

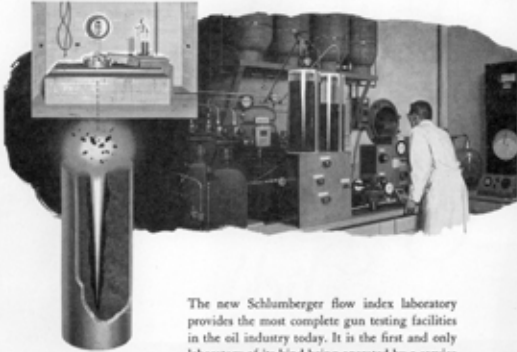
Schlumberger



## Productivity Enhancement Research Facility (PERF)

Simulating perforating and well performance at downhole conditions to optimize reservoir recovery

## New from Schlumberger--- MAXIMUM FLOW PERFORATIONS



The new Schlumberger flow index laboratory provides the most complete gun testing facilities in the oil industry today. It is the first and only laboratory of its kind being operated by a service company.

In the past, Schlumberger has tested gun performance under extremes of pressure and temperature. Now, it is also possible to fire guns under formation-to-hole pressure differentials identical to those existing underground.

As fluid is forced through the perforations, a definite flow index is accurately established for different types of perforations and formations.

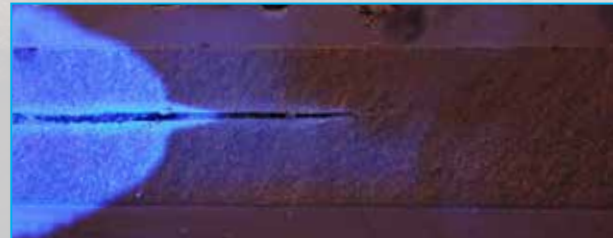
When you call Schlumberger, you can be sure that the perforator used on your well has been pre-tested under field conditions to give perforations with a maximum flow rate.

Schlumberger...to be sure!

THE EYES OF THE OIL INDUSTRY **SCHLUMBERGER**

# Productivity Enhancement Research Facility (PERF)

Schlumberger introduced the industry's first perforating flow laboratory in 1953. Today's understanding of perforating system performance at downhole conditions comes largely from the extensive test programs and innovative techniques that we pioneered at the lab over the last six decades. Then as now, operators require the best-possible reservoir-to-well connection, with reduced risk and uncertainty. We combine the industry's most technologically advanced testing systems and highly experienced people in directly determining how your reservoir will perform when perforated and how to optimize reservoir recovery during its life.



*Schlumberger has long led the industry in studying perforating performance.*

*Dye flow testing is one technique used for evaluating the clean perforating tunnel length.*



*PERF colocates perforating research, industry-leading technologies, and advanced manufacturing to maximize perforation performance and deliver optimal wellbore-to-reservoir connectivity.*

Now named the **Productivity Enhancement Research Facility (PERF)**, the laboratory's scope has expanded to integrate perforating and completion optimization across research, engineering, and the manufacturing of reservoir-specific shaped charges. Located south of Houston, Texas, PERF is equipped with state-of-the-art testing technologies for simulating perforating and well performance under your well conditions to optimize reservoir recovery. We provide indispensable insight into your well's wellbore-to-reservoir connection in a controlled environment, before field deployment, by testing in real rock samples and under realistic downhole conditions. The PERF scientists, researchers, engineers, and technicians employ advanced test cells, controls, and automation to accurately simulate the downhole environment during perforating and postperforating stimulation and flow. No longer do operators need to guess how charges will perform in their wells.

The image shows a complex industrial machine, possibly a core testing rig, with a computer monitor in the background. The machine is dark-colored with various components, including a large white cylindrical part on the left and a blue cylindrical part on the right. The monitor displays a graph with a blue line fluctuating over time. The overall scene is dimly lit, with the machine and monitor being the primary light sources.

# Understanding the reservoir

## Core selection and preparation

The PERF lab is equipped to conduct core analysis of cores up to 10-in diameter and 36-in length. Using core samples from your reservoir or a comparable rock sample, we directly determine how your reservoir will perform when perforated. Our core preparation tests replicate reservoir conditions and damage from drilling.

