Perforations on Target

Exploration and production companies rely on new oriented perforating technology to optimize well productivity, minimize sand production and reduce overall completion costs in difficult environments. Careful planning, technology selection and postjob evaluation are keys to an optimized perforation strategy.

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DepthLOG, eFire-CT, OCD (Orientation Confirmation Device), OrientXact, PowerJet, PowerJet Plus and PURE (Perforating for Ultimate Reservoir Exploitation) are marks of Schlumberger.

1. Morton N: "Screening Out Sand," *BP Frontiers*, issue 2 (December 2001): 18–22.
2. Almaguer J, Manrique J, Wickramasuriya S, Habbtar A, López-de-Cárdenas JE, May D, McNally AC and Sulbarán A: "Orienting Perforations in the Right Direction," *Oilfield Review* 14, no. 1 (Spring 2002): 16–31.
3. Sulbarán AL, Carbonell RS and López-de-Cárdenas: "Oriented Perforating for Sand Prevention," paper SPE 57954, presented at the SPE European Formation Damage Conference, The Hague, The Netherlands, May 31–June 1, 1999.

Sand production can create such serious problems that a well costing millions of dollars to drill and complete becomes worthless. To protect their investment, exploration and production (E&P) companies today can orient well perforations. Oriented perforations can minimize sand production, improve productivity and reduce completion costs.

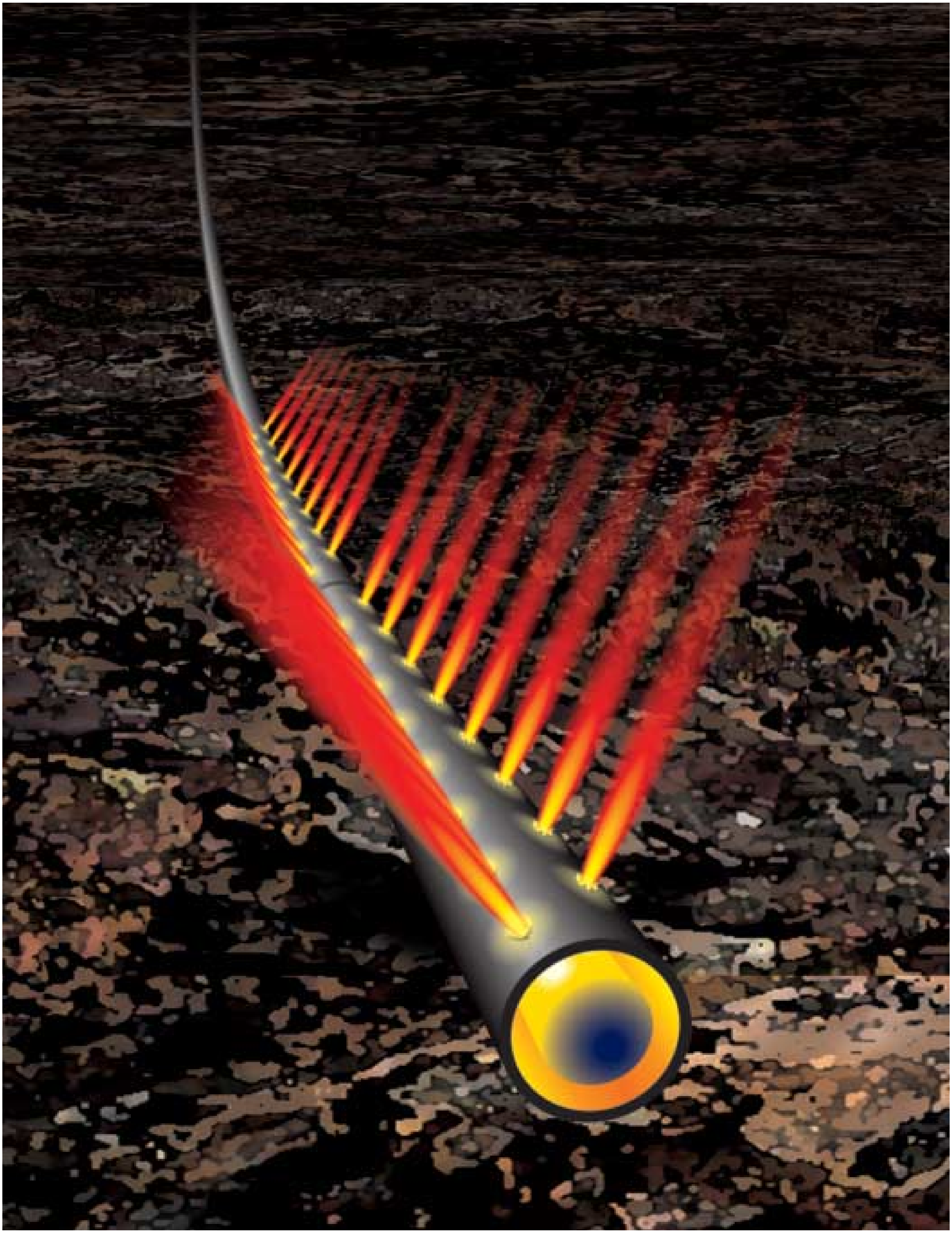
In 2001, a major oil producer reported 60% of its worldwide production, around 2 million barrels [317,800 m^3] of oil equivalent per day, was producing from fields requiring some level of sand management.[1] Left unchecked, sand production erodes downhole equipment, plugs the wellbore and ultimately chokes off fluid flow. Operators gather significant amounts of data relating to formation composition, bedding plane and stress orientation either through logging while drilling (LWD) or with wireline-conveyed logging techniques. These data, in conjunction with core analysis and offset-well performance, help operators establish a reservoir's potential to produce sand.[2]

In reservoirs presenting anisotropic stress profiles and a likelihood of sand production, the integration of stress-analysis modeling, conveyance techniques, new advances in perforation tool and charge design, and postfiring evaluation can offer overall completion and productivity optimization.

