Operators routinely perforate with the pressure in the wellbore lower than that in the reservoir. This static underbalanced condition promotes the removal of damaged rock and debris. Researchers have found that this technique often results in disappointing well performance because of inadequate cleanup. Recent studies have shed more light on the transient effects that occur during shaped charge detonation. Engineers are exploiting dynamic underbalance to create cleaner perforation tunnels. Wells perforated using these new techniques typically perform better than those perforated using traditional methods.

Completing an oil or gas well is the culmination of work from many disciplines. Geologists, geophysicists and petrophysicists analyze formations and select drilling objectives. Engineers place the well, run casing and then cement it in place. Petrophysicists interpret well logs and identify productive zones. These efforts lead to a defining moment: The perforating guns punch holes through casing, cement and rock, establishing communication between the reservoir and the wellbore. Failure at this juncture is not an option. But for a technique referred to as dynamic underbalanced perforating, failure is not just an option; it’s the operational objective.

Perforating involves firing a gun loaded with explosive shaped charges. Within a few tens of microseconds, the shaped charges are detonated and fluidized particles are expelled, forming a high-velocity jet traveling at speeds up to 8,000 m/s [26,250 ft/s], creating a pressure wave that exerts as much as 41 GPa [6 million psi] on the casing and 6.9 GPa [1 million psi] on the formation. The immediate result is a perforation tunnel lined with a layer of shock-damaged rock and filled with debris. Unless removed, the damaged rock impedes fluid flow, and the debris—pulverized rock and charge remnants—can plug the tunnel and pack the pore throats.

The industry standard for cleaning these newly formed perforation tunnels has been to use a static underbalanced approach. Typically, perforating guns are deployed in cased wellbores that contain some fluid. The fluid column creates a static hydrostatic pressure that is a function of the fluid-column height and the fluid density. If the hydrostatic pressure is lower than that of the reservoir, a static underbalanced condition exists; conversely, if the pressure is greater, the well is overbalanced. Operators perforate with a static underbalance in the hope that the negative pressure differential will create an immediate inflow of reservoir fluids and remove perforating debris. The production that results from this method, however, is often disappointing.

A new method, dynamic underbalanced (DUB) perforating, exploits information gained from research into the transient forces that occur in the gun system, wellbore and reservoir during perforating. Shattered rock in the zone damaged by the forces of the shaped charge explosion is removed, and the flow of reservoir fluids sweeps crushed rock and other perforation debris into the wellbore. An added benefit of DUB perforating is that these effects can be created in wellbores that are initially underbalanced, balanced or even overbalanced. The results are cleaner perforations and better well performance.
In the past, design engineers typically focused on creating charges that delivered cleaner, bigger and deeper holes. In contrast, DUB perforating demonstrates that, although these characteristics are important, maximum productivity requires more than just better shaped charges. Exploiting the transient phenomena occurring in the perforation tunnels during and after detonation improves the perforation geometry and flow effectiveness, which directly impact well performance.

Perforating performance in downhole environments depends on many factors, so predicting penetration depth and entrance-hole size may not be possible from surface tests. However, operators use data from standardized tests to compare different shaped charges. Simulation programs also use the test data to predict charge performance based on rock properties and downhole conditions. In 2000 the American Petroleum Institute (API) released the Recommended Practices for Evaluation of Well Perforators, RP 19B, to provide guidelines and procedures for qualifying charges from different suppliers. API RP 19B replaced the RP 43 standard. Also, the API now offers the Perforator Witnessing Program to lend greater credibility to test results.

This article explains the theory of DUB perforating and reviews recent applications in Canada and China. Test results from Malaysia demonstrate a perforating system for gravel-packed wells, which evolved from ongoing research in wellbore dynamics. An overview of API RP 19B recommended practices provides useful background information.

**PURE Process**

For many years perforating research has focused on developing shaped charges that create deep penetration, large entrance holes in the casing and limited debris in the perforation tunnels (see “API RP 19B—Standardizing Perforation Testing,” next page). These criteria are important but they are not the only factors that impact perforation results. Ultimately, well performance is the most critical quantitative measure.

