The New Dynamics of Underbalanced Perforating

Controlling the transient pressure differential in a wellbore during perforating is a key to more effective cased-hole completions. This technique uses an innovative design process and specialized hardware to significantly improve well productivity and injectivity.

Eelco Bakker
Kees Veeken
Nederlandse Aardolie Maatschappij (NAM) B.V.
Assen, The Netherlands

Larry Behrmann
Kuala Lumpur, Malaysia

Phil Milton
Gary Stirton
CNR International
Aberdeen, Scotland

Alan Salsman
Ian Walton
Rosharon, Texas, USA

Lloyd Stutz
Anadarko Petroleum Corporation
Houston, Texas

David Underdown
ChevronTexaco
Houston, Texas

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CIRP (Completion Insertion and Removal under Pressure equipment), eFire, HSD (High Shot Density gun system), NODAL, MDT (Modular Formation Dynamics Tester), PosiTrieve, PowerJet, PURE (Perforating for Ultimate Reservoir Exploitation) and SPAN (Schlumberger Perforating Analysis) are marks of Schlumberger.

Every cased well must be perforated so fluids can flow from subsurface zones or be injected downhole. The controlled detonation of specially designed and manufactured shaped charges creates holes—perforations—in steel casing, cement and the surrounding formation. Optimizing production or injection requires careful design, prejob planning and field implementation to obtain clean, conductive perforations that extend beyond formation damage into unaltered reservoir rock.[1]

Unfortunately, explosive perforating also pulverizes formation rock grains, causing a low-permeability crushed zone in the formation around perforation cavities and creating a potential for migration of fine particles. This process also leaves some residual detonation debris inside the perforation tunnels. Elastic rebound of the formation around newly created perforations generates additional shock damage and loose material (next page).[2]

Minimizing flow impairment and conductivity restrictions caused by this induced perforating damage are crucial for obtaining effective perforations. For 25 years, standard completion procedures have relied on a relatively large static pressure differential, or underbalance, to eliminate or minimize perforating damage.

Underbalanced pressure is the most widely accepted technique for optimizing perforated completions. This method establishes a static wellbore pressure before perforating that is less than the adjacent formation pressure. Conventional wisdom suggests that surge flow from a reduction in near-wellbore pore pressure mitigates crushed-zone damage and sweeps some or all of the debris from perforation tunnels.

Schlumberger scientists analyzed transient perforating pressures during laboratory tests and found that static underbalance alone does not ensure clean perforations. Results indicated that previously neglected fluctuations in wellbore pressure immediately after shaped charges detonate, not the initial pressure differential, actually govern perforation cleanup.

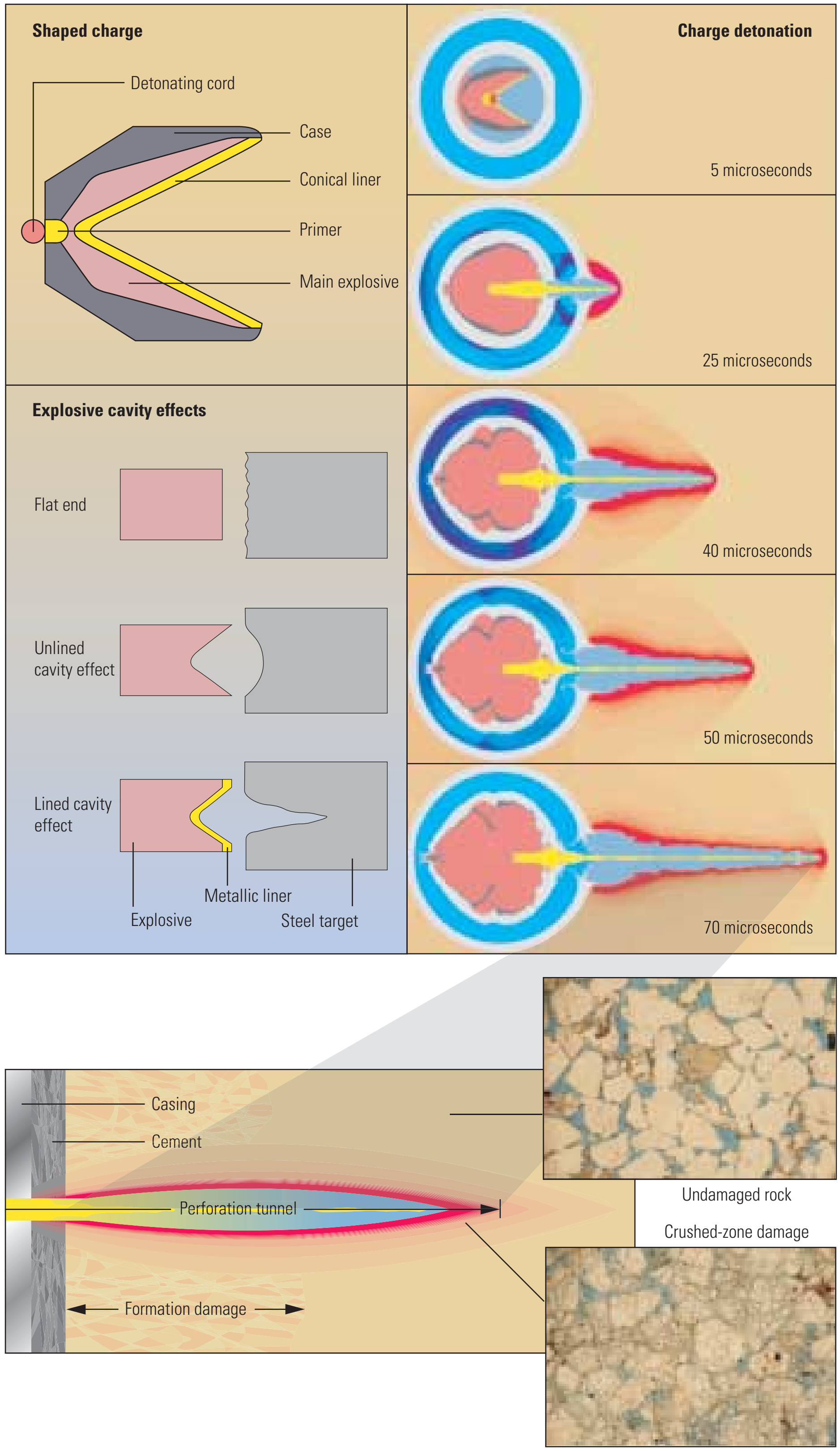
Researchers applied this improved understanding of dynamic wellbore pressures to develop the patented PURE Perforating for Ultimate Reservoir Exploitation process.[3] This new technique is applicable for wireline- or slickline-conveyed charge carriers, or guns; and coiled tubing or tubing-conveyed perforating (TCP) systems in either vertical or high-angle completions, including horizontal wellbores.

The PURE process uses customized perforating designs, specialized shaped charges and fit-to-purpose gun configurations to generate a large dynamic underbalance from modest static underbalanced or overbalanced pressures. This proprietary technique significantly improves well productivity or injectivity. The PURE perforating process also improves well-completion operational efficiency.

Eliminating the need for large static pressures differentials makes well preparations prior to underbalanced perforating more straightforward. Controlling surge flow limits produced fluid volumes during perforation cleanup, which reduces the risk of sand influx that can result in stuck guns. Small acid jobs, or perforation washes, that are often required to remediate perforating damage may not be needed.

In addition, dynamic underbalanced perforating increases the number of open perforations, thereby enhancing the effectiveness of larger acid and fracturing treatments. A higher effective shot density, or number of shots per foot (spf), also optimizes pumping operations by decreasing horsepower requirements. Another benefit is the reduction in perforating shock intensity, which minimizes disruption of the cement-sandface hydraulic bond and helps ensure zonal isolation after perforating.

This article describes innovative perforating and completion design methods, gun systems and associated hardware designed specifically to control dynamic underbalanced pressure. Case histories from North America and the North Sea demonstrate results from PURE perforating designs based on specific reservoir properties and well configurations.



^ Perforating and perforation damage. Shaped charges consist of four basic elements—primer and main explosives, conical liner and a case. The conical cavity and metal liner maximize penetration through steel casing, cement and rock. As charges detonate, the liner collapses to form a high-velocity jet of fluidized metal particles. Perforating shock waves and high-impact pressure shatter rock grains, break down intergranular mineral cementation and debond clay particles, creating a low-permeability crushed zone in the formation around perforation tunnels. Perforating damages in-situ permeability primarily by crushing formation material impacted by the jet and reducing pore-throat sizes. Photomicrographs show undamaged rock and microfractures in the crushed zone.

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Underbalanced Perforating

In the 1970s, completion engineers recognized the potential of underbalanced pressure for improving perforated completions. Research during the 1980s and 1990s confirmed that a high static pressure differential between wellbore and formation often yielded more effective perforations. These studies concluded that rapid fluid influx was responsible for perforation cleanup and recommended general underbalanced perforating criteria.[4]

Research focused on two primary assumptions: first, that wellbore pressure remains essentially constant during perforating and perforation cleanup; and second, that the static underbalanced pressure prior to gun detonation is effective across the perforation tunnels of an entire completion interval. Research concentrated on establishing specific underbalanced pressure criteria and predicting the degree of underbalance needed to ensure clean perforations.

