Advances in Seismic Stimulation Technologies

by Susan Jackson, RMC, Inc. for DOE's National Petroleum Technology Office, Peter Roberts, Los Alamos National Laboratory, Ernie Majer, Lawrence Berkeley National Laboratory
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Seismic wave stimulation technology has the potential for being a relatively low-cost procedure for enhancing oil recovery in depleted fields, or returning some shut-in wells to production. Tests indicate that potential is greatest in fields with high water-cut and large amounts of immobile oil, making mature domestic reservoirs a prime target. Field tests of the technology, however, have yielded promising but mixed or inconclusive results.

Interest in seismic stimulation started in the 1950s with observed correlations between water well level and seismic excitation produced from railroad trains and earthquakes. It was noticed that a rise in well fluid levels and an increase in fluid (pore) pressures were associated with earthquakes and cultural seismic noise. Similar effects were observed in producing oil fields where distant earthquakes caused increases in production, and wells close to operating machinery, highways or railroads appeared to produce more oil than wells in quieter areas. These anecdotal observations motivated Russian researchers to perform surface Vibroseis stimulation tests in several producing oil fields. The results of these early field tests were mixed. In some fields, production increased after Vibroseis stimulation, but in others the production actually declined. It became clear that a better understanding of the stimulation phenomenon was needed before it could be exploited reliably. This led to numerous research efforts beginning in the early 1970s and continuing today. Beresnev and Johnson (1994) provide a comprehensive review of over 100 Russian and U.S. technical articles and patents on the effects of seismic and acoustic stimulation on fluid flow in porous media, including laboratory investigations, theoretical studies and field tests. Documented work covers the use of a wide range of stimulation wave types and energy coupling modes, with frequencies spanning the range of one Hz to five MHz.

Another potential application that is being investigated is using seismic stimulation for enhancing environmental remediation efforts, particularly at oil refineries where large spills of petroleum products are threatening groundwater quality. Numerous oil companies and seismic source providers have expressed interest in pursuing this application. Recent research has indicated that seismic waves could enhance the extraction rate of groundwater contaminants by as much as a factor of 20 under ideal conditions (Roberts et al., 2001). However, the technology has been even less well tested in the field for environmental remediation than it has for oil production enhancement

This article summarizes recent research efforts and describes several existing field stimulation technologies. During the last ten years industry interest in seismic stimulation technologies has grown enormously. Along with this increased interest, our understanding and validation of the phenomenon are also beginning to improve. Industry and government supported research efforts are largely responsible for this. The science and technology are at a critical stage of development now, where continued research and applications testing efforts have an excellent chance of answering many of the important questions that have been raised regarding when, where and how seismic stimulation can be used reliably.

Mechanisms of Increased Recovery

Mechanisms responsible for improved recovery are not well understood and remain the subject for further research. The following mechanisms have been proposed to explain the changes in fluid flow characteristics resulting from seismic stimulation.

- *Changes in Wettability*. Some laboratory work indicates that the wettability of a core saturated with oil can be made more water wet, resulting in increased oil recovery rate by waterflooding in conjunction with seismic stimulation.

- *Coalescence and/or dispersion of oil drops*. This school of thought speculates that attractive forces acting between oscillating droplets of one liquid in another (Bjerknes forces) induce the coalescence of oil drops, enabling continuous streams of oil to flow.

- *Reduced viscosity*. Laboratory work has indicated that, immediately after a 30- to 60-minute long exposure to an acoustic field, oil viscosity dropped by 20-25%, then gradually returned to pretreatment level over a 120-hr period. Similar viscosity reductions of 18-22% have been noted with polymers exposed to an acoustic field. One researcher suggests that heat generated by ultrasound absorption contributes to viscosity reduction.

- *Surface tension.* Under some theories, it is suggested that the fundamental source of the increased permeability is the reduction in surface tension caused by the differential velocity between the rock matrix and the pore fluid.