The high-velocity jets and extremely high pressures generated by shaped charges can penetrate beyond drilling-induced formation damage into virgin rock. In the process of creating the perforation tunnel, the jet shatters matrix grains and alters the mechanical properties of the rock surrounding the tunnel. A slice through the perforation tunnel reveals three separate zones: loose (continued on page 8)
Many factors influence the creation of perforation tunnels. It is practically impossible to duplicate downhole charge performance using tests conducted at the surface. An objective standard to evaluate charge performance can, however, offer a means of comparing charges and provide a baseline for modeling programs that predict penetration geometry and inflow performance.

The American Petroleum Institute (API) published RP 19B, *Recommended Practices for Evaluation of Well Perforators*, in November 2000, replacing RP 43. The second edition was issued in September 2006. It provides manufacturers with five sections outlining specific testing procedures. The “B” designates recommended practices rather than prescribed specifications; however, API registers charge performance only if manufacturers comply with these recommendations.

The two most significant updates in RP 19B are an independent witness program and a change to API 16/30-mesh frac sand for the concrete aggregate used in Section I test targets. The Perforator Witnessing Program is intended to lend more credibility to test results. Upon request by the manufacturer, the API will provide approved witnesses to review and certify test procedures. Because there were significant penetration differences observed using concrete targets made from sand at the extremes of the previous specification, the new standard more tightly controls acceptable mineralogy and sand grain size.

Section I

Section I testing, performed at ambient temperature and atmospheric pressure, evaluates the basic perforating system and is the only complete gun-system test recognized by the API. Service companies prepare targets by cementing a section of casing within a steel culvert. Briquettes from the concrete aggregate used to construct the targets, obtained during the middle portion of target pouring, are tested for compressive strength before proceeding with the testing.

Test charges must come from a production run of at least 1,000, except for high-temperature charges, which can be from a minimum run of 300. The gun position, shot density, phasing and number of charges in the gun are listed on the datasheet. Charge-to-charge interference, phasing, perforating hardware and shot density can alter performance, so the gun-system test is not always duplicated in single-shot tests. The test requires a minimum of 12 shots, and the gun hardware must be verified as standard field equipment. Casing entrance hole and penetration are measured and listed on the datasheet.

Although the total penetration in concrete is a relevant measurement, it does not reflect the actual penetration in formation rocks. If formation mechanical properties are known, modeling software such as the SPAN perforating analysis program can estimate downhole performance.

Section II

For Section II testing, charges are fired into stressed Berea sandstone targets at ambient temperature. These single-shot tests are performed in a laboratory fixture. Both confining stress and wellbore pressure are initially set to 3,000 psi [20.7 MPa], and any induced pore pressure is vented to atmospheric pressure. Although this test does not replicate the conditions of a particular reservoir, the stressed rock provides a significant qualitative improvement in realism compared to the Section I unstressed-concrete target.
Section III
The heat test of Section III evaluates performance degradation of a gun system resulting from thermal effects. A minimum of six charges are fired from a heated gun system into steel plates welded to the gun body. Penetration and entrance-hole diameter resulting from guns fired at elevated temperatures are compared with those from guns fired at ambient conditions (above).

Section IV
Section IV testing evaluates flow performance by perforating a confined rock sample in a single-shot laboratory gun module (above). The test vessel consists of three essential parts: a confining chamber to impart overburden stress on the rock core, a system to pressurize the pore fluid and simulate far-field reservoir response, and a pressurized wellbore chamber. This test provides a measurement of core flow efficiency (CFE). The CFE can be related to skin damage of a single perforation and can be used to quantify the essential characteristics of the perforation’s crushed zone. In practice very few researchers conduct “by-the-book” Section IV tests. This is due mainly to the operator’s desire to either predict what will happen in a particular reservoir or evaluate the optimal perforating technique for a given application. 

Observations on New Testing
The API RP 19B recommendations were published in 2000, and many tests made under the API RP 43 recommendations have been recertified using the new ones. The differences in the results range from trivial to significant. For example, a 14% reduction in total penetration was observed in retests of the Schlumberger PowerJet charge. But the 0.07% difference in the penetration measurement of the 2 1/8-in. [5.4-cm] Enerjet III charge was insignificant. Tests in concrete targets may not accurately represent charge performance in downhole conditions, but they do provide the industry with a benchmark for comparing charges from different suppliers. The stricter guidelines of API RP 19B, along with the witnessing program, provide greater confidence in the reliability of published test results.
fill comprising unconsolidated sand and charge debris, mechanically damaged rock with altered flow and strength characteristics, and virgin rock identified by its unchanged intrinsic values of permeability, porosity and rock strength (above).