A 1985 Amoco study correlated results from 90 wells that were acidized after perforating with tubing-conveyed guns and a range of underbalanced pressures.[5] Results did not imply that all perforation damage could be removed, but suggested that acid stimulation was not necessary or as effective when sufficient underbalanced pressure was achieved.

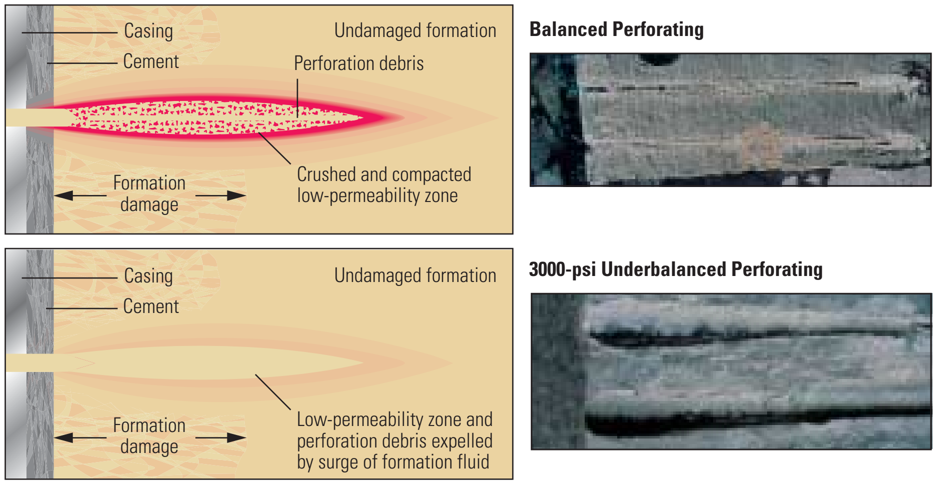
In 1989, researchers calculated underbalanced pressures in gas wells based on sand-production potential determined from sonic logs.[6] Their study combined new data with data from the prior Amoco project to develop equations for the minimum underbalance required to eliminate the need for acid stimulation.[7] Another study indicated that flow and surging after perforating were less critical in damage removal, but might sweep debris and fines into the wellbore.[8]

Until recently, scientists believed that the magnitude and duration of surge flow after underbalanced perforating dominated perforation cleanup.[9] Immediately after charge detonation, pore pressure drops and reservoir fluids decompress around new perforations, causing a sudden fluid influx. This instantaneous surge minimizes pore-throat invasion by completion fluids and solids, loosens damaged rock, and cleans some loose material out of the perforation tunnels (top right).

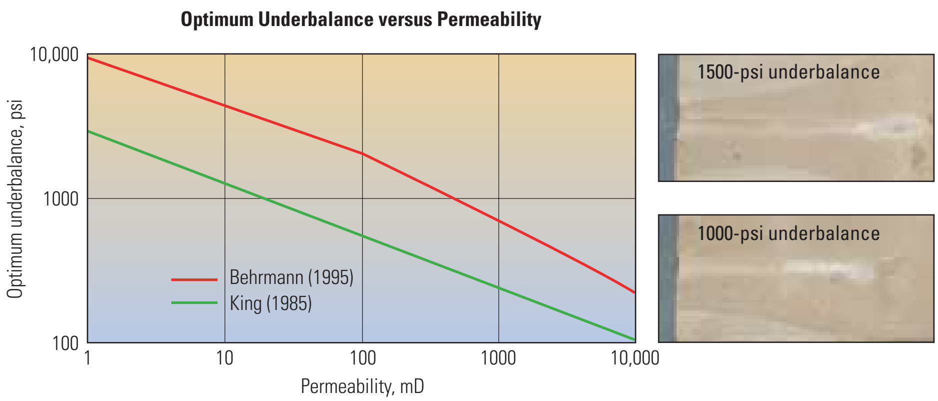
Laboratory tests indicate that turbulent flow is not required to remove perforating damage. One theory suggests that perforation cleanup is related more to viscous fluid drag during surge flow. However, most data suggest that higher underbalanced pressures than those commonly used in the past are required to effectively minimize or eliminate perforating damage.[10] A less than optimal underbalance can result in variable flow rates per perforation and different degrees of damage removal.

Dynamic forces—pressure differential and drag—that mitigate permeability damage by eroding and removing fractured formation grains from perforation walls are highest immediately after perforating. This is the starting point for developing semi-empirical equations for underbalanced pressure and perforation damage, or skin, from historical datasets. The key factors are maximum transient pressure differential and subsequent drag from slightly compressible radial flow, either laminar or turbulent.

Behrmann proposed equations to calculate the optimal underbalance for zero-skin perforations, or conversely, to calculate the skin if underbalanced pressure is less than optimal.[11] Now the most widely accepted underbalanced-pressure criteria, these equations were the result of more than a decade of perforating research. This technique recommends underbalanced pressures that are two to four times greater than those used in previous methods (above).



^ Over- and underbalanced perforating. After overbalanced or balanced perforating and before cleanup, perforation tunnels are plugged by shattered rock and debris, and surrounded by a low-permeability crushed zone (*top*). Before PURE perforating, conventional theory held that the initial surge flow generated by a static underbalanced pressure differential at the time of perforating removed crushed-zone damage as well as some or all of the debris from perforation tunnels (*bottom*).



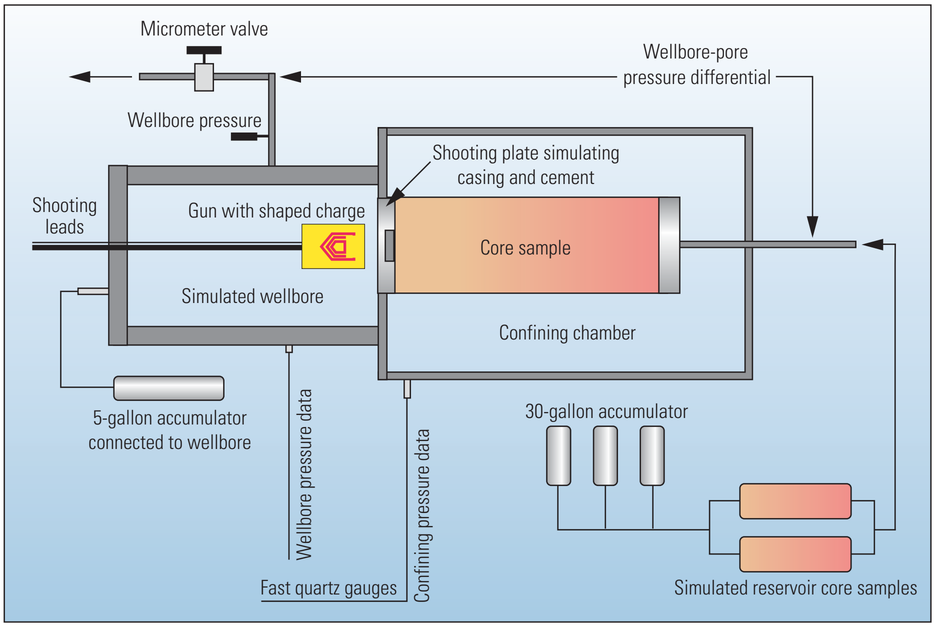
^ Underbalanced pressure. The criteria for degree of optimal pressure underbalance increased significantly during the past decade as the result of hundreds of laboratory tests (*left*). Field observations by King et al developed criteria based on sandstone acidizing efficiency (green). Behrmann correlated laboratory data with the viscous drag force required to remove fine formation particles (red). Laboratory tests confirmed that higher underbalanced pressures than those used in the past were required to obtain clean perforations (*right*).

A static pressure underbalance alone does not necessarily deliver consistent results. Well productivity after static underbalanced perforating can be disappointing, while results from perforating with initially balanced or overbalanced pressures sometimes are surprisingly good. Until recently, researchers focused little attention on exactly how much pressure underbalance actually occurs. That changed with the advent of pressure gauges that have extremely fast sampling rates. These new gauges provide more detailed, higher resolution data about wellbore pressure variations immediately after perforating.[12]

More recent investigations indicated that shear failure of the crushed zone, not erosion due to surge flow, removes perforation damage.[13] Shear failure depends on rock strength and effective formation stress. In turn, shear forces are related to the magnitude of the pressure differential during underbalanced perforating. Therefore, underbalanced pressure controls cleanup, but the required magnitude depends on the rock strength rather than its permeability. For sandstone formations, rock strength and permeability are somewhat related, although no such relationship exists for carbonates.

Experimental Investigation

Laboratory tests indicate that wellbore pressure oscillates for a few hundredths of a second as the explosive detonation, high-velocity jets and shock waves pass through wellbore liquids. Detailed studies of these transient phenomena are performed in the Productivity Enhancement Research Facility (PERF) at the Schlumberger Reservoir Completions (SRC) Center, Rosharon, Texas, USA (above).



^ Single-shot perforate and flow tests. The Productivity Enhancement Research Facility (PERF) laboratory at the Schlumberger Reservoir Completions (SRC) Center includes two vessels for investigating perforating processes, and transient pressures and perforation flow under simulated downhole conditions of overburden, pore and wellbore pressures (*top*). One vessel is for cores up to 7 in. [17.8 cm] in diameter and 18 in. [45.7 cm] long; the other accommodates cores as large as 11.5 in. [29.2 cm] in diameter and 24 in. [61 cm] long. This setup allows flow tests through outcrop or reservoir cores that can be oriented from horizontal to vertical (*bottom*). This facility is available to Schlumberger clients for custom testing.

