Quo Vadis, Extreme Overbalance?

Perforating and surging techniques using very high wellbore pressures promise dramatic, cost-effective improvement in initial well productivity—under the right conditions. But what are those conditions, and how do the procedures work? Leading investigators look at the basics of these new completion methods, and examine lessons learned to date from Prudhoe Bay, Alaska and the North American midcontinent.

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In the vast majority of wells today, the moment of truth—do we have a producer, or a hole in the ground?—is revealed through underbalance perforating. When perforating guns fire, pressure in the wellbore is below that of the reservoir, creating a pressure differential that helps clean the perforation tunnels. Formation fluids rush into the tunnels and flush out metallic charge debris, surrounding crushed rock, and sands or clays that were driven into the tunnels. If the drawdown is large enough, inflow can sweep away enough debris to open the most conductive natural path between the formation and wellbore.

Two-way communication along this path is essential for optimal well completion and productivity. When a well goes straight into production, clogged perforations will limit inflow of hydrocarbons. If intervention is planned, perforations need to be clear to accept treatment fluids carrying proppant for fracturing, gravel for sand control, or acid. Hydraulic fracturing and prepacking perforations ahead of gravel packing benefit from removal of crushed sand that can reduce injectivity and elevate fracture initiation pressures or lead to early screenout of proppant during fracture stimulations.1

Underbalance perforating works across a broad range of rock properties and reservoir conditions. Its applicability decreases, however, with a decline in reservoir pressure, permeability or rock strength. The trick is to achieve enough underbalance to generate sufficient flow rate for cleaning, but not too much to collapse the perforations and drive sand into the well. Theoretical and applied studies have focused on defining the optimal underbalance for ranges of reservoir pressure, permeability and rock strength.2

With a good theoretical foundation and a record of favorable results, underbalance perforating reigned as the unchallenged champion until a few years ago, when a handful of investigators turned underbalance on its head (next page). Building on experimental work by the US Department of Energy and others, Oryx Energy and ARCO independently developed new completion techniques utilizing extreme overbalance—perforating with wellbore pressure significantly above the level required to fracture the formation. The patented Oryx and ARCO methods differ in their approach, but each involves a process that may generically be called extreme overbalance perforating (EOP) and a related method of forcing an extreme overbalance pressure into existing perforations, called extreme overbalance surging (EOS surging).3

Perforating underbalance or with extreme overbalance are in many ways opposites, but they are not mirror images of each other. In underbalance perforating, the goal is to create a channel and clean the channel with
The first 130 years of perforating. 1865: Tin torpedoes filled with gunpowder, and later with nitroglycerin, are lowered to the depth of interest and detonated. 1910: The single-knife casing "ripper" involves a mechanical blade that rotates to puncture a hole in the casing. 1948: The first shaped charges, developed by Welex Jet Perforating Company, are applied to oil wells, generally with a slight overbalance for well control. 1970s: Underbalance, under investigation for 20 years, is tied with perforating by Roy Vann. Continued work by others through the 1980s accelerates its popularity. 1980s: Propellant fracturing produced fractures from the burst of pressure developed by rapid burning of propellant. Although still under investigation, the method encounters problems operationally and in reproducibility. 1993: Extreme overbalance perforating, pioneered by Oryx Energy Company, succeeds in commercial wells.

Since extreme overbalance methods became commercial in 1990, their application has taken a roller coaster ride. Follow ing an initial wave of interest, only a small but devout core of proponents continues to carry the torch—last year about half the extreme overbalance jobs in North America were performed by only five operating companies. Nevertheless, limited but persistent curiosity from the industry refuses to die. In 1994, seventeen operating and service companies jointly sponsored experiments on large blocks of sandstone to investigate EOP fracture mechanics and ways to optimize pressure requirements and perforation design. Field experience has also broadened, with about 900 EOP jobs performed to date, mostly in North America. Marathon performed extreme overbalance procedures in 20% of its wells in 1995 and expects that number to reach 35% in 1997. As more data accumulate, the case for extreme overbalance resurfaces, each time with a bit more ammunition. The technique has clearly established a niche, yet its applicability remains incompletely defined. Where are extreme overbalance methods today, and what promise do they hold?

1. Screenout is the point at which no more proppant can be pumped into a hydraulic fracture system without an increase in pump pressure. Early, or premature, screenout is caused by an impermeable bridging of material across the fluid pathway that prevents further extension and propping of the fracture.


3. Three early works:

The EOP Why and How
John Dees and Pat Handren, extreme overbalance pioneers at the Sun Company (now Oryx Energy), began investigating overbalance methods in the late 1980s when underbalance failed to give good results in West Texas fields. The Oryx team found what others had also observed for some time: Correctly applied underbalance perforating can be compromised by fairly common reservoir and operational conditions. If reservoir pressure is low or depleted, the pressure differential may be insufficient to clean perforations. Likewise, if permeability is low—probably less than 10 millidarcies (md), but the value depends on reservoir pressure and oil viscosity—formation fluid may not flow vigorously enough for cleaning. And if rock strength is low, underbalance pressure differential large enough for effective cleaning may collapse the formation and necessitate further intervention to save the well.

Underbalance perforating can also be hindered by more complex problems. Improper killing of a well, for example, can replug perforations with filter cake that may not be dislodged during production. Sometimes, despite good reservoir pressure and permeability, the damaged zone reaches deep enough to limit the effectiveness of underbalance. Also, when permeability varies dramatically—such as a thin, 1-darcy layer sandwiched between two thick 10-md layers—the thicker sections will dominate the flow properties and can reduce the effectiveness of underbalance.