In this article, we discuss the deleterious effects of misaligned perforations and then describe how careful application of interdependent technologies improves perforating results. Case histories illustrate recent advances in tubing-conveyed oriented perforating for optimizing initial well productivity and for intervention in underperforming wells.

Exacting Orientation

In 1999, a major operator noted severe sand-production problems in the Eocene C reservoir in Lake Maracaibo, Venezuela. This reservoir is competent and consolidated but has high in-situ stresses resulting from a complex tectonic environment. By orienting perforations in the direction of maximum stress, the operator decreased the average sand produced from around 14 lbm/1,000 bbl [40 g/m^3] of oil to an average of less than 2 lbm/1,000 bbl [6 g/m^3], a reduction in produced sand of more than 85%.[3] The first four wells with oriented perforations had 30% higher production rates than the field average. This experience demonstrates that properly applied oriented perforating can significantly reduce sanding and enhance well



productivity (see "Practical Approaches to Sand Management," *page 10*).

Although oriented perforating has been successful in many areas, perforating tool designs have proved inadequate in highly deviated wellbores. During placement, tools experience varying degrees of frictional, bending and torsional stress, causing drag and gun-tube misalignment. Perforating gun manufacturers typically isolate the gun string from these stresses and the rotational force of the conveyance string by placing a number of swivel subs above the gun tubes to promote gravitational self-orientation.

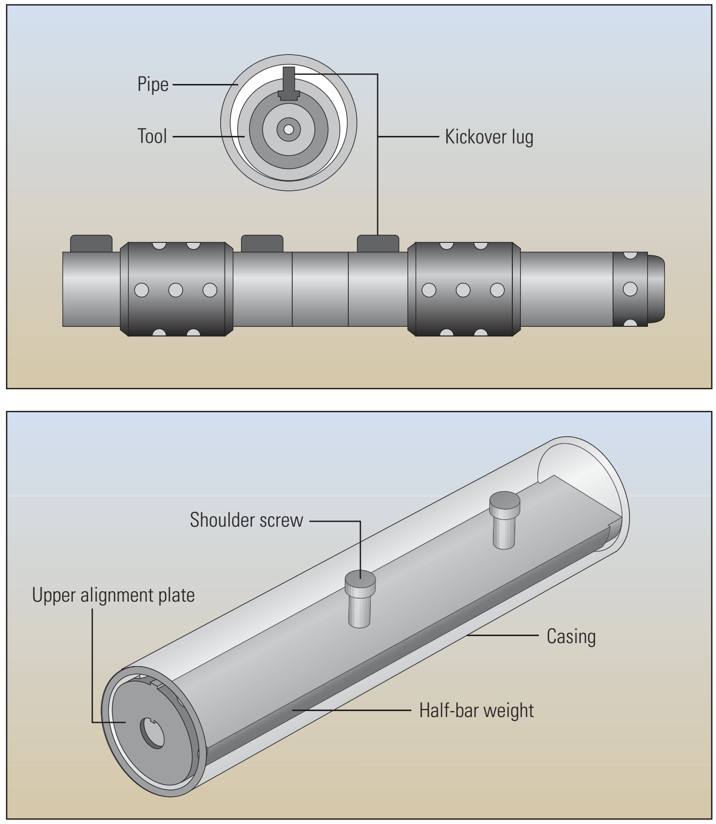
Manufacturers have employed various methods to generate gravity-driven perforation-tool alignment.[4] A common method uses fins, or kickover lugs, welded on the gun tube (right). Kickover lugs alter the gun-tube center of gravity and promote an eccentered orientation. The orientation accuracy using kickover lugs is generally better at low angles of wellbore deviation.

In an effort to overcome inherent shortcomings in this method, some manufacturers increased fin, or lug, height, while others made them shorter. Taller fins provided a tighter fit, but increased the potential for the gun string to become stuck in a wellbore. Shorter fins gave more clearance, but allowed the gun assembly more freedom to rotate, thus introducing an orientation error.

Early Schlumberger designs used internally weighted spacers to help orient the gun string. A solid, half-round steel bar occupied the lower half of a spacer, typically 20 ft [6 m] long. This design worked well for short intervals in straight wells, at moderate deviations and in situations requiring only minimal orientation accuracy.

In longer extended horizontal wellbore sections, 250 or more individual gun tubes are sometimes run on one string. Each gun section must be closely aligned with the next to assure perforation alignment. However, compressionsal forces acting on the connectors squeeze any manufacturing clearance tolerances, slightly twisting the right-hand connector threads and generating a gradual clockwise orientation error. Although each twist is small, the cumulative orientation error can be significant across perforation intervals with many connections (next page).[5] Although the allowable deviation from optimal perforation angle varies from reservoir to reservoir, a variance of more than 25° from maximum horizontal stress may promote sand production.[6]

Until recently, service providers tried to minimize the accumulation of alignment and subsequent orientation error by keeping gun-section length between swivels short. However, short sections often generate insufficient gravity-derived torque to orient guns in more deviated wellbores.



^ Kickover-lug designs. Older designs incorporating kickover lugs may become stuck inside casing. Often, the kickover lug is configured as large as possible relative to the inside diameter of the casing (*top*). With this close tolerance, sand and debris accumulating in and around the gun tube after firing may cause the gun to stick, or hang up, in the hole. Smaller lugs allow the gun assembly to fall to one side resulting in perforation misalignment. During conveyance in highly deviated boreholes, the eccentric shape of the gun-tube assembly can promote rotational torque and friction resulting in perforation misalignment. Other designs use weighted spacers (*bottom*) to generate rotational torque. If insufficient torque is generated to overcome frictional resistance, the result is perforation misalignment.

