

Proppants Open Production Pathways

From sand to ceramics and beyond, specially designed proppants provide economic advantages.

By Don Lyle, Contributing Editor

As operators tap tighter formations from sands to shales, improved proppant characteristics and techniques in placement help them reach vast quantities of oil and gas previously beyond the scope of oilpatch technology.

Producers realized early in industry history that the greater the formation surface exposed to the well bore, the greater the production. They started with large numbers of wells and delved briefly into mechanically directed horizontal wells, but fractures that reached far into formations surpassed economic production potential of both systems.

Horizontal wells crossing natural fractures in formations such as the Austin Chalk and Bakken Shale shared the limelight, but hydraulic fracturing still held the top spot for improving production in a wide variety of applications.

The role of proppants

As drilling completion technology advanced, horizontal wells with multistage fracture treatments moved to the top of the completion technology ladder, and operators looked for still better ways of making fracture treatments produce more at a lower overall cost. The key to those gains in economic conductivity often lies in the proppants the operator chooses.

“We start with the closure stress that proppant will be subjected to and our desired conductivity at that stress,” said Tim Beard, engineering advisor, completions, in Chesapeake Energy Corp.’s Engineering Technology Group. That group conducts more reservoir analysis than the rest of the industry combined as the parent company maintains its position as the most active driller of new wells in the US and its leadership position in the Barnett, Fayetteville, Haynesville, Marcellus, and Bossier gas shales and in liquids-rich unconventional plays such as the Eagle Ford and Granite Wash.

“A high closure stress and a proppant not capable of handling that stress leads to crushing and fines generation,” Beard said.

Proppant that crushes under formation pressure either allows the fracture to close or produces fines that reduce hydrocarbon flow.

According to SPE by Coulter, et al., a 5% generation of fines reduces flow through fractures by 60%. That laboratory test used only 60/100 mesh sand fines mixed into 20/40 Brady sand at 3,500 psi.

Crush resistance is just the start of the analysis that leads to the final selection of proppant combinations that could include:

- Brady (brown) sand;
- Ottawa (white) sand;



- Lightweight, intermediate, and high-density (bauxite) ceramics;
- Pre-cured resin-coated sand;
- Curable resin-coated sand; and
- Newer proppants that combine light weight and high strength through the use of nano-structuring.

Chesapeake also analyzes rock properties, but that has more to do with the selection of frac fluids than proppant, Beard said. It also shows the potential for proppants to embed in softer rock. Embedment potential deals with the proppant and concentration of the proppant pack and the ability of the proppant to resist sinking into the fracture walls.

Spherical proppant typically handles higher stress better than non-spherical sands, and smaller proppants tend to spread farther into the fractures, he added. It also provides superior conductivity.

Curable resin-coated sands, which form a consolidated pack at a determined temperature and pressure, can resist proppant flowback to the well bore.

In a liquids well, the company typically looks at bigger and stronger proppants to maximize conductivity.

Chesapeake rarely uses Brady sand, Beard said, since it crushes more easily than other proppants, but if the company cannot get its ideal selection, it might choose Brady in low-closure-pressure reservoirs. It also pumps curable resins in some reservoirs, including the Barnett, for flowback control.

The 'ideal' proppant

Some have said the ideal proppant is lighter than water, stronger than diamonds, and cheaper than dirt. In short, it does not exist. At the same time, different formations have different ideals, particularly when economics enter the picture.

In the Haynesville Shale, Chesapeake wants a low specific-gravity proppant with high strength to flow deep into fractures with a slickwater frac and still hold the fracture open under high pressure.

The company uses Ottawa sand more than any other proppant. Ottawa sand is more spherical and more crush-resistant than Brady sand, and it is less expensive than ceramics or resin-coated sands.

The company has looked at the newer nano-structured proppants, Beard added, but "It looks to be fairly cost prohibitive."

Industry presentations offer proof that proppant selection can be complex and operators too often use selection techniques that lead to inferior results.