The mechanically damaged rock in the crushed zone reduces fluid inflow and can be a significant contributor to the mechanical skin. Also, loose fill in the perforation tunnel can plug the pore spaces, potentially complicating such future operations as injection, matrix acid treatments, gravel packing and fracture stimulation.

Traditionally, when possible, wells are perforated with a static underbalanced condition to facilitate inflow of formation fluids after detonation. Laboratory tests demonstrate that greater static differential pressures than previously recommended are required to effectively remove damaged rock and to sweep debris from the perforation tunnels. Analyses of data from fast and slow pressure gauges, acquired during single-shot perforating and flow experiments, indicate wellbore pressure varies widely during and immediately after charge detonation. The differential pressure may repeatedly swing from overbalanced to underbalanced in a matter of milliseconds. Such pressure oscillations are not very effective in removing damaged rock or flushing out debris.

Another possible consequence of perforating with a static underbalance is that the initial transient overpressure generated during detonation can force debris deep into the perforation tunnel, creating an impermeable plug. In wells where static underbalance produces at least some level of inflow, it may be disproportionate: The most permeable perforations will experience the highest degree of cleanup. Perforations in less permeable rock, which need the most help to fully clean up, may not experience an inflow of sufficient duration before the pressure equalizes. The result is fewer, if any, clean perforations and fewer perforations contributing to the total flow.

Because the damaged zone is partially deconsolidated and its strength is much lower than that of the surrounding rock, a rapid surge flow—strong enough to generate tensile forces that exceed the strength of the damaged zone—will cause the rock to fail. Sustained flow following rock failure flushes the material from the tunnel (next page, top). This is the essence of DUB perforating. The process is derived from understanding and controlling the transient phenomena. The first step is understanding the grain-scale mechanisms.

The matrix grains along the surface of the perforation tunnel shatter during perforation. Although this creates more paths for fluid flow in the crushed zone, they are narrower and more restrictive than those of the original pore structure. This is the mechanism for reduced permeability along the tunnel wall. The permeability varies from near zero at the edge of the tunnel to that of the virgin rock at some distance into the formation.

Direct measurement of the permeability in the crushed zone is difficult. However, researchers at the Productivity Enhancement Research Facility (PERF) at the Schlumberger Reservoir Completions Center in Rosharon, Texas, USA, employed an indirect method to quantify changes in this zone. Permeability is estimated from the fractal dimension of the pore space.
Failure of the crushed zone. Two of the most important aspects of DUB perforating are the magnitude and the rate of the pressure drop. The left plot compares wellbore pressure during PURE perforating (blue) with that of static underbalanced perforating (orange). In the PURE example the wellbore pressure is initially in balance with the reservoir pore pressure, then drops rapidly. In the static underbalanced example the pressure is initially below that of the reservoir, rises rapidly from the release of gases during gun detonation and then drops slowly, creating an underbalanced condition. Data from fast gauges (far right) reveal the pressure transients for each gun system. Tensile stress from the peak pressure differential during DUB perforating (blue) exceeds the strength of the rock; the rock in the damaged zone fails and becomes loose fill in the tunnel. The intersection of the rock strength (magenta) and the flow strength indicates the postsurge tunnel width (red dashed lines). Little damaged rock is removed by the slow pressure differential typical of static underbalanced perforating (orange). Using DUB perforating, additional damaged rock is removed (light blue).

Perforated Berea sandstone samples were vacuum impregnated with blue-dyed epoxy. Engineers then cut thin sections perpendicular to the axis of the perforation tunnel. Radial panoramic photographs depict perforation effects from the tunnel edge to the virgin rock. Thin-section color photographs are rendered as binary black-and-white images; the pore space is black and the rock matrix is white.