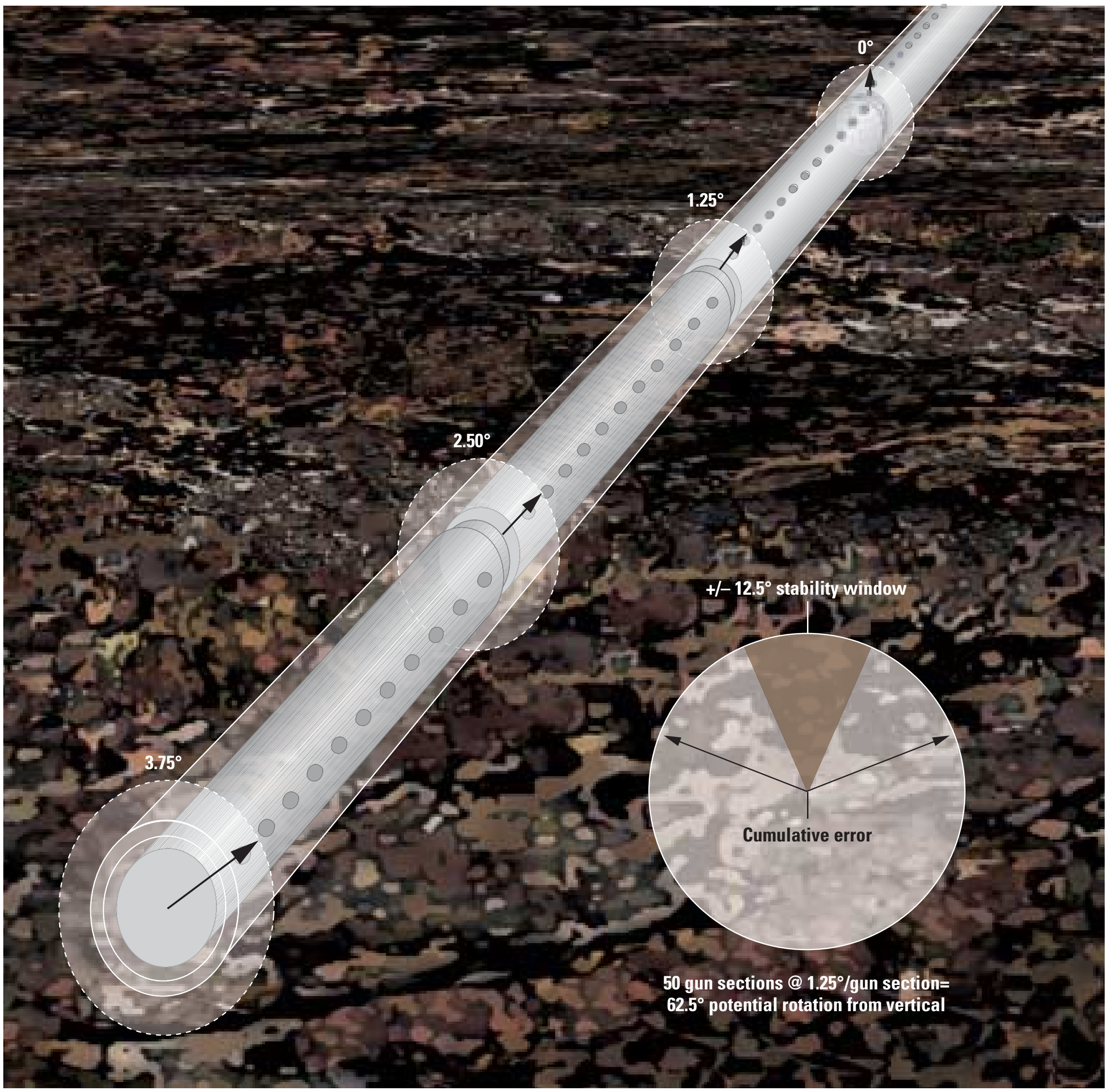
Intervention in the North Sea

Hydro found that attempts to orient perforations in highly directional wellbores in the North Sea often resulted in as much as 45° perforation misalignment. In 2001, lower than expected performance from early wells in the Visund field led Hydro to assess the effects of perforating techniques on sand production and well productivity.

The Visund field, operated by Statoil since 2003, lies about 150 km [90 miles] off the coast of Norway, northwest of Bergen. Production began in 1999 while the field was operated by Hydro. The first two wells in the Visund field were completed using sand screens. Over time, Hydro engineers found that zonal isolation was required to properly manage production from the field. Production liners were placed across the productive intervals and cemented in place; the wells were completed using a standard oriented perforating system with zinc-cased charges.

The reservoir in the Visund field is geologically complex and comprises weak sandstones with permeabilities ranging from 300 to 3,000 mD and an unconfined compressive

4. Benavides SP, Myers WD, Van Sickle EW and Vargervik K: "Advances in Horizontal Oriented Perforating," paper SPE 81051, presented at the SPE Latin American and Caribbean Petroleum Engineering Conference, Port-of-Spain, Trinidad, West Indies, April 27–30, 2003.
5. Stenhaug M, Erichsen L, Doornbosch FHC and Parrott RA: "A Step Change in Perforating Technology Improves Productivity of Horizontal Wells in the North Sea," paper SPE 84910, presented at the SPE International Improved Oil Recovery Conference in Asia Pacific, Kuala Lumpur, Malaysia, October 20–21, 2003.
6. Sulbarán et al, reference 3.