Mike Vincent, an independent consultant who specializes in fracturing optimization and training, said, "There are some situations in which both our intuition and our mathematical tools have led us astray. For instance, it is intuitive to believe that any propped fracture would be infinitely more conductive than the microDarcy or nanoDarcy rock it penetrates. Our industry has constructed both analytical solutions and

numerical simulators that can reinforce and 'validate' that mistake. However, what many fail to contemplate is the relative proportions of fractures. They are truly massive in length, often reaching hundreds or even thousands of feet laterally from the well bore, but they are very narrow sheets, typically less than 0.01 ft wide."

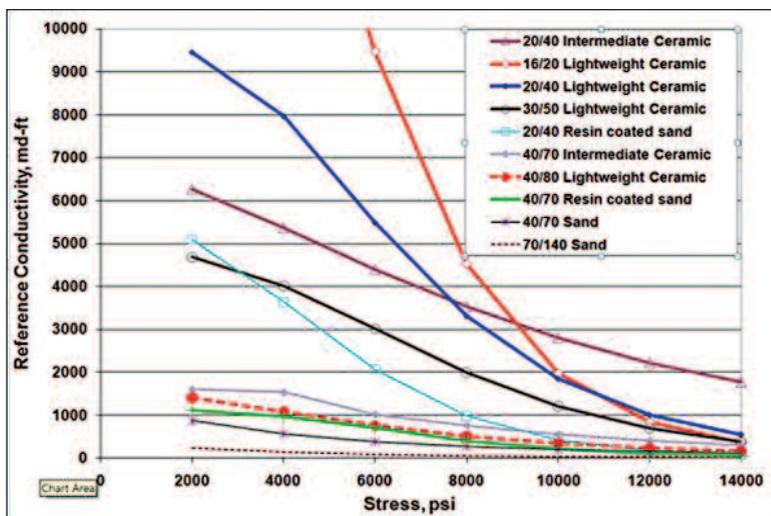
Fractures gather hydrocarbons over an enormous surface area, but the area of intersection with the well bore typically is restricted, and in many completions, molecules of oil or gas must travel a million times faster in the proppant pack than in the formation rock. "Darcy's Law doesn't work in this flow regime; instead, pressure losses are actually proportional to the square of velocity," Vincent said.

"Pressure losses within propped fracs are almost always important and should be considered. We make similar mistakes when we implicitly assume fractures are simple vertical planes with uniform and durable conductivity throughout. The field production results should convince us that our simplified assumptions need to be improved," he added.

Further, he said, "Optimizing a fracture design involves balancing the investment in higher-quality proppants with the increased production and higher EUR [estimated ultimate recovery] achieved when the pressure losses are reduced."

The American Petroleum Institute (API) established procedures for standardized crush tests in the 1980s, but even then it said the procedures were not designed to provide absolute values of proppant conductivity under reservoir conditions and that elevated temperatures, fracturing fluid residues, embedment, and fines could reduce conductivity by 90% or more.

Actually, according to a graph presented by Vincent in the Society of Petroleum Engineers (SPE) Paper 119143 "Examining Our Assumptions – Have Oversimplifications Jeopardized



Downhole conditions can cut fracture conductivity by more than 99% compared with API standardized conductivity tests. All proppants were 20/40 sieve at 6,000 psi closure stress. (Graphic by Mike Vincent, used with permission from SPE Paper 119143)