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12. Behrmann LA, Li JL, Venkitaraman A and Li H: "Borehole Dynamics During Underbalanced Perforating," paper SPE 38139, presented at the SPE European Formation Damage Control Conference, The Hague, The Netherlands, June 2–3, 1997.
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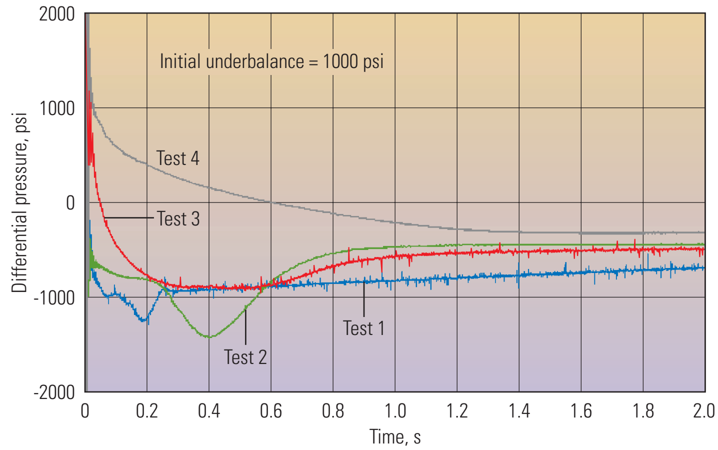
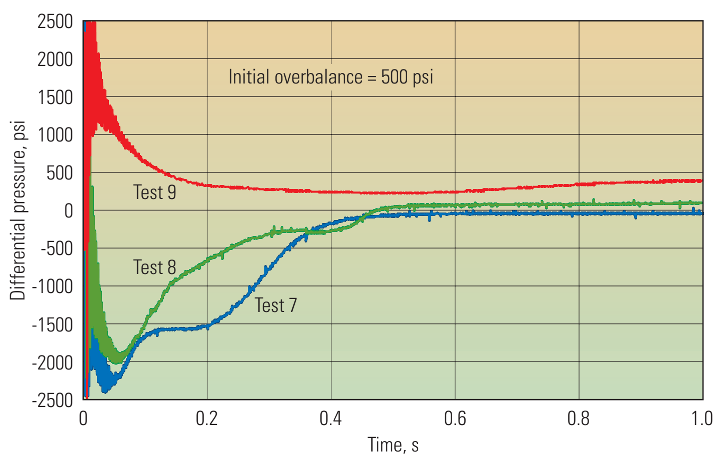


^ Static underbalanced single-shot perforating tests. Starting with an initial static underbalance of 1000 psi [6.9 MPa], the maximum dynamic underbalance in Tests 1 through 4 varied from 200 to 1300 psi [1.4 to 8.9 MPa]. In each test, with similar standard cores and identical charges, wellbore pressure increased immediately after detonation, but all four showed different pressure responses over time. Tests 1 and 2 achieved dynamic underbalanced pressures that were greater than the initial static differential and remained underbalanced throughout the test. Tests 3 and 4 demonstrated a short period of overbalance and a slow decline to underbalanced conditions. Static underbalanced conditions were not indicative of wellbore pressures during perforating or of the degree of perforation cleanup.



^ Static overbalanced single-shot perforating tests. Tests 7, 8 and 9 used similar cores and charges as Tests 1 through 4, but started with an initial static overbalance of 500 psi [3.45 MPa]. In Test 9, simulated wellbore pressure increased to 2500 psi [17.2 MPa] after charge detonation and remained overbalanced. Immediately after detonation, wellbore pressures in Tests 7 and 8 dropped sharply to –2400 and –2000 psi [–16.5 and –13.8 MPa], respectively. Test 7 remained underbalanced throughout, but Test 8 suddenly became overbalanced—a water-hammer effect—at 0.45 s, plugging the perforation tunnel. These results indicated that effective dynamic underbalanced pressures could be achieved starting from an initial static overbalance.

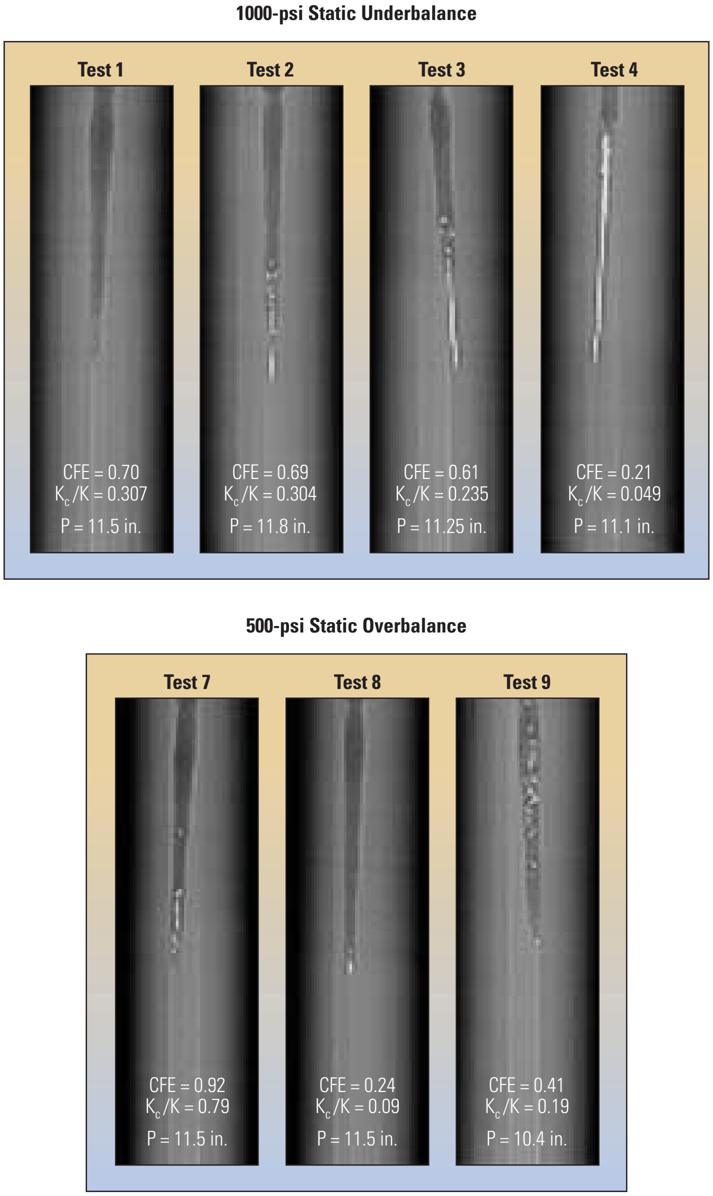
In contrast to previous studies, recent testing at SRC varied perforating configurations to investigate transient, or dynamic, pressures during single-shot tests.[14] Researchers collected microsecond-resolution—fast—and millisecond-resolution—slow—pressure data under simulated downhole conditions to better understand the resulting pressure transients.

In the first series of tests, researchers perforated four standard Berea sandstone cores with identical shaped charges and an initial underbalance of 1000 psi [6.9 MPa] (left). In another series of tests, three Berea cores similar to the first four were perforated with a 500-psi [3.45-MPa] static overbalanced pressure (below left). Results confirmed that wellbore pressure varies significantly immediately after shaped-charge detonation.

In each test, simulated wellbore pressure increases after extremely rapid transients associated with shock-wave propagation and then decreases as wellbore liquids enter spent guns. Wellbore pressure increases again as reservoir fluids flow into the wellbore and far-field wellbore fluid decompresses. Under certain conditions, wellbore pressure can change from underbalance to overbalance to increased underbalance within the first half-second.

Computed tomography (CT) provided X-ray images of each core after single-shot perforate and flow tests. These CT scans provided a qualitative analysis of perforation lengths and conditions. Researchers at SRC believe that the amount of debris remaining in perforations is indicative of variable levels of surge flow immediately after perforating. In addition, core flow efficiency (CFE) was analyzed to quantitatively evaluate the effects of dynamic underbalanced pressure (next page). The resulting consistent perforation length and shape are indicative of high-quality shaped charges and consistent Berea core targets.

CFE is the ratio of steady-state flow through a perforated core to theoretical flow through a drilled hole with the same dimensions as the perforation. A proprietary finite-difference numerical code calculates the flow through a drilled hole because the same core cannot be perforated and drilled.



^ Perforated core CT scans and productivity analysis. The four underbalanced (*top*) and three overbalanced (*bottom*) single-shot tests demonstrated that perforation productivity depends on more than initial static wellbore conditions. Perforation depths (P) for the two series of tests are similar, indicating high-quality shaped charges, but the debris (white material) inside each perforation differs. Tests 1, 2 and 3 each have a similar, but not identical core flow efficiency (CFE), because this loose material does not significantly impair well productivity. The amount of debris is, however, indicative of the magnitude and rate of surge flow. The CFE in Test 4 indicated a low productivity because of the extended time needed to reach a low underbalanced pressure. Overbalanced conditions during Tests 8 and 9 appear to have caused damage. Test 7 achieved the highest level of dynamic underbalance and the best CFE of any test, including the four performed with a static underbalance. Researchers concluded that maximum transient wellbore pressure responses directly influence variations in perforated core productivity. Higher values of the crushed-zone permeability to formation permeability (K_c/K) are better.