Permeability analysis from fractal dimension of pore spaces. Photographs of blue-dyed thin sections are rendered in black and white (binary image). Fractal dimension analysis is performed on the black-and-white images, and the data (red) are plotted as a function of distance from the edge of the perforation tunnel. The low-permeability zone (grey shading) ends about 10 mm from the center of the tunnel. Although damage extends to 10 mm, the zone of greatest permeability impairment is limited to a few millimeters from the tunnel wall and its removal is the most crucial for improving flow. Fractal dimension analysis was performed on several sandstone cores with different rock properties (right). Averaged fractal dimension data (blue dots) compare favorably with damage measured visually from thin sections (red dots). Note that the zone of reduced permeability (grey shading) is not directly related to formation strength. The Castlegate sandstone (top right) has a much lower unconfined compressive strength (UCS), yet the depth of damage is similar to that of two mechanically stronger Berea sandstone varieties (middle and bottom right). (Adapted from Heiland et al, reference 6.)
Researchers employed image-analysis techniques common to biological and material-science applications to determine the fractal dimensions of the pore spaces from the binary images measured in 1-mm [0.04-in.] sliding increments. They used changes identified in the geometric complexity of the rocks to establish a profile of the perforation damage. Test results from different Berea sandstone samples have an inflection point between virgin rock and damaged rock at about 8 to 10 mm [0.3 to 0.4 in.] from the tunnel edge, indicating the transition from shattered grains with reduced permeability to unaffected rock. The majority of damage is located within the first 5 mm [0.2 in.].

Breaking of the cementation between grains and debonding of the dispersed clay particles also occur during perforation. Radial displacement of the matrix grains creates a residual elastic stress in the far-field undamaged rock. As the rock decompresses, the stress causes the most-damaged rock, that adjacent to the perforation tunnel, to fail but remain in place.

Engineers use a rock profiler, or scratch tester, to measure the rock strength along the axes of perforated samples, providing the unconfined compressive strength (UCS) (above right). These data indicate the mechanically damaged zone extends almost 20 mm [0.8 in.] from the perforation tunnel and does not correspond exactly to the zone of shattered grains. Similar to the effects observed for permeability, maximum mechanical damage occurs along the surface of the tunnel walls, and the damage diminishes with radial distance from the tunnel surface.

A primary implication of this dual nature of the perforation-damaged zone is that the pressure differential needed to remove the majority of the permeability-impaired rock is only a fraction of the virgin rock strength. The experimental data indicate the few millimeters of rock with crushed grains and diminished permeability coincide with the rock strengths below 2,000 psi. If a pressure gradient is quickly generated across the perforation tunnels, as it is with a PURE perforating system, sufficient tensile and shear forces can be generated to cause the damaged rock to fail or to be pulled apart.

Special PURE hardware and job-design parameters combine to create the dynamic underbalance. Both standard and PURE shaped charges are placed in the gun string (right). The dynamic underbalance is generated when these charges punch very large holes in the carriers and establish maximum communication between the wellbore and the gun string, thus allowing

![Unconfined compressive strength from a scratch tester. A rock profiler (inset) measures the normal and shear forces required to create a 0.2-mm [0.008-in.] notch in a rock sample. By scratching progressively deeper along the axis of the perforation tunnel, engineers created a 3D representation of rock strength from tunnel edge to virgin rock. Four Berea sandstone samples were perforated, split and tested. The strength of the virgin sandstone exceeds 8,000 psi [55 MPa], but that of the first 10 mm of mechanically damaged rock is less than 2,000 psi [13.8 MPa]. A DUB pressure differential in excess of 2,000 psi can cause this rock to fail and fall into the perforation tunnel. (Adapted from Heiland et al, reference 6.)

![PURE gun system. Casing guns are loaded with both conventional shaped charges and PURE charges, which create large holes in the carrier (inset). The internal volumes of the guns alone are not sufficient to create the required dynamic underbalanced condition that causes the rock in the crushed zone to fail. Modeling software provides the number of hollow carriers, loaded only with PURE charges, that must be added to the gun string.]
Rapid fluid flow into the gun. The PURE charges do not penetrate the casing.

A gun carrier containing the conventional and PURE shaped charges rarely has sufficient internal volume to create enough dynamic underbalanced pressure to cause the damaged rock to fail, and then to sustain the inflow long enough to clean the perforation tunnels. To create additional drawdown and inflow, PURE chambers, loaded only with PURE charges, are added as needed to the assembly. They are fired at the same time as the rest of the gun string (above). For maximum effect, these chambers are placed as close as possible to the newly opened perforations.