Proppants

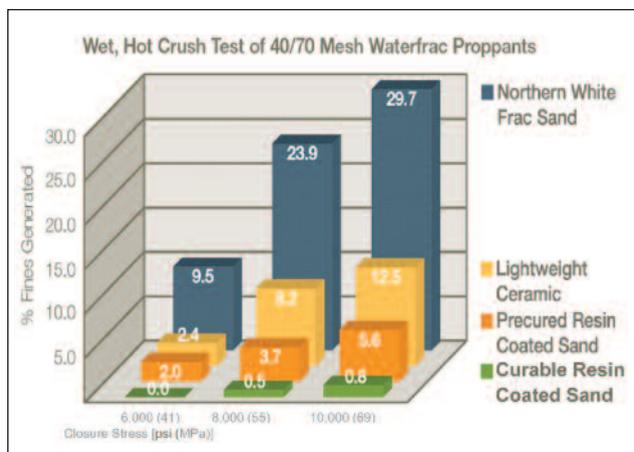
Our Ability of Design Optimal Fracture Treatments?” he demonstrated that a 50-hour test, non-Darcy effects, lower achieved fracture widths, multiphase flow, gel damage, fines migration, and cyclical stress could reduce effective conductivity by 99.9% with low-quality sand, 99.7% with best quality Ottawa sand, and 98.6% with premium lightweight ceramic proppants, compared with the API test.

“There have been many industry attempts to describe proppant based on median particle diameter, particle specific gravity, or measured crush in a wide variety of conditions. In my opinion, those parameters are interesting but woefully inadequate to select proppant,” Vincent said. “It’s like using tire diameter, crash rating, and engine-block density to buy a car,” he added.

The number of re-fracture treatments being conducted further indicates the original frac jobs were not adequate.

“The best way to examine performance of the proppant is to conduct an actual flow test under realistic conditions, directly measuring the conductivity in a manner that can incorporate elevated temperatures, stress cycling, fines migration, realistic fluid velocities, and any other conditions that may be unique to your reservoir,” he said.

Stronger than diamonds, light as water, and cheaper than dirt does not quite reach the qualifications for the holy grail of proppants, Vincent said. Proppant also must be transportable into the fracture, compatible with frac and wellbore fluids, allow acceptable cleanup of frac fluids, and resist flowback. It also must be thermally stable, chemically inert, environmentally benign, safe, and readily available in adequate quantities. However, he added, “The primary requirements of a fracture are to contact the reservoir and to maintain a durable connection which provides acceptable pressure losses. So, the technical merits are most concisely described in terms of realistic conductivity.”



In a wet, hot crush comparison test of 40/70 mesh waterfrac proppants, Momentive’s Prime Plus curable resin-coated sand generated fewer fines than Northern White sand, economy lightweight ceramic, or tempered resin-coated sand and at different closure pressures. (Graphic courtesy of Momentive)

Improving proppants

Worldwide, the current proppant market is approximately 17 billion lb/year, and more than 99% of that supply is met with sand, resin-coated sands, and ceramic proppant. Numerous other materials injected into wells during the past 40 years have not reached more than 1% of the proppant market. Vincent added that although no other product has reached a 1% market share to date, the continuing efforts to improve proppants and fracture conductivity promises better recoveries for operators in the future.

The SPE Paper 135502, “Proppant Selection and its Effect on the Results of Fracturing Treatments Performed in Shale Formations,” was written by John Terracina, fracturing technology manager, with co-authors J.M. Turner, D.H. Collins, and S.E. Spillars, along with all of Momentive, formerly Hexion, the world’s largest supplier of specialty proppants. This landmark paper examined a more thorough technique of screening proppants than the industry standard long-term baseline conductivity laboratory test.

API tests for fines measurement do not simulate the wet, hot conditions in real fractures. Those factors significantly increase proppant failure.

The company’s own wet, hot crush test yielded more accurate results. The test found curable resin-coated sands resisted fines generation and breakdown from cyclic stress. Curable resin coated sand was also found to resist proppant embedment, proppant flowback and rearrangement, and proppant scaling, all of which result in decreased effective conductivity.

The resin coating protects proppant grains from stress and scaling. As the resin cures under fracture conditions, the particles bond together to resist embedment and control proppant pack rearrangement and flowback that can reduce conductivity and damage down-hole and topside equipment, Terracina said.