Although crushed-zone damage is not visible on CT scans, its magnitude can be inferred from CFE ratios. A CFE of about one suggests that there was no flow impairment from injected debris and fines nor crushed-zone damage because surge flow occurred.

The estimated underbalance required to completely remove induced perforation damage is about 2400 psi [16.5 MPa] for Berea cores under these test conditions. Therefore, the 0.67 average CFE for the first three tests is reasonably close to expectations for a 1000-psi underbalance.

The high dynamic underbalance—more than 2400 psi—achieved during Test 7, which started with a 500-psi static overbalance, resulted in a CFE of 0.92. This level of perforated core productivity was better than in any of the static underbalanced tests.

Many industry experts believe that static overbalanced perforating cannot be effective because it precludes effective surge flow and potentially carries fine particles into formation pore throats. Indication of surge flow during two of these static overbalanced perforating tests surprised investigators and was counter to conventional wisdom.

Perforation damage cleanup now appears to be directly related to both the maximum dynamic underbalance and the rate of instantaneous surge flow, not the initial static wellbore pressure—underbalanced, balanced or overbalanced. This new concept helps explain occasional poor results from underbalanced perforating and unexpected good results from balanced and overbalanced perforating.

Results and conclusions from this project suggested a new approach to perforation cleanup and provided the basis for a new perforating technique. This PURE process specifies unique wellbore and gun configurations to optimize the sharp drop in pressure, or dynamic underbalance, that occurs after charge detonation. The next step was to apply the techniques in field trials.

14. Walton IC, Johnson AB, Behrmann LA and Atwood DC: "Laboratory Experiments Provide New Insights into Underbalanced Perforating," paper SPE 71642, presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, September 30–October 3, 2001.

Enhancing Productivity

ChevronTexaco performed the first trials of this new technique in the East Painter field near Rock Springs in southwestern Wyoming, USA.[15] Previously, the company perforated these wells, which were completed with cemented casing, using tubing-conveyed guns and moderate static underbalanced pressures—300 to 600 psi [2.1 to 4.1 MPa]. The wells typically required small coiled tubing perforation acid washes to establish flow after perforating.

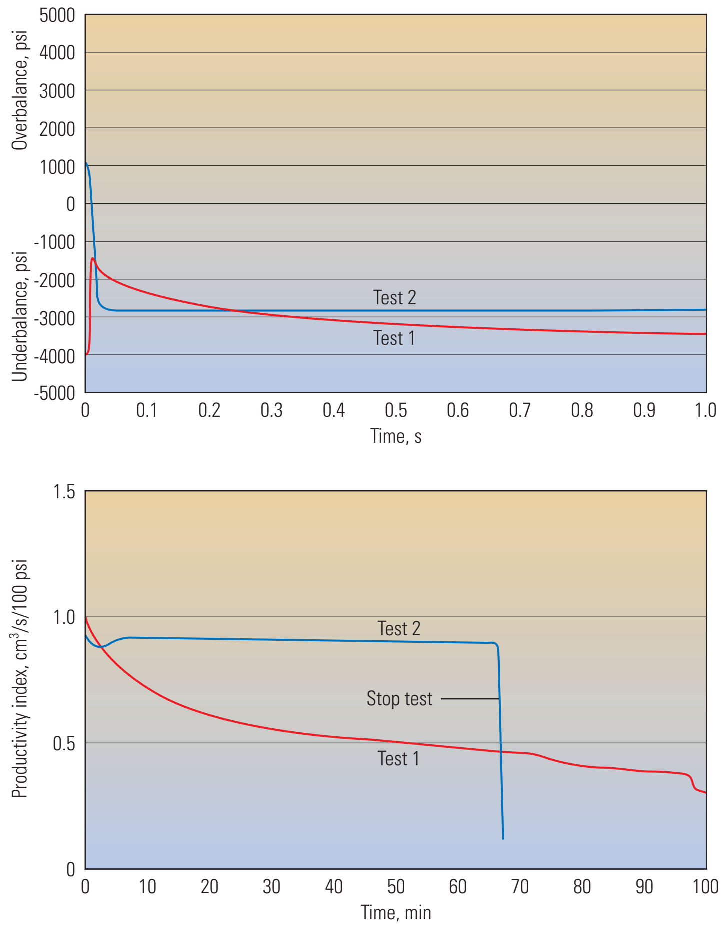
Large foam-diverted acid treatments followed these perforation washes to establish commercial production rates. Moderate economic success provided an incentive to evaluate other options. Engineering studies suggested that greater underbalanced pressure differential was required to improve perforating effectiveness and enhance well productivity.

Output from SPAN Schlumberger Perforating Analysis software based on designs using the Behrmann criteria suggested that an underbalance of about 4000 psi [27.6 MPa] was needed to achieve zero perforation skin in the Nugget sandstone reservoir with permeabilities ranging from 0.01 to 100 mD.[16] However, the existing 4600-psi [31.7-MPa] reservoir pressure required an extremely low initial wellbore pressure to achieve this large static underbalance, while conventional practices in this field did not provide sufficient underbalance to achieve clean perforations.

The PURE perforating process solved this problem by generating a high dynamic underbalance from a modest initial underbalance or overbalance. Two single-shot perforate and flow tests performed in the PERF laboratory at SRC simulated conventional and PURE perforating using actual Nugget outcrop cores (right).

The first test simulated conventional perforating with an initial 4000-psi static underbalance and the wellbore open to the atmosphere. The next test modeled PURE perforating starting from a 500-psi static overbalance and the perforated zone shut-in below a packer.

Schlumberger proposed a PURE perforating system based on Test 2 that started with an initial 500-psi overbalance. This design required a retrievable packer with a closed string above tubing-conveyed perforating (TCP) guns and a fast-opening production valve below the packer. However, the requirement for a profile nipple in the production tubing eliminated this option.

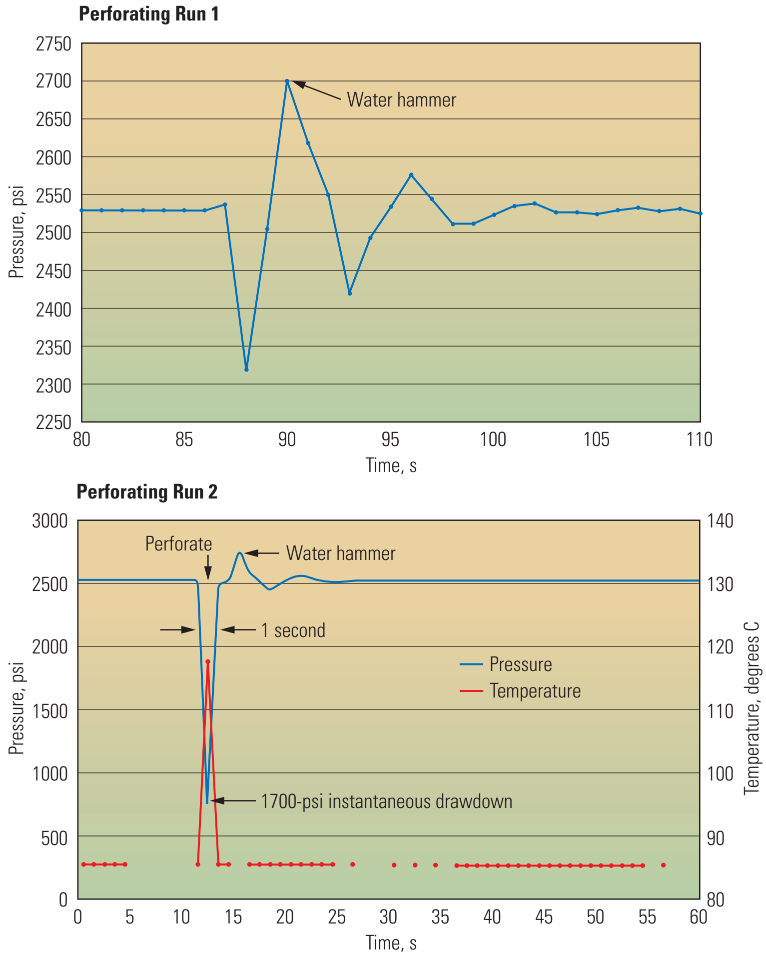


^ ChevronTexaco East Painter field testing and design. Schlumberger conducted two single-shot perforate and flow tests for ChevronTexaco to simulate proposed completion operations in the Nugget sandstone reservoir using cores from an actual Nugget outcrop (*top*). Test 1 simulated a conventional perforating job with a 4000-psi static underbalance with the well open at the surface. Transient wellbore conditions changed from initial underbalanced conditions to a reduced 1500-psi [10.3-MPa] underbalance before stabilizing at a 3500-psi [24.1-MPa] underbalance more than 1 s after charge detonation. Test 2 represented a PURE completion with the target zone shut-in below a packer and a 500-psi [3.4-MPa] static overbalance. Transient pressure rose rapidly to 1000-psi [6.9-MPa] static overbalance then decreased to 2900-psi [20-MPa] underbalance within 0.015 s. The PURE dynamic underbalanced test yielded a cleaner, more productive perforation (*bottom*). A finite-difference code calculated a CFE of 0.24 for Test 1 and 0.56 for Test 2, which equates to perforation skins of more than 3.2 and less than 0.8, respectively.

Engineers redesigned the gun system to generate a 2400-psi dynamic underbalance from a 400-psi [2.8-MPa] static underbalance. Based on previous laboratory tests, the resulting dynamic underbalance would result in a well productivity similar to that of Test 2.