- *Increased permeability*. It has been speculated that seismic waves can disrupt immobile fluid boundary layers on pore walls, which would increase the effective cross section of pores. In early laboratory work, the permeability of a core sample saturated with fresh water increased 82-fold after being exposed to an acoustic field, returning to its original value within minutes after removal of the sound field. It has also been demonstrated that stress cycling of core samples at 50 Hz can mobilize in-situ particulates that are plugging pore throats. The pore throats are unplugged and the rock's permeability increases.

DOE-Funded R&D in Acoustic Stimulation Technology Development

Two projects have been funded by DOE’s National Petroleum Technology Office in Tulsa, one with Los Alamos and Lawrence Berkeley National Laboratories involving laboratory, modeling, and field experiments and a second with Oil & Gas Consultants International, Inc. (OGCI) involving field testing of a vibration stimulation device in Osage County, Oklahoma.

Los Alamos National Laboratory and Lawrence Berkeley National Laboratory

Los Alamos National Laboratories (LANL) is partnering with Lawrence Berkeley National

Laboratories (LBNL), University of California at Berkeley (UCB), AERA Energy LLC, Applied Seismic Research Corp., Chevron, Conoco, Fluidic Technologies, Halliburton, Marathon, Oil & Gas Consultants International, Inc., PerfClean Intl., Phillips, Piezo Sona-Tool, and Texaco to study seismic stimulation.

The research objectives of this project are to investigate the physical conditions or mechanisms by which low-frequency (1-500 Hz) stress (seismic or acoustic) waves enhance oil production rates in marginal reservoirs. Anecdotal evidence and limited field testing have indicated that seismic stimulation can increase oil production rates by 50% or more, but it is currently difficult to predict how, when or where to apply the technique successfully. Research is focused in three main areas: (1) laboratory fluid flow and production enhancement experiments on cores, (2) numerical and theoretical modeling of wave stimulation effects on 2-phase fluid flow in porous media, and (3) full-scale experimental field stimulation testing, source characterization, and production monitoring.

Laboratory Experiments

Both steady-state constant flow and non-steady-state displacement tests were performed in Berea Sandstone using oil/brine and decane/brine systems. During steady-state experiments, the drop in pressure increased in the oil/brine system, while it decreased with the decane/brine system. Two possible explanations for the pressure increase in the oil/brine system are 1) additional oil and/or brine became trapped or 2) additional oil began flowing through a fraction of the pore space previously occupied by mobile brine. The pressure decrease observed during decane/brine flow could be explained by 1) previously trapped decane and/or brine becoming mobilized or 2) decane with its lower viscosity replaces flowing brine.

Non-steady-state displacement (flooding) tests using both oil/brine and decane/brine systems indicated that stress stimulation enhances brine production during drainage (oil flood) and decreases the oil displaced during imbibition (brine flood). These observations could be explained by the fluid-trapping mechanism mentioned above. Stimulation may cause the highly water-wet Berea sandstone to become temporarily more oil wet, causing oil to become trapped during stimulation. With the decane/brine system, stimulation had little or no effect on net fluid production during either drainage or imbibition. During imbibition, however, the rock reached residual decane saturation faster. Altered wettability cannot account for this observation.

Modeling

Modeling work strives to describe how each individual component of oil and water should respond to a pressure pulse in a porous medium. During the past year, the exact equations for mass and momentum balance among all three components in an elastic porous medium containing two immiscible fluids has been derived in the linear limit. These equations lead to diffusion equations for pressure/stress and for porosity (or total fluid mass) in the long-wavelength limit. The work will allow a more exact calculation and understanding of the coupling of different seismic and pressure effects. This work is being extended to the long-wavelength limit by developing coupled partial differential equations for wave propagation and solving them under boundary conditions appropriate for fluid pressure-pulsing experiments. The ultimate goal is to model performance in different geologies and formations as a function of porosity, and fluid and matrix properties.

Field Tests

LBNL and industry partners have conducted several field tests to monitor the seismic energy in the formation resulting from stimulation activities. The tests consist of careful measurements of the pattern of effects of the stimulation correlated with the measurement of seismic energy at various distances from the seismic source.