Examples in the paper showed improvements in groups of wells in the Fayetteville, Bakken, and Haynesville shales, comparing curable resin-coated sands with uncoated sands and ceramics.

A white paper titled “Using Long-Term Conductivity Tests to Differentiate Proppants,” written by Hexion before it combined with Momentive in October 2010, said, “With the growth of proppant choices, it has become increasingly difficult to determine if one proppant is superior to another or whether they are, in fact, interchangeable. This analysis becomes particularly important at times in which proppant suppliers are struggling to meet demand.”

Many companies have relied on performance from an independent testing facility and the long-term conductivity test that combines temperature, stress, and time.

That is acceptable, the paper said, as long as the test procedures are identical, including the size of the database, sample gradation/sieve distribution, and test duration.

In the case of the database, it said, nine test runs of pre-cured resin-coated proppant showed a performance variation of plus or minus 25% from the average. In sample gradation, generally larger-sized proppant provides more conductivity than smaller sizes. If a vendor

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offers acceptable performance characteristics for a sample, an operator should make sure the delivered proppant matches the sample. The operator also should ensure all performance results occur under equal testing times, usually 50 hours at each closure stress.

Better Conductivity

In general, published reports have reported better conductivity from high concentrations of quality proppant, but some have argued the best solution could lie in the opposite direction.

If proppant selection is complex, so is proppant placement. Some people in the industry consider a partial monolayer concept ideal in terms of conductivity and cost. A successful partial monolayer job would lay in just enough proppant to hold the fracture open with a single layer while leaving open spaces between proppant particles to allow maximum product flow.

Baker Hughes reached for the partial monolayer ideal, according to Ray Starks II, senior applied engineer of fracturing technology.

The company's LiteProp 108, a heat-treated thermostet nano-composite, has a specific gravity of 1.056 times the specific gravity of water. It is ultra-lightweight and transportable, but strong enough for harsh environments, he said.

Before ultra-lightweight proppants, Starks said, operators typically had to drop to 40/70 mesh proppant to reach far into fractures instead of the more standard 20/40 mesh.

Lightweight proppant is particularly important, he added, since injection rates start at 17 ft/minute.ft/minute at 300 ft).

"You need 8.1 ft/minute to transport 20/40 sand and 1.9 ft/minute for 40/80 lightweight ceramic. LiteProp 108 requires only 0.04 ft/minute in a 40/100 mesh," he added.

A partial monolayer treatment requires as little as 0.1 lb/sq ft of proppant for a half-monolayer where a similar multilevel heavier proppant pack might need 4 lb/sq ft. A BJ Services paper (SPE Paper 1291), written before the company became part of Baker Hughes, showed a partial monolayer would outperform a proppant pack 10 to 12 layers thick.

Ultra-light weight allows the company to deliver the proppant in a pre-mixed VaporFrac slurry – a mixture of ultra-lightweight proppant and nitrogen or CO₂ with a little water to create a foam. For the operator, that means no post-frac cleanup, no water disposal cost, no frac tank rental, no sand hauler, and no proportioning unit. Those are big savings when proppant costs can range from 20% of the total frac cost for a small treatment to half the cost of a large treatment.

The partial monolayer concept is just that, a concept. Because of the complexity of fractures, fluids, pressures, proppant, and a host of other factors that come into play, most industry experts believe it is impossible to achieve a uniform partial monolayer throughout a propped fracture.

"The problem with the concept is that, because of the small number of particles needed for maximum flow, the proppant particles must be really, really strong," said Mark Parker, technology manager with Halliburton's Pinnacle Technologies.

"It's difficult to achieve. The particles can embed, crush, and deform," added Dave Allison, tenet manager with Halliburton's Production Enhancement Group.

Halliburton developed MonoProp, a low-density, strong proppant. Its low density, 1.08, allows even a slickwater frac to transport proppant deep into the fracture system and prevent premature settling. For contrast, the specific gravity of sand is about 2.65. Depending on fracture conditions, Allison said, MonoProp can be effective with concentrations in the fracture at 0.1 lb/sq ft and lower.