PURE planning software helped engineers specify the appropriate gun system, including PowerJet deep-penetrating shaped charges, shot densities and specific charge configurations for each well to achieve an adequate dynamic underbalance. Gun lengths ranging from 15 to 20 ft [4.6 to 6.1 m] were chosen based on formation permeability. Short intervals used PowerJet 3406 charges at 6 spf; long intervals used PowerJet 2906 charges at less than 6 spf; intermediate-length intervals used PowerJet 2906 charges at 6 spf.

Four out five of wells completed with these PURE designs resulted in successful completions without additional stimulation. The first PURE completion attempt required an acid



^ Borgsweer 4 injection well, Groningen gas field, The Netherlands. Pressure data from gauges with a 1-s sampling rate confirmed that both perforating runs achieved dynamic underbalanced pressures. After the dynamic underbalanced surge, however, the data showed a cyclical pressure oscillation, or water hammer, from high-velocity fluid movement. This hydrostatic pressure increase after achieving a dynamic underbalance could have forced fine solid particles into the formation pore throats, causing perforation damage and impaired injectivity.

treatment to establish production after a mechanical failure resulted in post-perforating damage to the formation. The application of PURE technology saved more than $150,000 per well compared with previous completions that were perforated conventionally.

Increasing Injectivity

Nederlandse Aardolie Maatschappij (NAM) drilled the Borgsweer 4 well in The Netherlands during 2001 as a water injector for the giant Groningen gas field. Water disposal is critical to continuous operations in this field, and collapsed casing in an existing injector required that well construction be fast-tracked. The Borgsweer 4 targeted the Rotliegend sandstone reservoir, which has a porosity of 18 to 22%, a permeability ranging from 40 to 400 mD and a formation pressure of 2530 psi [17.4 MPa].

NAM typically perforates water-injection wells and establishes injectivity by pumping cold water to thermally fracture the formation. Completion engineers initially planned to establish a static underbalanced pressure before perforating by circulating nitrogen from about 1000 m [3281 ft] with coiled tubing. As an alternative, Schlumberger proposed the PURE technique using wireline-conveyed guns to generate an effective dynamic underbalance with static wellbore pressure initially equal to the formation pressure—balanced.

An initial perforating run with a conventional gun punctured the casing to allow wellbore pressure and formation pressure to equalize. This left the well in a hydrostatically balanced condition. These perforations were not expected to clean up completely, but they could potentially contribute some injectivity. For the two subsequent PURE perforating runs, engineers designed gun configurations to create a dynamic underbalance starting from balanced pressure conditions. Both perforating runs achieved dynamic underbalanced pressures (left).

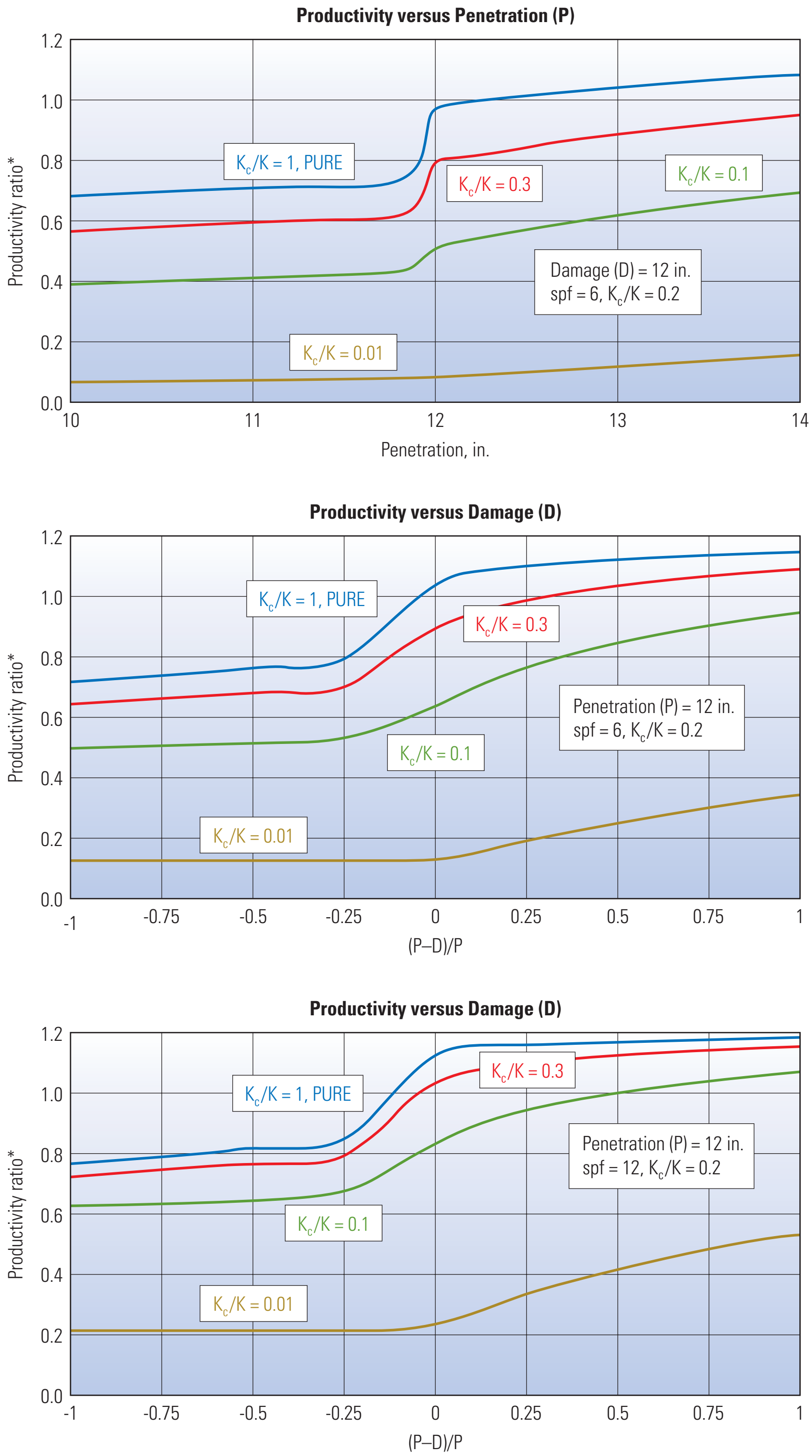
However, the initial injection rate after perforating was lower than expected because of slow initiation of thermal fractures in the formation and possible injection of fines into the formation pore throats. The cyclical pressure oscillation, or water-hammer effect, that occurred after achieving a dynamic underbalance could have contributed to perforation damage and impaired injectivity. The perforating string was subsequently modified to include PURE charges and PURE chambers that alleviate unwanted pressure increases by increasing the gun volume open to flow.

This was the first field trial of dynamic underbalanced perforating in continental Europe. Borgsweer 4 operations proved that PURE systems could achieve an effective dynamic underbalance starting from balanced hydrostatic conditions. It also showed that gun configurations could be modified to alleviate adverse fluctuations in wellbore pressure, such as the water-hammer effect.

Candidate Selection and Applications

All wells, producers and injectors alike, should be considered potential PURE candidates. Evaluating rock type, fluid types, and formation porosity and permeability, and performing simulation using SPAN software help determine if a well will benefit from the PURE technique. In most areas, many new and existing well completions will benefit from the application of PURE dynamic underbalanced perforating.

15. Behrmann LA, Hughes K, Johnson AB and Walton IC: "New Underbalanced Perforating Technique Increases Completion Efficiency and Eliminates Costly Acid Stimulation," paper SPE 77364, presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, September 29–October 2, 2002.
16. Behrmann, reference 11.



* *Perforated completion versus undamaged openhole*

^ Improving perforated completions. When perforation penetration (P) extends beyond the depth of damaged permeability (D), SPAN Schlumberger Perforating Analysis simulations demonstrate that the ratio of crushed-zone permeability to undamaged formation permeability (K_c/K) has a significant influence on well performance (*top*). PURE dynamic underbalanced perforating achieves high productivity levels with fewer (6 spf) perforations (*middle*). Clean PURE perforations (K_c/K=1) improve productivity more than increasing shot density (12 spf) or perforation length (*bottom*).

Most injection wells are excellent PURE candidates because clean perforation tunnels are essential for optimal injectivity. Achieving an adequate dynamic underbalance ensures sufficient surge flow to remove loose material from perforation tunnels before injection begins. It also prevents debris and fine formation particles from being injected and sealing off formation pore throats.