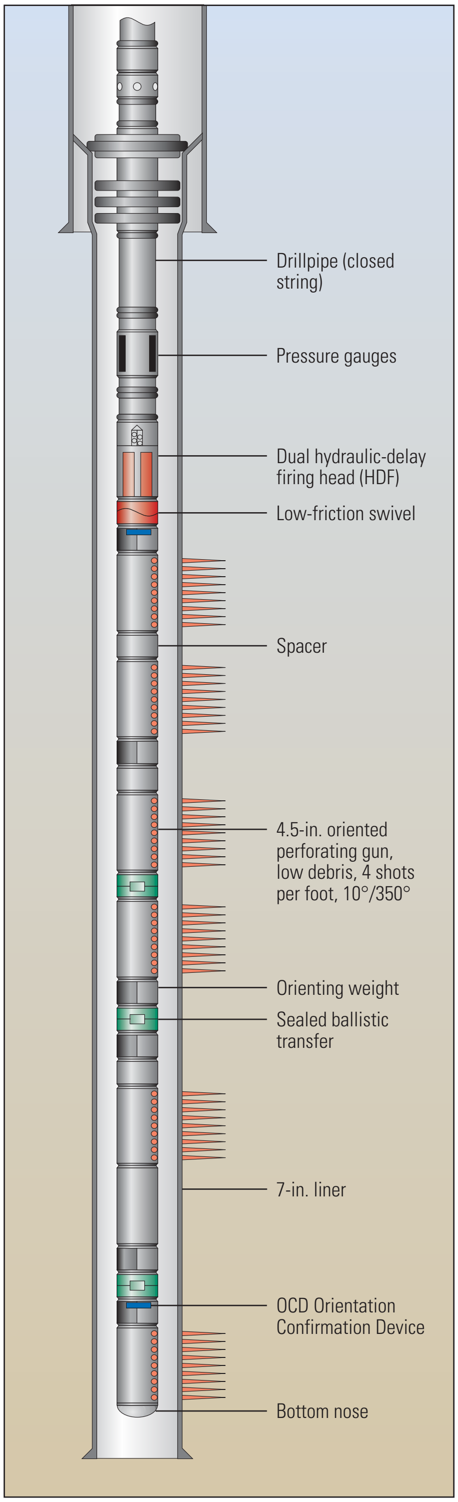
^ Accumulation of alignment error. In previous perforating gun designs, a slight rotational error was introduced at each gun section as the right-hand threads at each connection tighten under increasing compressional load. Although each rotational error may be small, the cumulative alignment error becomes significant, placing an indeterminate number of the guns outside the perforation-tunnel stability window. Bending and rotational torque from wellbore trajectory changes often exacerbate the total orientation error. In this example, a 1.25° error per gun section translates into 62.5° rotation from vertical if accumulated over 50 gun sections.

strength between 5 and 20 MPa [725 to 2,900 psi]. Rock mechanical studies indicated that sufficient perforation-tunnel strength could be maintained with a maximum 25° deviation from the vertical plane, the direction of the maximum stress.

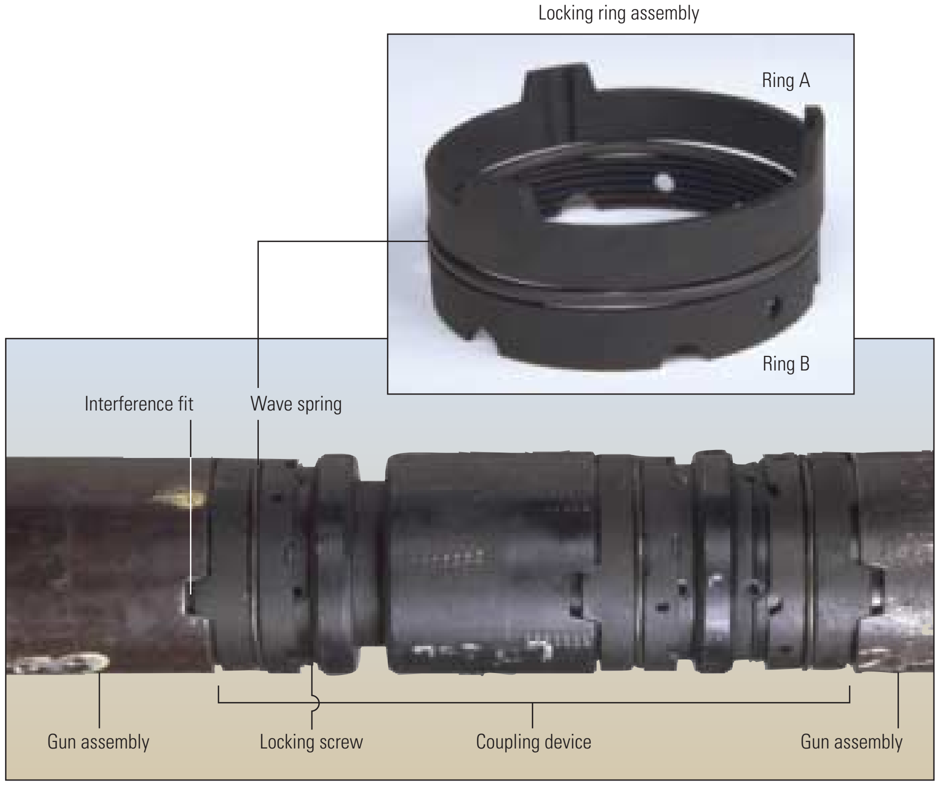
Hydro planned perforation intervals of more than 2,000 m [6,561 ft] across near-horizontal wellbore intervals. The combined allowable drift for gun alignment and orientation would be ±10°, an accuracy beyond the capability of ordinary perforating equipment. Engineers from Hydro realized that a new perforating system design could enhance productivity in the Visund field.

Hydro set performance targets for a new oriented perforating system. Gun tubes would be required to orient to within 20° of vertical through a 5°/100 ft [5°/30 m] bend, or dogleg. Charges would need to perform at 75% efficiency relative to standard steel-cased charges. Criteria were set for swivel performance under loads reaching 50,000 lbf [222 kN] in straight and deviated environments. Hydro also required a method of confirming perforation orientation with an accuracy of 2°. Lastly, postfiring criteria were set, including a requirement limiting gun debris to 50 gm/m [0.5 oz/ft] of nonzinc material.

Schlumberger engineers developed an advanced, tubing-conveyed perforating system capable of accurate perforation orientation



^ Design of the OrientXact tool tubing-conveyed oriented perforating system. The OrientXact design directs all perforations in a vertical direction with 10°/350° gun phasing. Pressure gauges may be used to record pressure changes during discharge. One or more low-friction swivels support the gun string. Two OCD Orientation Confirmation Device units are located at opposite ends of each swivel-supported section. The need for orienting weights is determined based on rotational torque requirements.