The tests have been conducted by lowering a three-component geophone and hydrophone array into wells at distances varying from 200 feet to 2300 feet during the stimulation period to record the seismic energy. With these data, the level and bandwidth of energy produced in the reservoir can be observed. The data collected are also correlated with production increases in the wells to deduce the relationship to other factors, such as differences in geology.

To date, three different sources in three different formations have been tested. The tests have been in the sandstone formation of the oil fields just north of Loveland, Colorado, the diatomite in Central California and a shale formation also in Central California. Bandwidth ranged from 2 to 2,000 Hz. In all of these tests, no seismic energy above background was observed. It is thought that monitoring equipment was too far away. Future tests will place sensors much closer (within 100 feet). In addition, the pulse in the source will be monitored by placing a wide bandwidth and large range pressure transducer in the perforated sections of the source well.

For additional information, visit http://www.ees4.lanl.gov/stimulation or contact Peter Roberts, Los Alamos National Laboratory, phone: 505-667-1199, email: proberts@lanl.gov or Ernie Majer, Lawrence Berkeley National Laboratory, phone: 510-486-6709, email: elmajer@lbnl.gov.

Field Testing in the Osage Reservation, Oklahoma

Oil & Gas Consultants International, Inc. (OGCI) is partnering with the Osage Tribe, Calumet Oil Company, the field operator, and Phillips Petroleum Company (Phillips) to test vibration stimulation in the North Burbank Unit, a mature waterflood field located on Osage tribal lands. Discovered in the 1920s, the North Burbank Unit still has more than 200 million barrels of movable oil in place, but currently produces only 1200 bbls/day at 99% WOR. The Burbank sand is at about 2800 ft with permeability ranging from 50 md to one Darcy. Seismic Recovery LLC, a subsidiary of OGCI, has designed and built, and will test, a new version of a downhole vibration tool based on their patented whirling orbital vibrator. The tool developed by OGCI uses a backward whirling motion to create both compression and shear seismic waves from 5 to more than 500 hertz, and is capable of generating controllable force levels up to many tens of thousands of pounds. Two sets of mechanical slips are used to transmit the vibration energy from the backward whirling mass into the producing formation. A schematic of the tool is shown in Figure 1.

The direct mechanical contact with the formation allows the device to be used in reservoirs with a gas cap—a situation that would dampen a fluid pressure pulse technique. The tool can be used to mitigate the effects of near wellbore condensate dropout and for groundwater remediation, and functions equally well in producing and injection wells.

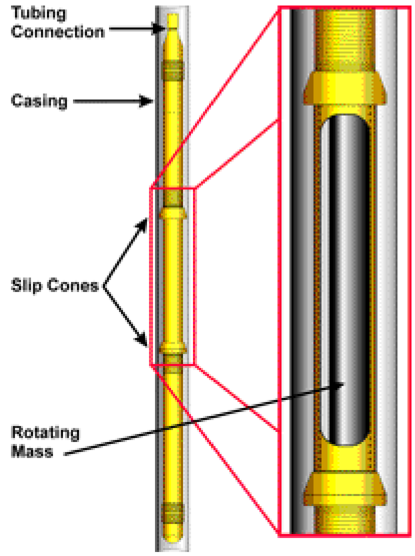

Figure 1. Schematic of Seismic Recovery LLC's 7-inch downhole vibration tool.

The downhole tool and surface power source will be tested in a newly drilled well that will be cored, logged and completed with 7-inch production casing. Phillips will conduct laboratory tests using their proprietary sonic core apparatus to determine fluid flow response to a range of vibration frequencies. Results will guide final adjustments to the frequency generation mechanisms of the downhole vibration tool. Drilling is planned during July 2001. Once baseline data are gathered, vibration stimulation will begin.

One or more offset wells, adjacent to the vibration test well, will be equipped with downhole geophones to determine strength of signal and if the producing formation has a dominant frequency response. Surface geophones will also be set out and arranged to pick up the signal generated by the downhole vibration tool. The results of the data collection will be a matrix of varying vibration stimulation conditions corresponding to changes in production fluid rates and seismic responses.

