Oil and gas wells have been stimulated with high explosives since the late 1800s. It appears however, that the term ‘well shooting’ originated many years before, in the days when a water well was sometimes rejuvenated by shooting a rifle down the well. Nowadays, classic high explosives, such as nitroglycerine or gelatin, are rarely used to stimulate oil and gas wells due to problems of wellbore damage, safety hazards and unpredictable results. Extensive research on solid propellants that deflagrate rather than detonate have led to safe and much more effective options.

In the last 50 years, hydraulic fracturing has been the predominant method of well stimulation. Sophisticated techniques, software, equipment, fracturing fluids and proppant have been developed to optimise the hydraulic fracturing process. However, hydraulic fracturing has disadvantages including a lack of control over the vertical fracture growth and the high cost of treatment.

Fundamentals

Figure 1 displays generalised pressure-time profiles for three stimulation methods. Hydraulic fracturing is conducted by isolating a specific zone or formation in the wellbore and applying hydraulic pressure sufficient to overcome the compressive stresses surrounding the borehole. Quasistatic pressure is applied until tensile stresses are created and breakdown occurs. Hydraulic fracturing creates a single bi-wing fracture oriented perpendicular to the least principal in situ stress.

At the other extreme of the pressure-time regime of Figure 1 is the profile for high explosives. High explosives detonate and...
create a shockwave. Pressures created are extremely high but last only a few microseconds. Due to inertial effects, tensile stresses are not produced and instead, extreme compressive stresses enlarge the wellbore by crushing and compacting the rock\(^1\). The enlarged wellbore is left with a zone of residual compressive stress. These residual stresses and compacted rock can actually reduce permeability near the wellbore. Extensive cavings often fill the wellbore with debris that require days, even weeks, to clean up. The use of high explosives is limited to openhole completions.

Between these two extremes, solid propellants can generate a pressure pulse that creates a fracturing behaviour that is dramatically different from either hydraulic fracturing or explosives. Solid propellants do not actually detonate; they deflagrate. Deflagration is a burning process that takes place without any outside source of oxygen and creates large quantities of high pressure gas at a rapid rate. Propellants offer a very wide range of burn durations, from milliseconds to seconds, and not all will produce the desired fracturing behaviour.

The goal is to tailor the pressure-time profile so that it is slow enough to load the rock in tension, avoiding the inertial effects that create extreme compressive stresses in explosive loading; and rapid enough so that a single fracture cannot take all of the high pressure gas being produced. If the burn rate is high enough, pressures reach levels sufficient to put other parts of the wellbore in tension, creating multiple fractures that propagate in directions not governed by the earth’s in situ stress state. This provides the desired benefits of optimum nearbore drainage and fracture propagation that is contained to the zone of interest. The required pulse duration is approximately 10 000 times longer than for explosives and 10 000 times shorter than for hydraulic fracturing. The fracture patterns resulting from the three pressure profiles of Figure 1 are depicted in Figure 2.

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**Table 1. Averaged results from pressure transient analyses for GasGun and sand fracs**

<table>
<thead>
<tr>
<th>Number of wells</th>
<th>BHP (psi)</th>
<th>Skin factor</th>
<th>Frac half length (ft)</th>
<th>Effective permeability (millidarcies)</th>
<th>Production (thousand ft(^3)/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GasGun</td>
<td>5</td>
<td>213</td>
<td>-4.58</td>
<td>86</td>
<td>0.60</td>
</tr>
<tr>
<td>Frac</td>
<td>6</td>
<td>176</td>
<td>-4.51</td>
<td>92</td>
<td>1.27</td>
</tr>
</tbody>
</table>

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**Figure 1. Pressure-time profiles of three stimulation methods.**

**Figure 2. Fracture behaviour of three stimulation methods.**
Some of the effective applications of these stimulations are summarised as follows:

- Remove skin and damage from perforators, drilling fines, scale, mud cake, cement, etc.
- Improve effectiveness of acidising.
- Prepare well for hydraulic fracturing.
- Increase injection rates in waterfloods, waste disposal and gas storage wells.
- Stimulate naturally fractured reservoirs.

**A solid propellant tool**

The approximate values of peak pressure and duration noted for the intermediate pressure pulse of Figure 1 are for the GasGun®, which is one of several propellant stimulation devices commercially available today. The pressure profile of the GasGun has been shown to achieve the multiple fracturing behaviour described above from research conducted at Sandia National Laboratories in the 1970s. Depending on well conditions, peak pressures can range from 10 000 - 50 000 psi, and burn times vary from 5 - 30 milliseconds.

In contrast, there are at least three propellant stimulation devices currently being marketed that have burn times in the order of seconds rather than tens of milliseconds. These tools are basically solid propellant rocket motors and will only produce a single hydraulic-like fracture that can wander out of the pay zone, following the path of least resistance. They will not produce the desirable pattern of multiple fractures. Another drawback of these slow burning devices involves the high level of energy lost uphole.

The Sandia research included full scale experiments conducted in a tunnel complex at the Nevada Test Site, and direct observations of the fracturing were made by mining out the borehole after stimulation (Figure 3). Based on these findings, coupled with refinements made to the tool and extensive empirical evidence, GasGun fractures are believed to radiate 10 - 50 ft from the wellbore, depending on depth and rock properties.

The GasGun propellant is similar to that used in large bore military guns. While the concept of using solid propellants to stimulate oil and gas wells is not entirely new, the propellant incorporates a new design with progressively burning propellants. Progressive burning means that the rate at which the propellant burns increases with time, producing gas faster as the material is consumed. This feature is accomplished with multi-perforated propellant grains that increase their surface area as the propellant burns (Figure 4).

