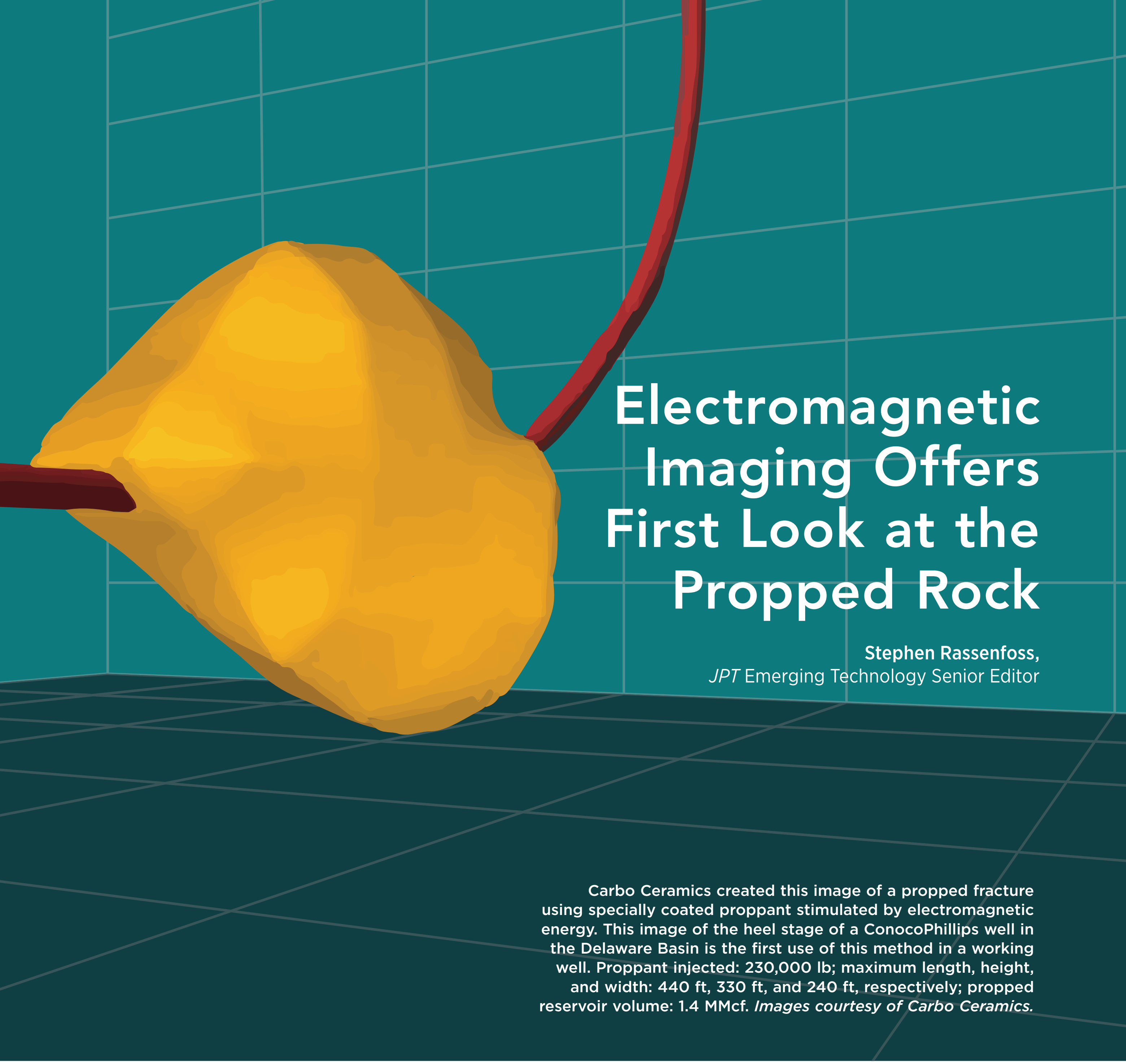


Electromagnetic Imaging Offers First Look at the Propped Rock

Stephen Rassenfoss,
JPT Emerging Technology Senior Editor

Carbo Ceramics created this image of a propped fracture using specially coated proppant stimulated by electromagnetic energy. This image of the heel stage of a ConocoPhillips well in the Delaware Basin is the first use of this method in a working well. Proppant injected: 230,000 lb; maximum length, height, and width: 440 ft, 330 ft, and 240 ft, respectively; propped reservoir volume: 1.4 MMcf. *Images courtesy of Carbo Ceramics.*

