Advances in Perforating Technology Continue

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Perforations represent the critical link between the wellbore and reservoir in cased wells and, thus, have a significant impact on well productivity and ultimate recovery. Important advances have been made in the past several years in the technology of perforation through the incorporation of reactive materials into oilfield shaped charges and through the advancement of stressed-rock testing of charge systems, as opposed to testing performed in cement. A new and potentially powerful extension to stressed-rock testing is the use of 3D digital-imaging technology and advanced analytical methods.

The advances being achieved in perforating appear likely to play a vital role in meeting the challenges of maximizing the productivity and recovery of wells drilled in the hard, low-permeability rock increasingly being targeted by the drill bit today. And although not yet exploited commercially, the capability already exists to design charges for application in specific lithologies, possibly even individual formations.

Testing Under More Realistic Conditions

In practical terms, penetration into cement under surface conditions is an unreliable indicator of the performance that can be expected when charges are shot under real, downhole conditions. Stressed rock does not behave like unconfined cement. More specifically, the new reservoirs of the 21st century—such as hard, subsalt carbonates or shales with nanodarcy permeability—are fundamentally different, and several orders of magnitude more difficult to understand than the sandstones on which predictive correlations from cement penetration to rock penetration were based (Behrmann et al. 2009). New science and products have been needed to complete wells effectively in these environments.

The first step toward developing solutions for such environments was the construction of perforator-evaluation facilities in which shaped-charge systems could be tested under conditions more closely representing the wellbore and reservoir (API RP 19B 2006). In this type of facility, frequently referred to as a flow lab, natural-rock targets are subjected to realistic levels of effective stress, while wellbore and pore pressures are accurately simulated to create appropriate static and dynamic pressure effects. If these tests are designed and executed successfully, they can provide a whole new level of insight into how effectively a particular perforating system will connect a wellbore to its target formation. It is fair to say that only the handful of companies that have invested in such flow-lab facilities are uncovering perforating solutions suitable for the increasingly complex reservoirs that will be the industry's focus in the years ahead.

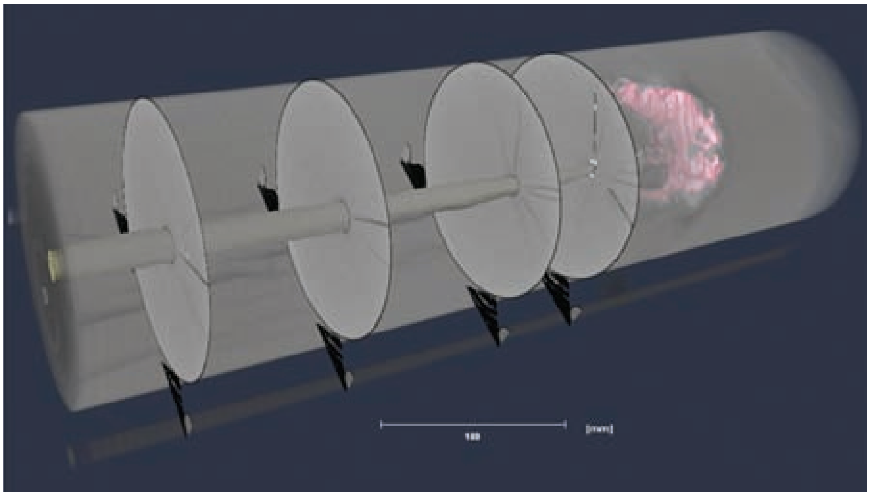

Fig. 1—A processed macro CT image showing sample points for micro CT analysis.

Technology Developed Through Stressed-Rock Testing

The first shaped-charge product line that was developed from the ground up using stressed-rock targets was the CONNEX system launched by Geodynamics in 2007 (*JPT* 2007). This charge system incorporates a reactive liner, which creates a secondary reaction within each perforation tunnel only microseconds after it has been formed. This effect breaks up and expels compacted debris and crushed rock from the tunnel, resulting in a much more effective connection to the formation but without depending on traditional cleanup methods driven by underbalance. Reactive materials have been used in military ballistics systems for more than 2 decades. This was the first system to use reactive materials in shaped charges designed for oilfield perforating applications.