With a controlled release of fluids in the fractures, an operator can avoid losing proppant as the fluid flows back to the well bore.

MonoProp, a thermoplastic alloy, is effective in temperatures less than 200°F and formation closure pressures less than 8,000 psi. That should cover 80% to 90% of the requirements of fracturing in the oilpatch, Parker said. There is some overlap with natural sands, but sands are more likely to generate fines, Allison added.

Computer models in the MonoSim program also can predict how well the proppant will perform under given temperature and pressure conditions, and a tailored slurry can optimize delivery.

A partial monolayer treatment requires a high level of testing by the operator. For example, if softer formations allow proppant par-



Field crews add ceramic proppant to a hydraulic fracture in the deep, hot Haynesville Formation. (Photo courtesy of CARBO)

ticles to embed, a fracture could close on a single layer of proppant, according to Terracina. Multiple proppant layers would hold the fracture open and maintain conductivity.

Proppant selection

Proppant selection can make a big difference. A Haynesville field study of 16 wells compared a lightweight ceramic with Momentive's Prime Plus curable resin-coated sand. The Prime Plus wells produced an average of 26% higher cumulative gas production than the lightweight ceramic wells over a seven-month period.

Operators always seek ways to improve fracture treatments, including proppant behavior in the fracture. Momentive's predecessor introduced the industry's first non-radioactive tag, PropTrac, an environmentally acceptable material added to the coating of resin-coated proppant.

With PropTrac in the fracture, a gamma spectroscopy logging tool and a fast neutron source temporarily activates the tagging additive. That identifies the presence of the proppant and can reveal fracture width and height. That helps the operator design better fractures in following treatments. Since it has no radioactive half life, the tag can be activated at any time during the life of the well, Terracina said.

The company started a new production line for resin-coated sand at its Cleburne, Texas, plant and planned an expansion at its Brady, Texas, plant.

Service and supply companies continue to introduce innovative products with the potential to improve production.

Oxane Materials Inc. is another company pushing advantages of nano-structured proppants. In an August 2010 *E&P* article, Chris Coker and Steve Thompson with Oxane said their OxFrac has a specific gravity of 2 in a 40/70 mesh and shows better conductivity than sand in a formation with closure pressure to 6,500 psi and 2.2 in a 20/40 mesh size with better conductivity than sand at closure pressures to 8,000 psi.

The company's OxBall proppant offers Darcy conductivity comparable to intermediate strength ceramic proppants through 10,000 psi for 40/70 mesh and 12,000 psi for 20/40 mesh. Oxane expected operators to use its proppants for 20% to 30% of the job and other proppants for the remainder.

Coker and Thompson said the lightweight proppants will lessen proppant density and allow lighter fluids and lower pumping rates, reducing costs and environmental impact for that portion of the job in which the operator uses lighter proppants.

Santrol, a division of Fairmount Minerals, produces Ottawa and Jordan sands, but its technical resources are heavily focused on resin-coating technology, according to Tim McMillin, director of market development.

Scott Greenbauer, technical sales engineer, added that the market is changing. Horizontal wells in the major shale plays, particularly the liquids-rich plays, are driving the proppants markets now.

Their company has seen the higher demand for resin-coated proppants in the industry, and it is expanding its production capacity, both in sand mining and in resin-coating capability, over the next 18 months.

Santrol also recently released a new proppant, PowerProp, designed to compete with lightweight ceramic proppants. In laboratory tests conducted by Stimlab, this resin-coated proppant achieved excellent conductivity and permeability results at closure stresses up to 14,000 psi. The company did not detail conductivity at that stress level.

According to McMillin, the multicoat technology and resin chemistry provide stronger bonds compared to traditional coatings. This allows PowerProp to withstand higher closure stresses while maintaining conductivity and permeability. Normal resins catastrophically fail at peak stress, he said, but this resin maintains structural integrity longer.

