New Perforating Switch Technology Advances Safety and Reliability for Horizontal Completions

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The Problem

This paper focuses on a critical component of electric wireline perforating technology for oil and gas well completions; namely, the switch connections that selectively control voltage to gun systems. When a switch applies proper voltage to a perforating gun assembly, an explosive detonation results in plugs or packers being set, or perforating holes being jetted into the casing, cement and formation. Today, the ability to selectively position plugs and guns downhole is a key requirement for completions in both vertical and horizontal applications, and has led to development of a new addressable switch for select-fire perforating. The new switch replaces current pressure switches which can inadvertently detonate the guns should stray (unwanted) voltage be applied. Such an event downhole can be costly in terms of requiring substantial resources to repair the damaged wellbore, or in lost or sub-optimized production. If the inadvertent detonation occurs at surface, the results can be life threatening.

To prevent such incidents and provide the highest level of safety, the new switches are electrically addressable and must be in direct communication with the surface system and wireline operator before they will pass current to the perforating gun and allow detonation. As a result, they are inherently safer to use for explosive operations, and have been proven to be more reliable.

In describing this new switch technology, the paper presents a case for its quick adoption by the industry.

Perforating History – Importance to Well Completions

Perforating has been a key component of well completions since the introduction of oil well cementing in the 1920’s1. Cementing casing was a major technological innovation and allowed E&P companies to isolate production intervals, but since the formations were sealed behind a cement annulus, a means to connect the reservoir with the wellbore was required. To allow the formation fluids to flow into the wellbore, techniques for perforating the casing were developed, one of the earliest being use of bullet guns deployed on electric wireline. Bullet guns used electrically detonated explosives to fire steel bullets perpendicular to the gun carrier at a high velocity to penetrate the steel casings and cement annulus. Unfortunately, this technique was not efficient, and a large percentage of the bullets were ineffective in penetrating the casings and cement annulus.

In the late 1940’s, explosive shaped charge technology, developed for use in WWII as an anti-tank weapon (bazooka), was adapted to oil well perforating2. Shaped charge perforating was commercially introduced by 1950, and this technique soon became the primary means for casing perforating (see figure 1). Shaped charge perforating guns deployed on electric wireline utilize electrical detonators (blasting caps) to initiate the explosive train that produces the jet perforations. The electrical conductor inside the steel wireline is the means by which voltage is applied to these detonators. As shaped charge perforating advanced, new designs of gun carriers and shaped charges were developed for a multitude of casing designs and formation characteristics.
As completions became more complex, there was a need to perforate multiple intervals (select-fire) with a single trip in the wellbore. To select-fire perforate, voltage to individual gun sections had to be controlled, and a seal maintained between guns as they were shot. The earliest select-fire methods utilized the same select-fire technique deployed with bullet guns (i.e., igniters from bottom up, requiring progressively higher current to fire). In the 1960’s, electrical rotary selectors were introduced and were combined with a dart and baffle system to seal between carriers. These rotary selectors were hard to maintain and unreliable, plus the dart and baffle pressure sealing method was prone to leaks. In the 1970’s an enhanced dart and baffle system was introduced that combined polarity sensitive diodes for select-fire perforating. A polarity sensitive diode will pass current of one polarity (positive or negative) and block the other. By this method, diodes of alternating polarities could be placed between individual gun carriers and one could position the wireline deployed perforating gun over a formation interval, shoot the bottom gun, then pull the perforating gun to the second interval, reverse polarity and shoot the next gun. This worked well for dual interval perforating, but was not effective for multiple gun deployment, especially at higher temperatures and well pressures.

In the late 1970’s a new generation selector system was developed that combined a pressure actuated, hermetically sealed switch with polarity sensitive diodes (pressure switches – see figure 2).³ This technique eliminated the dart and baffle seals, thus dramatically improving reliability, plus it allowed more guns to be deployed. Pressure switches became the preferred system for select-fire perforating by the early 1980’s, and continued with minor technical advancement for two decades.

This new select-fire perforating method significantly improved reliability, but the operation was sequential, bottom to top, and any misfire in the sequence forced retrieval and repair of the perforating gun assembly. Another weakness was inadvertent switch actuation when a sub failed under pressure downhole. When a seal fails, the quick influx of wellbore fluid can cause a pressure switch to actuate and arm the next gun in sequence; when the assembly is positioned to set a plug, or fire a gun, a gun further up the string would be detonated, causing an off-depth perforation (ODP). Since the sequence of diodes dictate the firing sequence (positive or negative), it is absolutely necessary that the wireline operator and the gun loading be perfectly coordinated. If the polarity selection is inaccurate, the wrong gun will fire. These ODP events could be costly for operators to repair.

