extend. Conventional perforating adopted from vertical well completions does not promote transverse fracture initiation regardless of spacing between perforations, or phasing around the casing. The axial distribution of perpendicular perforation tunnels can create multiple fractures and narrow paths with considerable turbulence at the wellbore, resulting in high wellbore pressure. The result can be reduced fracture lengths, higher pump pressures, obstructed proppant path at the wellbore and potential for screen-outs.

According to Daneshy (2009), a better method for perforating would be to align all perforations in each cluster in a single plane perpendicular to the borehole axis, Figure 6. Figure 6 (a) shows a spiral perforating pattern created by a 60° phase gun assembly. Figure 6 (b) shows those perforations collapsed to a single plane. Unfortunately, with a perforating gun assembly it is impossible to align the shaped charges to perforate the casing on a single plane. Explosive shaped charges must be axially displaced along the gun carrier due to space limitations inside the gun body and to eliminate explosive interference, thus explosive shaped charge perforations are axially displaced along the casing circumference. Since it is impossible to align all the explosive shaped charges to a single plane inside a perforating gun body, an alternative was proposed (Sites 2012). By changing the angle for the perforating charges inside the gun body to orient each of the perforations back to the center of
the gun assembly, the perforation energy and tunnels can be converged to a single plane, Figure 7. The perforating tunnels will converge at a distance from the casing depending upon shaped geometric orientation and target penetration (i.e. deep penetrating charges set at a higher alignment angle will converge deeper into the reservoir rock).

DEVELOPMENT AND BALLISTIC TESTING

To test the performance of the converging (FocusShot) concept, a series of ballistic tests were performed in concrete targets at a shaped charge perforating testing facility. The tests were designed to evaluate gun stability, charge performance (interference), target penetration, casing integrity and perforation exit hole diameters. The test was setup to shoot a series of one and two ft. long, 3.125 in. OD perforating guns loaded with standard shaped charges aligned at varying angles, Figure 8, into five ft. diameter flowerpot concrete targets with 4.5 in. OD casing centered, Figure 9. The FocusShot (converging) configuration was tested against conventional load and down shot, Figure 10.

It was noted during and after the test detonations that the concrete targets in the FocusShot configurations were more completely broken at intersection of the perforation tunnels, indicating the power of the converging energy.

There are two sets of converging perforation tunnels in opposite directions in the top portion of the target, Figure 11. These perforations can be traced from the casing exit point to the edge of the remaining target. The tunnels at the bottom of the target are single down shot perforations. The upper section of the target is completely crushed (missing target) where the perforating energy converges.
Table 1 summarizes the results of the tests. All shots were through the targets and it was noted that as charge angle increased, so did EHD.

### Table 1. FocusShot Test Data

<table>
<thead>
<tr>
<th>Shot</th>
<th>Distance</th>
<th>Angle</th>
<th>Diameter</th>
<th>Area</th>
<th>Penetration</th>
<th>New Angle</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Through</td>
<td>0</td>
<td>0.31 x 0.31</td>
<td>0.075</td>
<td>Through</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Through</td>
<td>0</td>
<td>0.30 x 0.31</td>
<td>0.073</td>
<td>Through</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Through</td>
<td>0</td>
<td>0.30 x 0.31</td>
<td>0.08</td>
<td>Through</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Through</td>
<td>0</td>
<td>0.30 x 0.31</td>
<td>0.073</td>
<td>Through</td>
<td>0</td>
</tr>
<tr>
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<td>Through</td>
<td>0</td>
<td>0.29 x 0.29</td>
<td>0.066</td>
<td>Through</td>
<td>0</td>
</tr>
</tbody>
</table>

As the angle of incidence increased from 0 to 45 degrees the X an Y diameters of the perforation entry hole increased. For a 30 degree shot the average areas increased by 20%. For a 45 degree shot the diameter increased by 30%.