CARBO senior staff engineer Terry Palisch said ceramic proppants were developed in the late 1970s when Claude Cooke with Exxon looked for a proppant stronger than sand. That led to the first bauxite ceramic proppant and its benefits of higher strength for deeper, hotter formations.

The development of intermediate and lightweight ceramics followed as the industry realized the benefits of a uniformly sized, spherically shaped, crush-resistant manmade proppants.

"The best way to identify the appropriate proppant is to determine the conductivity of the proppant under realistic conditions. The benefits of increasing the conductivity of the fracture (better production, higher EUR) can then be compared to the required investment, and the solution which provides the greatest rate of return for your investment will be preferred. We call this the Economic Conductivity proposal," Palisch said.

Proppant performance can be enhanced by additional elements. For example, CARBOTAG is a traceable proppant that, if it comes back up the well bore, can be analyzed to identify a well (offshore) or completions (onshore multistage fractures) that failed. CARBONRT is a newly introduced non-radioactive tracer that can help measure fracture height and proppant location. CARBOBond is a curable resin that can be applied to any of the company's proppants to eliminate proppant production in reservoirs prone to flowback of frac sand.

Like other companies, CARBO is expanding. It plans to increase ceramic proppant manufacturing capacity by 40% in the next 12 months with new production lines at its Toombsboro, Ga., plant. That will bring total production capacity to 1.75 billion lb/year.

Schlumberger, recognizing that hydrodynamic drag forces are intimately linked to the proppant pack pore structure, created the means to generate pore structures that are intrinsically more effective at conducting fluids. The HiWAY* flow-channel fracturing service allows for the heterogeneous placement of proppants into the fracture, such that produced fluids flow through wide-open channels that traverse the fracture. The channels are supported by agglomerations of proppant.

The means of creating the fracture channels involves a sophisticated combination of geomechanical modeling, perforation design, and engineering placement technique to correctly size and position proppant agglomerants and the resulting flow channels. Because the wide-open flow channels provide the pathways for the

Proppants

produced fluids in the HiWAY technique, the materials comprising the proppant agglomerations do not themselves create high permeability packed beds, as is required of conventional proppant in conventional propped fractures. HiWAY proppant does require certain engineered properties, but the HiWAY technique has resulted in a decoupling of the fracture performance from proppant pack permeability.

This service is currently focused on tight gas and oil wells and provides exceptionally high fracture conductivity and longer effective fracture half-lengths. Wells treated with the HiWAY* technique produce, on average, 25% higher than comparable offsets (reference SPE 135034 co-authored by YPF S.A. and SPE 140549 co-authored by Encana).

Saint-Gobain specializes in ceramic proppants, including its Ultraprof sintered bauxite for high-stress applications and Versaprop for applications that need less stress resistance.

It strives for increased fracture conductivity by producing a larger median particle size (MPD) for its proppants. For example, "While Ultraprof Sintered Bauxite is not a standard API sieve distribution, it most closely resembles a 20/40 mesh proppant. Its MPD is slightly larger than other 20/40 high-strength proppants – the reason for its increased conductivity – but Ultraprof Sintered Bauxite is nearly 30% smaller than 16/30 proppant products," according to the company.

Measurable benefits

Benefits of proper fracture treatments are overwhelming. In his SPE Paper 119143, Vincent said more than 200 SPE papers from 150 companies cataloged those gains.

For example, more than 100 hydraulic fracture treatments at wells in Hassi Massoud Field in Algeria resulted in average production increases of 700 b/d of oil per well, according to SPE 36904.

SPE 67299 revealed that Chevron compared proppant types and found higher conductivity fractures increased productivity by 10% to 60% with an average first-year-improvement of 34% in the Bear River and Frontier tight gas sands in the Green River Basin of Wyoming.