Progressive burning propellants are more effective at controlling peak pressures, thus allowing more propellant energy to be delivered to the formation without causing casing damage. It also creates longer fractures by producing more gas late in the process when crack volumes are the greatest. In the Sandia research cited previously, a multi perforated propellant was 300 times more effective in enhancing formation permeability than a standard regressively burning propellant in a direct side by side comparison.

**Propellant stimulations compared to hydraulic fracturing**

Solid propellant stimulations will never replace hydraulic fracturing. Large hydraulic fracture treatments can create a fracture hundreds of feet in length, which may be necessary to produce reservoirs with extremely low permeability. But many small pay zones in marginal wells cannot justify the expense of these treatments. A propellant stimulation can be an economical alternative, requiring less onsite equipment, and can in some cases replace small hydraulic fracture treatments.

For example, in December 2005, a major Canadian producer decided to test the GasGun against traditional stage fracs in shallow gas wells of the Basal Belly River formation. They stimulated five wells with the GasGun and six using 5 t sand fracs. The operator then conducted a pressure transient analysis on each well. Results are presented in Table 1.

As stated previously, hydraulic fracturing creates a single bi-wing fracture oriented perpendicular to the least principal in situ stress. Unfortunately, the fracture can propagate vertically as well as laterally seeking the path of least resistance. Many hydraulic fractures have been known to break out of the producing formation and into aquifers and thief zones. While the fractures produced by the GasGun are more limited in length, vertical fracture growth will be no more than 1 - 3 ft above or below the treated zone. The advantages of GasGun stimulations over hydraulic fracturing are summarised as follows:

- Minimal vertical growth out of pay.
- Multiple fractures.
- Selected zones stimulated without the need to set packers or ball off.
- Minimal formation damage from incompatible fluids.
- Homogeneous permeability for injection wells.
- Minimal onsite equipment needed.
- Much lower cost.

**Fielding**

The propellant is conveyed to the formation in a high strength hollow steel carrier under a minimum fluid column of 300 ft that tamps the charge and assures that the energy is restricted to the pay zone. Simple calculations based on Newtonian mechanics (F = ma) show that a typical GasGun pressure pulse will lose less than 1.5% of its energy when fielded under a 300 ft water column.

It is the mass of the fluid column and the short duration of the pressure pulse, tens of milliseconds, that prevents the fluid column from moving more than a few inches during the fracturing process. High pressure gas is forced into the perforation tunnels immediately adjacent to the tool and not into other open zones above or below. This allows the operator to selectively treat zones of interest. There is no need to set packers to isolate the treatment zone as would be the case for hydraulic fracturing in wells with multiple open intervals.

The same cannot be said for propellant stimulations based on rocket motor technology. The relatively long duration pressure pulse will significantly raise the fluid column and allow gases to enter other zones. Also, energy losses uphole can reach 50% or more in these stimulations.

The fluid tamp over the GasGun tool can be anything compatible with the formation such as fresh water, brine, oil or solvent. The tool is usually fielded by wireline but can also be tubing conveyed. The tool is ignited while being suspended at...
the correct depth. Pressure control equipment, such as a lubricator, can be used when needed. Typically little or no cleanup is required, and the well can usually be put back on production immediately after the stimulation.

Case studies
The following two case studies demonstrate the advantages of solid propellant stimulations over traditional explosive and hydraulic fracture stimulations.

Bradford sand waterflood
In November 2006, four injection wells in Cattaraugus County, New York, were stimulated - two with the GasGun and two with nitroglycerine. The wells are part of a large waterflood and were completed openhole in the Bradford sandstone formation at 1600 ft. Prior to stimulation, injection rates were zero in all four wells. Approximately 130 ft of formation was treated in each well.

The wells stimulated with nitro involved significant cleanout expenses and achieved injection rates of 15 bpd of water. In contrast, the wells treated with the GasGun had no cleanout expenses and achieved injection rates of 60 and 90 bpd of water. Based on these results, all the injection wells and many of the producing wells in the field were stimulated with the GasGun, with similar success.

Arbuckle dolomite
Stimulating oil wells in the Arbuckle dolomite of Kansas presents special challenges. This formation is known to lie just above vast quantities of water. Hydraulic fracturing and even light acidising commonly results in vertical fracture migration into the water bearing zone. As a result, many operators have adopted a strategy of using the GasGun to create a fracture network that does not migrate out of zone, followed with a light acid treatment that usually goes on vacuum. Oil production typically increases with little or no change in the percentage of water production. Nearly 200 Arbuckle wells have been treated with this method and economic success has been achieved in approximately 75% with an average three to tenfold increase in production.

Conclusions
Solid propellants have a wide range of burning characteristics and can produce large quantities of high pressure gas. If burn times are selected in the proper range, the resulting behaviour of multiple radiating fractures confined to the treatment zone has many distinct advantages over conventional hydraulic fracturing.

In the last 10 years, over 4000 GasGun propellant stimulations have been performed in the USA, Canada, Europe, Africa and the Middle East. Well depths have ranged from 200 - 15 000 ft. Some of the most successful treatments have been in formations that are known to produce large volumes of water when hydraulically fractured. Examples include the Arbuckle formation in Kansas, the Aux Vases, Cypress, and Tar Springs formations in the Illinois basin. Successful stimulations have been achieved in many lithologies including sandstone, limestone, dolomite, shale, coal, chert, chalk, marlstone and diatomite.

References