**Wireline Setting Tools**

In conjunction with electrical wireline perforating, methods and tools were also developed for wireline deployed bridge...
plugs and packers to aid in isolation of different intervals of the wellbore\textsuperscript{4}. These setting tools combined electrically detonated explosives with hydraulically actuated pistons to compress plugs and packers and then shear and release. For decades, these setting tools were wireline deployed on a separate trip from perforating operations; but with the introduction of the sealed, polarity sensitive pressure switches, plug-shoot adapters were developed that allowed the combination of perforating guns and setting tools (see figure 3). This plug and perforate (perf) technique was important for multi-zone stage completions, as it significantly reduced the trips in the hole with wireline. This operation utilized an explosively detonated, hydraulically operated setting tool at the bottom of the tool string, with multiple perforating guns stacked above. The switches were sequenced to set the plug on a designated polarity, and then to alternate polarity in order to shoot guns bottom to top as the tool assembly was moved to predetermined formation intervals. A stage (predetermined interval of formation) could be then be produced or stimulated. For multi-stage stimulation completions, a stage run for wireline included a bridge plug (to isolate between stages) and multiple guns (clusters for stimulation).

![Figure 3](image)

**Perforating Safety Issues**

While many advances were made in perforating technology over several decades, one problem remained. The electrical detonators used to initiate the explosives train (detonating cord and shaped charges) in a perforating gun could be discharged inadvertently if enough voltage at the proper polarity was misapplied to the wireline. This misapplied voltage could be from a number of sources, including stray (cathodic protection, leaking electric cables on rigs, etc.), radio frequency (RF), or human error. Over the past several decades wireline services companies have developed thorough procedures for safe explosive perforating operations. There are also published recommended best practices for oilfield explosives safety\textsuperscript{5}. When executed flawlessly, perforating can be performed in a safe and effective manner, but even with a focus on training and service companies following standard operating procedures, there continues to be instances of inadvertent detonations. When an inadvertent detonation occurs downhole, the economic impact can be high; when it happens on the surface, the event can be life threatening -- and indeed there have been a number of inadvertent surface detonations over the years that have resulted in deaths and/or severe injuries to personnel.

It has been proven that radio frequency (RF) transmitted signals can initiate detonation of an electrical blasting cap; therefore, RF-safe procedures must be in place when performing electrical wireline perforating. To maintain RF safety, standard electrical detonators require an RF-free perimeter be maintained around the perforating operation. Decades ago, an RF-free well site was not difficult to achieve, but with the proliferation of cell phones, GPS devices, radios, etc., and the large operational footprint for multi-stage completions requiring continuous communication to properly coordinate, it has become very difficult and expensive to maintain an RF-free zone around the perforating operation. Over the past two decades, several RF-safe ballistic initiating devices were introduced that allowed perforating to continue without clearing the perimeter of RF devices\textsuperscript{6, 7}, but some of these RF-safe systems were complex, thus adding significant costs, or reducing reliability.

Some of the same advances in technology to shield detonators from RF also required much higher levels of voltage to initiate\textsuperscript{6, 7}. Such technology shielded the detonators from most sources of stray voltage, but even with these advances, human error continued to be a factor in inadvertent detonations. If a mistake was made and enough voltage at the proper polarity was applied to the wireline, explosives would be detonated. When that occurs on the surface the results are tragic.
Addressable Switches – A New Technology

A new method for controlling voltage directed to individual perforating guns has been developed\(^8\)\(^,\)\(^9\). This new select-fire perforating method replaces pressure switches with smart switches that include intelligent electronic circuits with unique digital addresses that can be addressed through simple telemetry systems (see figure 4). The new system includes a surface panel that can communicate with each of the downhole circuits. Through the surface panel, the wireline operator can identify each of the gun modules, determine their status, and then control the circuits to direct voltage to a detonator connected to the digital switch.

A very important feature is the integrated protection circuits (A and B in Figure 4) that will block the unintended flow of electricity through the switch and will stop inadvertent voltage from initiating a detonator. In addition, when integrated with electrical detonators, the switches are certified RF safe, so there is not a need to create a RF-free perimeter while perforating (almost impossible to guarantee with the large footprint frac jobs). The voltage protection circuits and RF certification make this technology an evolutionary advancement in perforating safety.

The system was designed to improve reliability. During pre-run checks the new switches can be polled with a test panel to verify circuit integrity to insure the tool assembly is wired correctly and all components are working properly. Each of the switches can also be checked while running into the wellbore to continuously verify the integrity of the electrical circuit. Unlike pressure switches, which are passive and cannot be checked downhole, these new switches can be addressed and their status verified at any point before (test panels), or during the run in hole (wireline surface control panel). In the event of a system failure (leaking cable-head, shorted wireline, failed CCL, pinched gun wire, bad switch, etc.), the assembly can be repaired before pumping to total depth and attempting to set a plug or fire a gun. This improved troubleshooting can reduce failed runs, minimize the potential for stuck tools, and significantly reduce non-productive time. This can be very important for pump-down completions on horizontal wells, as there is generally a significant footprint of stimulation equipment standing by while wireline services are being conducted. Also, sticking and leaving tool strings in horizontal wells can be expensive, and POOH after a failed pump-down run to bottom on a long lateral can be risky.