- **Rock strength:** Perform scratch test to determine the unconfined compressive strength (UCS) of the rock.
- **Saturation:** Saturate the rock sample with simulated formation water.
- **Irreducible water saturation:** Coreflood with mineral oil for oil reservoirs or nitrogen gas for gas reservoirs.
- **Permeability:** Determine the axial and radial permeabilities of the core.
- **Baseline productivity and injectivity:** Conduct initial production and injection tests.
- **Damage from drilling:** Inject drilling fluid to simulate mud damage to the reservoir.



*The computerized tomography (CT) scanner nondestructively detects any defects in the core before perforating tests and subsequently images the open perforation tunnel and perforating debris.*



# Testing perforating productivity under downhole conditions



*Determining perforating performance on a real-world basis means simulating the downhole stress regime for a representative core.*

Perforating productivity testing under downhole conditions—replicating the perforating gun system including charges and the pressure dynamics of the well and reservoir—is necessary to investigate reservoir performance when perforated.

- Obtain core from your reservoir or an analog outcrop.
- Replicate the field gun system.
- Recreate the field well and reservoir pressure dynamics.
- Perforate the core.
- Replicate field shut-in and production procedure.
- Perform stimulation (acidizing) as needed.
- Measure perforation flow efficiency and expected well skin in the field.
- Obtain comparable results qualified to API RP 19B Section II and Section IV.



*Laboratory test results in rock are used to optimize your stimulation treatment or reservoir-drive injector with critical charge, fluid, and perforating gun design data that testing just in concrete targets cannot provide.*

# Evaluating performance to optimize reservoir recovery



*Perforating and flow tests at high-temperature conditions per API RP 19B Section IV quantify dynamic underbalance, depth of perforation, and skin.*

Simulating reservoir response and reservoir-to-wellbore interactions gives you a basis for optimizing your well productivity.

## **Match critical shot-time conditions**

- Understand wellbore dynamics to generate a productive tunnel and minimize shock.
- Establish pore fluid and core boundary conditions.

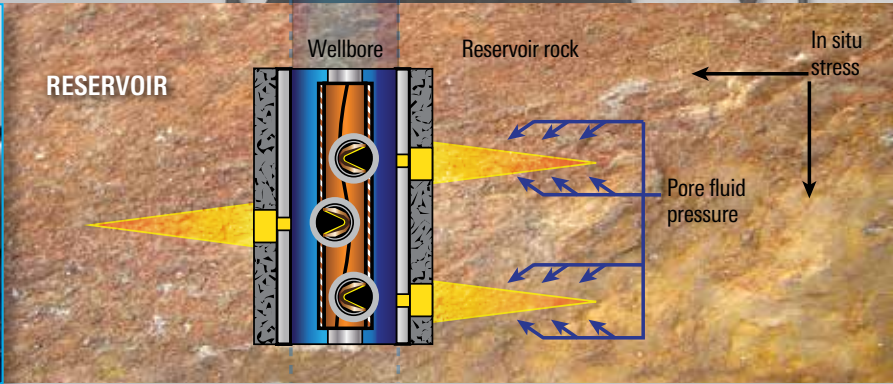
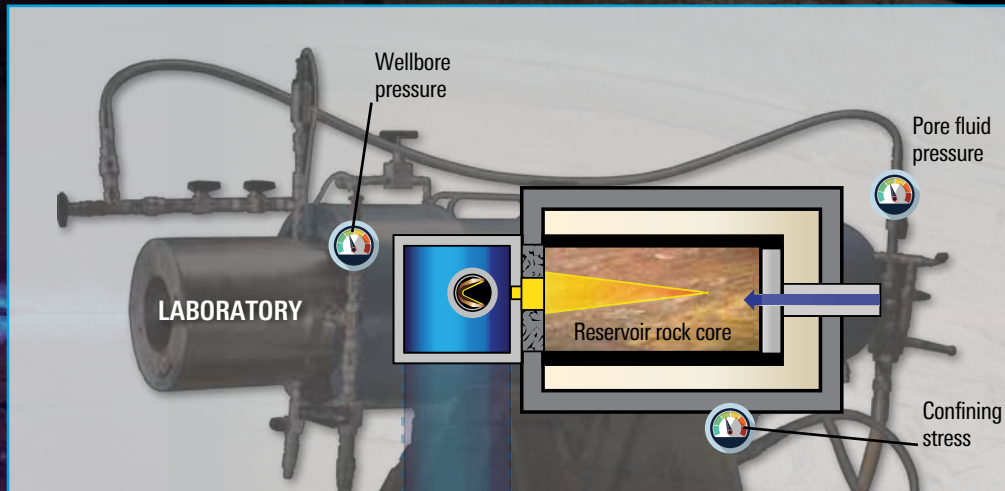
## **Match flow regime**