Extreme overbalance perforating can sidestep these problems. In EOP completions, tubing pressure is increased before the guns are fired and then released into the wellbore with gun detonation. At this point,
because wellbore pressure exceeds rock yield strength, perforating initiates one or more small fractures. These fractures do not develop the length or height of conventional hydraulic fractures, but the event lasts long enough to push the fractures beyond the zone damaged by invasion and past the tip of the perforation (previous page, top). While EOP fractures are shorter in length and height, they may develop greater width and so possibly have a higher conductivity per foot than hydraulic fractures.

Most EOP jobs follow the same basic procedure (previous page, bottom). Perforating guns are lowered to the depth of interest, then spotted to the top of the guns is a small amount of liquid selected for the well conditions—brine, lease crude, fracturing fluid, acid or liquid with proppant. All or most of the wellbore above the liquid is filled with compressible gas, usually nitrogen, less often carbon dioxide or air. The gas column is then pressured up, like a tightly squeezed coil spring. Sometimes liquid is also spotted above the gas to further compress it. Rarely does the liquid fall through the gas because compressed gas, typically at about 4000 psi [27,500 kPa], develops a density of 1 to 3 lbm/gal [0.12 to 0.36 g/cm³] and a high surface tension. This creates an interface which, in the small diameter of tubing, prevents liquid from displacing gas. Because the surface pressure of gas can reach 10,000 psi [69 MPa] or more, tubing-conveyed perforating (TCP) guns are usually preferred over wireline-conveyed guns because they are operationally easier to handle at high pressures.

With detonation of the guns, the liquid is driven at very high flow rates by the rapidly expanding gas and rushes into the perforations. Because the liquid is nearly incompressible, it acts as a wedge that initiates fractures, extending the effective wellbore radius. Erosion from the liquid and any entrained proppant flowing at more than 100 bbl/min [16 m³/min] may scour the formation, creating stable flow channels. In many EOP jobs, the event is timed to stop just when the gas reaches the perforations, since the gas would quickly leak off into the formation. Some operators, who have wells with large tubular volumes, continue applying pressure as the gas enters the perforations. The gas also acts as an abrasive that scour the perforation. In either case—stopping as the gas hits the perforations or continuing—the higher the pressure and larger the gas volume (a larger “spring”), the greater the fracturing power.

Pressure generated at the perforations during EOP or EOB surging must be high enough to overcome two obstacles: it must exceed the minimum in-situ rock stress, and it must fracture through any impermeable debris barrier remaining in the perforation. The debris barrier often defeats the conventional process of perforation breakdown and cleanup. Modeling shows that to overwhelm the barrier, the extreme overbalance pressure gradient usually needs to reach at least 1.4 psi per foot [31.6 kPa/m] of well depth. This gradient produces a fracture radius that is on the order of 10 to 20 ft [3 to 6 m] although it may extend up to 30 ft [9 m].

In the high-energy context of extreme overbalance, flow restriction due to perforation damage has such a minor effect on perforation productivity as to become almost irrelevant. Charge debris has no time to harden and is thought to be pulverized and blown far back into the created cracks, like a mashed up cork pushed into a wine bottle. The low permeability of the shattered zone is more than compensated for by the high permeability of the fractures. In addition, gas jetting into the tunnel at nearly the speed of sound may erode and scour walls of the tunnels and fractures.

An extension of this method involves pumping additional fluid at a high rate immediately following EOP or EOB surging, with or without proppant, to drive the fractures farther (left). Pump rates have to be

8. Prudhoe Bay seems to be the exception. ARCO reports good results there with only 1.1 psi/ft [24.2 kPa/m].

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**Extreme overbalance surging.** Surging is performed on wells with existing perforations. It may follow immediately after perforating or a few hours to a few days later. In general, the sooner after perforating, the more effective the surge. Comparison of time 1 (left) and time 2 (right) shows the penetration of fluid into the rock and propagation of the fracture over time.

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high enough to keep the fluid above the formation fracture pressure. The injection rate needed for success depends on formation characteristics and in some cases, up to 15,000 ft³/min [420 m³/min] has been used. ARCO also developed a gas-surging technique that enhances hydraulic fracturing in wells previously perforated. (see “Elements of EOP Design: Operations,” page 31).9

What can be expected from an extreme overbalance operation? Recoverable reserves may be increased, and under favorable conditions production rates can increase dramatically, due to reduction in near-wellbore pressure loss and in reservoir leakage—70% of EOP wells show a negative near-wellbore screenout during a subsequent frac job. Marathon, for example, will later frac more than a third of its EOP wells, and about 80% of wells that were surged after EOP. Marathon finds that EOP operations average one day longer, but produce first oil one to three days earlier.

Some operators use EOP as a cost-effective way to identify hydraulic fracturing candidates, as a means to minimize near-wellbore tortuosity and thereby reduce hydraulic fracturing costs (less fluid pumped and lower surface pressures), or as a low-cost way to identify a high flow rate early. The biggest benefit of EOP, however, is the ability to place more sand and prevent a near-wellbore screenout during a subsequent frac job. Costs for EOP can vary widely, and depend mostly on availability of compressed nitrogen. With easily accessible nitrogen, tubulars fit for EOP pressures, and a completion fluid that would normally include TCP guns, EOP costs slightly more than a small hydraulic fracture. If nitrogen is not readily available,

**EOP for Skin Reduction**

In 1994, Marathon stood at a completion crossroads in an eastern New Mexico gas field. In the 30-year-old field, Marathon and other operators produced from 35 wells, each making 4 to 6 MMcf/D. In a typical completion, skin averaged around 50 but reached as high as 150. The reservoir, an upper Pennsylvanian carbonate, averaged 39 md with a reservoir pressure of about 1000 psi [6890 kPa]. Could skin be reduced?