The system has now been used by more than 50 operators in a broad range of well types, with applications ranging from mature-well recompletions to prehydrofrac perforation of unconventional gas wells, and many

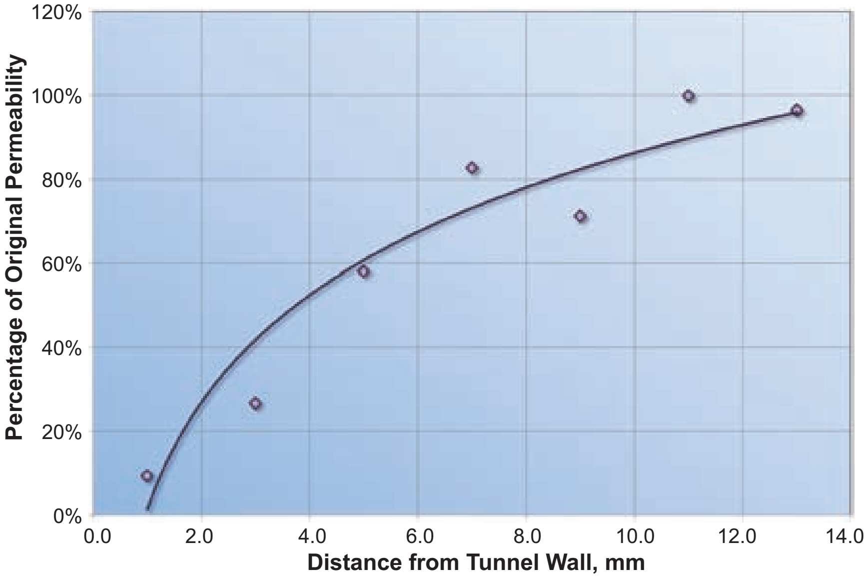

Fig. 2—An example of a permeability profile plotted from the perforation tunnel wall to undamaged rock.

other perforating operations (Bell et al. 2009). Benefits have included increased well productivity and the elimination of rig time and expense required to create underbalanced perforating conditions. A number of operators have been able to lower stimulation pressures dramatically, increasing the effectiveness and reliability of their treatments (Bell and Cuthill 2008). Some operators have been able to treat zones previously considered untreatable.

R&D to improve the effectiveness of perforating systems continues. Under one project, carbonate rocks perforated with both conventional and reactive charges are being acidized and analyzed at a major US university. The study, which involves computed tomography (CT) scanning of the cores before and after stimulation, is casting new light on the influence that perforation geometry and quality can have on the effectiveness of acid stimulation. By gaining a deeper understanding of these phenomena, scientists will be better able to develop perforating systems specifically optimized for carbonate formations and acid stimulation.

Digital Rock Physics Provides New Understanding

Another cutting-edge project involves the detailed study of damage mechanisms within and around the perforation tunnel. Recently developed techniques in micro CT scanning are being applied by Ingrain, a Houston-based digital rock-physics laboratory company, in conjunction with Geodynamics.

Permeability is traditionally measured in the laboratory on regularly shaped rock samples by forcing a fluid through the rock and recording the resulting fluid flux and pressure drops. This technique is almost impossible to apply on the small-scale, irregular surface of a perforation tunnel. Because physical measurements of rock properties can be difficult to perform and are slow to obtain, costs are high, turnaround time is lengthy, and the measurements themselves are usually sparse. Digital rock physics offers a way for obtaining rock properties from a much greater number of samples.

By using advanced micro- and nanoscale CT scanning techniques, and through the processing and segmentation of the resulting images, high-resolution 3D digital representations of the pore-space geometry and grain structure—called vRocks—can be created. These are fed into fluid-dynamics and rock-physics computational engines, by which the properties of the original rock samples are determined. This approach can provide information about the porosity, permeability, resistivity, and elastic properties of the rock sample. These measurements are integrated into a single procedure, increasing the quality and the quantity of reservoir-rock information.