- Determine fluid and field rates.
- Assess flow efficiency (well skin, productivity index).
- Evaluate sanding propensity over the life of the well (depletion, stress, water cut).

## **Perform advanced diagnostic techniques**

- Measure rock mechanical properties.
- Visualize the reservoir fluid flow path.
- Optimize the perforation strategy.





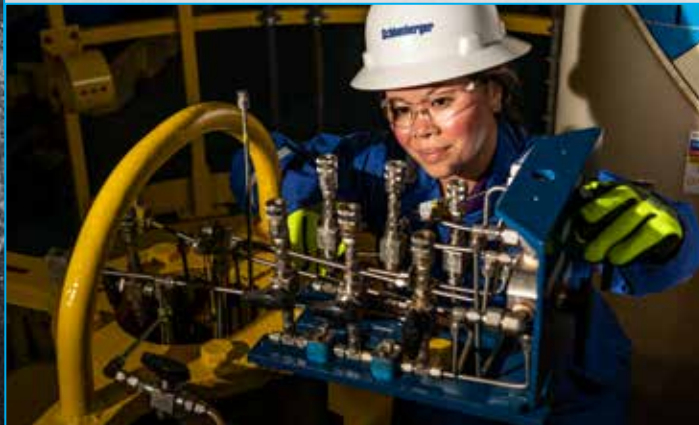
Section IV pressure vessel enables performing testing under extreme high-pressure and high-temperature conditions.

The advanced diagnostic techniques and analyses conducted at PERF in high-pressure and high-temperature downhole simulation vessels enable you to see damage mechanisms and visualize the path reservoir fluids take as they travel toward perforations. With this insight you can optimize your perforation strategy for maximum reservoir recovery.

# Investigating wellbore fluid and reservoir interactions using full-size core samples



*The continuous gas delivery system at PERF simulates gas flow rates up to 300 MMcf/d.*



- Drilling fluid damage to the reservoir
- Acidizing and stimulation
- Sand consolidation treatments
- Well control with nondamaging control fluids while perforating

## **From low-rate oil to high-rate gas, and everything between**

- Simulate production flow of oil or gas at realistic downhole rates for accurate system performance validation.
- Investigate water cut to understand how your reservoir responds to a spectrum of fluids and flow rates.
- Simulate a wide range of gas flow rates with continuous gas delivery.
- Replicate depletion stress, flow, and water cut to study if sanding may be a concern later in your well's life.

*Cores are prepared by saturating them prior to testing.*

# Testing perforating systems, 3D reservoir flow, and hydraulic fracturing with the industry's largest polyaxial stress frame

The PERF polyaxial stress frame is the industry's only system that can simulate the entire gun or downhole tools and their interactions with the wellbore and reservoir. It is essentially a well-controlled small-scale field test.

- Shoot a full perforating system.
- Simulate the downhole stress field with three independent stresses.
- Investigate gun, wellbore, 3D stress regime, reservoir, and perforation-to-perforation interactions.
- Document 3D stress effects on perforating, hydraulic fracture initiation, and propagation.
- Perform propellant perforating and fracturing.
- Simulate perforation clusters for unconventional resource development.