Because the inflow of fluid into the gun and chambers creates the dynamic underbalance, the PURE system works only in liquid-filled boreholes. If perforating is scheduled for multiple intervals and any may produce gas, the gas flowing from lower zones can disrupt the process. To avoid this potential problem, it is best to perforate from the shallowest to deepest zone in gas-bearing formations. This is a departure from the traditional approach.

^ Dynamics of DUB perforating. DUB perforating uses special charges to open large holes in the gun carriers and PURE chambers (top left, middle charge). An initial increase in wellbore pressure resulting from charge detonation, as seen in the pressure plot (top right, blue curve), is followed by a rapid decrease in pressure (center right) created by the inflow of fluids into the empty gun carrier (center left). The rock in the crushed zone fails and falls into the perforation tunnel. This failed rock, along with charge debris, is then flushed into the wellbore and the empty carriers (green arrows) by fluid flow from the reservoir (black arrows). The final result is an enlarged perforation tunnel with improved flow characteristics (bottom left).

To design the specific gun-system volumetrics to create the PURE effect, perforating specialists employ proprietary software to model transient-pressure behavior (left). The software simulates the creation and propagation of transient-pressure waves generated during perforation and predicts wellbore pressure at any point in the well. A unique gun string is created based on wellbore specifics and gun hardware. Because a pressure gauge located at the perforating gun could rarely survive the impact of detonation, the model provides a simulated pressure plot or extrapolates wellbore pressure at the guns from pressure-gauge data acquired farther up the downhole assembly.

Research into the transient forces that occur during perforating highlights the importance of considering the contributions of the wellbore, reservoir, gun system and other external factors when designing a perforating system. By exploiting the forces created with the downhole hardware, dynamic underbalanced perforating produces more-effective perforations and enhances well performance (next page, top left).

Overcoming Environmental Challenges
The Terra Nova field, 350 km [220 mi] off the coast of Newfoundland, Canada, produces from highly faulted Jurassic reservoir sands. The wells in this field are drilled using a mobile offshore drilling unit (MODU). Subsea completions are tied to a floating production storage and offloading (FPSO) vessel (next page, top right).

To maximize recovery, the development plan for the field calls for drilling high-productivity producer-injector pairs. Standard practice is to perforate the producers with 114.3-mm [4½-in.] wireline-conveyed guns loaded with 32-g charges. Up to six runs per well are usually required. Static underbalance—wellbore hydrostatic pressure less than that of the formation—for the initial gun run is maintained with the fluid column. To achieve underbalanced conditions during subsequent runs, the wells are flared at the MODU.

The multiple flowbacks inherent to this perforating program waste oil and increase the risk of environmental incidents from unintentional fluid release. Although the results were satisfactory, the waste and risk prompted the operator to investigate alternative completion methods.

A test of DUB perforating with the PURE system was first proposed for water injectors in the Terra Nova field. These wells were to be slightly underbalanced for the initial gun run and statically balanced for subsequent runs. The gun design would create a dynamic underbalanced condition and clean perforations for subsequent runs without the need to flow to the MODU during each run. Flaring at the MODU would be reduced to a single event for recovery of completion fluids and perforating debris, which was necessary before putting the well into operation.

When schedule changes delayed drilling of the water injectors, the operator decided to use the PURE system in a production well. For the first well, six wireline perforating runs were made. Fast-gauge data from the initial run indicated an initial static underbalance of 4.77 MPa [690 psi]. Immediately after perforating, a maximum DUB of 12.9 MPa [1,870 psi] was achieved and a 3.2-MPa [464-psi] underbalance was sustained for approximately 0.55 s, during which the perforation tunnels were purged.

Mobile offshore drilling unit (MODU) and floating production storage and offloading (FPSO) vessel. Petro-Canada uses a MODU (right) for both drilling and completing Terra Nova wells. Production is sent to the storage vessel for transport back to the mainland. To create an underbalanced condition downhole, oil is flared at the FPSO vessel (left) while perforating operations take place onboard the MODU. Production logging, conducted after perforating, is performed while oil is flowing; it must also be flared. (Image used with permission of Suncor Energy.)

Bigger and cleaner perforation tunnels. Perforations of core samples in a simulated downhole environment demonstrate the different results obtained with the PURE perforating technique (top) and without DUB conditions (bottom). Casing entrance holes and penetration depths are similar, but damaged rock and debris have been removed from the tunnel by the DUB perforating system.

