# Sonication Stimulation of Stripper Well Production in East Gilbertown Field, West-Central Alabama

**FINAL REPORT**

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**ABSTRACT**

This study evaluated the potential of sonication or acoustic energy to increase oil production in a stripper well located in the East Gilbertown Field, West-Central Alabama. Two field tests were performed; in each test production was increased by a minimum of 15% to as much as 30% for an initial period following sonication. Production levels gradually returned to pre-testing levels in a few weeks. All of the project's objectives were met. In addition, two first-time accomplishments were realized: 1) the system was operated downhole continuously for more than 40 hours, and 2) a method was devised that allowed simultaneous sonication and pumping of the produced fluid. Operating data on optimal frequency levels and power intensities were collected. Preliminary economics indicate a payback of the sonication system in 10-30 months depending on the additional amount of oil produced (0.32-0.48 $m^3$) (2-3 barrels/day) and the price of oil at the time of production. Recommendations are made for a series of long-term tests comparing and contrasting continuous and intermittent acoustic stimulation, evaluating chemical additives to aid in viscosity reduction, and determining the lateral extent of acoustic stimulation. Recommendations are also made for the development of the next generation of actuators and sensors.

## TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

## LIST OF PHOTOGRAPHS

Photograph | Page

## INTRODUCTION

Currently, world oil demand almost equals world oil supply; within the next few years demand will exceed supply. World oil production is almost 12,789,600 million $m^3$ (80 million barrels) a day; in 25 years the world will need 19,984,125 million $m^3$/day (125 million barrels/day). At the present, oil demand in the U.S. consumes 25% of the world's oil production. Demand in China recently has seen a phenomenal growth – 33% in 2003, 20% more in 2004. China now consumes about 9% of the world production. Many of the oil-producing nations are in politically unstable situations. The geopolitical pressures on oil are only going to get worse. In the short term, expanded and enhanced technology use in oil and gas exploration and production, plus the role of conservation, will provide some relief. In the medium-to-long-term, alternative sources of energy will be needed.

In the United States the situation is challenging. The U.S. has long been an importer of oil. We use about 3,357,333 $m^3$ of oil per day (21 million barrels of oil per day), but produce only about 1/3 of our needs. In 1970, U.S. production peaked at 1,598,730 $m^3$/day (10 million barrels/day); since then there has been a gradual fall-off in production. In 2002, production averaged 927,263 $m^3$ of oil per day (5.8million barrels of oil per day). Many reasons exist for the fall-off in production; the two most commonly cited reasons are market conditions and reserve depletions. Many wells and well fields have been shut-in. In the case of heavy oil deposits, the cost of generating steam to produce the oil has risen substantially. Environmental issues associated with developing new oil prospects are also mentioned as increasing the cost to produce oil.

Many of the oil fields in the U.S. are in declining primary (initial) recovery (as opposed to secondary or aided recovery), yet still have the capacity for further development. This project was conducted in such an area, the East Gilbertown Field in West-Central Alabama.

East Gilbertown Field, established in 1944, is the oldest oil field in Alabama. Production is from the Cretaceous Eutaw Formation sandstones and the Selma Group fractured chalk. From a peak production level in the early 1950's, oil production has declined to borderline profitability today, following a brief recovery period in the late 1970's. Today the focus of production efforts is on the Eutaw Formation. Eutaw wells normally produce for 20-25 years (average), peaking within the first two years of production at an average of 2,734 $m^3$/year (17,100 barrels/year). Average cumulative production from Eutaw Formation wells approximates 25,580 $m^3$ (160,000 barrels) or between 2.4-3.0 $m^3$/day (15-19 barrels of oil/day) of heavy (API 18°) oil.

East Gilbertown Field is typical of many fields throughout the United States that are in declining primary recovery and remain underdeveloped. Many of the wells in these fields are “marginal” wells. Marginal oil wells produce no more than 2.4 $m^3$/day (15 barrels of oil per day) or produce heavy oil, i.e., oil with an API index of less than 20. The average marginal oil well produces approximately 0.35 $m^3$/day (2.2 barrels of oil/day), but they comprise 84% of domestic oil wells (over 400,000) and produce more than 20% of our domestic oil – an amount equal to imports from Saudi Arabia (Fuller, 2004). Limited profitability and produced-water environmental issues have prevented many companies from attempting to increase production. Recompletion, in-field drilling and borehole extension are all possible conventional techniques to increase production. Secondary recovery via water flooding is not viable for the Eutaw Formation.