The results of the downhole vibration stimulation test will be made available though Society of Petroleum Engineers papers and workshops. A technical session on vibration stimulation will be offered at the SPE/DOE Thirteenth Symposium on Improved Oil Recovery in Tulsa, April 2002, bringing together the world's experts in this emerging technology.

Seismic Recovery LLC is actively seeking other opportunities to field test its tool for vibration-enhanced recovery, ground water remediation, and condensate dropout mitigation. *For more information contact: Bob Westermark, Seismic Recovery LLC, Phone: 918-828-2543, Email: bwestermark@ogci.com*.

Other U.S. Work by Producers

BP is looking into the use of pressure pulsing for EOR, well-bore cleanup, pipeline problems and drilling. In preparing for field trials, they have screened reservoirs looking for onshore, low gas content, and “softer” rocks to allow fluid-rock coupling. Five candidate reservoirs have been selected from about 300 reservoirs.

Chevron is currently applying in-situ seismic stimulation technology in their Lost Hills Field to lower their stimulation costs. Results of the stimulation are being monitored through observation wells and will be published.

AERA Energy has tried seismic stimulation (in cooperation with LANL) in their Lost Hills, San Ardo, and Belridge fields. Two or three additional field tests are planned. Lost Hills and Belridge fields, among others, are being considered for the test.

Marathon conducted a test in the Tensleep in Wyoming, a high viscosity oil reservoir. Tool failure and lack of resources prevented completion of the test. The formation was hard and fractured, resulting in water cycling problems. The resulting reduction in injectivity was attributed to mobilization of high viscosity oil. Marathon is considering another test of the technology.

Future Research Directions

Although tests and applications of seismic stimulation technology have been generally successful, further work is required to improve the reliability of the technology. Some of the areas that need further work include:

- Increased understanding of fundamental science and physical mechanisms governing the phenomenon
- Well-controlled field tests of vibration technologies
- Application of the technology to enhance other recovery methods, such as thermal recovery and chemical flooding
- Use of acoustic, elastic wave stimulation to obtain reservoir imaging information along with reservoir stimulation

Commercially Available Acoustic Stimulation Tools

Service companies with commercially available acoustic stimulation tools were invited to describe their tools, and four –Applied Seismic Research, PerfClean, Prism Production Technologies Inc, and Sonic Production Systems --responded. Some other known suppliers were not able to respond.

Applied Seismic Research, Plano, TX

Applied Seismic Research (ASR) uses in-situ seismic stimulation (ISS) to mobilize immobile oil through creation of high-energy (up to 10 million watts of power) low-frequency shockwaves that enhance oil mobility. The ISS Tool has increased oil recovery and production by as much as 30%

and has improved recovery in wells as far away as 1½ miles from the tool.

The ISS Tool consists of two modified tubing pumps separated by several sections of tubing (Figure 2). A conventional pumping unit powers the ISS Tool. On each cycle of the pumping unit, the tool releases highly compressed wellbore fluids creating seismic (hydrodynamic) shockwaves. In an oil-bearing reservoir, the shockwaves transform into localized, high-frequency wave fields that act to dislodge oil droplets and/or coalesce thin oil films into mobile oil droplets.

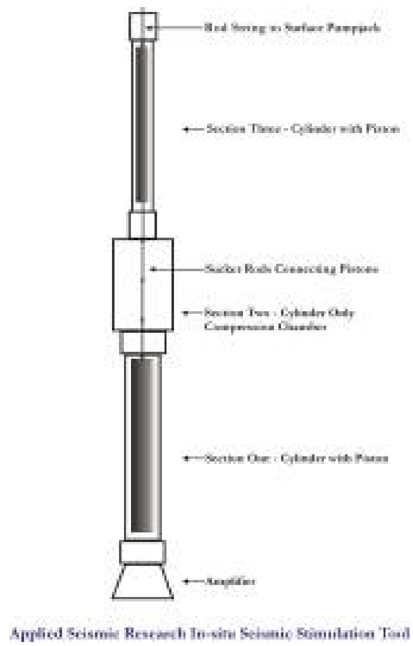

Figure 2. The Applied Seismic Research In-situ Seismic Stimulation Tool.

