The complexity of completing a modern oil and gas well increased dramatically with the rise of unconventional plays. Wellsite operations employ a large variety of equipment, often working on multiple wells. Simultaneous operations and communications are essential to working efficiently and cost-effectively but pose safety risks that must be effectively managed.

Most horizontal wells use plug-and-perf (PNP) completions involving multiple stages and 12 or more perforating guns per stage. More than 12,000 horizontal wells with an average of 20 or more stages per well were expected to be completed in the U.S. during 2015. Because each gun in each stage uses its own switch and detonator, the number of detonators used has grown dramatically.

Despite the increasing complexity, many companies still use detonating technology invented more than 50 years ago. These resistorized detonators are low-cost and reliable, but they can initiate with any potential difference higher than the no-fire current of the detonator’s fuse. Wireline companies have well-established safety procedures and training programs to address potential issues and ensure worker safety when using resistorized detonators.

Nonetheless, the potential for human error and wiring failures remains. Surface detonations still occur because this technology is not intrinsically safe—it does not fail safely and will initiate a perforating gun that can injure or kill oilfield workers. Unfortunately, a small number of fatalities and injuries occur each year at oilfield operations around the world.

**Selective perforating**

The majority of PNP operations still use pressure diode switches and resistorized detonators. These switches depend upon the successful initiation of one perforating gun to create an electrical connection with the next gun. Radio silence is required, so simultaneous operation is typically prohibited. If the wireline cable is powered, there is a direct electrical connection to the detonator, and the gun will initiate. The current from a cable electrical insulation tester also can initiate the detonator if mistakenly applied to a gun string.

Electrical switches are an alternative. Standard electrical switches require wireline service companies to manually wire the switch to the detonator. If a wire is pinched, damaged, miswired or comes loose, the wires on the detonator can operate like an antenna. If resistorized detonators are used, enough energy can be generated around the well site to risk an unintentional initiation.

As a next step, the industry introduced radio-frequency (RF)-safe detonators to ensure safety and allow uninterrupted communications. They are immune to being initiated by the energy from high-frequency communication devices. With RF-safe devices, maintaining radio silence is not required when a perforating gun string enters and exits the well.

While the industry has put great effort into ensuring RF safety, oilfield studies from the last two decades have shown that direct voltage on the wireline and human error are the primary causes of unintentional detonations. A still higher level of safety is necessary to ensure every oilfield perforator is safe at the end of each shift.

**Design optimization for safety**

Intrinsically safe integrated switch detonators have been used in PNP applications for the past four years. These systems incorporate microprocessors and a multistep logic sequence to establish communication and to arm and enable the detonator prior to initiation. Intrinsically
safe systems are fail-safe so that a surface detonation cannot occur. DynaSelect and the DynaStage detonator are examples of such devices.

Using rigorous design techniques, the microprocessor elements can be integrated into the detonator to form a single compact device. This eliminates manual wiring between the switch and detonator, and the connection between the components is verified during manufacturing. Reliability and safety are markedly improved.

The firing logic incorporates four steps (power up, arming, enabling and initiation). Each circuit component is separated by a normally open logic gate. A unique and progressively more complex digital code is required for each gate, and the probability of an unintended initiation of an integrated switch detonator is $1.38 \times 10^{-17}$.

Any wrong code will reset the detonator to its normally open state, and the entire sequence must be rerun. If power is interrupted, any energy stored in the system is discharged to a safe level below the required initiation voltage. A high voltage or current spike will destroy the main logic unit, thereby disabling transmission of the digital codes required to initiate the detonator.

Extensive testing verified the intrinsically safe integrated switch detonator is RF-safe and will not initiate due to stray or induced current and voltage. The following tests results were validated by three different independent test laboratories:

- Safely-tested at 50 V and 20 A;
- Protection ensured against maximum static electricity of 2,500 PF, 30 kV;
- Burst-tested to a maximum of 4.4 kV;
- Surge-tested to a maximum of 6.6 kV and 2,500 A; and
- Immune to a maximum frequency of 4 GHz and 300 V/m.

These results exceed the most extreme conditions encountered at a well site. The burst test voltage is 4.4 times greater than the maximum output of a Megger tester. Similarly, RF-safe performance is assured through maximum frequency results five to 10 times greater than the RF energy emitted by a mobile phone or two-way radio. Intrinsically safe devices ensure workers are protected from electrical hazards associated with test equipment, generators, telecommunications, high-voltage power lines and indirect lightning strikes.

**Improved operational efficiency**

Intrinsically safe integrated switch detonators provide the highest level of safety while enabling an operational protocol that reduces the cost of completions. Radio silence is not required, so simultaneous perforating and frack activities can be performed. On a three-well, 25-stage-per-well pad, this can shorten the time it takes to carry out completion operations by more than a day.

A surface tester verifies communication with each integrated switch detonator in the gun string prior to running in hole. The tester is a low-power device and cannot initiate any detonator. Surface testing can be conducted without risk to worker safety, and lost time is minimized by screening for errors at the earliest possible point.

The firing panel communicates with all the devices in a gun string without arming any of the RF-safe circuitry. The gun string can be continuously verified as it travels downhole without concern of an off-depth perforation. When at depth, the guns can be selectively armed and initiated. A gun can be skipped in the event of an issue, and perforation can continue without gun string retrieval and a second trip downhole. This can save 3 to 4 hours of down-time and several thousand dollars in operating costs.

**Real-world results**

Intrinsically safe integrated switch detonators have been employed for PNP applications in the U.S., Canada, Europe and China. These devices have established a proven safety record with more than 300,000 detonations without a single safety incident.

Several wireline service companies employ intrinsically safe integrated switch detonators in wireline operations in the Bakken, Eagle Ford, Permian Basin, Marcellus and other plays. In addition to the safety record, a notable improvement in operating efficiency was achieved.

Prior to implementation, the wireline runs-to-miss-runs ratio neared 25. With the introduction of the intrinsically safe integrated switch detonator, this ratio improved more than fourfold to a ratio ranging from 100 runs to more than 300 runs—a benefit delivering hundreds of thousands in savings to E&P operators from improved operating efficiencies from reduced frack standby times and the associated reduction in the cost of operations.