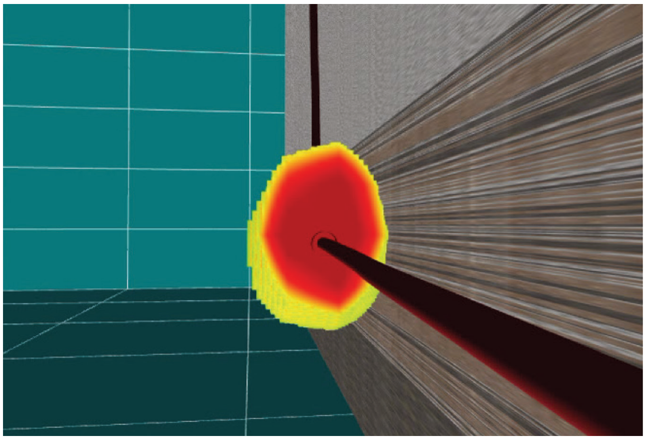
A series of images that look like yellow lumps on a line are the first-ever images of the area around the wellbore where fractures have been propped open using specially coated proppant stimulated by electromagnetic (EM) energy.

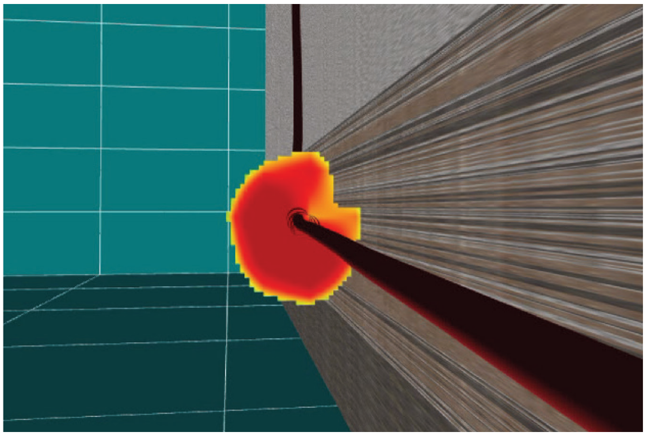
The images created by Carbo Ceramics could represent a milestone on the journey to find an answer to a critical question facing unconventional producers—how much rock is being stimulated and propped with grains of sand or ceramic for maximum production?

"People see the value in this area; they are starved for this," said Terry Palisch, global engineering adviser for Carbo, who described what is seen in the images as the propped reservoir volume.

Four groups of researchers are seeking a direct way to visualize what is left behind after fracturing. Three of the projects involve getting images by using proppant specially treated to be visible when stimulated by EM energy.

Microseismic images currently used in the industry to show fracturing results are based on the popping sounds of rocks rubbing against each other, like fingers snapping, but not the quiet, productive work of opening fractures and pumping in proppant to ensure they stay open.





Cutaway views of the first (left) and last (right) perforation cluster show a gap in the earlier one, and a lighter area indicating lower proppant density at the edge of the later stage. *Source: SPE 179161. Image courtesy of Carbo Ceramics.*

"Microseismic doesn't really tell us where the proppant has gone. It shows where failure events are occurring," said Mukul Sharma, a petroleum engineering professor at the University of Texas (UT) at Austin. He heads the Hydraulic Fracturing and Sand Control Joint Industry Project (UT Fracturing JIP) at UT, which is leading one of the projects mentioned earlier. "What matters is where the proppant is. In many rocks, the propped part of the fracture is the primary contributor to well productivity. That is the main advantage of electromagnetic (visualization) over microseismic."