A number of patents developed at Stanford University are under exclusive license to Ingrain. In connection with this, company geoscientists, mathematicians, and software engineers have created algorithms for computing rock properties from 3D images. Included in this body of work is a multiphase lattice Boltzmann methodology (LBM) that incorporates fluid-flow properties as parameters in the computation. Simulations are made of fluid flow through the digitally captured rock sample. Rather than using simplified models, access to on-demand supercomputing clusters is maintained, and their use accelerates processing time.

By numerically simulating fluid flow through a direct digital representation of the real pore space, analyses can be readily performed on samples of irregular shape and size that would be impossible to handle in the physical laboratory. Furthermore, the 3D representations are entirely reusable, enabling multiple "what if?" analyses under varying reservoir conditions.

The slow viscous flow needed for permeability estimates is simulated using the LBM. The methodology mathematically mimics the Navier-Stokes equations of viscous flow by treating the fluid as a set of particles with certain interaction rules. The advantage of this approach over directly solving flow equations is that it directly handles the boundary conditions of a complex realistic pore surface. Absolute permeability is computed in a manner analogous to a laboratory measurement: a pressure head or body force is directly applied to a digital sample. The resulting fluid flux is then computed, and permeability is calculated according to Darcy's equation.

Rock cores perforated in the flow lab are being analyzed with the aid of CT scanning. Each core first is prescreened by conventional macro CT scanning techniques to record overall perforation geometry and identify any local rock anomalies that might prejudice subsequent detailed measurements. Pencil-sized samples are then obtained by sectioning the core perpendicular to the tunnel at a series of points along its length. Sample points within both clean and obstructed tunnel sections are selected, on the basis of the macro CT image **(Fig. 1)** to compare and contrast tunnel-wall properties in each zone.

These samples then undergo a patented micro CT scanning process, where minutely detailed virtual rock images (vRocks) are created by integrating a series of scans through the sample. In the case under discussion, each virtual rock image is only a few millimeters in cross-section but may extend several centimeters away from the tunnel wall. Using advanced analytical techniques, the virtual image can be decomposed into rock fabric and pore space, and the local grain-size distribution, porosity, and polyaxial permeabilities can be determined. By plotting these parameters at intervals away from the wellbore until properties consistent with the undamaged rock are observed, a detailed description of the damage profile surrounding each perforation tunnel can be built **(Fig. 2).**

This work (unpublished) represents the first time that a measurement of near-tunnel permeability has been reliably obtained. Earlier efforts to do so involved either impregnating the sample with resin, cutting thin-section samples and visually estimating permeability under a microscope, or attempting to determine the local permeability directly by means of a micropermeameter and measurement of fluid flow and pressure (Behrmann et al. 1991; Asadi and Preston 1994; and Heiland et al. 2009). These techniques were laborious and prone to significant uncertainty and experimental error. The new method allows multiple samples to be analyzed with ease and can be calibrated by cutting and analyzing samples in undamaged rock away from the tunnel, with the results compared to macro measurements made on whole core. While the technique is still experimental, it will continue to be refined as a potentially useful tool for designing, evaluating, and optimizing shaped charges.

Once a more complete understanding has been built of the relatively well-understood damage mechanisms occurring in sandstones, plans call for extension of this work to other lithologies. To date, very little is known about perforation damage in carbonates, shales, and other unconventional reservoir rocks. Much more may yet be learned through the technology-development process that has recently been established.

Looking Ahead

While the timetable for developing effective new perforating systems cannot be certain, it is likely that future generations of shaped-charge perforators will be tailored toward particular lithologies and perhaps even to specific formations. Rather than deploying a one-size-fits-all charge that has been optimized to shoot deep into unconfined cement, operators will be able to select a product optimized for the rock properties—the hard sandstone, soft chalk, or plastic shale—that the detonation will penetrate. **JPT**

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