ISS has been proven effective in sandstone, dolomite, and diatomite reservoirs with permeability ranging from 0.0001 to 1 Darcy, API gravity ranging from 17 to 38 degrees, and on both fractured and non-fractured systems. Typically, ISS is most effective in reservoirs having a relatively low (field-wide) gas-oil ratio, less than 2000 scf/stb, API gravities greater than 20-22 degrees, and heterogeneous reservoirs containing areas of by-passed or trapped oil. Reservoir rock type, depth, and wettability do not significantly affect performance.

Requirements for technology implementation are a pumping unit of 120 or 144" stroke length having 6 to 7 strokes per minute, tubing, and rods. ASR provides the tool and on-site consulting for installation. The tool can be installed in active injection wells that remain active during ISS and in production wells provided the tool can be set at or below the bottom set of perforations.

A recent field test conducted in conjunction with Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, and Chevron in Chevron's Lost Hills field illustrated the ability of the ASR ISS tool to enhance oil production and recovery. The ISS tool was placed in an active injection well at a depth of approximately 800 feet. It was run continuously at seven strokes/minute using a 120-inch conventional pumping unit. The seismic waves created every 8.5 seconds by the slimhole version of the tool had an average power of 1.5 megawatts (million watts). The seismic shockwaves traveled down the wellbore to connect hydraulically with the formation through the perforations at 2,200 to 3,600 feet.

A continuous 12-day stimulation test conducted during July 2000 increased oil cut with no overall increase in fluids. A longer 38-day test performed during October-November 2000 in a group of 60 wells increased oil cut and oil production by 11% and 17%, respectively. Because many of the 60 wells had undergone various types of workovers and fracture stimulation, a control group of 26 wells that had not been disturbed by stimulation procedures was also monitored. By the end of the second stimulation treatment, oil cut from the 26 control wells had increased 29% and oil production had increased by 26% (see Figure 3).

Increases in oil production and oil cut attributed to a series of earthquakes occurring in September and October of 1999; the epicenters of which were located approximately 230 miles from the Lost Hills field, are also evident in Figure 3. The earthquake and ISS events are statistically significant as each event has pre- and post-event trendlines. Since oil production and oil cut curves both return to original trendlines, continuous application of ISS in the Lost Hills reservoir is required.

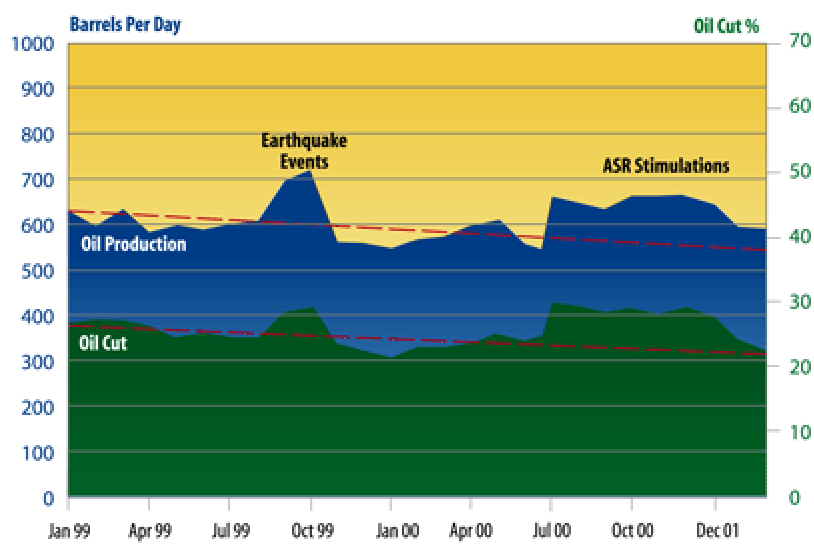

Figure 3. Oil production and oil cut data from a controlled subset of 26 producing wells from the Lost Hills field, California. Historic production data show a clear response to a magnitude 7.1 earthquake in October 1999 and to downhole stimulation treatments performed during July - November 2000.