Imaging the area that has propped fractures is a starting point for multiple investigations into how to efficiently extract more than 10% of the oil in unconventional plays. It can define the length and height of propped fractures, offer more accurate measures of the productive rock for modeling, and tell engineers how to space wells to effectively stimulate the reservoir without hitting nearby wells.

"There are several E&P (companies) that are very interested in that because finally we will be able to tell, 'Are we effectively stimulating these rocks and should we have our well spacing at X, Y, or Z, or in between?'" Gary Kolstad, president and chief executive officer of Carbo, said in a recent call with stock analysts. "Now you can take a look and say, 'Am I really spending my capital how I should?'"

A fourth project for visualizing fracturing is aimed at adding proppant location information to microseismic imaging by pumping in tiny sound emitters, which produce a distinct noise when the microdevices are lodged in a fracture.

Depressed oil and gas prices, which have made most unconventional development unprofitable, add pressure to find tools to understand why so many fractures are not productive. Björn Paulsson, chief executive officer of Paulsson Inc., which is developing the in-well receivers, pointed out that "80% of production comes from 20% of fractures, wasting a vast majority of the fracturing cost."

Electromagnetic Testing

The microseismic approach is aimed at creating a 3D array showing points where proppant is present, but it will be years before the partners on that project have built the equipment needed for its first test. EM-based methods are already being tried in the ground.

A technical paper by Palisch et al. (SPE 179161) presented at the 2016 SPE Hydraulic Fracturing Technology Conference was a first look at what is possible in a producing well. The imaging involved using 230,000 lb of proppant covered with an electrically conductive coating, which made it visible when stimulated by electromagnetic energy from the well casing in an 8,000-ft deep well.

Multiple new technologies were required for this method, including development of the conductive coating, a transmission method to send out a strong EM field using the steel casing, and new algorithms for processing.

When Carbo did the test last summer in the ConocoPhillips well in the Delaware Basin, it was not sure what, if anything, it would get. "When we did the first test the number 1 goal was, 'Can we pick out an EM signal from all the noise?'" Palisch said. "We were looking at a needle in a haystack."

The test was the product of years of development work aimed at creating the strongest possible signal and the most effective way to record and process the data. "We removed as much hay as we could, and did what we could to make the needle as big as possible," Palisch said. The system worked in a shallow test, and when an opportunity arose to try it again, they took a larger-than-expected next step.

The result was an image, and a long list of things to work on. In January, Carbo was still working though the large body of data gathered to reduce the noise in hopes of improving the image. After the injection of the 180,000 lb of white sand, 230,000 lb of treated ceramic proppant was injected through four perforations in the last stage fractured. One unknown is what the propped area would have looked like if all the proppant had been conductive.

The company has been refining its image-processing method to sharpen the resolution from 25-m grid blocks to a fraction of that measure. Over the next year, the largest maker of ceramic prop-

Seeing Where the Proppant Goes

Three projects are developing ways to use specially treated proppant and electromagnetic (EM) energy to create images of where proppant is concentrated in fractures, and a fourth is working on a microseismic alternative.

First Test in Well

Funding: Carbo Ceramics

Involves: ConocoPhillips, Sandia National Laboratories, GroundMetrics, Weatherford

Method: A proppant coating containing a metal that is an electric conductor is stimulated using an EM device in the well. The activated proppant is monitored by an array of surface receivers, and data processing and imaging are done by Carbo Ceramics.

Status: A successful test in a west Texas well showed it is able to observe where the proppant has gone.

Next: More tests are planned this year to image larger areas and increase the ability to observe smaller details.

For more information:

SPE 179161 Recent Advancements in Far-Field Proppant Detection *by Terry Palisch, Wadhah Al-Tailji, Carbo Ceramics, et al.*

Models Verified in the Ground

Funding: Advanced Energy Consortium at the University of Texas at Austin

Involves: Multi-Phase Technologies, FRx, Clemson University, Duke University, and University of North Carolina at Chapel Hill

Method: EM energy is used to stimulate conductive proppant to image it in the ground. Physical evidence is gathered to verify testing results.