The new switch technology also provides real-time feedback of the detonation event. This helps the wireline operator know with some certainty if a plug sets or a perforating gun fires. Prior techniques to verify downhole detonation included surface measurements that were not reliable. This downhole shot detection is especially important since, unlike the pressure switch technology that fired bottom up in sequence, the new switches allow the wireline operator to bypass a failed gun and shoot the next gun in sequence. Many times shooting all but one gun is adequate for a stage completion, thus reducing the number of failed runs and improving run efficiency.
The adoption of this technology has had a dramatic impact on the reliability of wireline perforating (figure 5). Prior to adopting addressable switch technology, the wireline runs/misrun ratio was very close to 25 (4% failure rate or 96% efficiency). As the new technology was implemented, improved, and became the standard for select-fire perforating, the wireline runs/misrun ratio more than quadrupled. At a ratio of 100 runs/misrun, the failure rate had dropped to 1% and run efficiency improved to 99%. The impact on well-site efficiency was appreciable, with reduced stand-by for frac spreads, fewer opportunities to stick gun assemblies, and overall lower cost of operations for the E&P companies.

Summary and Conclusions

A key aspect of such plug and perf operations is the ability to safely control and selectively apply voltage to individual sections in the downhole wireline assembly, so pressure switch technology has developed over the years to allow multiple gun sections to be combined with setting tools for single trip wireline runs, significantly improving efficiency. Yet the technology still suffered a number of deficiencies, which have now been overcome with a new addressable switch technology for controlling voltage directed to individual perforating guns:

- Addressable switches provide the ability to block inadvertent current from the electrical detonators in the tool string. This includes all sources of voltage: stray, RF signal or human error.
- The switches, when integrated with standard detonators, are certified RF safe, so we no longer need to attempt to create a RF-free perimeter at the well-site.
- The wireline operator can now communicate with and control each of the sections of the downhole assembly, and the new switches can be checked before and during the wireline run, thus improving reliability.
- Real-time shot detection gives the operator immediate feedback on whether plugs have set or guns have fired.
- Individual gun sections can now be skipped in the event any section fails to detonate, thus preventing a mis-run and resulting in better efficiency.

The adoption of this new technology has increased in recent years; however, the majority of wireline perforating continues to be performed with conventional pressure switch technology. One of the arguments against addressable switch perforating is the incremental cost when compared to the older technology. Due to this increased cost, both wireline service companies and E&P operators have been reluctant to change. This argument is no longer valid. As addressable switch volumes have increased, suppliers have found ways to cut the cost of production and unit prices have come down. Those savings are being passed on to E&P operators. As addressable perforating systems designs are continuously improved and innovation occurs, the costs will continue to decline. Regardless, at current unit prices the improved reliability and gains in efficiency will more than pay for the incremental costs associated with replacing pressure switches and diodes with the new addressable switches. When accounting the total cost for perforating, including costs for failed runs, stuck tools, fishing and well remediation, the new addressable switch systems will prove to be a solid investment with a high rate of return. Bottom line, if this new technology can prevent surface detonations and loss of life, that is the ultimate prize.
This new technology is an evolutionary advancement in well-site safety and is significantly more reliable. It should be adopted by the oil & gas industry as the new standard for select-fire perforating. In fact, a comparison of probabilities (shown below) makes a compelling case for its immediate adoption based on the safety merits alone.

<table>
<thead>
<tr>
<th>What are the odds...</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolling a pair of sixes</td>
<td>1: 35</td>
</tr>
<tr>
<td>Killed in a road accident</td>
<td>1: 8,000</td>
</tr>
<tr>
<td>Getting hole in one</td>
<td>1: 12,000</td>
</tr>
<tr>
<td>Getting an injury from fireworks</td>
<td>1: 19,000</td>
</tr>
<tr>
<td>Date a supermodel</td>
<td>1: 19,556</td>
</tr>
<tr>
<td>Struck by lightning</td>
<td>1: 750,000</td>
</tr>
<tr>
<td>Spotting a UFO today</td>
<td>1: 3,000,000</td>
</tr>
<tr>
<td>Killed in a tornado</td>
<td>1: 5,000,000</td>
</tr>
<tr>
<td>Struck by lightning – twice</td>
<td>1: 9,000,000</td>
</tr>
<tr>
<td>Killed in an airplane crash</td>
<td>1: 11,000,000</td>
</tr>
<tr>
<td>Killed by a falling coconut</td>
<td>1: 250,000,000</td>
</tr>
<tr>
<td>Killed by a shark</td>
<td>1: 300,000,000</td>
</tr>
<tr>
<td><strong>Unintended initiation of Addressable Switch detonator</strong></td>
<td><strong>1: 72,000,000,000,000,000</strong></td>
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Authors

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