1999 Natural Gas and Oil Technology Partnership Continuation Proposal

PROJECT TITLE: Seismic Stimulation for Enhanced Production of Oil Reservoirs

ACTIVE PARTICIPANTS: AERA Energy, Applied Seismic Research, Chevron, Conoco, Fluidic Technologies, Halliburton, Marathon, OGCI Management., PerfClean Int., Phillips Petroleum, Piezo Sona-Tool, Texaco, Wave Energy Resources, Wellington Operating Co., Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), University of California at Berkeley (UCB)

STATEMENT OF PROBLEM: Roughly 60% of domestic oil resources remains unproduced, partially due to limitations in existing EOR methods. Anecdotal production data, as well as historic field and laboratory experiments performed by Russian and U.S. researchers, have shown that seismic (stress) wave stimulation can enhance oil mobility and total recovery in mature reservoirs. Unlike high-intensity ultrasonic stimulation, which is effective only for reducing near-wellbore formation damage, low-amplitude seismic waves in the frequency range of roughly 10-500 Hz can directly increase oil mobility over much larger distances. Previous field tests with different seismic sources have yielded mixed or inconclusive results for enhancing oil production. In some cases seismic stimulation increased production rates by 50% or more, but in other cases production was unchanged or actually declined. This is due primarily to the fact that existing laboratory and field experimental data are not comprehensive enough to allow development of a reliable, versatile field application methodology. We are performing the additional laboratory, theoretical and field research needed to quantify the conditions and physical mechanisms under which seismic stimulation can enhance oil recovery. Major objectives are 1) to determine the optimum wavefield parameters for effective treatment over a wide range of field conditions and 2) to identify the dominant physical mechanisms at play and obtain a fundamental scientific understanding of their relative importance.

TASKS AND CONTRIBUTIONS: Our research focus is on three main task areas: (1) laboratory fluid flow and production enhancement experiments on formation rock cores, (2) numerical and theoretical modeling of wave stimulation effects on 2-phase fluid flow in porous media, and (3) full-scale field stimulation testing, source characterization, and production monitoring. The emphasis in year 1 was to perform proof-of-concept laboratory core flow experiments that were designed to provide evidence about whether or not flow enhancement can be observed at the core scale. During year 2 laboratory efforts were aimed at obtaining precise measurements of fluid production rates and pressure drops during non-steady-state displacement (flooding) tests. Also, several industry-supported field stimulation tests were performed which were monitored by researchers at both LBNL and LANL. Our plan for year 3 is to implement some new approaches to the laboratory testing, as outlined below, to expand on our involvement in monitoring industry field tests, and to begin the theoretical work. Although the specific contributions from LANL, LBNL and the industry partners overlap in all three areas, the bulk of task 1 will continue to be performed by LANL. Task 2 will be shared by UCB, LANL and LBNL, with UCB providing the initial leadership and theoretical modeling codes. Task 3, as in the past, will be supported primarily by in-kind, cost-sharing from the various industry collaborators, with LBNL supporting downhole and surface seismic monitoring and LANL participating in the planning and on-site monitoring. By combining existing capabilities and research facilities at LANL, LBNL and UCB with complementary field support, production experience, reservoir characterization expertise and acoustic source technologies from the oil and gas industry, we have assembled a formidable team that is capable of solving the complex problems that have hindered the advancement of this promising technology.