*The polyaxial stress frame easily accommodates large blocks of rock for testing at simulated 3D stress conditions and pore and wellbore pressures.*





*The industry's largest polyaxial stress frame makes it possible to test perforating systems from charge detonation through flowback and measure flow under realistic well conditions, including the stress field specific to your well for wellbore, pore, and vertical and horizontal stresses.*



### Small polyaxial stress frame for cost-effective scaled block tests

The small polyaxial stress frame enables conducting parametric studies based on scaling theory for a full perforating gun system in a 3D stress regime.

- Block dimensions, in: 18 × 18 × 18
- Three stresses, psi: 10,000
- Wellbore pressure, psi: 10,000

### Downhole simulation vessels

The laboratory is equipped with several high-pressure and high-temperature vessels with different capabilities to accommodate your specific perforating conditions.



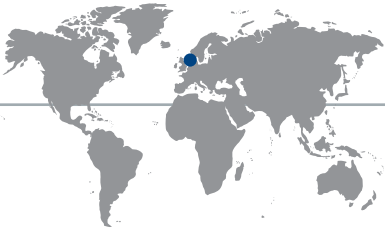
*Section IV testing can be conducted on a wide variety of core samples, such as this sandstone core sample.*



*Perforating system performance in a block of sandstone is captured in a polyaxial stress frame.*

	PV-93	PV-94	PV-550	PV-550
Core dimensions, in	7 × 18	7 × 36	10 × 36	10 × 36
Confining pressure, psi	10,000	10,000	40,000	50,000
Simulated wellbore pressure, psi	5,000	5,000	30,000	40,000
Pore and reservoir pressure, psi	5,000	5,000	30,000	40,000
Temperature, degF	Ambient	200	550	200

## Case Studies



### Engineered perforating system boosts productivity across 6,200 ft in offshore HPHT gas condensate wells



*The PowerJet Nova shaped charge is engineered to perform in stressed rock and HPHT environments.*

#### Formation damage limits production in hostile environment

An operator producing in an HPHT gas condensate field in the North Sea wanted to optimize well deliverability via an engineered perforating strategy. Existing high-temperature shaped charge technologies, however, have historically been unreliable in adequately bypassing drilling-induced damage.

The ideal approach would achieve reservoir contact, perforate long intervals, sufficiently bypass formation damage, and improve productivity index (PI) while remaining within strict safety and barrier requirements and minimizing skin.

The operator collaborated with Schlumberger at the Productivity Enhancement Research Facility (PERF) to develop and customize a solution that would meet the productivity objectives without compromising safety standards.

#### Customized perforating system bypasses damage

Focus was placed on enhancing penetration as well as optimizing wellbore dynamics by using underbalance to ensure clean perforations. SPAN Rock\* stressed-rock perforating analysis was used to calculate setup pressures for optimal cleanup and to predict expected shock loads on the bottomhole assembly and coiled tubing.

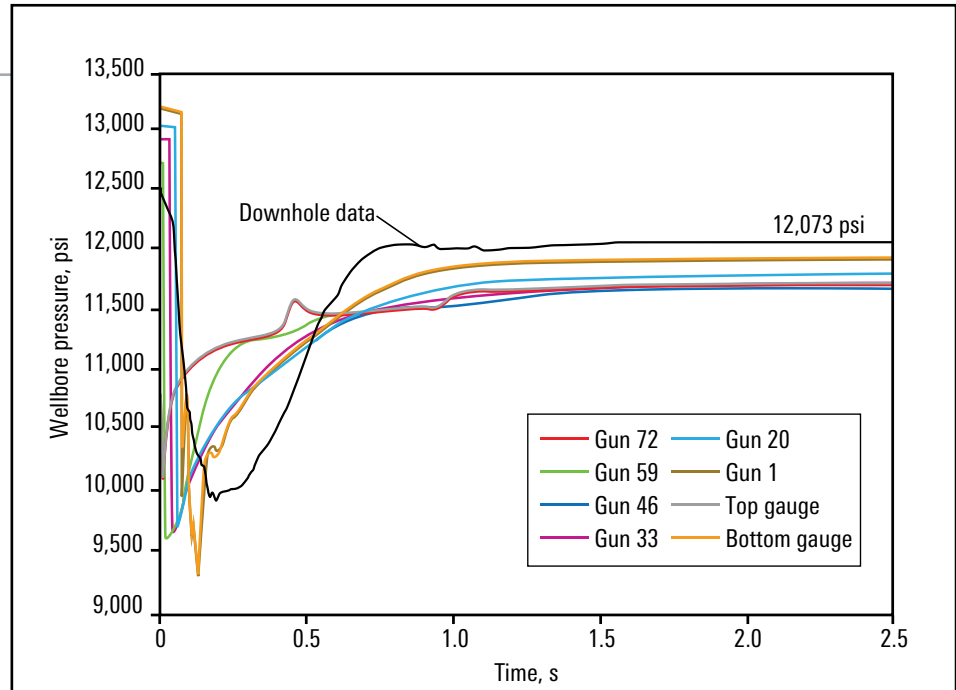
Evaluating the results of SPAN Rock analysis also determined that PowerJet Nova\* extradeep penetrating shaped charges would bypass the drilling damage. These high-temperature-rated charges improve penetration in stressed rock by 5% compared with previous-generation charges and provide up to 50% more formation contact.