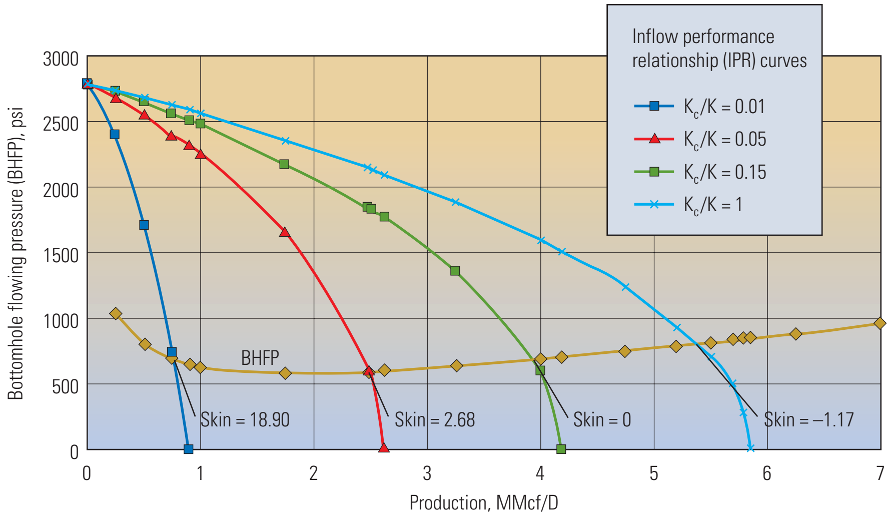
The PURE technique has been particularly effective in low-permeability formations that require extremely high underbalanced pressures for perforation cleanup. Such large pressure differentials are often difficult to achieve during conventional perforating operations with static underbalanced pressures.

In horizontal or deviated wells, displacing drilling or completion fluids to obtain the required static underbalance is often difficult. Dynamic underbalanced perforating helps avoid costly and inconvenient displacement of wellbore fluids with a lighter liquid or inert gas to achieve the required pressure underbalance. Conventional static overbalanced perforating with potentially damaging fluids in a wellbore may cause damage that only near-wellbore acid treatments can remove.

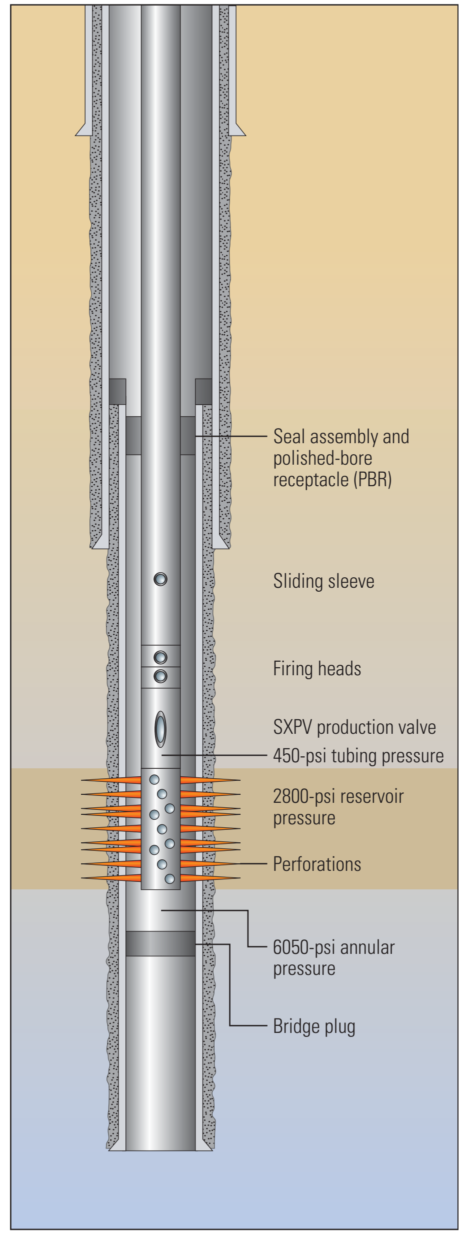
The highest priority well candidates, those that provide the most value to operators, are wells with significant potential for productivity improvement. Also included are well conditions that require expensive operations to establish an adequate static underbalance, wells that typically require near-wellbore acid perforations washes after perforating and those that require high underbalanced pressures.

The PURE candidate-selection process focuses on improving the ratio of crushed-zone permeability to formation permeability (K_c/K) to increase well performance (left). Dynamic underbalanced pressures result in K_c/K ratios close to 1. The K_c/K ratios for conventional static underbalanced perforating range from less than 0.1 to about 0.3 for the best-case scenarios.

Both pore pressure and permeability should be considered during the candidate selection process. Wells have been perforated successfully using PURE techniques in reservoirs with pressures as low as 1000 psi and permeabilities as low as 0.5 mD, but these were difficult perforating designs and operations. The limits of PURE perforating are still being established and will become clearer as more wells are completed.



^ The effect of reduced perforation skin. Part of the PURE design process involved determining what to expect from dynamic underbalanced perforating. A prejob NODAL analysis was performed to match past well-performance data and estimate what production rate zero-skin perforations would yield. Brady field wells historically had perforation skin in excess of +20. The PURE technique yielded a perforation skin of –1.17, or slightly stimulated, and a corresponding flow rate exceeding 5 MMcf/D [143,200 m^3/d].



^ Dynamic underbalanced perforating in the Brady field, Wyoming, USA. Both Brady field wells were tubing-conveyed permanent completions as shown in this 38W wellbore diagram. Existing cement-squeeze perforations above the target recompletion zone in the 38W well potentially limited the feasibility of remedial stimulation treatments. The PURE perforating process offered the best chance of a successful completion. A SXPV fast-acting production valve isolated the tubing, TCP guns and annular space below the packer to create the initial static pressure conditions needed for creating a dynamic underbalance. The SXPV valve is designed to open automatically shortly after perforating guns fire to allow almost instantaneous flow from this low-pressure Weber reservoir.

Perforating Tight, Low-Pressure Formations

In 2002, Anadarko Petroleum Corporation applied dynamic underbalanced perforating in the Brady gas field of Wyoming.[17] In addition to containing high concentrations of H_2S, the Weber formation comprises about 600 ft [183 m] of interbedded sand, shale and dolomite stringers. Permeability ranges from 0.5 to 1.5 mD with a current reservoir pressure of less than 2800 psi [19.3 MPa] at 14,000 ft [4267 m].

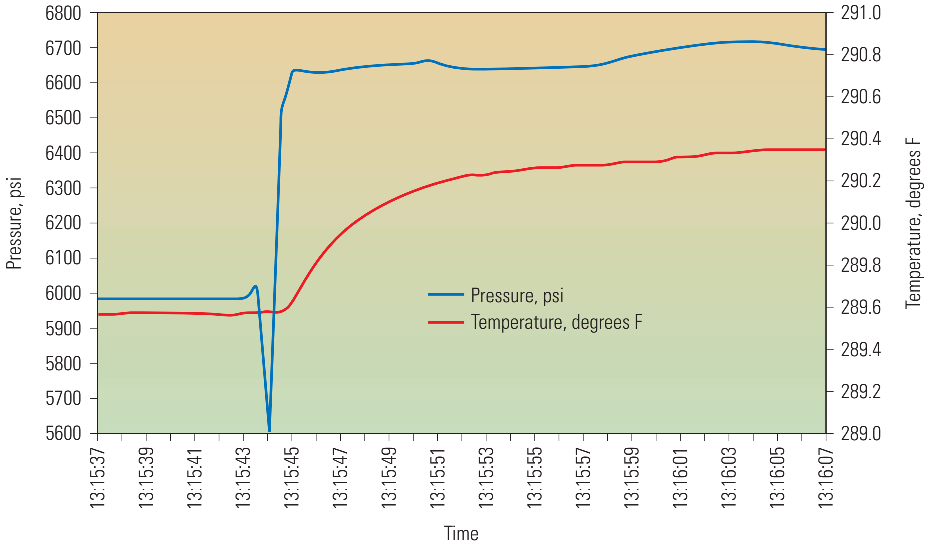
The 18 existing well completions in this field used wireline-conveyed guns and static overbalanced perforating techniques, which resulted in minimal flow. Anadarko performed perforation-wash treatments using hydrochloric-hydrofluoric [HCl-HF] acid to establish commercial production. After acidizing, these wells typically flowed 1 to 5 MMcf/D [28,640 to 143,200 m^3/d] of gas. Three of the wells required fracture stimulations.

Anadarko chose the PURE perforating technique to recomplete the Brady 38W well in an upper section of the Weber formation. Cement-squeezed perforations above the target zone made remedial acidizing and hydraulic fracturing difficult if perforating did not achieve desired results. Dynamic underbalanced perforating provided the best chance for a successful completion without additional stimulation.

A prejob NODAL production system analysis indicated that the well should produce about 3.85 MMcf/D [110,260 m^3/d] with zero perforation damage (above). However, completion skin historically exceeded 20 after perforating overbalanced and before acidizing. The PURE technique achieved a sustained flow rate of 5.2 MMcf/D [148,930 m^3/d] just hours after perforating with an initial 3250-psi [22.4-MPa] overbalance. The estimated perforation skin was negative 1.17, or slightly stimulated.

Later in 2002, Anadarko drilled the 56W well, the first new Brady field well in more than 17 years. The success of the Brady 38W recompletion convinced Anadarko to use the PURE technique again. Both wells used permanent TCP completions (above right).

17. Stutz HL and Behrmann LA: "Dynamic Underbalanced Perforating Eliminates Near Wellbore Acid Stimulation in Low-Pressure Weber Formation," paper SPE 86543, presented at the SPE International Symposium and Exhibition on Formation Damage Control, Lafayette, Louisiana, USA, February 18–22, 2004.



^ North Sea gas-well completion. During completion of a NAM well in the gas-bearing Rotliegend sandstone of the southern North Sea, pressure data from gauges in the gun string confirmed that the PURE perforating design achieved the required dynamic underbalance.