As stated in a December 1998 U.S. Department of Energy report (Pashin et al., 1998), "it is imperative that recovery efficiency be optimized and that unconventional opportunities be pursued to avoid premature abandonment of existing fields".

In order to avoid premature abandonment of these fields (and their remaining resources), the oil and gas industry needs to look at innovative, unconventional technologies for stimulating production. One of these technologies is sonication, i.e., acoustic energy. This project was designed to evaluate the potential for using sonication as a stimulation tool for increasing production from stripper wells.

The objectives of the project were:

1. To evaluate the use of sonication to stimulate oil production in stripper wells;
2. To develop "learning curve" data and know-how on methods and techniques of employing a sonication system downhole in an active well; and
3. To collect first-cut data on the economics of the process.

## EXPERIMENTAL

In this section the science of sonication is discussed, the sonication device and auxiliary equipment are described, the field setup is explained, and the experimental protocol is presented.

### The Science of Sonication

The science of sonication has been studied for more than 200 years. Early experimentalists used tuning forks (frequency) to show how acoustic/sound energy could cause ripples on the surface of water, and they also noted the extreme agitation caused when a tuning fork came in contact with the water. By the 1840's, materials had been discovered or developed which allowed the conversion of electrical and electromagnetic energy into mechanical energy. In 1842, James Joule discovered that an applied magnetic field (coil) could change the length of a bar of iron by "constricting" it. This magnetostrictive effect, named the Joule effect, is measurable and can be repeated virtually without fatigue in the metal. The physical dimension changes in such a bar of magnetostrictive material can be transformed into sound energy. Magnetostriction became the basis for numerous acoustical devices, including naval sonar. The materials favored in magnetostrictive devices, mainly nickel, became somewhat scarce during the period of the First World War due to demand for nickel for use in gun barrels and barrel liners. There was substantial incentive to develop other materials for transduction and these efforts led to investigations into piezoelectric (pressure-electric) materials and effects.

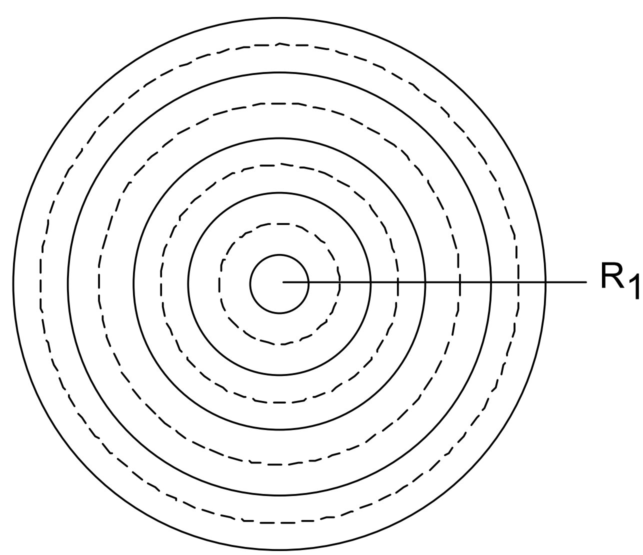
In a piezoelectric material, the application of a force or stress results in the development of an electrical charge in the material. Conversely, the application of a charge to the same material will result in a change in physical dimensions (strain) of the object. This movement can be converted from mechanical to sound energy. The development of piezoelectric ceramic sonar and the use of nickel as an energy converting material (transducer) reached their peak during World War II and for the ensuing 30 years, but eventually the physical limits of these materials were reached.

In the early 1970's, scientists at the Naval Ordnance Laboratories (now the Naval Surface Warfare Center) began experimenting with using the rare earth metals in magnetostrictive devices. Certain metal alloys of the lanthanide series showed tremendous potential for extremely high levels of magnetostriction. When a magnetostrictive rod is activated by an alternating current produced magnetic field, the oscillations (250-400 times a second) create an intense acoustic energy pressure wave that can be transmitted through a material.

Following the declassification of various sonication technology materials and data by the military in the early 1990's, considerable scientific and engineering innovations have been made in the application of acoustic energy to systems in order to affect physical and/or chemical changes in system components. Equipment and materials have evolved to the point that much larger amounts of energy can be generated for sonication purposes permitting larger and more efficient applications for a variety of different uses.