High-speed pressure gauges positioned below the guns recovered downhole pressure data from each perforation run; results confirmed that SPAN Rock analysis accurately simulated the actual dynamic underbalance that was achieved at the perforations.

To remove the long gun strings from live wells with a potential 6,000-psi surface pressure, a lubricator valve and subsurface safety valve provided a dual barrier. A 5.125-in-ID CIRP\* completion insertion and removal under pressure system, complete with remotely activated 15,000-psi hydraulic gate valves installed above the tree, would ensure successful gun retrieval should the downhole barrier be compromised and surface pressure was present.

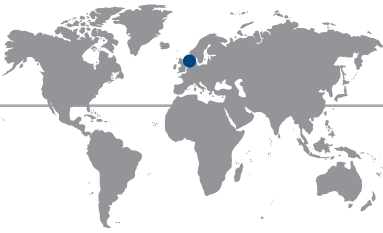
### PI is surpassed and skin minimized

Five wells were completed with a total 6,200 ft of perforating guns. Production data indicated that the PowerJet Nova charges bypassed drilling-induced damage while the dynamic underbalance delivered clean, lower-skin perforations.



*Downhole gauges confirmed that the measured peak dynamic underbalance correlated with the pressure simulated prejob through SPAN Rock analysis. The rapid drop in pressure removed skin damage, creating cleaner perforating and improving the productivity index.*

## Case Studies



**“Testing conducted in the PERF laboratory helped achieve high well productivity after overbalanced perforating.”**

**Statoil**

## Advanced testing and completion fluid development improve operational safety and well performance

**In-depth design and testing of a customized completion fluid and unique perforation strategy enable Statoil, now Equinor, to optimize well productivity in the North Sea**

### **Optimize perforation performance in overbalance environments**

To perforate long horizontal North Sea wells, Statoil sought a safer, more efficient technique that would not compromise well performance in the process. An overbalanced shoot-and-pull technique using conventional completion fluids would have resulted in unclean perforations, leaving the operator with low productivity. However, with a completion fluid customized to meet specific reservoir needs, Statoil could continue using the shoot-and-pull technique while obtaining optimal productivity.

### **Design field-specific technique and fluid**

To address Statoil’s specific needs in this North Sea scenario, a custom completion fluid was designed with the operator’s reservoir characteristics in mind. Additionally, a proposed perforating system and dynamic underbalance technique were designed and tested to further optimize production.

Both the fluid and the technique were evaluated at the Productivity Enhancement Research Facility (PERF) near Houston using the same perforating gun technology and dynamic underbalance that were used in the field. Prior to deployment, studies from the PERF laboratory demonstrated that the combination of a customized perforating strategy and fluid system could deliver superior well performance in challenging conditions.



## Enhance productivity and efficiency

After efficiently perforating several wells in its program with the proven, optimized technique developed at PERF, Statoil recorded excellent productivity in the field. According to the operator, the development of a unique perforating fluid designed specifically for long horizontal wells played an important role in the overall perforating strategy. In addition to improving the productivity of Statoil's completions program, the customized fluid and dynamic underbalanced perforating technique contributed to the cost-effective operation.