### FIELD TEST RESULTS

A field test was setup to evaluate conventional versus FocusShot on a Marcellus project in Pennsylvania. This was a horizontal well pad with two ~4,050 ft. laterals; 750 ft. spaced; ~5,100 ft. TVD; drilled in the same northeast direction. The frac design (water, proppant, chemicals) and stage lengths were comparable between wells. Each stage was perforated with 5 clusters using 3.125 in. 6 spf (12 holes) 60° phased perforating guns with standard “good Hole” charges. The Conventional well was perforated with conventional guns and the FocusShot with converging. In general, the FocusShot well treated with lower pressure and higher sand volumes.

Figure 12 compares two of the stages for pressure, rate and proppant concentration. With the FocusShot perforations, the pressure build-up indicates the probable creation of a single transverse fracture. At pump rates > 90 bpm (barrels per minute) the pressure remained constant as proppant concentrations were increased well above the target level. The Conventional well shows an erratic high-pressure response, likely indicating the production of multiple and/or axial fractures. The 90 bpm target pump rate could not be achieved and proppant concentration was well short of the target. In this stage, proppant displacement was curtailed and fell well short of design.

The average treating pressure for the FocusShot well was -6%, or 340 psi lower, Figure 13, than the Conventional well.

An X-Y-Z plot, Figure 14, compares all stages for maximum pressure (Y axis), sand volume (X axis) and friction reducer volume (Z axis). Most of the FocusShot stages trend to the lower right portion of the graph (lower treating pressures and higher sand volumes). These treatment profiles would suggest that the FocusShot perforations were more effective in the initiation of single transverse fractures at cluster depths and allowed higher sand volumes to pump at lower pressures (a characteristic of ideal perforations).

Better fracturing treatments should result in better production. The first 31 days on the two wells shows approximately 9% better production from the FocusShot well, Figure 15.
SUMMARY AND CONCLUSIONS

A new perforating technique has been developed for horizontal well completions. This perforating design utilizes angled shaped charge configurations to converge perforation tunnels and energy at the center of the perforating gun/cluster. This technique converges the perforating tunnels on a single plane perpendicular to the casing axis at a fixed distance from the casing outside diameter. It is proposed that converging perforating will be more effective for the initiation of transverse fractures at

Figure 1. Average Treating Pressure per Well and Maximum Treating Pressure per Stage

Figure 14. Maximum Pressure vs. Sand Volume and Friction Reducer
the center of the perforation clusters. If the new design can reduce the propensity for perforations to create axial and multiple fractures, then more effective stimulations and better production will result.

Field test results indicate that FocusShot is an effective method to perforate horizontal wells to optimize fracturing and improve production. FocusShot has the potential to reduce treating pressures and increase proppant delivery to the reservoir. To date, there have been several hundred FocusShot stages completed in Marcellus, Utica, Woodford, Hunton and Eagle Ford wells without a single occurrence of a screen-out.

REFERENCES:


BIOGRAPHY:

Larry Albert is a BSc graduate of Oklahoma City University. He joined Gearhart Industries in January 1977 as an open-hole field engineer. After Halliburton acquired Gearhart in 1988, he held key management assignments at corporate and field locations around the globe. Prior to leaving Halliburton, he was Senior Director of Wireline Operations. In May 2010, Allied Wireline Services was formed and he served as President and CEO until Allied merged with Horizontal Wireline in 2014. He is currently Vice-Chairman and member of the Board for Allied-Horizontal Wireline Services, one of the largest independent wireline services companies.

Larry has been a member of SPWLA since 1977 and has held officer level positions in chapters around the globe. As a member of SPE since 1984, he has published technical papers and been an active speaker and contributor. He is also a member of API, AADE and AESC.

Gregg Frasure joined Welltec in 2005 as a Field Engineer. He spent 8 years with Welltec holding various positions in operations and sales. Prior to leaving Welltec, Gregg was Account Manager for the GOM helping drive opportunities in the riserless sub-sea intervention market. In 2013, he joined Superior Energy Services in Business Development. In 2014, he joined Horizontal Wireline Services as Sales Manager, after merging with Allied Wireline he became VP of Northern Sales.

Gregg is a member of SPE and has published two technical papers on wireline deployed intervention technologies. He is a graduate of Texas Tech University.