An Integrated Approach to Seismic Stimulation of Oil Reservoirs: Laboratory, Field and Theoretical Results from DOE/Industry Collaborations

Peter M. Roberts[1], Ernest L. Majer[2], Wei-Cheng Lo[3], Garrison Sposito[3], and Thomas M. Daley[2]

[1]*Los Alamos National Laboratory, EES-11, MS D443, Los Alamos, NM 87545;*
E-mail: proberts@lanl.gov;
[2]*Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., MS 90-1116, Berkeley, CA 94720;*
E-mail: elmajer@lbl.gov, tmdaley@lbl.gov;
[3]*University of California at Berkeley, Hilgard Hall #3110, Berkeley, CA 94720;*
E-mail: lowc@uclink4.berkeley.edu, gsposito@nature.berkeley.edu

Abstract. It has been observed repeatedly that low-frequency (10-500 Hz) seismic stress waves can enhance oil production from depleted reservoirs. Until recently, the majority of these observations have been anecdotal or at the proof-of-concept level. The physics coupling stress waves to multiphase fluid flow behavior in porous media is still poorly understood, even though numerous underlying physical mechanisms have been proposed to explain the observations. Basic research on the phenomenon is being conducted through a U.S. Department of Energy funded collaboration between Lawrence Berkeley National Laboratory, the University of California at Berkeley, Los Alamos National Laboratory and the U.S. oil and gas industry. The project has focused on three main areas of research: 1) laboratory core flow experiments, 2) field seismic monitoring of downhole stimulation tests, and 3) theoretical modeling of the coupled stress/flow phenomenon. The major goal is to obtain a comprehensive scientific understanding of the seismic stimulation phenomenon so that field application technologies can be improved. Initial developments and experimental results in all three research focus areas confirm historic observations that the stimulated flow phenomenon is real and that a fundamental scientific understanding can be obtained through continued research. Examples of project results and developments are presented here.

INTRODUCTION

Roughly 60% of oil resources in the U.S. remains unproduced, partially due to limitations in existing enhanced recovery methods. Anecdotal production data, as well as historic field and laboratory experiments, have shown that low-amplitude seismic waves in the frequency range of roughly 10-500 Hz can enhance oil mobility and total recovery in mature reservoirs [1, 2, 3]. However, previous field tests with different seismic sources have often yielded mixed or inconclusive results for

enhancing oil production. In some cases seismic stimulation increased production rates by 20% or more, but in other cases production was unchanged or actually declined. This is due primarily to the fact that historic laboratory and field experimental data are not comprehensive enough to allow reliable prediction of the physical conditions under which stress-wave stimulation is most effective. Laboratory, field and theoretical research is beginning to provide the experimental data and scientific insights needed to identify the physical mechanisms which govern the seismic stimulation phenomenon [4, 5, 6]. Numerous mechanisms have already been identified but their relative contributions to the stimulated flow phenomenon is not completely understood. The detailed cross-coupling of various proposed mechanisms will not be determined until sufficient experimental laboratory and field data are obtained that can be used to validate and refine theoretical models that are currently being developed. As our knowledge of the governing physical conditions and processes continues to advance, stress-wave stimulation technologies should improve and become one of the more reliable and cost-effective enhanced recovery tools available to the oil and gas production industry.
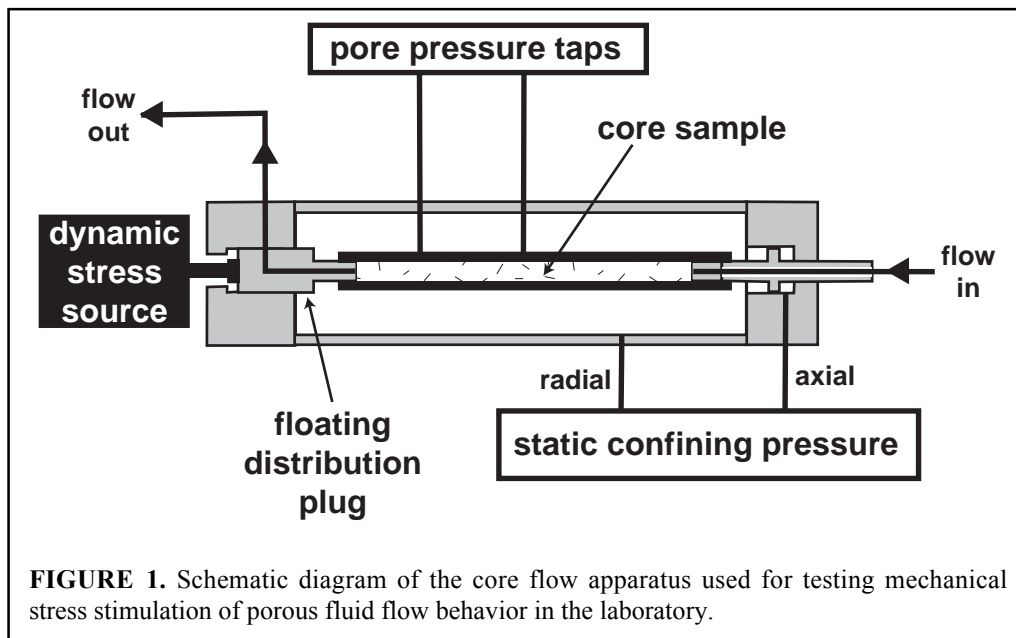
The following summarizes selected laboratory, field and theoretical results produced by an ongoing DOE research effort involving Lawrence Berkeley National Laboratory (LBNL), the University of California at Berkeley (UCB), and Los Alamos National Laboratory (LANL). These efforts rely heavily on cost-shared collaboration with numerous private companies from the oil and gas production and service industries, who provide the bulk of the support for performing field stimulation testing and production enhancement monitoring. The initial research results confirm previous reports [1] that stress waves can have a profound effect on porous fluid flow behavior and that, with sufficient physical understanding, the phenomenon can be harnessed reliably.