For further information about the ISS Tool, contact Bill Wooden, phone: 972-381-4236, email: wow@zowi.to

PerfClean, Midland, TX

Although the PerfClean© Tool System is used primarily for near wellbore clean up, a field test to demonstrate applicability for enhancing recovery is planned in a South Texas field. The system uses a patented fluidic oscillator that creates pulsating pressure waves within the wellbore and formation fluids. These pressure waves break up any type of near wellbore damage, restore, and enhance the permeability of the perforations and near wellbore area. The PerfClean© Tool System is run into the well via coiled tubing, conventional tubing, wash pipe or drill pipe. The desired treatment fluid (acid, water, seawater, diesel, nitrified fluids, etc.) is pumped down the tubing through the PerfClean© Tool.

The kinetic energy of the pressure pulse travels through the wellbore fluid with no appreciable energy loss. When the pressure wave contacts the formation, the energy is "dumped" and the process of removing the near wellbore damage is initiated. As the damage is removed and the permeability is restored, these pressure waves penetrate deeper and deeper into the formation. The pressure waves expand in a spherical fashion from the point of origin, which ensures that 360-degree coverage is accomplished, while moving the tools through the interval. The acoustic streaming induced by the oscillator focuses the treatment fluid and tool energy and allows for treating specific intervals.

The PerfClean© oscillators are true fluidic oscillators. There are no moving parts. They do not rely on cavitation to create pressure waves. There are no packer elements to fail. Unlike mechanical tools, which suffer from high-energy losses, the PerfClean© oscillator maximizes the energy potential of the pumped fluid.

PerfClean tools have been used to treat over 2,500 wells in 12 states and 7 international areas. The majority of these treatments have taken place in the Permian Basin region of Texas and New Mexico where PerfClean International Inc. is currently based. The tools have been successfully used to treat and correct near wellbore damage in wells ranging from 90' to 27,000' deep. The treatment design and execution varies according to well conditions and the goals of the operator.

Applications of the technology are best in formations that can support a full column of fluid. This allows for easy manipulation of the wellbore pressures during the treatment. Theory and experience show that incompressible fluids provide the best coupling of the pressure pulse generated by the tool to the formation.

For further information, contact David Facteau, phone: 915-686-7432, email: PerfClean@hotmail.com.

Prism Production Technologies, Edmonton, Alberta, Canada

Prism Production Technologies provides Pressure Pulse Technology (PPT), a technology that improves recovery through large but elastic-range (reversible) excitation implemented through tailored pressure impulses within the borehole. The method concentrates energy in the right frequency range for porosity dilation wave generation, and because the tool is at hole-bottom, energy losses that occur as a pressure pulse travels down a wellbore are avoided.

PPT has been used to solve environmental problems. Here, the types of problems are physically similar to those encountered in the petroleum industry except for two major factors; the pressures are much lower because of the shallow burial and there is often a phreatic interface close to or within the aquifer.

PPT can be used to increase production of conventional and heavy oils using primary, secondary, and tertiary recovery methods as well as single well stimulations. The greatest potential of PPT lies in the application of the technology to the field scale where fluid flow rates to individual wells or groups of wells are increased. In past applications, perforations were kept open and flowing by continuous destabilization of perforation sand arches. In heavy oil reservoirs, incidents of sudden massive sand influx into sand producing wells, causing pump blockages were reduced. In low permeability reservoirs, injectivity of liquid floods was increased.

The PPT increases flow rates, reduces mechanical and capillary flow blockages, and improves sweep efficiency and resource recovery ratios. To achieve these effects, dynamic energy at an appropriate magnitude and frequency is introduced to the reservoir through pressure pulsing. This must be applied correctly, in an optimum configuration, as with any other type of enhanced oil recovery process. To decide the optimum approach to PPT in a producing reservoir requires knowledge of reservoir history, current reservoir conditions, and the options available for continued development.