Studying the success of nearby operators who use extreme overbalance methods, Marathon decided to try extreme overbalance surging to reduce skin. The first candidate well was in the North Indian basin section, with a perforated interval of 171 ft [52 m].

A fairly conventional completion design was used for extreme overbalance surging with acid. A 60° shot phasing was chosen to evenly distribute 20% HCl acid and encourage development of a bi-wing fracture. Previous jobs were at two shots per foot (spf), but this low shot density was thought to contribute to high skin. Inflow performance and NODAL analysis indicated that 4 spf would probably result in more effective acid placement. Deep penetrators were used to reduce flow restriction thought to be associated with big-hole charges. And the pressure gradient was designed to be 1.4 psi/ft—low by today’s standards, in which some jobs are designed at 2 psi/ft [45 kPa/ft].

About 500 ft [152 m] of fluid was spotted at the bottom of the string, and the tubing was charged with N₂. Fluid pumped after the gas achieved a flow rate of 200 bbl/min [31.8 m³/min] after the guns had fired. When the well came in, skin was computed at 5, a dramatic 10-fold reduction. Well production was higher than expected—over 5 MMcf/D, compared to 4 MMcf/D for conventionally completed wells. Although completion costs were about 8% higher, the initial rate gain quickly paid back the higher cost. Today, the well continues producing at a higher rate than conventionally completed wells of similar age.

Since this job in 1994, Marathon has moved toward a new completion strategy. During the two years of production, decline in reservoir pressure from 1000 to 800 psi [5512 kPa] means that skin plays an increasingly significant role in well productivity. Because every well intervention risks an increase in skin, Marathon is attempting the least intrusive completion strategy: air drilling in slight underbalance and completing open hole (barefoot), without perforations. The carbonate is fractured enough to produce without perforations, yet competent enough to withstand production. Other operators in the region report wells producing over 5 MMcf/D with this approach.

If reservoir pressures were 2000 to 3000 psi [13.8 MPa to 21 MPa], according to Ron Folse, a Marathon engineer who works in the field, then extreme overbalance might be the method of choice. But with the lower reservoir pressures, Marathon is able to drill underbalance with air, and with the barefoot completion achieve the benefit of minimizing completion skin. Proof of this new method is pending pressure transient analysis, which is expected to indicate a lower skin and less fluid invasion than with EOP.
EOP can cost more than twice that of a conventional completion. While EOP wells pay out faster, with higher initial production, it remains unclear under what conditions the long-term payout from EOP is comparable to that of hydraulic fracturing.

Economic uncertainty aside, the lack of early enthusiasm for these methods also resulted from unclear explanations for their success and benefits, and inconsistent results probably related to misapplication. Today, with the analysis of more data, the proper role of EOP is coming into focus. Central to this understanding is an appreciation of EOP mechanics.

Are EOP Fractures Different?
The most effective fracture, regardless of the generating mechanism, paves an autobahn between the reservoir and wellbore: a single, straight parting of significant width with few smaller, competing fractures. This ideal fracture propagates as long as the treatment continues—and it doesn’t screen out or dehydrate. This gradual buildup of pressure is equivalent to opening a door by pushing it slowly (above). Two events probably take place. First, multiple fractures may develop from the perforation base or tip, depending on proximity of perforations to the PFP and on shot phasing. If perforations are more than 30° from the PFP, fractures may take circuitous routes around the cement-formation interface before turning to align in the PFP (right).

The ideal relationship between perforations and the in-situ stress field. Fractures aligned with the direction of maximum horizontal stress will open in the plane of least resistance, against the minimum horizontal stress. The closer the fracture and maximum stress planes align, the less tortuosity fractures develop, resulting in less pressure drop. Fractures generally initiate at the sandface, the base of the perforation where it meets the formation.

Timing of down-hole events. Whereas hydraulic fracturing can last tens of minutes to hours, extreme overbalance perforating is finished in 20 or 30 seconds.

A long way to Tipperary. Hydraulic fractures may have to march around the borehole circumference before extending into the formation, depending on the distance between the perforation and the preferred fracture plane (PFP). Here are two scenarios for a 120° phased gun with conventional hydraulic fracturing. If the perforation lies in the PFP (A), one wing of the fracture will initiate from the perforation, and the other winds around the borehole from the perforation base until it turns into the PFP. If the perforation is 30° or more from the PFP (B), multiple parallel fractures may develop from the perforation.

(Adapted from Behrmann and McDonald, reference 7.)
The second event is development of a single, dominant biwing fracture initiating at the borehole wall aligned with the PFP, rather than wind around the wellbore from another initiation point (A). The channel shown between the perforation and fracture develops after the fracture initiates and is eroded during the EOP process. Where perforations are within 45° of the PFP (B), fractures initiate from the perforation. Only small fractures initiate from perforations more than 45° from the PFP. These fractures do not grow. Note that fractures initially ignore the in-situ stress field and probably extend straight from the wellbore. Within a few wellbore diameters they turn into the PFP. The absence of multiple parallel fractures is thought to be related to the sudden pressure load on the cement-by-formation microannulus, sealing off a path for the development of secondary fractures.