LABORATORY EXPERIMENTS

Core Flow Stimulation Apparatus

A specialized laboratory core flow apparatus, shown schematically in Figure 1., was assembled to study the effects of low frequency stress oscillations on fluid flow behavior in rock core samples. The main component of the system is a triaxial core holder, capable of applying up to 70 MPa (10,000 psi) axial and radial confining pressure to the core samples. It is designed to hold cores 2.54 cm (1 inch) in diameter and up to 61 cm (24 inches) long, and accommodates single-phase and two-phase flow at static fluid back-pressures up to approximately 62 MPa (9,000 psi). Constant-flow-rate pumps are used to produce pulse-free flow of oil and water mixtures through the cores. Currently, accurate flow rates of 0.02 to 800 mL/min can be achieved. Axial stress cycling at frequencies from DC to approximately 2000 Hz are generated by direct mechanical coupling of the core to a Terfenol-D magnetostrictive

actuator attached to one end of the core holder apparatus. The actuator can deliver dynamic force as high as ±890 N (200 lbf) P-P with a maximum displacement of ±0.005 cm (0.002 inches) P-P. Thus, Young's mode strains as high as approximately

FIGURE 1. Schematic diagram of the core flow apparatus used for testing mechanical stress stimulation of porous fluid flow behavior in the laboratory.

10^{-4} can be created in a 2.54-cm-diameter sandstone core. Permeability of the samples is obtained by measuring the pressure drop across various sections of the core during constant flow. A load cell in series with the actuator and core provides calibrated measurements of applied stress and strain gauges attached to the side of the core allow dynamic measurements of Young's modulus and Poisson's ratio to be made during stress excitation of the samples.

Results of 2-Phase Flow Experiments

Steady-state 2-phase oil and brine stimulated flow experiments were completed for different flow-rate ratios in Berea sandstone. Mechanical stimulation was applied at 25 Hz (CW mode) with an RMS amplitude of 1 MPa (150 psi) during steady-state flow. The pore pressure fluctuations induced by this stimulation were less than 2 kPa (0.3 psi). The results showed that stress stimulation increased the fluid pressure drop during constant flow through the core regardless of the oil-to-brine flow rate ratio. However, the amplitude and duration of the pressure increase appear to depend on the flow rate ratios. At least two possible explanations for these results can be proposed. First, stimulation may have caused additional oil to flow through pore channels previously occupied by flowing brine. Because the oil-to-brine flow ratio is fixed by the pumps, the induced change in mobile fluid saturation inside the core will cause the pressure to increase because of the higher viscosity of oil relative to brine.