The presence, quantity, and distribution of free interstitial gas affect the physical propagation of the porosity dilation wave. Wave propagation is impeded by free gas in either a continuous phase or a bubble phase. The gas compresses during the transit of a porosity dilation wave and can lead to an increase in the attenuation rate of the wave.

The area influenced by PPT depends on a number of factors. In one case, flow enhancement propagated slowly outward for a distance of 1000 m in a heavy oil ($\mu \approx$ 10,800 cP) reservoir after a period of 10 weeks. Because the porosity dilation wave follows all the laws of physics associated with waves, it attenuates because of geometric spreading. However, because there is a pressure build-up effect associated with the porosity dilation wave, pressure diffusion spreads out from the source at a rate controlled by the permeability and the viscosity of the liquid phases. If the outward propagating pressure front is intercepted by production wells (sinks), they will arrest propagation of the effects. The spatial distribution of the PPT impulse devices with respect to the existing or proposed well locations must be optimized.

The PPT method is based on a rigorous theoretical construct that successfully predicts a number of phenomena that have now been observed and that follow the laws of physics. These include spatial attenuation, pressure diffusion, and gravity segregation of fluids of different density. For example, although PPT increases the rate of flow through the application of additional energy in the optimum dynamic range, the rate of flow is still controlled by viscosity, pressure drop, and permeability. Therefore, the presence of permeability barriers is as serious an impediment to successful PPT as it is to other methods that depend on permeable connections. In addition, it is important to remember that PPT suppresses the various viscosity-dominated instabilities such as fingering, channeling, and coning. The suppression occurs because the pulsing energy is applied in the right area to push forward protruding fingers and increase sweep efficiency. Permeability barriers, disposition of strata, permeability ratios, and similar factors all have an effect on the fluid flow regime, even if flow rate is enhanced by PPT. These factors, therefore, must be assessed before implementation.

Requirements for implementing the PPT include well production history from the date of the last re-completion or significant operational change that would affect the ability to produce fluid, as well as the production history of the six-month period immediately preceding the pulsing, irrespective of interventions. The instantaneous background production rate and trend of each well immediately prior to pulsing initiation can then be more or less rationally extrapolated from the historical data. Since the reservoir production rate evolves dynamically and tends to follow the natural (expected) trends, this background period is considered sufficient, particularly since a number of offset production wells will likely be used for project evaluation. This approach allows project success to be evaluated rationally, despite difficulties in developing clear well histories and standard concerns about data quality. Production history details and intervention activity for the six to twelve months prior to the proposed date of PPT implementation must be used to develop base line trends that are used to evaluate program success.

For further information, contact Brett Davidson, phone: 780-486-2222, *email:* brett@prismpt.com

Sonic Production Systems, Aimes, IA

Sonic Production Systems, a business unit of Etrema, offers the PowerWave technology for enhancing production. The technology consists of two magnetostrictive (an alloy that changes shape and produces a powerful force in the presence of a magnetic field) actuators opposing an acoustic element. The set up of the tool is similar to that of an electric submersible pump. The PowerWave tool is a solid-state source with only three moving parts-two output shafts and one acoustic element. This provides for a long tool life. The tool runs at 250-400 Hz (cycles/second) continuously. Produced pressure waves act to decrease surface tension between oil and pore walls; destroy surface films that cover pore throats, allowing the oil to move out of the pore; and coalesce oil droplets so they can move to the wellbore.

Field tests are ongoing, with applications in Alabama, Oklahoma, and Indonesia. A short test was run in San Ardo field, California, where the tool operated for a period of 6 days in a cyclical steam flood. Production before installation was about 450 barrels of oil per day. Six days of stimulation resulted in a production increase to about 885 barrels per day. Water cut was above 90% in both cases, and even when production nearly doubled, water production did not increase.

Screening criteria include high water cut, high flow, consolidated formations (the harder the better), good production history, 5.5-inch or larger casing, and 440-480 V 3-phase power available. Well temperature needs to be less than 180 F. Formations at depths less than 5,000 feet are preferable.

*For further information, contact Tim Drake, phone: 816-246-0566, email:*tim.drake@sonicproduction.com.

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