SPE 110679 indicated horizontal Middle Bakken wells stimulated with 20/40 or 16/20 lightweight ceramic proppants "significantly outperformed offset wells completed with sand or a broadly sieved ceramic."

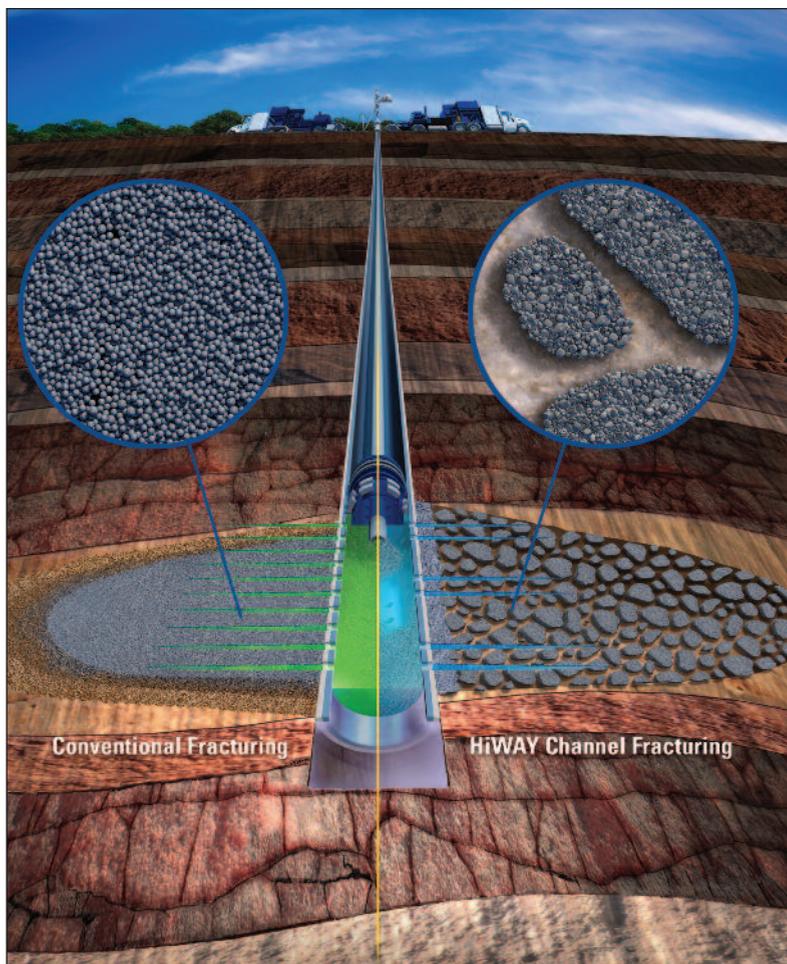
Service and supply companies also offer case histories on production gains offered by their products. Halliburton noted four North American wells were fractured, one with MonoProp and three offsets with conventional proppants. After seven months online, the MonoProp gas well produced 25% more gas than the best of the offset wells.

Momentive's SPE Paper 135502 described the results of testing on 16 Bakken horizontal wells in Dunn and McKenzie counties in North Dakota. All had similar vertical depths, lateral lengths, and completion techniques. The wells treated with curable resin-coated sands produced 23% more oil in the first month on production and 35% more oil in the first two months online than wells treated with uncoated frac sand, according to the paper.

There are no perfect proppants, and operators must continue to balance concerns of cost, availability, and performance. However, there is growing recognition that the proppant is the only part of a fracturing treatment that provides a sustained connection between the well bore and the reservoir, and more attention needs to be paid to assure selection of the correct material.

More than 200 SPE papers are not wrong. Fracture treatments work. Properly designed fracture treatments work better, and optimum proppant selection is a key component of a properly designed fracture treatment. ■

**Mark of Schlumberger*



A comparison of a fracture packed with proppant (left) and HiWAY flow channels (right). (Image courtesy of Schlumberger)