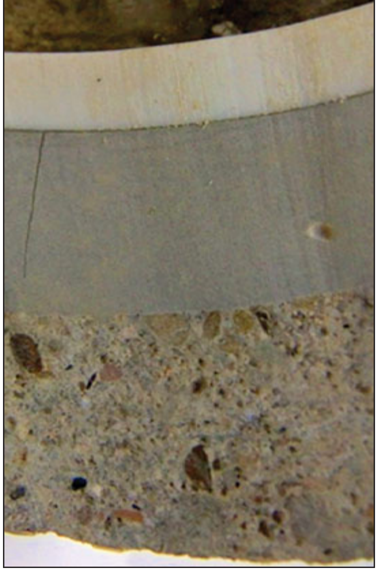

The debate around the environmental risks of hydraulic fracturing reveals a need for more research about how cement seals behave in the field.

Cement performance impacts integrity of oil and gas wells

By **Melissae Fellet**
Feature Editors **Michael Marder and Tad Patzek**

The ability to retrieve fossil fuels from deep shale formations has sparked a revolution in oil and gas development. It has also triggered a complicated political debate involving energy, economics, and the environment. Concerns about groundwater contamination and stray methane leaking from compromised wells grow with the increasing number of unconventional wells in production.

The process of preparing an unconventional well, commonly called "fracking," involves two technological advances: horizontal drilling through shale deposits and hydraulic fracturing through the well casing by inj ecting pressurized fluid into the well. The result is a network of interconnected cracks in the shale, similar to a web of cracks in a broken windshield, through which oil and gas can flow.

Preparing a well for production involves rigorous engineering and materials design to accommodate the sub-surface conditions at each unique site. Cement fills the space between a well's casing and the surrounding formations. But placing those seals becomes increasingly challenging as bores travel deeper underground, turn horizontal, and face high reservoir pressures and temperatures. As geoscientists, environmental engineers, and researchers in the petroleum industry formulate new cements in the lab, they seek to test the materials under the varying temperatures and pressures found inside a wellbore.

Maintaining well integrity to prevent stray gas migration has been an issue for the industry since the earliest gas wells were drilled in the United States in the 19th century. Today, industry experts, academic researchers, and environmentalists agree that properly constructed wells can mitigate the environmental risks of oil and gas production, which increasingly comes from unconventional shales.

The basic barriers that insulate a gas well from surrounding rock are steel pipes and cement seals. After drilling a wellbore, operators center a steel pipe in the opening, leaving about an inch of space between the outside diameter of the pipe and the inside diameter of the bore. Then they pump cement into the pipe. When the cement reaches the bottom of the bore, perhaps a mile underground, it travels into the annulus—the gap between the pipe and the rock—and returns to the surface. For some wells, equipment at the bottom of the well contains a one-way valve to prevent backflow of cement into the center of the steel pipe. Modern wells can have multiple cement and steel pipe barriers, especially through critical portions of the bore.

"Getting a solid sheath of cement between a steel casing and a well bore is one of the most difficult engineering tasks that I can think of," said Richard Jackson, a consultant at Geofirma Engineering in Canada. The steel pipe should be centered in the bore so that the cement seal exerts even pressure on the surrounding rock. The cement should withstand the temperature, pressure, and shear forces it encounters while traveling down a well and returning to the surface. The cement slurry should harden with minimal particle settling that leaves free water on the surface of the material. The slurry should also resist any influx of gas that could leave channels in cured cement.

Many cement seals start with a base of Portland cement. Industrial cementers then formulate a material with the appropriate properties for a particular job using computer models that account for the geology of a well site, geometry of the bore, and operating conditions at the well, said cementing expert and consultant Glen Benge. They introduce various additives to tune the material's density, viscosity, and hardening time to accommodate the pressures and frictional forces at each site. Sugar can slow curing, while calcium chloride accelerates it. Specialized additives alter the viscosity of cement so that it moves like ketchup: a flowing gel when agitated and a stiff solid when stationary. These thixotropic materials work best at cold temperatures, Benge said, and they may not be appropriate for every situation.

Well operators also tune cement density so that the material is heavy enough to replace the fluid used to flush the drilling mud, but not so heavy that it damages the surrounding rock. One way to reduce the density, as well as the viscosity, is to add bubbles of nitrogen gas to create a foam cement.

Researchers at the National Energy Technology Laboratory in the United States are studying foam cements using equipment that simulates pressures and temperatures inside a wellbore. They also use computerized tomography to image foam cements created at atmospheric conditions, mixed using equipment and methods identical to those on an offshore rig, and compressed up to 1,000 psi in a laboratory. By comparing the quality and

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the physical properties of materials created under these different conditions, Barbara Kutchko and her colleagues hope to develop a model that connects material performance in the lab with behavior in the field.

As the cement slurry sets, it experiences a period where the hydrostatic pressure of the material has decreased, but the material hasn't fully hardened yet. During this transition period, gas from shallow formations can seep into the seal and create channels.