The long and short of EOP. If a perforation is more than 45° from the PFP, EOP fractures tend to propagate immediately from a point on the wellbore wall aligned with the PFP, rather than wind around the wellbore from another initiation point (A). The channel shown between the perforation and fracture develops after the fracture initiates and is eroded during the EOP process. Where perforations are within 45° of the PFP (B), fractures initiate from the perforation. Only small fractures initiate from perforations more than 45° from the PFP. These fractures do not grow. Note that fractures initially ignore the in-situ stress field and probably extend straight from the wellbore. Within a few wellbore diameters they turn into the PFP. The absence of multiple parallel fractures is thought to be related to the sudden pressure load on the cement-by-formation microannulus, sealing off a path for the development of secondary fractures.

By contrast, an EOP fracture is produced by a sudden burst of pressure. This high-rate pressurization of the rock results in a rate-dependent fracture mechanism that approaches the ideal fracture system more closely than hydraulic fracturing. Instead of opening the door by pushing gradually, an EOP operation is analogous to breaking the door down with a sledgehammer. Because extreme overbalance pressure overwhelms the fracture breakdown pressure, EOP fractures initially overwhelm the in-situ stress field and probably extend straight from the wellbore, like spokes from the hub of a wheel, then turn gradually into the PFP (left). Fractures may form at all perforations, but extend only from those nearest the PFP, creating a biwing fracture.

Multiple parallel fractures are not seen in EOP studies, possibly because the sudden pressure load closes the microannulus between the cement and formation, shutting off a path for secondary fractures. Another possible explanation for the absence of multiple fractures is that rate-dependent fracture initiation favors only weakest portions of the rock. This observation is borne out in conventional fracturing, where high-rate injection is known to minimize creation of multiple fractures. EOP also allows a larger angle between the PFP and perforations before fractures ignore the perforations and initiate at a site on the wellbore aligned with the PFP (right).

EOP Candidates

Widely accepted candidate criteria for EOP are low permeability (below about 10 md), reservoir pressure insufficient to achieve cleaning with underbalance, a highly mobile clay content, and the need to establish a fracture in multiple layers, even those with different mechanical or flow properties. Other reasons to use EOP are reduction in near-wellbore damage and pressure drop associated with poor linkage of fractures following underbalance perforating, to avoid several days of swabbing before the results of underbalance perforating are known, and to eliminate near-wellbore tortuosity during hydraulic fracture stimulation of extended-reach wells.

Dees lists two leading reasons for EOP: immediate indication of well producibility (which can be delayed with underbalance perforating) and skin reduction. Behrmann and McDonald also list as applications diversion of acid in carbonates and intersection of natural fractures. Other authors...
present several scenarios for application of EOP in high-permeability settings, often for placement of acid or proppant. Marathon engineers, on the other hand, use EOP in the Rocky Mountains of the USA mainly in hard rocks, where they assume perforations penetrate only 10 in. [25 cm] and so remain in the damaged zone. In hard rocks, EOP drives the effective wellbore radius well beyond the damaged zone.

The majority of extreme overbalance proponents view it as complementary to conventional underbalance perforating and as a precursor to conventional hydraulic fracturing. Bryan McDonald, who studies extreme overbalance methods for Schlumberger, has ranked variables that influence the choice between EOP and underbalance perforating. In order of importance, the leading variables are as follows:

- **Well depth**—The limiting influence with depth is friction between the fluid and tubulars, which reduces ability to deliver sufficient pressure at the perforations. The minimum pressure gradient was originally placed at 1.2 psi/ft [27 kPa/m], but this has inched up as insufficient pressure was thought responsible for early failures. Some operators today use gradients as high as 4 psi/ft [90 kPa/m]. In general, deeper wells require a lower pressure gradient because the energy available to propagate a fracture is proportional to:

\[(\text{pressure gradient} \times \text{depth}) - \text{in-situ stress}\]

in which the in-situ stress is given by the fracture gradient \times depth, so the expression becomes:

\[(\text{pressure gradient} - \text{fracture gradient}) \times \text{depth}\]

The fracture gradient may vary from 0.4 to 1 psi/ft [9 to 22 kPa/m], with a typical value of 0.7 psi/ft [15.8 kPa/m], so that with increasing depth, the gradient difference can be reduced. Even with the lower pressure gradients required in deep wells, depth can become a limiting factor at 10,000 to 15,000 ft [3000 to 4500 m].

Technique, however, sometimes compensates for physical limitations. Oryx has successfully treated an interval at 19,000 ft [5790 m] by placing calcium bromide water above nitrogen to deliver 24,000 psi [165 MPa] at the perforations. “We always place less than 1000 ft [300 m] of fluid on bottom,” said Pat Handren of Oryx. “This way, energy goes into fracturing, not into overcoming fluid friction.” Still, most operators are more comfortable performing EOP above 10,000 ft true vertical depth.

- **Permeability**—There may be no more controversial an EOP topic than how permeable is too permeable. The concern is that leakoff will outpace the flow rate needed to maintain a pressure that exceeds rock strength and extends the fractures. High rates of spurt and leakoff result in significantly shorter fractures (above).

Work by Petitjean and Couët indicates that at 100 md, up to 80% of fluid can leak off in less than 10 seconds, limiting an already short fracturing event. Some operators place the cutoff at 100 md, although others have claimed success at 1 darcy. John Dees, who has a patent on continuous pumping immediately after the extreme overbalance event, maintains that EOP followed by surgeing with resin can succeed even with permeability in the 1-darcy range.