Task Area 1: LANL has constructed a specialized core flow laboratory facility to allow low-frequency mechanical stress cycling and fluid pore pressure oscillations to be applied, during constant pulse-free flow, to core samples held at triaxial confinement pressures typical of reservoirs as deep as 10,000 feet. Proof-of-concept experiments on Berea sandstone and unconsolidated sand samples have yielded promising results for enhanced permeability and increased mobilization of trapped immiscible-phase liquids. The apparatus was modified to provide precise production and pressure drop data during flooding experiments and to allow control over the fluid pore pressure. We are currently completing initial experiments on the effects of a single mode of mechanical stimulation on absolute and relative permeability to brine and oil, and fluid production changes during stimulated brine and oil floods. In year 3 laboratory

experiments will be expanded to cover a more comprehensive range of stimulation wavefield parameters, formation rock and fluid types, confining pressures, back pressures and fluid flow rates. Two of the more important changes being made are to begin coupling the low-frequency oscillations through the pore fluid pressure rather than mechanically through the solid rock matrix, and to focus more on higher-viscosity oils for the displaced fluid phase. We also plan experiments to investigate the fluid boundary layer mechanism for enhanced permeability using, initially, cores with very low clay fines content. The laboratory work will continue to address the questions of 1) why previous field tests were successful in some cases and unsuccessful in others and 2) when successful, why the increased production has been short-lived in some cases, but lasted for months after stimulation in other cases. LANL is responsible for conducting the lab experiments but will continue, as in the past, to receive valuable advice and assistance from industry and LBNL, as well as from our new collaborators at UCB.

Task Area 2: This task will be initiated with a different approach than originally planned. In contrast of the numerical Lattice-Boltzman simulation proposed previously, this new theoretical approach is based on the statistical mechanics describing wave propagation. A relationship is established between permeability and frequency, with separate energy transfer in the solid and fluid phases, i.e., the fluid phase pressure fluctuations are related to permeability. The theory predicts "resonant" frequencies at which permeability spikes should occur. This methodology provides a completely general model for the conductivity of an arbitrary porous medium with fluids of any type and arbitrary external disturbances that drive fluid flow. The fundamental equations have already been developed and initial solutions have been obtained at UCB. Further work is needed on specific cases and extending the modeling to actual in situ conditions. Realistic input parameters for the theoretical models will be obtained initially from results of the laboratory experiments.

Task Area 3: All relevant production data from previous, ongoing and future field tests by our industry partners will be available to the project. Seismic monitoring data will also be obtained for selected tests. Two field stimulation tests that were monitored with downhole geophones by LBNL have already been performed in year 2 by Wave Energy Resources and AERA Energy (see accomplishments). Plans for year 3 are to continue to obtain data from different field tests as they are performed by these and other companies in various promising fields. Wave Energy is planning to start 2 or 3 new tests by January 2000. OGCI Management and Applied Seismic Research each have several field tests either planned or under discussion for the upcoming year. AERA Energy (and possibly Chevron) will be continuing and expanding (based upon 1999 success) their stimulation activities in California fields using the ETREMA swept-frequency source. Several more of these sources will be deployed in horizontal and vertical wells, which will provide the opportunity to get geophones much closer to the sources to monitor the source strength. As before, most field costs will be covered by industry, with LANL and LBNL providing on-site technical and seismic monitoring support.

DELIVERABLES: In FY00, laboratory results will be reported by LANL on enhanced absolute and relative permeability, increased oil phase mobilization, production rates and reduction of residual oil saturation during water floods while pulsing the fluid pore pressure. Starting with existing theoretical models, predictions of stimulated flow behavior using realistic input parameters will be reported and compared with both laboratory and field results. The results of numerous controlled field stimulation experiments performed by industry, using several different existing downhole sources, will be summarized. Production data and seismic source propagation characteristics will be accurately monitored and summarized by LBNL and LANL.

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FUNDING LEVEL REQUESTED FOR FY2000: $350K to LANL; $230K to LBNL and UCB

FUNDING LEVEL RECOMMENDED TO DOE FOR FY2000: $220K to LANL; $90K to LBNL and UCB

ACCOMPLISHMENTS TO DATE

Laboratory Experiments: The laboratory system for measuring applied stress, strain, displacement, pore pressure, and stimulation parameters was implemented and calibrated for a 1"-diameter Berea sandstone sample. This apparatus had already been tested successfully for accurate measurement of fluid flow parameters. This core flow system allows us to determine lower and upper stimulation threshold parameters (such as frequency, power, and duration) and the resulting effects on permeability and elastic moduli. Initial tests on Berea sandstone were designed to investigate permeability enhancement and reduction of residual oil saturation. Axial stress cycling at 20-50 Hz successfully mobilized in situ clay fines and increased the permeability of the core by as much as 15% during single-phase brine flow.