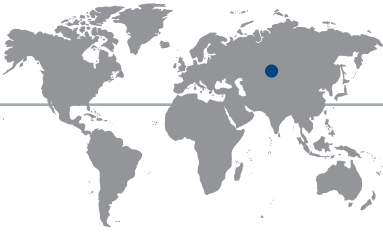
*Statoil was able to enhance production in long horizontal North Sea wells with a customized completion fluid and dynamic underbalance technique that were proved through laboratory testing prior to field deployment.*

Additional reading:

Chang, F.F., Kageson-Loe, N.M., Walton, I.C., Mathisen, A.M., and Svanes, G.S., "Perforating in Overbalance—Is it Really Sinful?" SPE paper 82203, presented at the SPE European Formation Damage Conference, 13–14 May, The Hague, Netherlands, 2003.

Chang, F.F., Mathisen, A.M., Kageson-Loe, N., Walton, I.C., Svane, G., Midtbo, R.E., Bakken, I., Rykkje, J., and Nedreba, O., "Recommended Practice for Overbalanced Perforating in Long Horizontal Wells," SPE paper 94596, presented at the SPE European Formation Damage Conference, 25–27 May, Shevingen, The Netherlands, 2005.

## Case Studies



### Multistage perforation enables 300% production increase in an ultradeep HPHT gas well

#### **Multiple factors impede effective production**

An HPHT gas field in the northern portion of China's onshore Tarim Basin lies in a tight sand reservoir at a depth of 6,000–7,500 m [19,685–24,606 ft] with pressures from 15,229 to 20,305 psi and temperatures up to 170 degC. With high compressive strength (17,405 psi), low porosity (5%–8%), and low permeability (<10 mD), most wells in the reservoir require stimulation to improve productivity.

#### **Stimulation concept verified by laboratory modeling**

To overcome challenging reservoir conditions, PetroChina and Schlumberger used the stimulated reservoir volume (SRV) concept. In this new method, multiple short clusters are perforated throughout the entire reservoir section and large volumes of slickwater (low proppant

concentrations) are pumped at a high rate with fibers for diversion. A wireline-conveyed 2.25-in perforator using 15,000-psi pressure control equipment was selected to accommodate a 68-mm [2.68-in] restriction in the downhole safety valve and operate in the completion of 4½-in tubing and a packer set above the pay zone, which is lined with 5½-in high-strength TP140V casing (12.09-mm [0.48-in] wall thickness).

Because perforation entrance hole size and penetration depth are critical, particularly with the relatively small perforating gun for the casing size, a two-step laboratory program was designed and executed at the Productivity Enhancement Research Facility (PERF). First, screening tests assessed perforation hole diameter in the casing at ambient surface conditions. Then, two laboratory

tests were conducted at downhole pressure and temperature to confirm perforation casing hole diameter and penetration depth into a stressed sandstone core. The results indicated that perforation performance at downhole conditions would enable successful stimulation operations and confirmed predictions made with SPAN Rock analysis.

### Production increased threefold following perforation

The perforation operation was conducted successfully in a total of three runs made using an addressable-switch firing system with 12 guns (six stages total). The multistage stimulation was then executed and resulted in a 300% production rate increase for the well compared with PetroChina's nearby wells.

#### Laboratory Testing Results

Test Number	Core ID	Core Average UCS, psi	Gun-to-Casing Clearance, in	Casing Hole Diameter, in	Residual Rock Penetration Depth, in
Test 1	NG7-17	14,718	0	0.22 × 0.24	3.7
Test 2	NG7-16	14,981	2.302	0.13 × 0.13	2.4



Comparison of split core and casing assembly from 0°-phased test 1 (top) and 180°-phased test 2 (bottom) illustrates the more than 50% improvement achieved in penetration depth.

# Productivity Enhancement Research Facility (PERF)



[slb.com/perforating](http://slb.com/perforating)

\*Mark of Schlumberger  
Other company, product, and service names are the properties of their respective owners.  
Copyright © 2019 Schlumberger. All rights reserved. 19-PE-523963

# Schlumberger