Second, stress stimulation may cause immobilization (trapping) of one or both fluid phases. This would reduce the net pore volume available to flow (permeability) and cause the pressure to increase. In either case, it has been proposed that stress stimulation may be affecting the wettability of the rock and thus causing redistribution of the 2 immiscible phases. The hypothesis is that the wettability is increased for the non-wetting phase. Because Berea sandstone is highly water wet, stimulation would increase its affinity for oil.

During non-steady-state 2-phase displacement (flooding) tests an oil/water separation column was used to measure real-time changes in fluid production history during drainage and imbibition runs, again in Berea sandstone. The results indicated that stimulation enhanced brine production during the oil floods (drainage) and decreased the net oil displaced during water floods (imbibition). Although contrary to the desired effect, these results further support the altered wettability hypothesis. Discussions with industry partners indicate that there are numerous examples of oil reservoirs that are in a state of mixed wettability and it is likely that some of the successful field stimulation tests reported were conducted under these conditions. If this is the case, it is possible that reservoirs that are at least partially oil wet will respond better to stimulation treatments than water-wet reservoirs. This is because, for oil-wet reservoirs, the stimulation may cause the formation to become more water-wet. Thus, previously mobile water may become trapped and previously trapped oil may be mobilized, increasing the oil cut of produced fluids. More accurate characterization of field conditions for future reservoir stimulation tests, as well as results from future laboratory tests on oil wet cores may help confirm this.

FIELD STIMULATION EXPERIMENTS

Background and Approach

The DOE projects have partnered with numerous production and service companies from the U.S. oil and gas industry. The typical working relation is that the DOE-funded investigators are responsible for the basic scientific research and industry provides in-kind, cost-shared contributions to these efforts. In particular, field testing of new stimulation technologies is fully supported and carried out by industry and the DOE-funded researchers' primary role is to obtain seismic measurements of the wavefields generated by the various sources and to correlate these measurements with induced production changes. The selected field sites must provide the necessary control and background production and hydrogeologic information required to validate stimulated production changes. Different fields and seismic sources are being investigated to provide a wide range of geologic conditions, scales of measurement, and a variety of wavefield modes. Both vibrational and pressure pulsing devices will be used. During stimulation tests, multi-component geophones, accelerometers, hydrophones, and pressure transducers will
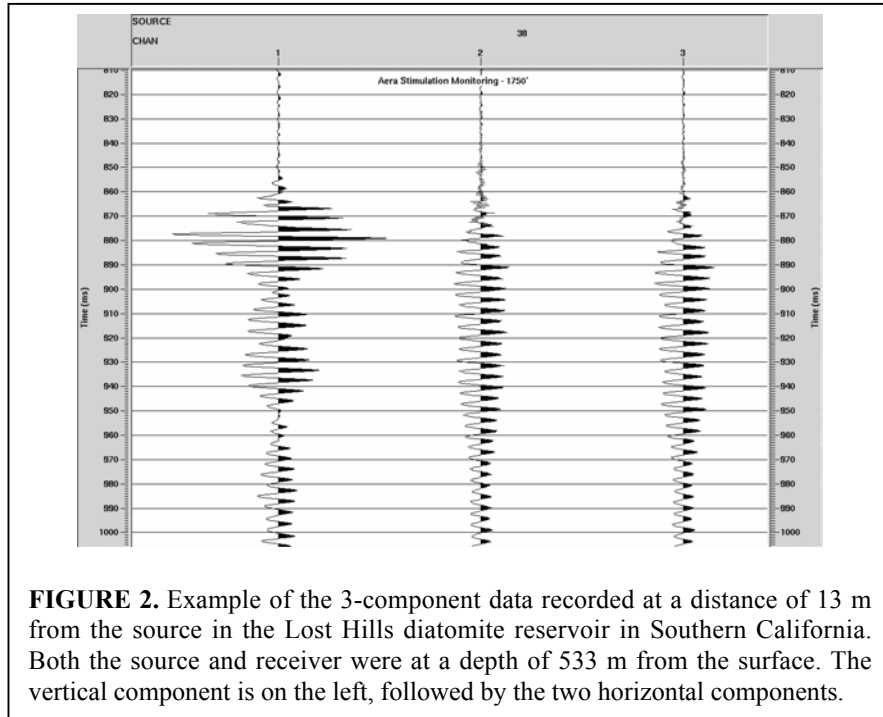
be deployed in wells at varying distances and depths from the seismic stimulation sources. The goals of the field tests are to provide experimentally controlled data sets that can be compared to determine the most effective physical conditions for stimulation and to provide insight on the dominant physical mechanisms.