Status: Early testing using EM imaging to observe the location of grains made of steel shot or petroleum coke showed it could accurately image fractures in six shallow test plots, each covering a 10 m×10 m area.

Next: Seeking to do a test in a 100-m deep well.

For more information:

SPE 179170 Remote Imaging of Proppants in Hydraulic Fracture Networks Using Electromagnetic Methods: Results of Small-Scale Field Experiments *by Douglas La Brecque, Russell Brigham, Multi-Phase Technologies, et al.*

Logging Tools and Electrodes

Funding: Hydraulic Fracturing and Sand Control JIP at the University of Texas at Austin and the US Department of Energy

Involves: University of Texas, Gearhart Companies, and an unnamed electronics maker

Method: A proppant made of electrically conductive material that can be stimulated using EM energy from

Electric transmission lines and a saltwater disposal site at this location are examples of noise that can interfere with electromagnetic proppant imaging. ***Photo courtesy of Carbo Ceramics.***

either a logging tool in an uncased hole or electrodes installed inside the casing.

Status: Tool components, software, and processing systems are being built and verified.

Next: In-ground testing outside of Austin later this year and, if that is successful, in a commercial well in the Marcellus Shale.

For more information:

SPE-168606 A New Method for Fracture Diagnostics Using Low Frequency Electromagnetic Induction *by Saptaswa Basu and Mukul M. Sharma, University of Texas at Austin.*

Search online for:

Fracture Diagnostics Using Low Frequency Electromagnetic Induction and Electrically Conductive Proppants. DE-FE0024271

Microseismic and Micropoppers

Funding: US Department of Energy, Research Partnership to Secure Energy for America (RPSEA)

Involves: Paulsson Inc., Fluidion, Southwestern Energy, RPSEA.

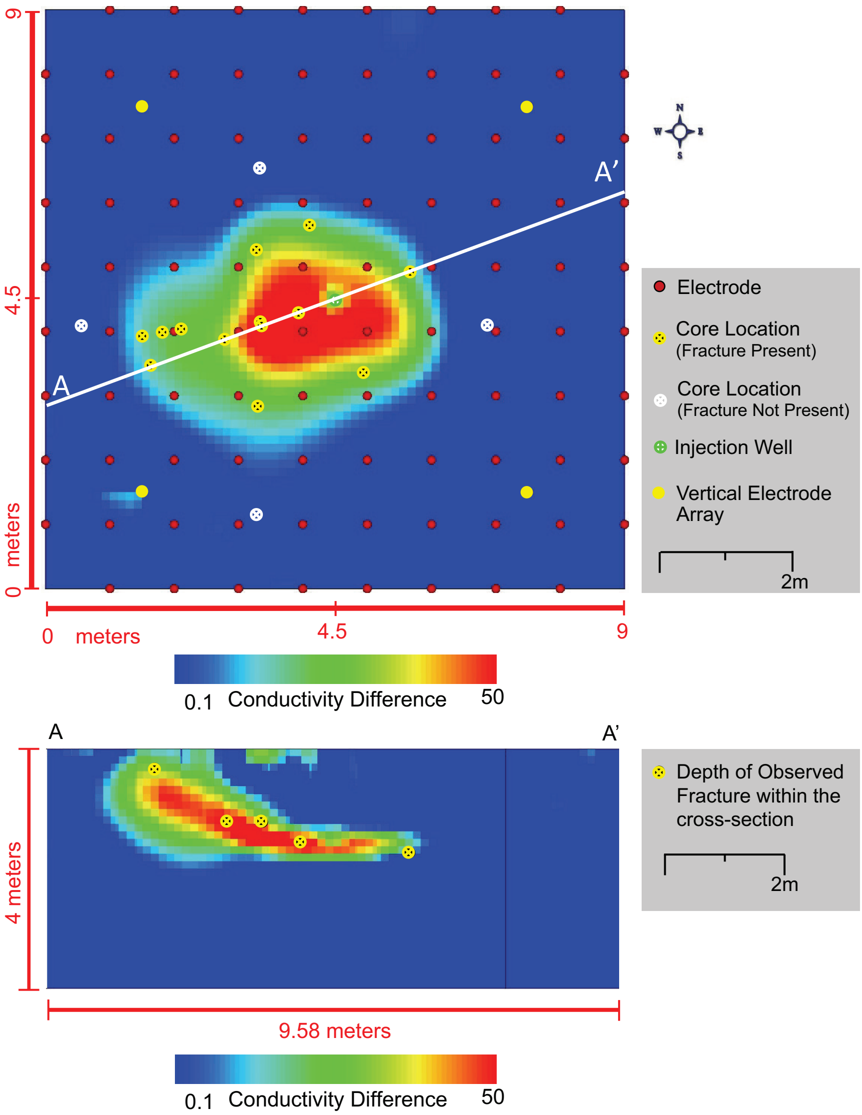
Method: Sound created by the collapse of tiny devices called acoustic microemitters is recorded by an ultrasensitive fiber-optic seismic sensor array inside a nearby wellbore for mapping fractures and propped areas.