The power available in today's generation of magnetostrictive sonication materials and equipment – 1,000-6,000 watts – dwarfs what was being used in the laboratory only a few years ago, i.e., units with 350-500 watts of power. The tremendous increase in power, plus the much smaller size of sonication equipment, allows users to apply sonication technology to a number of situations at power levels previously unavailable. Thus, the technology can be used in new applications in various industrial sectors.

The physics of sound and sonication are fairly well known. Sound is a mechanical wave that consists of a pressure disturbance transmitted by means of molecular collisions in a fluid (gas or liquid). The term sonication refers to the application of sound waves (acoustic energy) transmitted through a liquid medium (water, oil, etc.) as a wave of alternating cycles of increasing and decreasing pressure. An analogy to visualize the movement of sound through a fluid is that of a stone tossed into a pond or pool of quiet, standing water. Waves radiate outward in all directions from the point where the stone hit the water (Figure 1). These are surface waves consisting of two parts – a peak or elevated portion and a trough or depressed portion. If a cork or other floating object were in the water as a wave passed, it would move up and down (perpendicular to the direction of wave motion) as each peak and trough passes its location. These types of waves are termed transverse waves where the particles of the transmitting medium move perpendicular to the wave direction; light waves are transmitted in this form.




Solid Circles Represent Crest High Points and
Dashed Circles Represents Trough Low Points

**Figure 1 Illustration of Surface Waves on Water**

Figure 1 is drawn from a perspective of being above the liquid surface looking down at the waves. If a cross-section of this system were observed along any radius from the center outward (for example $R_1$ in the above drawing), it would look like the drawing in Figure 2. This illustration shows a cross-section of a single wave with the wavelength and amplitude labeled. Here the water surface is shown as a plane where the pressure is atmospheric ($P_a$).

Beneath the liquid surface, within the liquid itself, sound waves take on a longitudinal (compressional) form meaning that the particle motion is in the direction of wave propagation. Compression cycles exert a positive pressure on the liquid, pushing molecules closer together, while expansion cycles exert a negative pressure, pulling molecules away (rarefaction) from each other. These conditions are represented by the spacing of the vertical lines and the horizontal arrows in Figure 2. The molecules tend to be pulled apart (pressure decreases) as the trough of a wave passes and pushed closer together or compressed (pressure increases) as a wave crest passes. Thus, within the fluid, the passage of a single wave of sound energy represents an alternating decrease and increase in pressure, which can be visualized to be like the sine wave representation of a surface wave shown here. The unit of measure of sound frequency is the Hertz (Hz), which is one cycle of compression and expansion or rarefaction (passage of one wavelength) in one second; a kilohertz (kHz) is one thousand cycles per second and a megahertz (MHz) is one million cycles per second. Where sound energy falls within the spectrum ranging from below the threshold for human hearing (16 Hz) to the upper level (18 kHz) is determined by the sound frequency. Ultrasound is defined as that sound above the threshold of hearing with frequencies between 20 kHz and up to 500 MHz. Sonochemistry, a rapidly growing area of research and technology development, refers to the discipline and phenomena of affecting chemical reactions by the application of sound waves (see Mason, 1999; Mason and Lorimer, 2002). Figure 3 illustrates the sonic spectrum and some applications of sound energy of various frequencies.

When the amount of energy added to the system is increased, the amplitude of the sound waves will increase as the frequency (wavelength) is held constant. As this occurs, localized pressure in the sonicated liquid may drop below its vapor pressure during the rarefaction portion of individual sound waves (Figure 4). This will initiate the formation of microbubbles in the rarefaction zone when the liquid is locally vaporized and a bubble forms around the vapor pocket. These bubbles initially are very small, on the order of 1 μm ($1 \times 10^{-6}$m, 0.001mm). This phenomenon of bubble formation is called cavitation and is the basis for most of the physical and/or chemical changes that occur in the liquid medium during the sonication process. In addition to the vaporization process due to pressure drops, the rarefaction or extension phase of the cycle causes molecules of the liquid medium to pull apart when the negative pressures exceed the tensile strength of the material or the distance between the molecules exceeds the critical molecular distance necessary to hold the liquid intact. This forms cavities or voids in the liquid medium, which produces additional bubbles during cavitation. During the alternating cycles of pressure increase and decrease, the microbubbles fluctuate in size, growing in rarefaction phases and shrinking in compression phases. Eventually, some of the individual bubbles grow to a critical size and then implode violently (collapse to zero size), releasing a large amount of localized energy (Figure 5).