A NODAL analysis indicated that this well should produce about 3 MMcf/D [85,920 m^3/d] with zero perforation skin. The well actually flowed at a stabilized rate of 4.2 MMcf/D [120,290 m^3/d], indicating a negative 1.2 perforation skin. The low bottomhole pressure (BHP) resulted in a static overbalance of 3750 psi [25.9 MPa]. The 56W well would have required additional stimulation if perforated conventionally.

After perforating, the 56W well unloaded slowly because of a lower than expected BHP—2300 psi [15.9 MPa]. The low-permeability, low-pressure reservoir required immediate flowback and cleanup after perforating to avoid further completion damage. The TCP assembly consisted of 2⅞-in. PURE HSD High Shot Density gun systems designed to create a dynamic underbalance, a fast-acting SXPV production valve, mechanical and backup hydraulic-delayed firing heads, a sliding sleeve and a packer.

The TCP assemblies were run with the wellbores full of completion fluid and the sliding sleeves open. The sliding sleeve was closed after setting the packer, trapping pressure at 6050 psi [41.7 MPa] around the guns. Fluid level in the tubing was swabbed down to about 12,000 ft [3658 m], 1000 ft [305 m] above the packer. The initial wellbore condition in both wells was a pressure overbalance.

A drop bar released from surface initiated the mechanical firing head. The guns detonated and the production valve opened after a dynamic underbalance was generated. With the tubing open and previously swabbed to underbalanced fluid level, the well instantly flowed into the surface production system. If the drop bar malfunctioned, gas pressure on the tubing could activate the backup hydraulic firing head. The gas would be bled off during the firing delay to evacuate the tubing.

These PURE designs were also adjusted to account for the final wellbore pressure in case the SXPV valve failed to open. PURE charges and internal gun volume had to be designed correctly based on wellbore volume and pressure, otherwise perforating pressure could go from initial overbalance to an dynamic underbalance and back to overbalance, causing perforation damage. The 56W well required additional PURE chambers to ensure that wellbore pressure remained underbalanced or balanced after achieving a dynamic underbalance.

Dynamic underbalanced perforating eliminated the need for near-wellbore perforation washes with acid. Both wells flowed naturally after perforating. Completion operations were more efficient, resulting in relatively safer, quicker gas sales in this sensitive H_2S, or sour-gas, environment. The success of these two wells further confirmed the potential of PURE perforating.

Optimizing New Completions

In the southern North Sea, NAM also drilled a high-angle well along the eastern margin of the Broad Fourteens basin. The well targeted a 140-m [459-ft] gas-bearing reservoir in the Rotliegend sandstone. Formation porosity ranged from 5 to 15% and permeability varied from 0.2 to 20 mD. Reservoir pressure obtained from an MDT Modular Formation Dynamics Tester tool was 46 MPa [6672 psi].

Because of the low permeability in these reservoirs, NAM planned to use coiled tubing-conveyed perforating in conjunction with a CIRP Completion Insertion and Removal under Pressure system to achieve a high static underbalanced pressure and retrieve the long gun string without killing the well. Because of the completion configuration, NAM chose 2⅞-in. HSD guns with PowerJet shaped charges loaded at 6 spf for conventional perforating. Acidizing the well would finalize the completion.

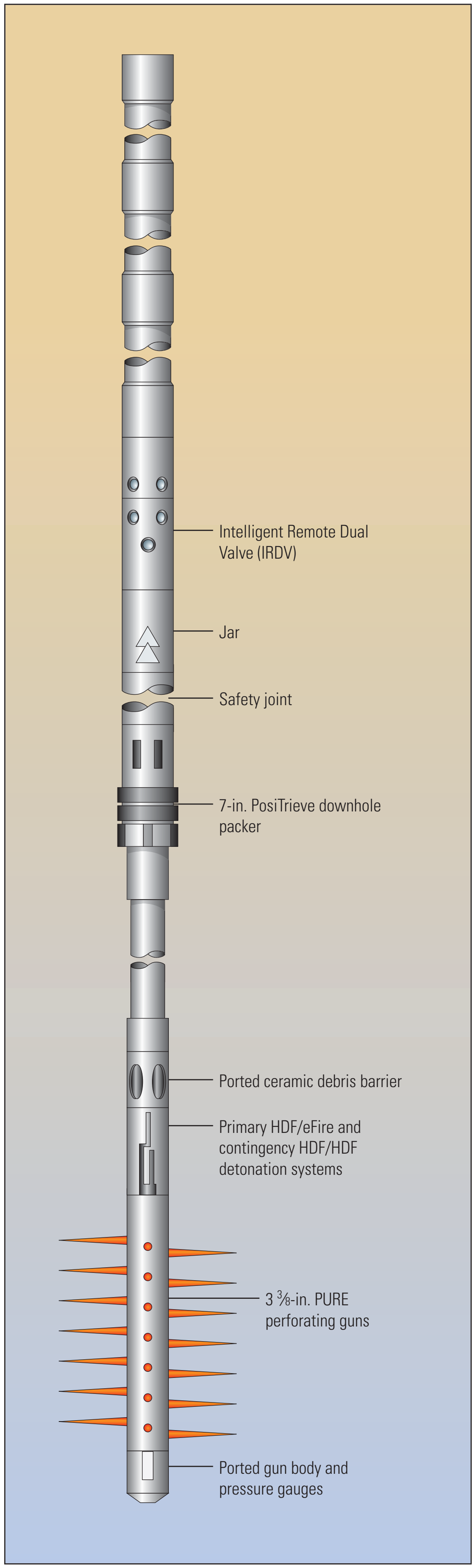
Prejob modeling indicated that this well could benefit from dynamic underbalanced perforating. In addition, the Borgsweer 4 injection well results and an ongoing field test of PURE gun systems in other NAM gas wells had provided encouraging results. As a result, the NAM team agreed to perforate this well using a specifically designed PURE gun system with charges loaded at 4 spf. The 195-m [640-ft] PURE gun string with a 7-m [23-ft] PURE chamber was run on 1½-in. coiled tubing and fired with an initial 700-psi [4.7-MPa] underbalance (previous page).

The well flowed about 2.5 million m^3/d [87 MMcf/D] of gas after PURE perforating, exceeding the expected flow rate of 0.5 to 1.5 million m^3/d [17 to 52 MMcf/D]. Because of this unexpectedly high flow rate, a planned acid treatment was cancelled. NAM is currently evaluating PURE designs for future gas-completion applications.

Dynamic underbalanced perforating is gaining acceptance throughout the North Sea and operators are applying the technique with equal success in other fields of the region. In mid-August 2003, CNR International performed two PURE jobs in the Ninian North field in the North Sea UK sector. The company perforated two wells designated N-41 and N-42 in the Ninian North field during shoot-and-pull operations with a drillstem test (DST) assembly.

To achieve a PURE perforation design, the DST string for these two wells created a closed system and the gun system was configured to achieve a dynamic underbalance (right). Pressure gauges with slow 1- and 5-s sampling rates recorded the pressure response at the bottom of each DST gun string.

In the first application, CNR perforated eight zones totaling 992 ft [302 m] of net pay across a 2200-ft [671-m] gross interval in the N-41 well. The TCP test string included 3⅜-in. HSD guns designed to generate a dynamic underbalance



< Gun configuration for wells in the Ninian North field. The drillstem test (DST) tools in the perforating string provide control of wellbore hydrostatic pressure for PURE perforating during shoot-and-pull operations. When closed, the tester valve trapped high pressure below the packer. After perforating, the tester valve was opened to displace the wells with kill-weight fluids before pulling the DST string and guns. The next step was to run completion equipment and production tubing.

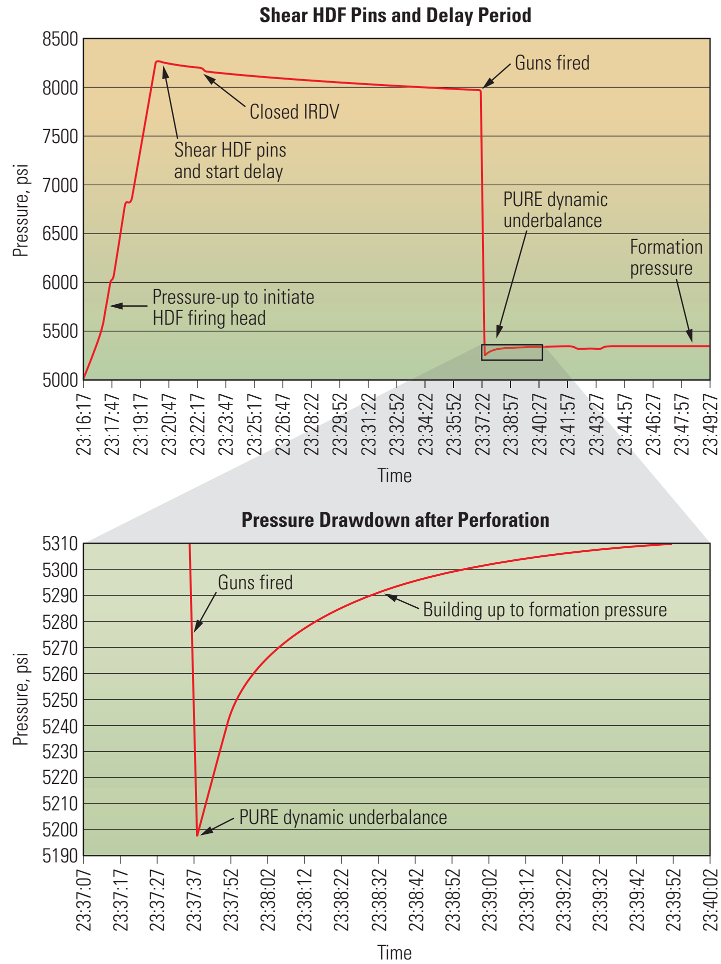
(right). This well produced at an initial oil rate of 9500 B/D [1510 m^3/d]. Well output stabilized at 7500 B/D [1192 m^3/d] oil, 50% higher than the original projection of 5000 B/D [795 m^3/d] for conventional perforating.