Status: The equipment and method are being built and tested.

Next: Testing when equipment is ready in a couple years.

Search online:

Injection and Tracking of Microseismic Emitters To Optimize Unconventional Oil and Gas (UOG) Development. DE-FE0024360



Two images show a fracture propped with conductive grains of coke breeze. Top image: The colors show the level of conductivity, with the red zone around the well having the strongest response, which declines toward the end of the saucer-shaped fracture. Bottom image: A cross-section of the test which is 1.5 m below ground. *Source: SPE 179170.*

pant will be doing more well tests. It is seeking to expand the number of stages covered, and to significantly reduce the cost and effort required for testing.

Those working on EM proppant imaging methods need to convince skeptical reservoir engineers that these images created using methods based on esoteric physics and mathematics represent reality in the ground.

A priority for the EM proppant imaging project put together by the Advanced Energy Consortium (AEC) is gathering physical evidence to see if its models provide "useful information of the extent and basic properties of fractures," which can be relied on, said Douglas La Brecque, chief scientist for Multi-Phase Technologies. The company is providing the EM technology for the effort by the AEC, which is part of the Bureau of Economic Geology at UT. The project also involves other universities and institutions (SPE 179170).

While there is value in knowing the height and length of the propped fractures—frequently measures of fracture lengths are too high, leading to exaggerated production estimates—there is a limit to what operators will pay and how much time and effort they will commit to answering these questions.

The US Department of Energy summed those limits up in a statement of goals for its proppant imaging research when it said it is seeking a new method that "will have a very significant impact on fracture diagnostics, as it is cheap, repeatable, and fairly simple to run."

At this early stage, the cost of EM proppant imaging is comparable to another widely used diagnostic test: collecting and analyzing core samples. Palisch said the next step is to reduce the cost so that it is comparable to microseismic, and reduce it from there.

"Ultimately, I would like the price of EM proppant detection to be like logging," which is low enough to be done on nearly every well, he said.