Overview of Field Tests

Field stimulation tests are either ongoing or planned at three different sites. One site is the North Burbank field in Oklahoma. This is a mature sandstone reservoir which has been under production for a number of years. A vibrational source developed by OGCI will be used to stimulate the reservoir. Initial tests at the Amoco Mounds test facility several years ago showed that energy can be recorded well over a thousand feet away. A second site is operated by AERA Energy LLC in the Central Valley of California, in the Lost Hills diatomite reservoir. Ongoing tests are being performed using a downhole fluid pulsation source, provided by Applied Seismic Research Corporation (ASR). This device is driven by a pump jack and creates a classic hydro-impact pulse wave, with an amplitude of 28-35 MPa (4000-5000 psi), in the wellbore fluid which travels down the well and out into the formation through the perforated casing. The ASR device has been successfully tested in numerous fields before and production increases of approximately 20% have been observed [2]. The current Lost Hills experiment is the first test where controlled seismic measurements are being made during operation of the ASR device. Preliminary reports indicate the ASR device may be inducing a 10% combined production increase for wells within roughly 500 m of the stimulation well, but the production data have not yet been corrected for typical background fluctuations. The third test site is planned in a harder rock environment in shales near Ventura, CA. This test will also use the ASR hydro-impact device. The three field tests planned will thus provide data for three distinctly different formation geologies: sandstone, diatomite and shale.

Seismic Measurements at Lost Hills

During operation of the ASR hydro-impact device in a stimulation well at the Lost Hills site at a depth of 533 m, LBNL deployed a 3-component locking geophone tool in an adjacent monitoring well 13 m from the source well. The purpose of this test was to determine the near-field strength and frequency content of the ASR source. The source pulses once every stroke of the pump jack, about every 10 seconds. Data were recorded at 2000 samples/s on a 24-bit, wide-bandwidth recorder. The geophone was then moved up and down the well to determine signal strengths at different distances from the source. Clear signals, with high signal-to-noise ratios, were recorded at distances up to 250 m above the source level. A sample of the 3-component data at 563 m depth (near the source level) is shown in Figure 2. The signals have a strong ringing character at approximately 200 Hz that is observed at

FIGURE 2. Example of the 3-component data recorded at a distance of 13 m from the source in the Lost Hills diatomite reservoir in Southern California. Both the source and receiver were at a depth of 533 m from the surface. The vertical component is on the left, followed by the two horizontal components.

all levels. The cause of the ringing is currently being investigated. The next plan is to record in two wells simultaneously at different distances, one sensor in the close well (13 m) and another between 30 to 60 m away. By stepping away from the stimulation well in the same horizon as the source we will measure the attenuation and signal strength in the reservoir formation, thus providing input to the theoretical modeling.
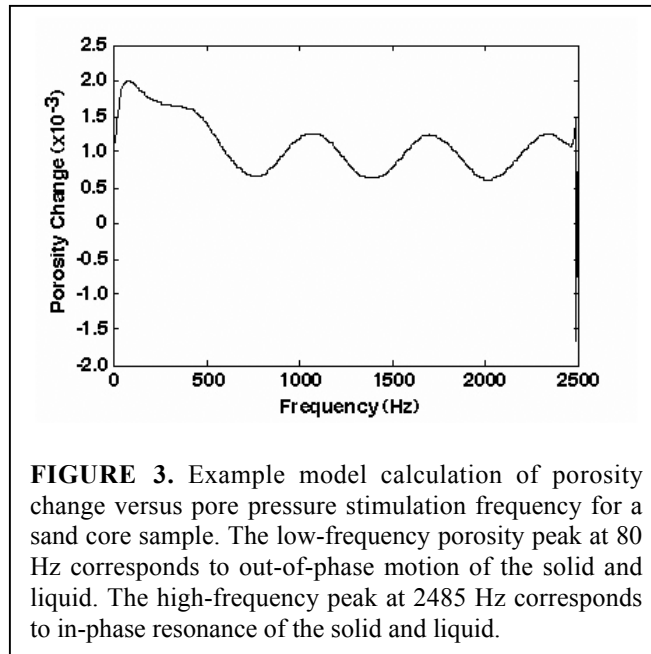
THEORETICAL MODELING