Pressure data from perforating runs. Fast downhole pressure gauges recorded data during perforation runs. For the first gun run (left), with an initial static underbalance of 4.77 MPa below the reservoir pressure (green), a DUB pressure of 12.9 MPa was achieved. Sustained flow after the maximum underbalance helped clean the perforations. Run 4 (right), made in an initial static balanced condition, achieved a 16.4-MPa [2,379-psi] dynamic underbalance. (Adapted from Baxter et al, reference 11.)

Mobile offshore drilling unit (MODU) and floating production storage and offloading (FPSO) vessel. Petro-Canada uses a MODU (right) for both drilling and completing Terra Nova wells. Production is sent to the storage vessel for transport back to the mainland. To create an underbalanced condition downhole, oil is flared at the FPSO vessel (left) while perforating operations take place onboard the MODU. Production logging, conducted after perforating, is performed while oil is flowing; it must also be flared. (Image used with permission of Suncor Energy.)
The five subsequent gun runs were made in a balanced condition. Pressure data from the fourth run showed an initial balanced state, but a DUB of 16.4 MPa [2,379 psi] was achieved. A very brief overpressure spike, typical of wells perforated balanced or initially overbalanced, was followed by the desired transient underbalanced condition. No flaring was conducted during any of the perforating runs (above).

The efficiencies and environmental benefits realized in the initial PURE test resulted in three injectors and two producers being perforated with this approach. The minimal amount of debris associated with well flowback has led to plans to evaluate flowing the production directly to the FPSO vessel for cleanup and production logging, avoiding the need for flaring entirely.

The PURE technique has lowered the environmental risks and eliminated the loss of oil from flaring during perforating, which reduces waste. Efficiency of the overall operation was also improved because the operating time associated with flaring to the MODU has been significantly reduced.

Underbalance in Overbalance

The Hui Zhou (HZ) fields, in the South China Sea, are under development by the CACT Operators Group, a partnership formed by field operator Eni, the China National Offshore Oil Company, and Chevron (below left). The reservoir consists of stacked, thin, high-permeability sandstones interlayered with low-permeability zones. In the past, shallower intervals were generally completed first because they have better permeability than deeper ones. The deeper, less permeable sands experience deeper invasion during drilling and are now being developed. Deep-penetrating charges are necessary to perforate past the drilling damage.

Efforts to reduce skin damage include drilling practices that minimize invasion, the use of non-damaging completion fluids and programs that minimize perforation-induced damage. Despite these efforts, traditional static underbalanced perforating has caused high skin values—and underperformance—in many wells. Because the reservoir consists of multiple layers, only the first interval in the well can be perforated at a static underbalanced condition with wireline-conveyed guns. Subsequent intervals are perforated balanced or overbalanced.

Tubing-conveyed perforating (TCP) has been used to achieve static underbalance across more than a single interval. Although TCP is an acceptable alternative in thick reservoir intervals, wireline perforating has proved more cost-effective in the widely spaced thin intervals of the HZ fields. The general practice has been to perforate with wireline-conveyed casing guns in a slightly overbalanced condition and accept the resulting positive skin. Adding to the problem, however, was postperforation invasion of clear completion fluids, such as brine, or high-solids kill fluids, which caused even higher skin values.
In a test of the PURE system, several zones, each with a different permeability, were to be perforated with nondamaging completion fluids. The objective was zero skin damage, or no damage caused by the completion fluids or perforating.

Researchers studied the formation damage resulting from the completion fluids used previously and recommended potassium formate as an alternative to kill pills or brine. Potassium formate forms a seal along the rockface of the perforation tunnel, which controls fluid loss into the formation. Flow into the well during production removes the seal.

Simulation tests demonstrated the importance of first cleaning perforation debris from the tunnel prior to creating the potassium formate seal. The researchers also determined an overbalance is necessary to form an effective seal. The PURE system offered the possibility of both: a dynamic overbalance for clean tunnels and a static overbalance for the potassium formate seal.

To benchmark the dynamic overbalanced system in potassium formate, reservoir engineers selected an existing well that had been perforated in clear fluids, typical of others in the field. The objective was to compare its productivity index (PI) with that of a well perforated using the new completion fluid and a DUB system. Because the wells encountered different pay thicknesses and permeabilities and were drilled with different deviations, normalization was required before comparisons could be made.