^ Eliminating rotation at connections. Each gun is aligned and locked to the next with an interference-fit notched and keyed coupling device. During assembly, locking Ring A on the coupling device is forced into the female notches in the gun barrel and held in place by a wave spring and shoulder Ring B. The design eliminates play, or rotation, between gun sections. Achieving cumulative alignment errors of less than 10 minutes of a degree per gun assembly is not uncommon.

independent of tortuosity in highly deviated wellbores. The new OrientXact tubing-conveyed oriented perforating system depends on several key components to attain the required orientation accuracy, including a combination of guns, gun-section locking adapters, orienting weights and swivels (left).

Special aligning and locking adapters assure a minimum buildup of alignment error within the gun-string sections. Each gun tube connects to the next with interlocking rings (above). Tight manufacturing tolerances virtually eliminate alignment errors caused by the small clockwise gun-string spiral inherent in the old threaded design. The average alignment error is reduced to 10 minutes, or 0.167° per gun assembly, satisfying the demanding requirements of the Visund perforation project.

The compressional and tensional load on swivels in long perforating strings can be as high as 55,000 lbf in horizontal sections and 250,000 lbf [1,112 kN] in vertical sections.[7] Schlumberger developed special low-friction swivels to withstand high loads while maintaining perforation accuracy. Under typical wellbore operating conditions, the new roller-bearing swivels produced a tenfold decrease in rotational friction. Tests conducted at the Schlumberger Reservoir Completions (SRC) Center in Rosharon, Texas, USA, verified that the new gun string could develop sufficient torque to overcome swivel resistance with tensional and compressional loads to 55,000 lbf with simultaneous bending to 10° per 100 ft [30 m] (next page, left). Orientation accuracy within ±10° can be achieved with sections longer than 1,600 ft [488 m] between swivels.

^ Making the bend in performance testing. At the Schlumberger Reservoir Completions Technology Center in Rosharon, Texas, USA, the OrientXact system was tested at bends ranging from 5°/100 ft [5°/30 m] to 10°/100 ft [10°/30 m]. Wireline-conveyed gyroscopes confirmed orientation variance at 6° or less through the bend sections, indicating that the OrientXact swivel and gun carrier designs would perform as required by Hydro in field applications with severe doglegs.

^ Bend-free gun carrier material. With conventional gun carrier materials, rotational torque generated by running the perforating string into the wellbore will rotate perforating guns away from their intended orientation. New bend-free carrier designs, advances in material science and tight manufacturing tolerances allow OrientXact gun strings to bend through wellbore deviations without causing gun misalignment.

Bending a gun string can generate significant torsional stress on the assembly, risking rotation away from the desired perforation orientation (above right). To address this problem, engineers developed a series of directionally biased gun carriers designed in increments of 30° preferred-bend direction. These gun carriers can be positioned in the gun string to coincide with the trajectory of the wellbore. When biased carriers are positioned in their preferred bend direction, they assist in the orientation of the gun string. After the guns are fired, the orientation system is designed to continue applying torque, keeping the carrier exit holes upright and preventing internal charge debris from pouring into the wellbore.

Later developments include a new gun-carrier material with no preferential bend direction. Gun carriers made from this bend-free, or nonbiased, material generate no torsional stresses. When used with other nonbiased internal gun hardware, they can be used anywhere in the gun string, independent of the wellbore trajectory.

To verify the system's orientation, engineers designed an OCD Orientation Confirmation Device. The OCD unit records perforation orientation to the nearest 0.5°. Data are downloaded when the tool reaches surface. Only two OCD units per section are required to confirm the orientation direction of all perforation tunnels.

The new OrientXact system met each of the Hydro engineering and performance requirements. Relying on novel passive, orienting weights and gun sections joined by roller-bearing swivels, the system is capable of handling high loads. It is self-orienting, requiring weighted spacers for only the most difficult deviated-borehole conditions. A new charge design provides deep and slim perforating tunnels, and prevents excessive debris and postfiring chemical precipitation. Dirty low-side perforation tunnels are avoided through 10°/350° phasing. The OrientXact system was first deployed for Hydro in the Visund field in November 2001.

7. Stenhaug et al, reference 5.

Linking Interdependent Technologies

Hydro identified several areas for improvement other than perforation orientation, including formation damage, depth of charge penetration, charge chemistry, detonation debris and fluids chemistry in the perforating environment.

Near-wellbore formation damage, or skin, occurs for various reasons. During drilling, reservoir rock is exposed to significant environmental changes, including pressure, shock from the bit, and invasion of mud filtrate and solids. Depth of damage is generally a function of rock porosity, permeability, pressure differential, exposure time and the characteristics of the drilling or completion fluid.

Long drilling times on the Visund wells resulted in deep mud-filtrate invasion. Engineers believed that standard deep-penetrating charges might not reach beyond the damaged zone. Even under ideal conditions, American Petroleum Institute (API) testing specifications suggest that the effective perforation-penetration depth under actual downhole conditions can be significantly less than predicted.[8] Laboratory analysis conducted on core sections from the Visund field indicated that 40- to 50-cm [16- to 20-in.] effective perforation-penetration depth would be required to bypass damaged reservoir rock.

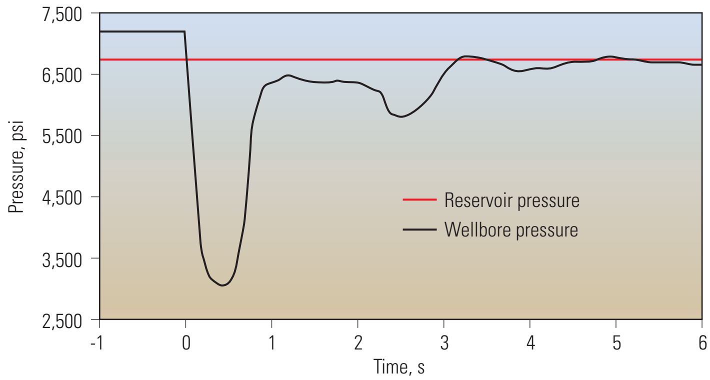
In early perforated completions, zinc-cased charges were thought to be the least damaging, because the zinc casing disintegrates into a fine powder during detonation. In theory, this should minimize the damage and debris that accompany standard steel-cased charges. As part of the Visund evaluation, engineers found that zinc-cased charges did not penetrate as deeply as previously thought. Further, powderized zinc-detonation by-products have the potential to react with the wellbore fluid and connate water to precipitate zinc oxide in near-wellbore reservoir rock and the borehole. Also, studies conducted at SRC demonstrated that interactions between zinc and calcium bromide-base kill pills could cause failure of fluid-loss control additives.[9] The result is excessive invasion of filtrate that leads to reduced productivity.[10]

In several early Visund wells perforated with zinc-cased shaped charges, zinc oxide precipitate was observed during postperforation cleanup. Hard nuggets of zinc oxide measuring 5 to 20 mm [0.2 to 0.8 in.] in diameter circulated to surface (below left). These nuggets plugged subsea chokes and other control equipment, posing a dangerous and difficult situation to remediate.