Julie Vandenbossche, at the University of Pittsburgh, and her colleagues work to characterize that period of vulnerability by recreating a portion of a wellbore in the lab. The researchers simulate a rock formation using cement with same porosity as rocks in Marcellus shale. Then they add steel casing and a cement seal. The researchers pressurize the seal to loads it would experience inside a wellbore, and they expose it to gas to simulate that possibly found in the upper portions of the bore. This setup enables them to study how construction variables like cement formulation, asymmetrical cement placement, or formation roughness created by drilling influence channeling caused by the gas.

"It's not like we can peek inside a regular well and look at what's going on," Vandenbossche said. "I think this gives us a more realistic approach to evaluating the conditions."

The cement-steel or cement-rock interfaces are also areas where seals can be compromised, because each material responds differently to temperature and pressure fluctuations. Stresses at these interfaces could create tiny cracks called microannuli, which can provide a path for gas to travel from a formation to an underground aquifer or to the surface.

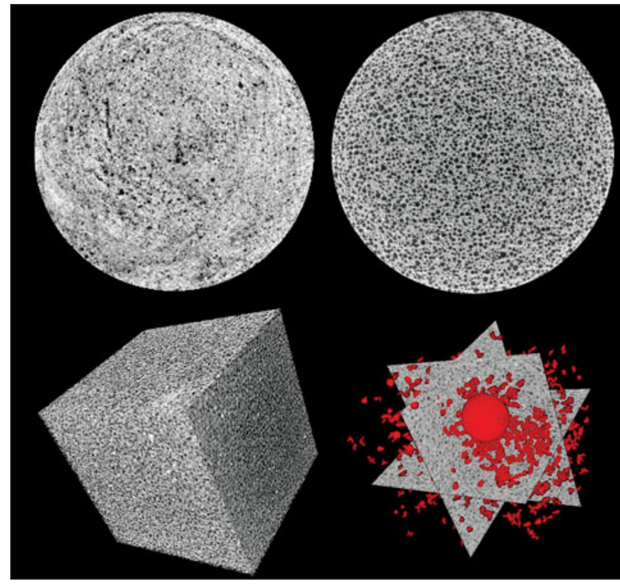
Bill Carey at Los Alamos National Laboratory is studying the stresses in those multi-material systems with experiments that also simulate pressures inside a wellbore. His results indicate that underground pressures deform cement so that it becomes more plastic than it is under atmospheric conditions. Sufficiently plastic cements may prevent or close microannuli more effectively than brittle cement, and Carey hopes his data will constrain situations that might cause leakage.

When microannuli are small and separate, the cracks spread slowly because the pressure at the tip of each is low. However, these cracks can grow vertically along the casing, and the driving force for further growth increases with vertical height. After decades, gas may appear at the surface.

Cement seals in the horizontal portion of an unconventional well are designed with enhanced mechanical properties to handle the pressure of the fracturing fluid without generating fractures that spread throughout the seal, Benge said.

Cement and steel barriers can last for decades, and industry experts say well construction continues to improve with environmental regulations and advances in construction materials and engineering.

A 2001 incident in Hutchinson, Kansas, reveals how compromised wells might be involved with groundwater contamination. There, an apparently compromised casing allowed gas to escape from a storage cavern 130 meters underground, travel over 11 km through natural fractures between shales, and seep into buildings. Predicting the potential for gas migration through natural fractures, while an uncommon event, requires information about the geologic conditions of a particular site combined with models of fracture propagation and gas flow.



Top: 2D slices of reconstructed CT scans of foamed cement samples, generated under field (left) and atmospheric (right) conditions. Bottom: 3D renderings of a digital subsection of a 10% foam quality cement sample. At left is the cement cube, and at right is an orthoslice of the cube with the largest bubbles marked in red. Credit: US Department of Energy's National Energy Technology Laboratory.

More research could improve the specificity of the parameters in those models and enable scientists to further quantify potential risks to groundwater. For example, the degree to which fracturing fluid might move through natural fractures is unknown; some models predict fluid would take six years to reach aquifers, while others find any upward movement unlikely. As explored in a story in the June 2014 *MRS Bulletin* Energy Quarterly, the interaction between hydrofractures and natural fracture networks is also unknown.

Reports prepared by expert panels for their respective governments in the United States, Canada, Australia, and the United Kingdom all identify well integrity as an area where regulations could help mitigate environmental effects of unconventional drilling. In the United States, states may regulate the location of intermediate casings, cement set time, or cement integrity tests before a well goes into production. Texas recently passed stricter regulations on well integrity tests and cementing criteria. And in early 2014, the European Commission recommended that member states consider environmental monitoring and site assessments as they craft regulations around shale gas drilling and exploration.

Constructing wells is getting more challenging as operators move deeper offshore or drill into deeper shales. Current methods of integrity testing can also miss small weaknesses in the cement. Carey says that improved diagnostics, as well as more basic research regarding materials' response to stresses in the wellbore, can improve well integrity. □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