Analysts evaluated the production characteristics of the existing well and computed the PI. Applying normalization factors consistent with differences between the two wells, they determined a PI of 13.2 bbl/d/psi [0.23 m³/d/kPa] would have been expected for the new well had it been traditionally completed. After being perforated with a DUB technique, the well had a PI of 25 bbl/d/psi [0.43 m³/d/kPa], a significant improvement over that of wells perforated with the previous method.

A multilayer production analysis conducted for the new well estimated the skin factor to be nearly zero for a low-permeability (9-mD) zone. A second zone, with high permeability, yielded a skin value of –0.97 (top right). Such low skin values could not have been achieved using conventional wireline perforating; for comparison, the skin values for other wells in the field range from +2 to +5.

The use of DUB perforating in low-permeability sandstone reservoir layers achieved the objective of zero to negative skin values. Intervals with high permeability also benefit from this system, and the gains in PI were even greater than those in low-permeability zones (below). The overall improvement in perforating results prompted CACT to approve DUB perforating on several more wells in the field.

**Perforating for Gravel Pack**

Weakly consolidated formations often produce sand, which reduces recovery rates, damages surface facilities and generates higher costs for remediation and repair. Of the many solutions available for sand control and sand management, gravel packing is the most common. In the Abu Cluster field in western Malaysia, PETRONAS Carigali implemented a gravel-pack technique that provides clean perforations for prepackaging. The reservoir, with extremely high permeabilities (1.5 to 3.0 D) and flow rates that reach 5,000 bbl/d [795 m³/d], poses significant concerns for sand production. Engineers investigated methods for optimizing oil production while minimizing sand production.

Efficient gravel-pack placement requires a large entry hole in the casing and a perforation tunnel that extends into the sand layer. The tunnel must be packed with gravel. Well-formed and packed perforations act as a granular filter, allowing communication between the wellbore and the reservoir while inhibiting the production of formation damage.

![Sample Well Multilayer, Multirate Reservoir Test](image)

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<th>Porosity, %</th>
<th>Reservoir pressure, psi</th>
<th>Effective permeability, mD</th>
<th>Estimated permeability from logs, mD</th>
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</table>

^ Multivariate well test results. The zones tested to benchmark the PURE system are thin (3.2 m or less) and have wide variations in effective permeability (9.4 to 1,605 mD). The skin values, which include both perforating skin ($S_p$) and dynamic skin ($S_d$), were approximately 0 to –1. Such low values were not attainable with conventional wireline perforating systems.

![Improved PI](image)

^ Improved PI. The ability to perforate and achieve zero or negative skin improves the PI. Although the improvement in PI achieved using the PURE system (blue), rather than a traditional system (red), is more obvious in the high-permeability sands, the need for improvement in the sands of lower quality is greater. (Adapted from Pizzolante et al, reference 12.)

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perforation tunnels in weak rocks. The tunnels are often poorly defined and filled with debris.

Experience has shown that perforating in tunnels filled with impermeable debris often results in no defined perforation tunnel or having strengths of 3.44 MPa [500 psi] or less—ing of charges into low-UCS formations—those of sand (above). At the PERF laboratory, test fir- of charges into low-UCS formations—those having strengths of 3.44 MPa [500 psi] or less—often results in no defined perforation tunnel or in tunnels filled with impermeable debris (below). Experience has shown that perforating in underbalanced conditions can cause the sand to fail mechanically, creating an influx of sand and potentially trapping the guns. The result is a costly fishing operation to free the gun string.

For gravel packs in low-UCS formations, the perforations should be prepacked immediately after perforating, if possible. Prepacking is car- ried out before the main gravel-pack stage is conducted; however, a significant reduction in production, a lower percentage of contributing perforations and the potential for early-onset sand production are possible if prepacking is performed without first removing perforation debris. There are several prepacking tech- niques, and most require multiple trips and time-consuming operations.

The TRUST transient rapid underbalance surge technique, developed from knowledge of perforating dynamics in unconsolidated forma- tions, creates clean perforations for prepacking. A nondamaging carrying fluid that can leak off into the formation is used to deliver the gravel to the perforations.