To address these problems, Schlumberger engineers developed the nonzinc PowerJet Plus low debris, deep penetrating shaped charge. While retaining the high performance of a deep-penetrating steel-cased charge, PowerJet Plus charges generate minimal debris, are weighted to aid in orientation, produce no residual zinc and, based on API penetration testing,

^ Zinc oxide precipitation. Zinc detonation by-products may react with wellbore and formation fluids to form zinc oxide precipitate. The material may precipitate within the formation, perforation tunnels and the wellbore, resulting in an increased reservoir-skin factor and plugged perforations. Large nuggets, such as those shown here, can plug downhole safety and well-control equipment, posing serious operational risk and remediation problems.

^ Deep penetration with PowerJet deep penetrating shaped charges. These charges produce long, narrow perforation tunnels. The concrete block in the photograph is an API Section 1 test target. The block was shot with steel-cased PowerJet charges through 7-in., 32 lbm/ft, L-80 casing. The average penetration in this target was 54.1-in. [137.4 cm]. The perforation tunnel being measured reached 60 in. [152.4 cm] into the target. Similar performance is seen with the PowerJet Plus low debris, deep penetrating shaped charges.



^ Achieving dynamic underbalance on the Visund A-21 well. Downhole pressure sensors recorded pressure changes throughout the perforating process. Changing wellbore pressure (black) is plotted against the previously measured reservoir pressure (red). The Visund A-21 well was overbalanced by 35 bar [508 psi] prior to perforating. The PURE perforating technique produced a 290-bar [4,206-psi] wellbore pressure drop within 1 second after perforating-gun detonation. A brief underbalanced condition just after firing perforating guns minimized formation damage and assisted in clearing perforation tunnels.

are capable of producing deep and narrow perforation tunnels (previous page, right).[11]

These long perforation tunnels can be difficult to clean. Underbalanced perforating is a common technique used to clear the perforation tunnel of debris and minimize formation damage.[12] Recent work conducted at SRC has indicated that maximum dynamic underbalance—not the initial static underbalance—determines perforation cleanup. The degree of underbalance required depends on several factors, including perforation-tunnel diameter, permeability, porosity and rock strength. However, in the Visund reservoir, it is generally accepted that a minimum underbalance of 50 to 100 bar [725 to 1,450 psi] is needed to minimize skin effects and remove perforation debris.

Achieving this level of static underbalance may or may not be practical on a given well. In some cases, wellbore conditions, method of conveyance and gun-string length may prohibit perforating with a static underbalance. The PURE Perforating for Ultimate Reservoir Exploitation system optimizes this critical step in connecting the well to the reservoir by maximizing the dynamic underbalance, or transient underbalance, established just after the creation of the perforation cavity. The PURE system creates an instantaneous decompression of reservoir fluids around a perforation immediately after perforating, assisting in removal of the crushed material from the perforation tunnel while under static overbalanced conditions. The result is cleaning of perforation tunnels with minimal production impairment.[13]

In most cases, the PURE technique will produce less skin effect than conventional static underbalanced perforating. Laboratory and field evaluations have shown that PURE system design concepts will often yield a crushed-zone permeability to reservoir-permeability ratio (k_c/k) of 1, indicating no permeability impairment. Less advanced underbalanced perforating techniques typically yield 0.1 to 0.3 k_c/k.

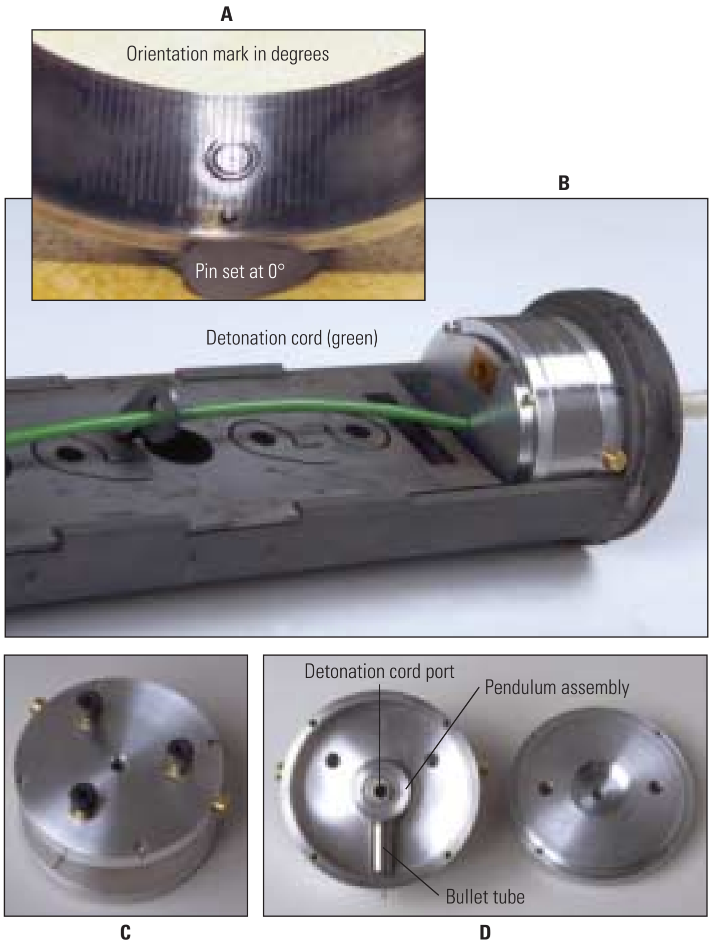
On the Visund completions, mechanical issues precluded use of conventional underbalanced perforating. Project engineers determined that perforating damage could be removed with an underbalance of approximately 120 bar [1,740 psi]. Laboratory tests suggested that with a correctly designed perforating string and application of PURE dynamic underbalance concepts, sufficient underbalance to clear the perforation tunnel and minimize formation damage was achievable.