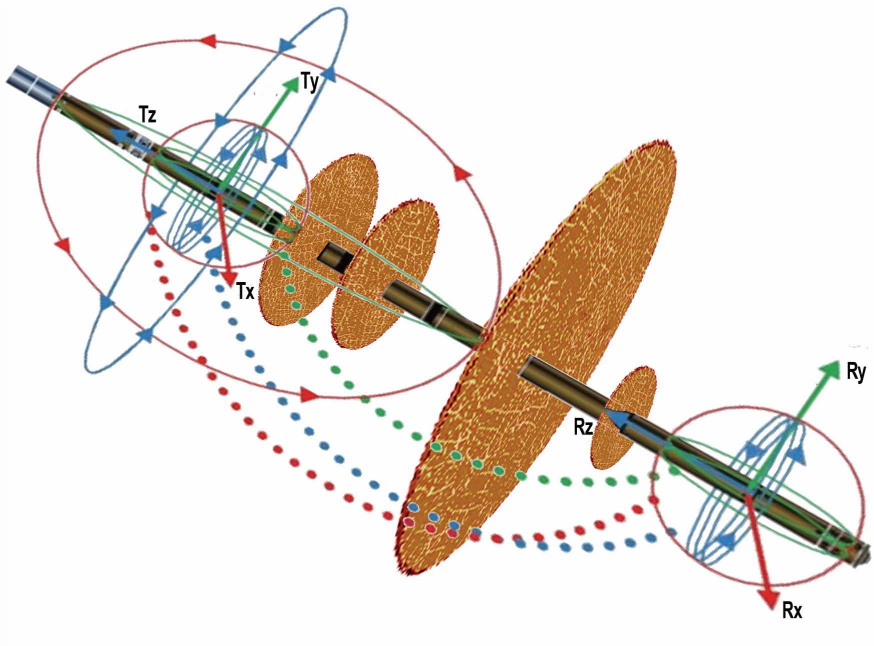
Visible Grains

Microseismic interpretation of fracturing requires judgment calls. It is common to detect seismic events thousands of feet from the wellbore the moment pumping begins to increase the pore pressure, said Mark Wilkinson, who worked for a microseismic company before becoming the vice president of unconventionals and geophysics at GroundMetrics, an EM-based company that worked on the Carbo test.

"No one interpreting that initial distant event would relate it to the fracture, but where do you draw the line?" he said, adding "more direct measure should create a better understanding."

The company has provided surface monitoring services for Carbo, and is working on a research project for the US Department of Energy to track the flow of a high-contrast formulated fracturing fluid—highly conductive brine—during fracturing.

Imaging fluid or proppant requires a chemical makeup that creates a sharp contrast to the background rock. Because reservoirs are also somewhat conductive, a good target must be really conductive, on the order of 1,000 times to 10,000 times more than the surrounding rock, La Brecque said.



An illustration of the area covered by an inductive logging tool being built by Gearhart Companies. The tool will transmit and receive an EM signal used to create a 3D image of proppant in fractures around a wellbore. *Image courtesy of the Hydraulic Fracturing and Sand Control JIP, University of Texas at Austin.*

Multiple electric and magnetic reactions happen when an EM field stimulates a conductive proppant. Research teams are looking for which of those effects offers the best signal for imaging.

The sand and ceramic normally used for propping is a poor conductor, so the three groups are all looking for alternatives. A durable, cheap material is required because large quantities of conductive proppant are required to create a strong enough signal to be detected at a distance.

The only EM project that has disclosed what materials it is using is the AEC-backed group, which tested grains of steel shot and a conductive form of carbon known as Loresco coke breeze. Both were used to create images of shallow tests in South Carolina, where fractures were created in 10 m×10 m plots. The unconsolidated rocky soil allowed them to use hand tools to observe the fractures created.

Later this year, the coke will be used on the next test in a well that is 100 m deep. But in a producing well, a stronger material will be required to stand up to the pressures at greater depths, said Mohsen Ahmadian, a project manager for the Bureau of Economic Geology.

Carbo and the UT fracturing consortium group did not disclose what materials they are using to create conductive proppant. When Palisch was asked, he referred to Carbo's patent application, which covers a wide range of possibilities.

Sharma said the UT fracturing consortium plans to make proppant from a commonly available material that costs more than sand but less than the bauxite used to make ceramic grains. Lab tests indicate this unnamed substance is strong enough to ensure "good fracture conductivity even at high stresses," he said.

While Carbo's initial test was comparable to the high cost of core testing, Palisch sees savings ahead because it will not have the one-time expenses associated with a first use.

GroundMetrics, which has been using EM for tracking carbon dioxide (CO_2) flows for enhanced oil recovery, has reduced its cost to less than the level common for microseismic by applying what it has learned from CO_2 tracking to cut the time required to do the jobs by 50%, Wilkinson said.

In this brutal business environment, Palisch is wary of the price rising as the technology is developed. Even a seemingly small increase in the cost per ton can be a significant negative because the proppant is such a large part of the completion cost, he said.