Pat Handren considers permeability-length a more useful parameter than permeability alone. This takes into consideration vertically variable permeability, which can affect flow properties. Handren’s breakpoint is about 20 md-ft. If permeability hits this value, Handren would choose underbalance perforating—unless reservoir pore pressure is below 0.35 psi/ft [8 kPa/m] in which case he prefers EOP to be sure perforations are cleaned. At permeability around 1 darcy, some formations may be friable enough to require EOP with injection of resin to prevent sand from...
flowing out the tunnel or to prevent the tunnel from collapsing.

_Tubular and wellhead ratings_—Tubing diameter and pressure ratings limit gas pressure and volume, which determine horsepower deliverable at the perforations. Bigger is always better, and biggest and strongest is best. At a minimum, tubing needs to endure 1.4 psi/ft. ARCO uses up to 7-in. tubing on the North Slope in Alaska, USA, and Marathon has moved from 3\(\frac{1}{2}\)-in. to 4\(\frac{1}{2}\)-in. tubing wherever possible.

Likewise, wellhead pressure control equipment must at least match tubular rating. The objective is to have tubulars that can safely withstand the pressures necessary to deliver a fracturing pressure at the perforations. ARCO’s rapid overpressured perforation extension, or ROPE, method owes much of its development to the opportunity at Prudhoe Bay, Alaska, of working on closely spaced wells with large tubing (more than 2 \(\frac{7}{8}\) in.).

_Perforated interval length_—Dissipation of pressure over distance limits the interval length that can be effectively treated with extreme overbalance. Treatments on intervals of up to 1000 ft have been performed in a few wells, but most operators are confident that uniform, effective treatments can be carried out over only 70 to 100 ft [21 to 30 m]. Shot density and permeability also influence treatable interval length. As a rule, Oryx finds that 1 shot every 2 ft [60 cm] will maintain sufficient pressure over several hundred feet. Marathon prefers to limit intervals to about 50 ft [15 m].

<table>
<thead>
<tr>
<th>Reservoir Conditions</th>
<th>Fluid Type</th>
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<tbody>
<tr>
<td>Sandstone (some carbonates)</td>
<td>2% KCl water</td>
</tr>
<tr>
<td>Sandstone with water retention</td>
<td>2% KCl water with alcohol</td>
</tr>
<tr>
<td>Carbonate</td>
<td>15 to 20% HCl</td>
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<tr>
<td>Sandstone with severe water sensitivity</td>
<td>Less crude</td>
</tr>
<tr>
<td>Carbonate and sandstone</td>
<td>10% acetic acid</td>
</tr>
<tr>
<td>Shaly low-pressure gas, or &lt;1000 psi</td>
<td>10% acetic acid or 1.5% HF</td>
</tr>
<tr>
<td>Heavy oil, paraffin present or well drilled with oil-base mud</td>
<td>Xylene</td>
</tr>
<tr>
<td>Gas sandstone &lt;1000 psi</td>
<td>Diesel</td>
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Elements of EOP Design: Hardware

To one degree or another, the first generation of EOP jobs was constrained by preconditions of the well completions. Now, operators recognize that success of the procedure often relies on planning completions to optimize EOP jobs. The main constraints are surface-control equipment and tubular ratings. ARCO makes routine use of a wellhead isolation tool, or tree saver. This device fits on top of the wellhead and has a mandrel that extends through the wellhead, sealing in the tubular. Downhole, Oryx will use casing with a higher pressure rating, and run cement bond logs to determine whether the interval to be perforated is fully cemented. When cement bond cannot be confirmed, Oryx prefers to keep pressure only on the tubing, using an isolation valve to avoid exceeding the casing burst rating. In addition, Oryx uses the largest possible tubing diameter to deliver the largest possible volume of gas, and always pressure tests tubing to be sure it meets its rating.

After the completion configuration, the next most important variable is wellbore fluid composition. All operators agree that whatever type and quantity of fluid are used, friction reduction polymers are a must. In many operations, they are already a given. A review of fluid design criteria and their application has been prepared by John Dees (below).

EOP calls for new thinking about downhole equipment, from the firing head to the guns. A new kind of firing head, for example, has been designed to better accommo-
date the special needs of EOP jobs. Conventional TCP firing heads are activated by positive pressure, but have a hydraulic time-delay mechanism that stalls firing for up to 15 minutes until activating pressure is bled off to achieve underbalance. This delay is unnecessary with EOP—good safety practice minimizes exposure of surface and down-hole equipment to high pressure. For this purpose, Schlumberger introduced the EOF-BA extreme overbalance firing head, which has no time delay (previous page, right). The firing head starts the train of events leading to gun detonation when pressure exceeds the predetermined strength of shear pins. This pressure drives an operating piston upward to release a firing pin. Because the piston must move against gravity, the firing head is unaffected by vertical drops.

The EOF firing head nests inside either a gun-release or an isolation valve system, depending on completion type. The Explosively Initiated Automatic Release (SXAR) system is used for permanent completions, in which the guns are fired and immediately dropped into the rathole, allowing the well to come on line immediately after perforating (right). The Explosively Initiated Production Valve (SXPV) is used for "shoot-and-pull" operations, in which the well is often killed and the guns removed to provide an unobstructed flow path, to run the completion string or to perform other work such as a frac job.