The Visund perforation program was designed with 35-bar [508-psi] static overbalance and PURE techniques, achieving a dynamic underbalance just after perforating. The dynamic underbalance removes the crushed-zone debris from the perforating tunnels. To prevent the wellbore from returning to an overbalanced state before the wellbore and pore pressure equalized, the design suggested a flow-restriction device to seal the top of the 7-in. liner hanger. The flow-restriction device would also serve as a depth-correlation tool. For these first applications, engineers installed downhole pressure gauges just above the firing head to quantify the magnitude of the dynamic underbalance and confirm that the job was executed as designed (left).

With the perforating environment defined, engineers at Schlumberger used a computer-based orientation simulator to design OrientXact perforating strings for six wells in the Visund field. The longest would encompass a 2,049-m [6,722-ft] gross perforation interval with 1,705 m [5,594 ft] of net perforations across a horizontal wellbore with high dogleg severity. Engineers chose a series of swivels and orienting weights sufficient to ensure accurate orientation. The length of individual gun sections between swivels ranged from 167 to 400 m [548 to 1,312 ft].

The OrientXact perforating system, integrated with PowerJet Plus charges, PURE underbalanced techniques and OCD perforation confirmation, has now been used on eight wells in the Visund field—seven producers and one injector. Net production intervals ranging from 150 to 1,705 m [492 to 5,594 ft] have been perforated successfully. When compared with previous designs, the PowerJet Plus charges produced only a fraction of the debris. Perforations were confirmed by the OCD detectors with a variance of ±5°, half of the maximum allowable deviation

8. Stenhaug et al, reference 5.
9. In this context, kill pill refers to a kill-weight fluid having a density sufficient to produce hydrostatic pressure greater than reservoir pressure, thereby shutting off flow of formation fluids into the wellbore.
10. Chang FF, Kageson-Loe NM, Walton IC, Mathisen AM and Svanes GS: “Perforating in Overbalance—Is It Really Sinful?,” paper SPE 82203, presented at the SPE European Formation Damage Conference, The Hague, The Netherlands, May 13–14, 2003.
11. American Petroleum Institute: publication API RP 19B (formerly RP 43): http://api-ep.api.org (accessed March 15, 2004).
12. For more on underbalanced perforating: Bakker E, Veeken K, Behrmann L, Milton P, Stirton G, Salsman A, Walton I, Stutz L and Underdown D: “The New Dynamics of Underbalanced Perforating,” *Oilfield Review* 15, no. 4 (Winter 2003/2004): 54–67.
13. Bakker et al, reference 12.



^ Confirming orientation. The OCD device was developed by Schlumberger to confirm performance of the OrientXact perforating system. Photograph B shows the OCD device installed in the carrier assembly with the detonation cord (green) passing through the OCD cell. In photograph D, the OCD device (C) has been opened. Shown is the internal pendulum assembly consisting of a freely rotating collar, bullet and barrel tube assembly through which the detonation cord passes. When the perforating guns are fired, energy emitted from the detonation cord forces a bullet inside the barrel tube toward the inside wall of the OCD device. On detonation, the bullet simultaneously marks the exact gun orientation relative to vertical—0° orientation is shown in A. The OCD unit measures perforation orientation with an accuracy of ±0.5°.

from optimum perforation angle (above). Downhole pressure gauges indicated an instantaneous underbalance of 250 bar [3,626 psi] generated within 0.1 s of detonation.

The linking of interdependent technologies to address formation damage, depth of charge penetration, charge chemistry, detonation debris and the perforating environment in the Visund field minimized sand production and resulted in a three- to sixfold production increase over that achieved with previous perforating practices.

Improving Efficiency in a Gullfaks Satellite Field

To improve production rates in a Gullfaks satellite field, Statoil reperforated three wells. Operations took place with the wellheads under pressure. Engineers recognized that sand cleanout operations might be necessary prior to reperforation. Typically, two coiled tubing reels would be required, one for sand cleanout and the other configured with an electric wireline used for accurate perforation-depth correlation. Engineers combined conventional coiled tubing with a real-time DepthLOG CT depth correlation log to establish perforation depth, thus eliminating the need for a second coiled tubing reel, saving time, improving efficiency and providing a safer work environment.

Statoil and Schlumberger engineers optimized operations by integrating multiple technologies. The OrientXact self-orienting gun system provided accurately aligned perforations. Pulse-telemetry through the wellbore fluid column transmitted real-time depth correlation data to the perforating team. PowerJet Plus charges deeply penetrated the reservoir leaving minimal gun debris in the casing. With the well still under production pressure, PURE techniques provided dynamic underbalance, minimizing perforation-tunnel skin effects and assisting in crushed formation debris removal. The eFire-CT electronic firing head for coiled tubing deployment addressed safety concerns by requiring a coded sequence of coiled tubing pump-rate changes while downhole to detonate the perforating guns. With the eFire-CT system, safety spacers are not required, allowing use of longer gun lengths.[14]