Distant Sensing

The idea of searching for oil by identifying differences in electrical resistivity goes back to first use of the method for subsurface mapping by the Schlumberger brothers 100 years ago. "The electromagnetic method is one of the earliest forms of geophysics. It has been around forever," Wilkinson said. What is new are the ways electromagnetic energy is injected into the reservoir and the receiver technology used to observe its impact.

In the Carbo test, power was sent down a cable to a point at the heel of a horizontal well where it was put in contact with the well casing, making the steel pipe a source of electric and magnetic fields that stimulated the specially prepared proppant.

Using casing as an antenna for EM has not been around long. It is used widely by GroundMetrics, which was hired to deploy 20 of its EM receivers for the Carbo test to gather data from the stimulated proppant. The image was created by comparing the difference between the data gathered during 30-minute periods before and after fracturing.

The new-generation receivers, developed with support from the US military, measure changes in the electrical potential in the ground. Wilkinson said they are more reliable than galvanic devices, whose readings fluctuate significantly, and the older receiver designs are more difficult to install and maintain.

At this early stage, no one is wedded to any particular combination of EM source and receiver. Multiple projects are likely to yield a variety of options that may be mixed and matched by future users based on the requirements of the job.

The UT fracturing JIP's technology program, which is funded by the US

New Technology Seeks To Give Voice to Proppant

A pair of inventive companies are working on a way to allow microseismic tests to visualize the otherwise silent process of propping fractures.

The project brings together a French creator of a microdevice designed to create a distinct sound when the hollow structure collapses after reaching its destination—Fluidion—and an inventor in California who created an ultrasensitive in-well seismic receiver array, which is the only one capable of recording and locating that faint pop—Björn Paulsson.

"We believe that with our sensor…we can more precisely locate where microfracturing is happening and where the proppant is going," said Paulsson, founder and chief executive officer of Paulsson Inc.

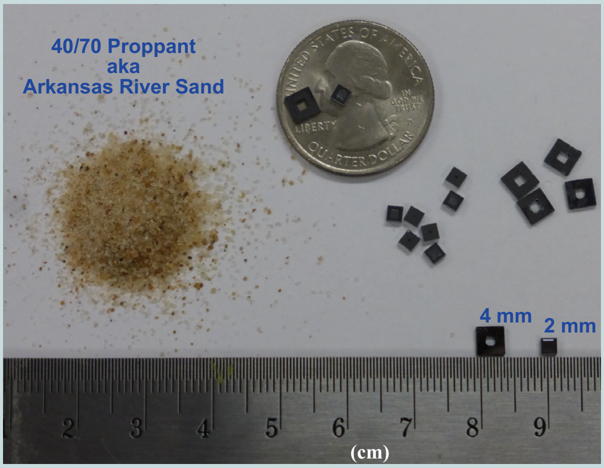
The joint effort is one of several research efforts backed by the US Department of Energy to develop improved ways of measuring the impact of fracturing. While others are working on using electromagnetic imaging to show the volume of propped rock, this project is aimed at mapping fracturing by locating points of sound from tiny devices collapsed by natural pressure, like squeezing the bubbles in a protective wrap.

The microdevices, which Fluidion calls acoustic microemitters, will be mass-produced using 3D printing techniques in large sheets, which are then cut into tiny bits.

Each emitter has a hollow core and includes a tiny version of a water clock that is activated when the device has been exposed to reservoir pressure. The microelectromechanical device delays the collapse long enough to ensure it reaches its destination in the ground before imploding. Testing verified that the vast majority of the emitters could survive a trip through a pump, Paulsson said.

The plan is to create emitters in two sizes: about 2 mm across or 4 mm across, each of which will produce a different sound. The number to be used per test is under consideration, but a working estimate is about 1,000 acoustic microemitters per stage, he said. That would create

40/70 Proppant vs. Acoustic Microemitters



The black squares are acoustic microemitters, which come in two sizes. At reservoir pressures, the hollow structures collapse, making a distinct sound that can be monitored to track where they travel in the ground. ***Photo courtesy of Paulsson Inc.***

"a cloud of these microemitters and we could listen to them and locate where they are in space," Paulsson said. The different sounds of the large and small microemitters could help identify the fracture size, as well as their extent and orientation.