Simultaneous 2-phase flow of brine and decane through the sandstone sample at several decane/brine ratios showed that when the decane-to-brine flow rate ratio was less than unity, stimulation at 25-75 Hz produced a significant decrease in the bulk fluid pressure drop across the core. This phenomenon was less significant, or absent, for decane-to-brine ratios larger than unity. For a decane-to-brine flow rate ratio of 0.1, the bulk fluid pressure drop across the core decreased by approximately 10% within 10-20 seconds after stress stimulation was applied. After the stimulation was turned off, the pressure drop returned to its initial higher value within several minutes. The magnitude of the decrease in fluid pressure depended significantly on the input stimulation amplitude and frequency. Lower frequency and higher amplitude produced the largest pressure decreases.

A custom oil/water separation column was designed and fitted with appropriate transducers to allow automated real-time measurements of changes in oil and water column heights during drainage and imbibition runs. This in turn gives real-time data on displaced fluid production history. This combined with real-time pressure-drop data allow measurement of relative permeability vs. brine saturation for both stimulated and unstimulated cases. Also, a back pressure regulator was added to the system to allow experiments to be run at static pore pressures as high as 5000 psi. Numerous flooding runs were performed with brine and 10-weight oil. The data are still being analyzed, but it appears at first glance that mechanical stimulation had only subtle effects on the production and pressure histories. This is one reason we will switch to fluid coupled stimulation modes for tests performed during year 3.

Field Testing: Field monitoring of production and seismic stimulation sources was conducted in two separate oil fields using two different seismic sources. In both cases, increases in oil production were reported. During the Wave Energy/Wellington test north of Fort Collins, CO, which lasted from mid-January to mid July 1999, eight producing wells were monitored for production changes during operation of a downhole fluid pressure pulsation device. One of the eight wells showed an increase in oil cut from 6% to 10% and an apparent increase in total fluid production rate from 63 to 85 barrels per day. The field as a whole showed no significant overall production changes. However, one of the eight wells went offline permanently during the experiment. The test terminated prematurely in July due to logistical problems.

The test in AERA Energy's San Ardo field in California utilized a new design, developed by ETREMA, for a downhole magnetostrictive swept-frequency (200-400 Hz) acoustic wave radiator. The test has been operational since July 1999 and initial reports from AERA are encouraging. The production data has not yet been released to the project but AERA plans to deploy additional sources based on the results so far.

Downhole seismic monitoring of both the Wave Energy and ETREMA sources failed to produce any recorded signals that were above the ambient background noise of the fields. At Wellington the nearest available seismic monitoring well was over 1000 feet from the source stimulation well and the peak ambient background noise particle velocity in the producing formation was very high, on the order of 10-100 microns/second (roughly a factor of at least 100 higher than "typical" oil fields). Under these conditions it is not surprising that the stimulation source was undetectable. Seismic monitoring of the ETREMA source yielded similar results. Although the ambient downhole noise was roughly 1 micron/second (much lower than at Wellington) and the

geophone well was 400 feet from the source (less than half the source-receiver distance at Wellington), no signals from the ETREMA source were detectable above the noise.

Applied Seismic Research performed a test in the Permian basin using their fluid pulsation device. Although no seismic monitoring was performed during the test, the production data was made available to the project. The results show that the stimulation halted the historic decline in oil cut that was observed in the field prior to stimulation. The effect lasted for at least 4 months after stimulation ended. The oil cut after 4 months was roughly 20% higher than the extrapolated historic production data for the field predicted.