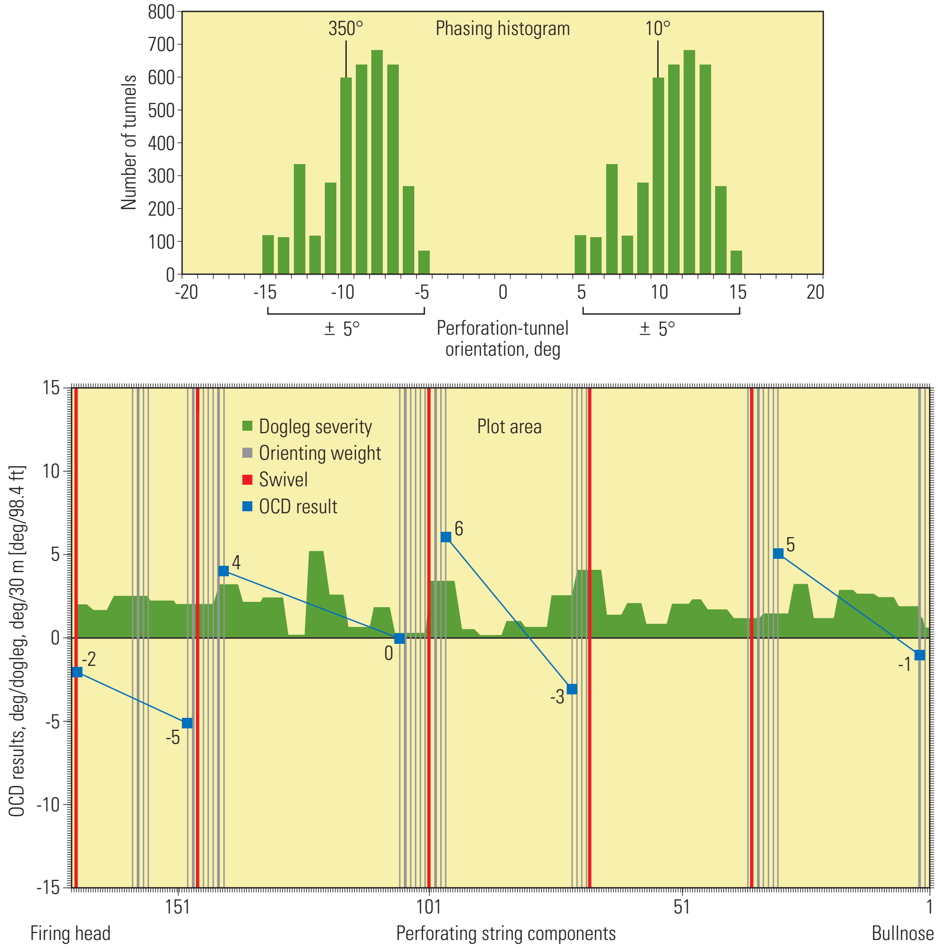
A total of 10 coiled-tubing perforating runs were performed in the three wells with guns ranging in length from 50 to 100 m [164 to 328 ft]. Engineers using DepthLOG correlations and universal tubing length monitor (UTLM) placed the perforating guns with an accuracy of ± 1 m [± 3.3 ft] at a depth of 4,500 m [14,764 ft] on all perforating runs. All guns properly detonated on target.

Ultimately, the OCD unit confirmed the perforations at +8, +4 and +3° on three separate perforating runs. The linking of interdependent perforating technologies in the Gullfaks field improved operational efficiency and optimized production rates.

Avoiding Sand in the Rimfaks Field

Avoiding sand production in Statoil's Rimfaks development is key to optimizing well productivity. Another satellite of the Gullfaks field, Rimfaks is located in the northern part of the Norwegian North Sea. The I-3H well produces from weak sandstone reservoirs that require perforating near the direction of maximum stress to minimize excessive sand production. Downhole flow-control hardware, including chokes, packers and associated equipment are used to control production rates across the multizone completion. Sand flow and postperforation debris must be avoided to prevent damage and erosion of the complex completion assembly.

14. Safety spacers are placed between the gun assembly and the firing head. This allows live guns to be loaded into or pulled from the hole, exposing personnel to only the firing head while explosive charges remain below the rig floor.



^ Perforation orientation at Rimfaks. The OrientXact system OCD units recorded perforation orientation across four reservoir sections after the Rimfaks I-3H well was perforated for Statoil (*bottom*). Shot with 10°/350° phasing, all perforations were within 6° of target (blue). Dogleg severity (green) varies from zero to approximately 5° from horizontal and appears to have had no effect on perforation orientation. Vertical red lines indicate swivel locations between gun sections—orienting weights are shown as vertical brown lines. The green bars in the histogram (*top*) identify the number of perforation tunnels at each orientation angle relative to vertical.

To minimize sand production, engineers combined OrientXact and PowerJet Plus technologies to simultaneously perforate targets along the 3,400-ft [1,036-m] horizontal section. With a total of eight OCD units, the largest perforation orientation variance measured only 6° (above). The PowerJet Plus charges provided narrow, ultradeep penetration, optimizing perforation-tunnel stability and maximizing communication with the reservoir past any formation damage in the near-wellbore area.

By design, PowerJet Plus charge debris is retained in the gun. On the I-3H well, only 130 g [4.59 oz] of small metal pieces and filings were recovered. The use of steel-cased PowerJet Plus charges eliminated zinc by-product precipitation and the associated near-wellbore formation damage seen on previous wells. Accurate oriented perforating combined with novel charge design produced deep, low-debris and precisely oriented perforations, eliminating the need for subsequent workover and stimulation treatments. Sand production was limited and well performance improved.

New Paths for Oriented Perforating

Operators have seen the value of oriented perforating in initial completions and in remedial productivity enhancement. Cost-efficiency gains, rig-time savings and production optimization are typical benefits of oriented perforating operations. Coiled tubing conveyance, combined with new orientation techniques, allows operators to accurately perforate under live-well conditions across tortuous and extended horizontal wellbores. When oriented perforating technology is combined with novel shaped-charge design, dynamic underbalanced techniques, real-time depth correlation capability, safety systems and OCD devices, operators optimize completions, costs and well productivity.

As the OrientXact system and related technologies mature, their application to fracturing and screenless-completion operations may allow even more flexibility in cost-effective production-enhancement operations through exacting perforation orientation. —DW