In both completion types, safety and well performance depend on quick and precisely timed release of pressure. The valve and gun-release system must assure that release of pressure from the tubing is synchronized with detonation of the guns, thereby keeping excess pressure off the casing. If unperforated casing is subjected to extreme overbalance pressure, it can damage mechanical components in the well, cause a packer leak, blow packers uphole (packers are often the weakest link), burst casing or collapse perforating guns.

For this reason, Schlumberger developed a unique mechanism that assures rapid release of pressure. Applied pressure (red), before and after activation, is typically 10,000 psi.

17. For a safety checklist prepared by Oryx, see the appendix in Handren et al, reference 3.
release of pressure only when perforation is certain. The heart of this device is a stack of break plugs that have high compressive strength, but low lateral strength (left). The plugs can support the compressive force of the pressure applied to the valve, but not high lateral stress. The detonating cord passes through the plugs and if it undergoes a high-order detonation—which virtually assures firing of the guns—the lateral shock of the cord detonation shatters the plugs and trips the mechanism. Because the SXPV and SXAR are activated by the detonation train that fires the shaped charges, there is little chance of loading the casing prematurely. The SXPV and SXAR belong to a family of five new completion tools, the X-Tools, that make use of this gun-activation method.

The SXPV design enhances EOP performance by opening the flow ports faster than any other valve (below left). Rapid transfer of pressure to the perforations is essential, since a typical EOP event lasts 15 seconds at most, and must take advantage of each second to maximize the amount of work applied to the formation. Loss of time conveying fluid from the tubing to the perforation tunnels translates into reduction in fracture length and possibly in fracture width.

The SXPV valve begins opening 8 to 20 milliseconds (msec) after gun detonation, and is fully open after another 4 msec (next page, top). This high-speed operation means the valve opens fully before fluid pressure starts transferring from the tubing to the perforation tunnels. With a conventional, hydraulically activated valve, detonation to full opening of the valve can take a full second, or 10% of a typical 10-second EOB event. This time delay means that less energy goes into creation of fractures, resulting in less fracture length (next page, bottom). In addition, the SXPV flow ports provide a flow area 1 1/2 times that of the tubing diameter, which minimizes friction and maximizes transfer of pressure from the tubing.

In permanent completions, where guns are dropped into the rathole after detonation, the release system must overcome two engineering challenges: It must assure isolation of completion hardware from gun shock, which can unseat packers, and it must overcome friction in deviated wells that prevents the guns from falling. Unassisted, guns usually will not drop until well deviation reaches 40 to 45°. Excessive sanding and debris can also prevent gun release.

SXPV equipment for EOP. This X-Tool is used when wells are killed to remove guns—shoot-and-pull—for unobstructed flow, running completions or to perform other work. Break plugs ensure rapid opening of the production valve. Red is applied pressure, blue shows hydrostatic and green is atmospheric pressure.
A simplified view of the first milliseconds of perforating. The SXPV valve begins opening as early as 8 msec after gun detonation, and is fully open after another 4 msec. Rapid opening means the valve opens fully before fluid pressure starts transferring from tubing to the perforation tunnels, maximizing energy that goes into creation of fractures.

How valve speed makes a difference. The more energy that goes into creating fractures, the greater potential to extend fracture length. In these five ARCO wells, examples A, B, D and E had enough nitrogen to cause significant erosion, whereas example C ran out of gas, literally, before the curve plateaued and fractures reached full extension. (From Pettjean et al, reference 3.)
The SXAR addresses both shock and friction problems by timing the firing of guns shortly after disintegration of the last break plug. At the instant the guns fire, they have already been released, so the shock wave is expended overcoming friction rather than traveling up the completion string. Tests and field trials show the system works in a range of settings. In vertical wells, guns drop at 20 ft/sec [6 m/sec] and reach terminal speed a few milliseconds after release. The SXAR system successfully released a 150-ft [46-m] gun that was deviated 76° at the top and 86° at bottom (above).

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The guns themselves provide the final link in the perforating chain. Charge type can significantly influence results. Failure of some early EOP jobs was traced to a kind of screenout caused by plugging of perforations with debris. Evidence for this was surface pressure that did not decline after the guns went off. Investigators discovered that perforator debris behaves differently under different settings. It can be permeable under the slowly rising pressures of hydraulic fracturing, which can pump through some debris. But to the high-speed extreme overbalance pressure pulse, debris can act as an impermeable barrier. Behrmann and colleagues demonstrated that in EOP jobs, accumulation of this debris, and subsequent increase in pressure required to blast through it, is minimized by use of deep penetrators instead of big-hole charges.

Shot phasing also plays a role. In vertical wells, a minimum of 120° phasing will typically result in two thirds of the perforations lying within 45° of the PFP, the maximum distance before EOP fractures start forming away from perforations. Phasing choice is also affected by procedures following EOP. If EOP is a precursor to hydraulic fracturing, a single biwing fracture is most desirable. In this case, 60, 90 or 120° phasing is optimal. However, if matrix acidizing is to follow, then a higher, 45° phasing will help distribute acid around the wellbore.

While most operators use 60 to 120° phasing, ARCO prefers 180°. Based on large near-wellbore pressure losses in Prudhoe Bay wells deviated 30 to 50°, ARCO determined that multiple fractures were developing from 60° phase shots. By changing shot phasing to 180°, the pressure drop fell from 2000 psi [13.8 MPa] to under 500 psi [3445 kPa], which contributed to placement of a larger amount of proppant. “We think this suggests a single, biwing fracture,” said Joe Schmidt, the ARCO engineer who helped develop the ROPE program. In gun systems with phasing other than 60°, maximum benefit is obtained by keeping the same alignment for all gun segments.