If all components meet specifications, the plan is to place the receiver in an idle well in the middle of a six-well pad, and observe the sounds in the other five as they are fractured.

A couple of years of work are expected before in-ground tests are possible, he said. The time is required for building a protective steel shell for the 2,500 ft-long string that will house the 100-level receiver array, and to develop the system needed to dependably mass-produce the microemitters.

Department of Energy, is working on two approaches that work within the well. One is a low-frequency induction logging tool for openhole completions, and the other is permanent contact electrodes that serve as EM transmitters and receivers for cased wells.

Its partner on the induction logging tool is Gearhart Companies, which is applying EM experience gained developing directional survey tools. The UT fracturing JIP is working with E-Spectrum Technologies for the hardware for cased holes, Sharma said.

The electrodes can cover an area that is "a few hundred feet," he said. This installed series of coils for transmitting and receiving could also be used to measure other geological features, such as fractures, and how they change. The tool from Gearhart has undergone laboratory testing and Sharma said they are aiming for a field test in a shallow well this summer.

Long Term

Carbo has seen the power of a picture. Its first image of the propped reservoir generated support, ranging from permissions from ConocoPhillips to add its name to the SPE paper, to companies interested in backing future in-well imaging tests.

While the fracturing business is in a deep funk, these projects are moving forward. "There is a good bit of interest in it. I think in the next 4 or 5 years there

In this test for the Advanced Energy Consortium, a fracture filled with sand and coke breeze was excavated to determine the accuracy of the software used to predict where it traveled based on EM imaging. A close-up (left) shows how the coke was concentrated along the walls. *Photo courtesy of AEC.*

will be some kind of commercial deployment," Sharma said.

While Palisch said Carbo wants to reach the market much sooner, there will be plenty of room for future development work. The process draws on advances in a range of disciplines from material science to geophysics. When Carbo began looking for a way to image where proppant goes, it sought help from a government research lab, Sandia National Laboratories, Palisch said.

It chose one of their suggestions, which coincided with work done by a Carbo researcher Lew Bartel. Since then, David Aldridge, a research geophysicist at Sandia National Laboratories, has advised Carbo on issues, such as how to interpret EM data over a long wellbore where it will be affected by the irregular and unpredictable geologic conditions.

In a presentation made at the Society of Exploration Geophysicists annual meeting last fall, he described that his project was adapting equations used by electrical engineers to model such things as the electromagnetic fields around power lines to predict the energy fields created when the steel casing within a vertical borehole is used as an antenna. Since then, he has been working on adapting these equations to model horizontal wells surrounded by irregular rock and fluids.

One of the most difficult aspects of proppant imaging is developing the inversion methods used to isolate and image that needle of useful EM data, and remove the noise added by electric fields around the wellsite. While seismic is based on a different sort of signal—sound waves—both methods require sophisticated algorithms to turn huge amounts of data into a useful image.

"Seismic inversion has occupied geophysicists for the past 50 years," Sharma said. "We are just starting out. Our work is just scratching the surface. We are at the beginning of this road."

The pace of onshore fracturing work requires quick, low-cost processing. A progress report filed late last year by the UT fracturing JIP said that its "method used to solve the equations is computationally intensive and efforts are under way to speed up the simulations by an order of magnitude."

For the AEC project, the processing side of things is a priority. "One of the deliverables is the best inversion software validated" by physical evidence, Ahmadian said.

To validate the code, the team carefully excavated the area fractured in its first test. "The site was shallow enough to excavate to test our prediction," he said, adding they were happy to see, "our code was very good."

The next step will be a UT test well, where coring will be used to observe if the imaging matched the fractures found at a much deeper depth than its initial test.

Over time the goal of these teams will be to find a lower-cost way to observe the propped fractured area in much greater detail.

"We know we can get the length and the orientation," of the fractured area, Sharma said. "We think we can get the distribution. A test of how good we are is whether we can model the geometry of the fracture. It is a nontrivial problem telling where the proppant is located." **JPT**