For the N-42 well, CNR used 3½-in. HSD guns configured for PURE perforating in the DST string. Three zones encompassing about 910 ft [277 m] of net pay across a gross interval of 1600 ft [488 m] were perforated with a dynamic underbalance (next page). The initial surface pressure after perforating indicated a reservoir pressure of more than 6100 psi [42.1 MPa], much higher than the 5300 psi [36.5 MPa] encountered in the N-41 well. While still cleaning up, the N-42 well produced 421 B/D [67 m^3/d] oil, 2633 B/D [419 m^3/d] water and 1.54 MMcf/D [44,110 m^3/d] gas.

Tubing pressure applied at the surface actuated a hydraulic-delay firing (HDF) head. During the time delay before gun detonation, an Intelligent Remote Dual Valve (IRDV) tester valve was closed, trapping hydrostatic pressure around the guns—about 8000 psi [55.2 MPa] in the N-41 well and about 8600 psi [59.3 MPa] initially in the N-42 well.

In both wells, the high static overbalance and a gun-to-wellbore volume ratio combined to create a dynamic underbalanced pressure estimated to exceed 4000 psi immediately after the guns were detonated. A slow leak from 8600 psi to 7500 psi [51.7 MPa] occurred during the N-42 firing delay. But with the tester valve closed, initial wellbore pressure remained high enough to achieve the required dynamic underbalance.

These data-acquisition rates were not fast enough to capture detailed transient pressures, but did indicate a dynamic underbalance immediately after the guns fired. The rapid pressure buildup in the two wells to the reservoir pressure of 5300 psi in the N-41 well and 6100 psi in the N-42 well indicated clean perforations with minimal induced damage. The N-42 well, originally drilled as an injector, produced for a short period before being recompleted. CNR has also applied PURE perforating techniques in five other wells, including a Ninian South field producer and a Murchison field injector.



^ Transient pressure response while perforating the N-41 well in Ninian North field. The dynamic underbalance for this PURE job was designed to exceed 4000 psi. The pressure gauge sampling rate was not fast enough to capture the peak pressure differential, but the trend was as expected for clean perforations. After achieving a dynamic underbalance, the wellbore pressure builds rapidly to the reservoir pressure of 5300 psi [36.5 MPa]. Time intervals are not all uniform.

What's Ahead for Dynamic Underbalance?

The use of static balanced and overbalanced pressures for well-completion operations has declined, except for niche applications such as extreme overbalanced perforating.[18] In contrast, underbalanced perforating continues to expand and evolve. As a result of ongoing research and development efforts, the prevailing static underbalance concept is being replaced by the new dynamic underbalance technique.

Innovative PURE technology optimizes gun designs, charge types and completion configuration to deliver clean perforations. The PURE technique provides control over the true level of underbalance by taking reservoir properties, completion parameters and gun configurations into account. This approach helps operators achieve the most effective dynamic underbalance and perforating conditions.

Well-completion and perforating parameters must be carefully designed to achieve a dynamic underbalance and generate zero-skin perforations. The degree of fluid-surge control possible with PURE perforating designs aids in avoiding stuck guns and associated fishing costs. In some applications, improved perforation conductivity and lower completion skins may avoid the need for near-wellbore acid washes to clean up perforating damage.

18. Behrmann and McDonald, reference 2.
Behrmann L, Huber K, McDonald B, Couët B, Dee J, Folse R, Handren P, Schmidt J and Snider P: "Quo Vadis, Extreme Overbalance," *Oilfield Review* 8, no. 3 (Autumn 1996): 18–33.

19. Stutz and Behrmann, reference 17.

In addition to eliminating remedial perforation washes, PURE perforating improves stimulation and pumping efficiency by increasing effective shot density. The PURE technique controls downhole pressure transients, resulting in less intense perforating shocks to wellbore and completion equipment. In some applications, this degree of control makes it possible to reduce the chance of cement-sheath damage and unwanted water flow behind casing.

Dynamic underbalanced perforating does not replace matrix acidizing and chemical treatments to remediate near-wellbore damage from drilling or completion fluid losses, organic deposits and mineral scale. The PURE technique is not a replacement for larger acid and hydraulic fracture treatments that address deeper damage and stimulate production and increase reserve recovery from low-permeability carbonate and sandstone reservoirs.

Dynamic underbalanced perforating also appears to minimize the degree of pressure differential required to achieve clean perforations. This advantage leads to safer operations in sensitive environmental areas and in dangerous well conditions, such as reservoirs that contain hydrogen sulfide. Conventional underbalanced criteria do not apply for the dynamic underbalanced system and, in fact, sometimes overestimate the pressure differential required for optimal results with dynamic underbalanced perforating.[19]

Laboratory tests are being conducted to confirm these findings and readdress underbalanced pressure requirements. Clearly, additional wellbore and reservoir physics related to gun detonation and pressure responses need to be considered to better understand perforation cleanup and to improve dynamic underbalanced perforating simulations.

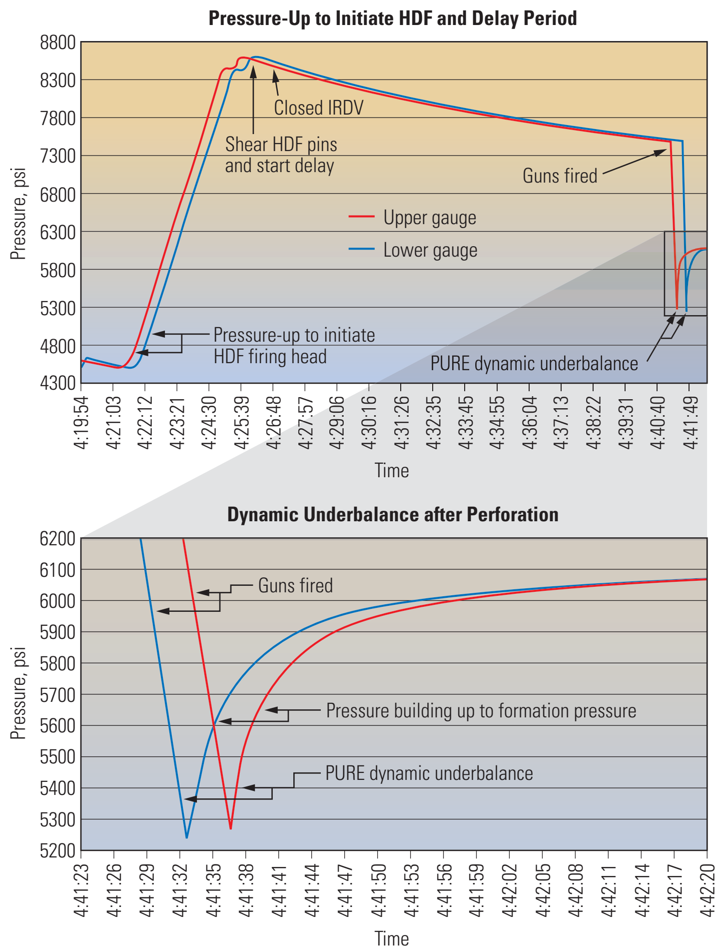
Even at this early stage of application, the major physical processes that lead to dynamic pressure variations are becoming clearer. Detailed modeling and analysis are likely to be difficult because of the complexity of these processes, but first-order predictions of dynamic underbalance and subsequent perforation cleanup are close to realization.

A mathematical model of transient wellbore dynamics, currently under development, will be included with the PURE planning software to incorporate laboratory observations in perforating designs and support the application of dynamic underbalanced operations. This software complements the SPAN design program to help design optimal PURE perforating systems.

Downhole gauges with extremely fast sampling rates can now be run with PURE systems to further optimize dynamic underbalanced perforating. Capturing transient pressure data in the field helps verify the maximum pressure differential and provides a more detailed picture of early-time pressure events during actual perforating jobs. When applied, this capability will improve our understanding of wellbore physics during perforating.

To date, more than 100 wells, ranging from wireline and TCP to coiled tubing-deployment and permanent completions, have been completed successfully using PURE perforating techniques. For the first time, operators can obtain effective new perforations in wells with existing open perforations.

This technique has tremendous potential—clean perforations even with multiple gun runs, elimination of high static underbalance requirements, a lower risk of wireline guns being blown uphole, reduced perforating shocks and wellbore damage, and potentially less need for remedial near-wellbore damage-removal treatments. —MET



^ Transient pressure response while perforating the N-42 well in the Ninian North field. The slow sampling rate of pressure gauges in the N-42 perforating string did not record the maximum dynamic underbalance during this PURE job, which was designed to achieve a 4000-psi underbalance, However, available data indicate a dramatic drop of 2246 psi [15.5 MPa] from 7480 to 5234 psi [51.6 to 36.1 MPa]. After perforating, wellbore pressure quickly increases to the reservoir pressure of 6100 psi [42 MPa], indicating clean perforations.