Shot density—the number of shots per vertical foot—becomes increasingly important in longer perforation intervals. Too high a density can result in excessive leakoff. Too low a density can result in longer exposure of tubulars to high pressure and increased risk of unseating a packer. In general, because extreme overbalance procedures produce instantaneous flow at 100 to 200 barrels per minute, a rule of thumb is a shot density two to four times normal. ARCO, for example, typically shoots EOP jobs at 4 shots per foot using 120° phasing over a 20-ft interval.
Elements of EOP Design: Operations
Today’s extreme overbalance operations follow one of two basic routes: perforating as a stand-alone event followed by pumping, or perforating and surging at the same time (right). In the Oryx method, EOP is followed by high-rate pumping. In wells that are already perforated, Oryx finds that continued pumping after overbalance surge can reduce skin, as long as the pumping precedes flow from the reservoir.19 The surge method, using a frangible disk or expendable plug, has proved to reduce pressure requirements of subsequent hydraulic fracturing.

ARCO, working on the Alaskan North Slope, reports similar results with its ROPE method and, since 1994, a high-energy version nicknamed HE ROPE. The main difference between the Oryx and ARCO methods is that ARCO uses nearby wells as holding tanks for high-pressure nitrogen. Instead of pumping, ARCO pressures up nitrogen in nearby wells, connected by hard line to the treated well. A plug is set in the tubing tail of the storage well, and both the target well and storage well are simultaneously pressured. At the appropriate time, the surge disk ruptures with firing of the perforating guns, releasing all the gas into the target well.

The HE ROPE method uses nearly 100% nitrogen, with a small amount—10 to 20 bbl (1.6 to 3.2 m³)—of liquid over the guns. Bottomhole pressure exceeds 10,000 psi, with an overbalance of about 6500 psi [45 MPa]. The high pressure and high volume of nitrogen lead to injection rates close to 270 barrels per minute [40 m³/min]. This rate results in greater fracture width, erosion of the formation by gas and reduced near-wellbore pressure losses.20 The high-energy version doubles fracture radius over conventional ROPE, and because fractures tend to propagate in a straight line, also allows for better

### Comparison of Extreme Overbalance Methodologies

<table>
<thead>
<tr>
<th>Reservoir Properties</th>
<th>ARCO</th>
<th>Marathon</th>
<th>Oryx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interval, ft</td>
<td>20 to 60</td>
<td>20 to 120</td>
<td>4 to 150¹</td>
</tr>
<tr>
<td>Depth, ft</td>
<td>8000 to 15,000</td>
<td>4000 to 9000</td>
<td>4000 to 15,000</td>
</tr>
<tr>
<td>Bottomhole pressure, psi</td>
<td>10,000 to 11,000</td>
<td>500 to 4000</td>
<td>500 to 11,000</td>
</tr>
<tr>
<td>Permeability, md</td>
<td>10 to 300</td>
<td>10 to 150</td>
<td>&lt;100 or 100 to 300 if pressure insufficient for underbalance perforating</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Job Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient,² psi</td>
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<tr>
<td>Fluid/gas</td>
</tr>
</tbody>
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<thead>
<tr>
<th>Guns</th>
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<tbody>
<tr>
<td>TCP guns; wireline guns with high-volume nitrogen for new completions; 60° phasing, 4 to 6 spf</td>
</tr>
<tr>
<td>TCP guns, usually 60° phasing, 4 to 6 spf</td>
</tr>
<tr>
<td>TCP guns, 60° or 120° phasing, 4 or more spf</td>
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<tr>
<th>Other</th>
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<tr>
<td>Surge disk for previously perforated wells</td>
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<tr>
<td>Proppant carrier over TCP carrier</td>
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<tr>
<td>Resin gel typical for sand control</td>
</tr>
<tr>
<td>Clean fluids essential to success</td>
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</tbody>
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<thead>
<tr>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>40% of wells with production increase of 10 to 20%</td>
</tr>
<tr>
<td>Negative skin on 88% of wells</td>
</tr>
<tr>
<td>No increase in recoverable reserves, just in recovery rate</td>
</tr>
<tr>
<td>Fractures likely to stay in zone due to low volume and short period of fluid/gas inflow</td>
</tr>
<tr>
<td>EOP as screening for other treatments: if no response to EOP, no further intervention planned</td>
</tr>
</tbody>
</table>

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¹ With significant wellbore storage effect, the interval maximum rises to 500 ft.
² Achieved gradients sometimes fall slightly below the designed value, mainly because crews may feel more comfortable with lower pressures. At the 1.4-psi gradient, however, the pressure on tubulars is usually no greater than that encountered during screenout of a conventional frac job, although EOP pressure may be applied for a longer period.
Work is just starting on EOP in horizontal wells, which present a new range of challenges related to gravity. An underbalance perforating experiment at TerraTek shows that detonation products could not be flushed from down-side perforations in a wellbore deviated 29°, even with a 400-psi [2756 kPa] underbalance differential. Based on this result, some operators are using oriented guns and perforating horizontal drains on the top and sides only. Applying extreme overbalance methods in this setting may require a higher pressure gradient, well above 1.4 psi/ft, to pulverize and move debris that tends to fall to the low side of the hole. Mobil and Halliburton have used EOP successfully in a horizontal well at 15,693 ft [4783 m] true vertical depth to tap a tight gas reservoir. Perforating guns were conveyed on drillpipe.22

Extreme Overbalance Perforating

Underbalance Hydraulic Fracturing

Hot proppant. A gamma ray tracer log in a Marathon well shows a concentration of tagged proppant in perforations (yellow). More proppant appears to have been injected into the upper two intervals than into the bottom interval. Subsequent production testing confirmed that there was no communication behind pipe. (From Snider et al, reference 21.)
Unanswered Questions

"Most of the time, we know when extreme overbalance will work," said Phil Snider of Marathon. "But the few jobs that go wrong are the ones driving our research."