The heart of the TRUST system is a downhole atmospheric chamber, with annulus pressure–activated valves at the top and bottom, which is positioned directly above the gun string. Following guidelines derived from laboratory studies, specialists size the volume of the chamber to provide a set inflow per perforation. The volume should be sufficient to clean the debris from the tunnels and flow only a limited amount of formation sand. A perforation packer above the gun string provides additional fluid control during the operations.

The perforating crew runs the assembly into the well, correlates it to depth and sets the packer. Maintaining an overbalanced condition after perforating inhibits sand production that can cause the assembly to become stuck at the perforating depth.

After the guns are fired the packer is released and the gun string and surge assembly are repositioned above the perforated interval. The weight of the hydrostatic column is sufficient for flow to be maintained into the formation and losses are monitored and recorded. The packer is reset to provide isolation before opening the lower valve. Opening the valve creates an immediate underbalanced surge that purges the perforations. To allow settling of the solids below the perforation interval, the well is left undisturbed for a prede- termined time. The upper valve is then opened, applying hydrostatic pressure to the surged per- forations, and losses are again monitored. A comparison of the flow rate immediately after perforating with that of the postsurge losses indi- cates the extent of cleanup and communication with the reservoir.

Positioning the chamber close to the perfo- rated zone creates the maximum drawdown in the wellbore, but if it is too close, flowing sand creates a risk for sticking the downhole assembly. The engineers preset the chamber volume to decrease the likelihood of excessive sand being produced and flowing up and past the gun assembly, and also position the assembly to reduce the risk. In the

Abu Cluster wells, the chamber volume created 0.5 galUS [2 L] of flow per perforation.

The next step in the TRUST technique usually involves spotting a fluid-loss pill in the well to establish an acceptable loss rate, which enables safe retrieval of the perforating assembly and running of the gravel-pack assembly into the well. The rig crew then begins to pump a series of acid, brine and gravel slugs to remove the fluid-loss pill and prepack the perforations. Finally, the full gravel-pack treatment is pumped, the gravel-pack service-tool assembly is removed, and the production string is run into the well (right).

To test this methodology, PETRONAS Carigali compared results from four wells in the Abu Cluster field. The operator completed Well A, surged the perforations and used a traditional high-rate water-pack technique. The carrier fluid was not sufficiently viscous to create an adequate pressure drop across the perforations. Well B was to be prepacked, but immediately after surging, the well was shut in because weather conditions required an evacuation. Gravel-pack operations commenced 10 days later. Wells C and D were completed with the TRUST technique. Well C had two intervals, one gas and the other oil. Well D was an oil well. Wells C and D had much higher pack factors than Well A, completed using the traditional technique.

Pack factor is a mass-balance calculation comparing sand volumes pumped during prepacking with those pumped during the gravel-packing operations. It provides an estimation of the amount of gravel actually entering the perforations and is empirically related to the PI. The PIs of the wells treated with the TRUST technique are significantly higher than those of the other two wells (right).

A pack factor of 5 for Well B indicates the perforations may have collapsed during the 10-day weather delay. These results emphasize the benefit of prepacking as soon as possible after perforating to achieve optimal results.

The TRUST technique offered an efficient method of gravel packing low-UCS reservoirs. The higher pack factors resulted in improved well performance, as indicated by the increase in normalized PIs. Removing the risk associated with sanding in the guns, inherent in conventional underbalanced perforating, is an added benefit of the technique.

Dynamic Future
Dynamic underbalanced perforating refers to the technology and methodology that creates underbalanced conditions after shaped charge detonation. Dynamic also describes the new techniques developed from ongoing research and applications of DUB perforating.

As scientists probe deeper into the transient effects that occur during perforating, innovative applications and methods continue to emerge. Perforating overbalanced in acid creates an initial dynamic underbalance to clean the perforations; this is followed by an immediate injection of acid to treat the perforations. Perforating with kill pills provides safer operations without losing the cleanup associated with underbalanced conditions. Opening existing perforations using PURE chambers can improve production in old wells. The drawdown created by PURE chambers can help remove the scale that has formed in the casing of underperforming wells and break down scale deposits in open perforations. Engineers continue to develop new methods to exploit DUB techniques.

Research for development of better shaped charges is ongoing, but the PURE perforating technique demonstrates that well performance is improved by focusing on the entire system—wellbore, formation, shaped charges and downhole hardware. DUB perforating brings the industry a system in which failure can actually deliver greater success. —TS