Macroscopic differential equations of mass and momentum balance for a multiphase system containing two immiscible fluids and an elastic solid matrix were derived in an Eulerian framework using the continuum theory of mixtures. After inclusion of constitutive relationships, our resulting momentum balance equations feature terms characterizing the hydrodynamic interaction between the fluid phases and the solid matrix caused by their relative accelerations. These equations generalize earlier work on bulk elastic wave propagation through unsaturated porous media [7, 8]. When specialized to the case of an elastic porous medium permeated by one compressible fluid, the momentum balance equations reduce to the well-known Biot model of poroelasticity.

Mass balance alone is adequate to derive the Biot model stress-strain relations, provided that a closure condition for porosity change is invoked, as suggested by de la Cruz and Spanos [9]. In general, this closure condition need only be a linear relation between porosity change and the dilatations of solid and fluid.

Our results also show that the Biot expression for the linearized increment of fluid content can be deduced in the context of mass balance. Using a similarity transformation and applying a relation between elastic parameters and inertial coupling coefficients, we decouple the partial differential equations of the Biot model into a telegraph equation and a wave equation whose respective dependent variables are two different linear combinations of the dilatations of the solid and the fluid, or equivalently, into two different linear combinations of fluid pressure and total dilatational stress.

To investigate physical mechanisms of seismic stimulation, a boundary value problem involving the decoupled Biot equations subject to a periodic fluid pressure pulse imposed on a constant pressure gradient was solved analytically. The solutions were modeled numerically with elastic and hydraulic data for unconsolidated sand and stimulation characteristics corresponding to recent laboratory experiments. The stimulation optimal frequency required to obtain maximum fluid flow was determined theoretically for the first time. Thus the induced pore pressure distribution and the flow rate at the stimulation optimal frequency can be predicted. Resonant behavior in response to fluid pressure pulsing occurs in the high frequency range when the motions of the solid and the fluid are in phase and in the low frequency range when opposing phase motions dominate. The numerical results also suggest that stimulation driven by pulsing pore pressure is more effective than that driven by pulsing total dilatational stress. An example calculation is shown in Fig. 3. The model is for single-phase fluid flow

FIGURE 3. Example model calculation of porosity change versus pore pressure stimulation frequency for a sand core sample. The low-frequency porosity peak at 80 Hz corresponds to out-of-phase motion of the solid and liquid. The high-frequency peak at 2485 Hz corresponds to in-phase resonance of the solid and liquid.

through a sand core, 0.3 m in length, subjected to a static axial confinement stress of 100 kPa and an oscillating pore pressure of 100 kPa amplitude. The static background pore pressure gradient was 22.5 Pa/cm and the initial (unstimulated) porosity of the sample was 0.44. The low-frequency porosity resonance peak at 80 Hz is of primary interest because it is within the appropriate frequency range for field stimulation and roughly agrees with laboratory experiments. The frequency at which the peak occurs and the magnitude of the porosity resonance both depend on the physical properties of the sample and the applied stress and flow conditions.

CONCLUSIONS

The initial results of U.S. DOE-funded research projects lend further credibility and quantification to the well-established phenomenon that low-frequency stress waves in the Earth can, under appropriate physical conditions, enhance the transport of oil in marginal reservoirs. Despite the growing experimental evidence, however, the fundamental science and physical mechanisms governing the phenomenon remain poorly understood. Ongoing research should eventually allow this important EOR technology to be further developed to the point where its results can be predicted reliably in the field. It is critical, however, to increase the collaborations and open communication among various international research groups currently investigating the stimulated flow phenomenon.

ACKNOWLEGEMENTS

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