This sentiment informs much of today's investigations into extreme overbalance methods. But as knowledge increases, so do the apparent number of unknowns. Most workers in EOP have a wish list of what would make their lives easier and more productive. Highlights of this list include the following questions:

What is the pressure-rise time? Knowing the shape and exact length of the pressure-time curve from the moment of gun discharge will allow calculation of the number of fractures and fracture width. In addition, watching what happens in the first few seconds can shed light on friction levels to optimize job design. To achieve this, Snider is using a downhole high-speed pressure gauge that measures 20,000 data points per second. Early results indicate that perforation and fluid influx may behave more as a single event than as two distinct ones. In addition, results indicate that optimization requires limiting flow restrictions in tubing and reducing the height of liquid in tubulars.23

How does gun system design affect fractures—big hole or deep penetrators?24 Marathon's experience indicates that big-hole charges may lay down filter cake that prevents injection of the surge. Except for gravel packing, deep penetrators are generally the charge of choice.

How conductive are EOP fractures, and how long do they work? Experience shows that short, unpropped fracs have a useful life of 6 to 12 months. As Marathon has observed, proppant may pack EOP perforation tunnels, but may function more as an abrasive than a proppant. And the abrasive action decreases near the fracture tip, as flow velocity decreases. In support of this claim, large gains in well productivity with the addition of a small volume of proppant—100 to 200 lbm [45 to 90 kg]—suggest scouring as the mode of action. Bauxite has proved to provide better scouring than conventional frac sand.

Over what distance do EOP fractures turn? Experiments in large blocks of rock indicate turning is complete in two or three wellbore diameters, but there is evidence that in situ turning may take 5 to 10 ft [0.6 to 3 m].

Does EOP mean that subsequent frac jobs require more or less horsepower? Again, experience is ambiguous. Some operators report always needing less horsepower, while others say sometimes less, sometimes more. Oryx finds that regardless of horsepower required, EOP jobs always result in placement of a higher proppant concentration during subsequent frac jobs. The treatment screens out, for example, at 8 lbm/gal [958 kg/m³] instead of 4 lbm/gal [479 kg/m³].

Where Are You Going, EOP?

There are parallels between the development of extreme overbalance perforating and tubing-conveyed perforating. In the 1970s, TCP burst on the scene with Roy Vann's innovative designs for downhole equipment. Hailed by proponents as a perforating panacea, and by others as an aberration that would soon disappear, it was initially adopted by a few operators. Trial and error smoothed out the rough edges, convincing the industry at large of its technical and economic benefits. Eventually, TCP settled in as a niche service, which today accounts for more than 25% of the perforating business.

EOP emerged in a slightly different context. After 1986, low and stable oil prices instigated a flurry of engineering creativity, moving completion designs toward further specialization and producing a change in perspective. The idea of "completion equals plumbing"—seals, tubulars, valves and packers—began to give way to the view that "completion equals well optimization." By the beginning of the 1990s, the completions world was no longer neatly divided into wellbore conductivity, slickline, tubing and coiled tubing techniques. Now the approach is to find the best mix of solutions to optimize recovery.

Extreme overbalance is one such development that blurs old boundaries. Usually performed on tubing, EOP can be achieved with wireline; it also marries perforating and pumping, and inches toward stimulating, but stops short at near-wellbore enhancement. In the continuum of well treatments, it more closely resembles matrix acidizing than hydraulic fracturing, although its techniques borrow more from the latter.

Whether EOP will join the mainstream in the style of TCP or remain a small niche service depends mainly on proof of its economic viability. This proof requires further technical refinements so that results can be clearly related to technique.

One trend that may prove fruitful is the recent move away from the pressure gradient rule and toward the tubular limit rule—selecting the highest pressure safely allowed by the tubular rating. ARCO, for example, keeps pressure to within 80% of tubular burst rating. However, it is still unclear whether more pressure is always better. By contrast, there is a move toward larger diameter tubing, which typically has a lower pressure rating but allows a higher volume of gas. Also under investigation is the use of proppant carriers, which have been tried in only a few dozen wells.

ARCO has been looking to test the ROPE method, with its precise control of fracture height, on coal degasification projects, where water intrusion often limits development. Another possible use of this method is in remote wells, where highly mobile nitrogen generation equipment could be readily moved on site.

"We think of EOP not as a replacement for the hydraulic frac," said Joe Schmidt of ARCO, "but as a pretreatment for fast return. If we have trouble with a conventional frac because of earth stresses or well deviation, this works."

Schmidt's view represents that of many workers trying to define the limits of the EOP frontier. True, it is known to work in some settings, and yes, the mechanics may not be clear, but that is simply a problem that will wash away with more study.

"We know just about all we can about underbalance perforating," said Phil Snider of Marathon Oil Company. "Extreme overbalance still presents the possibility of discovering new benefits."

—JMK


24. A big-hole charge increases hole diameter at the expense of penetration depth. Hole diameter in casing is two to three times greater than with a deep penetrator, but penetration is substantially reduced.