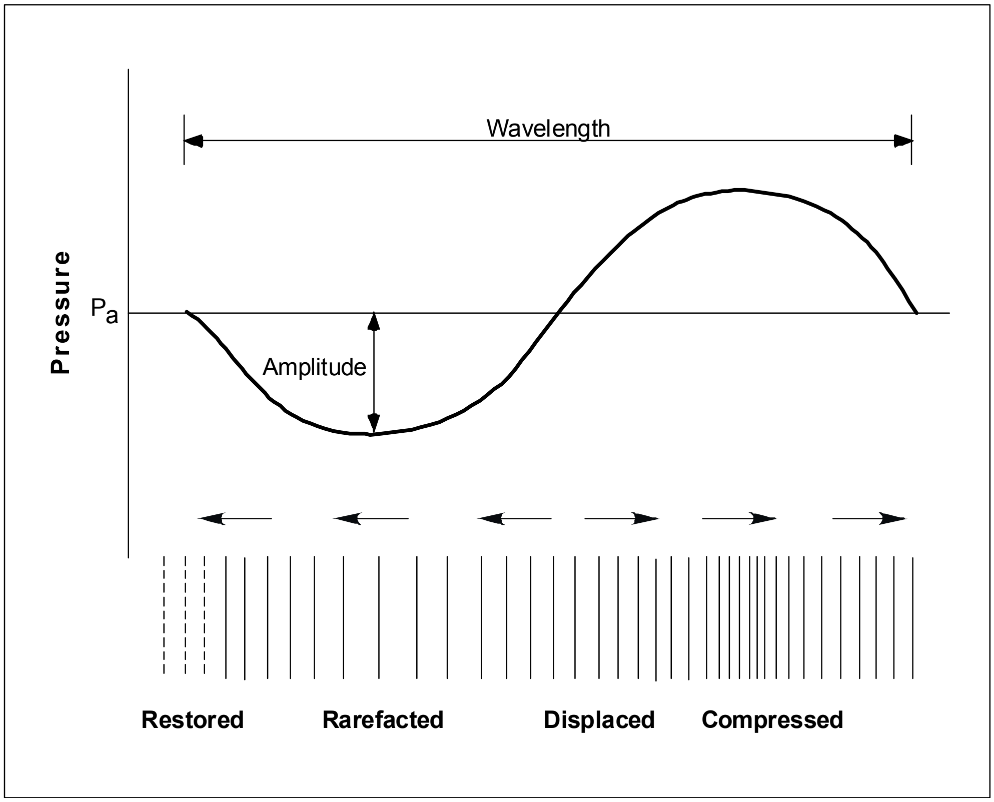



**Figure 2 Illustrations of a Single Sound Wave and the Alternating Increase and Decrease in Pressure**

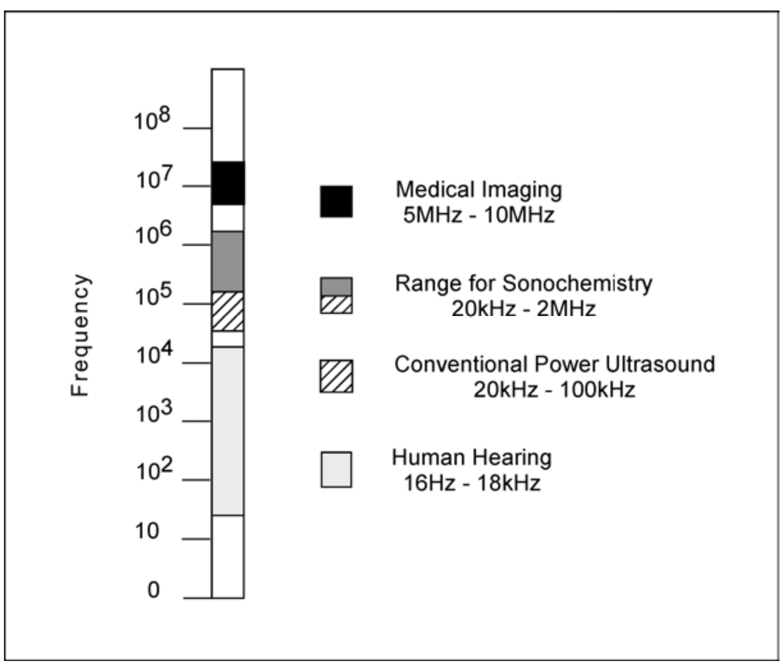



**Figure 3 Sound Frequencies**

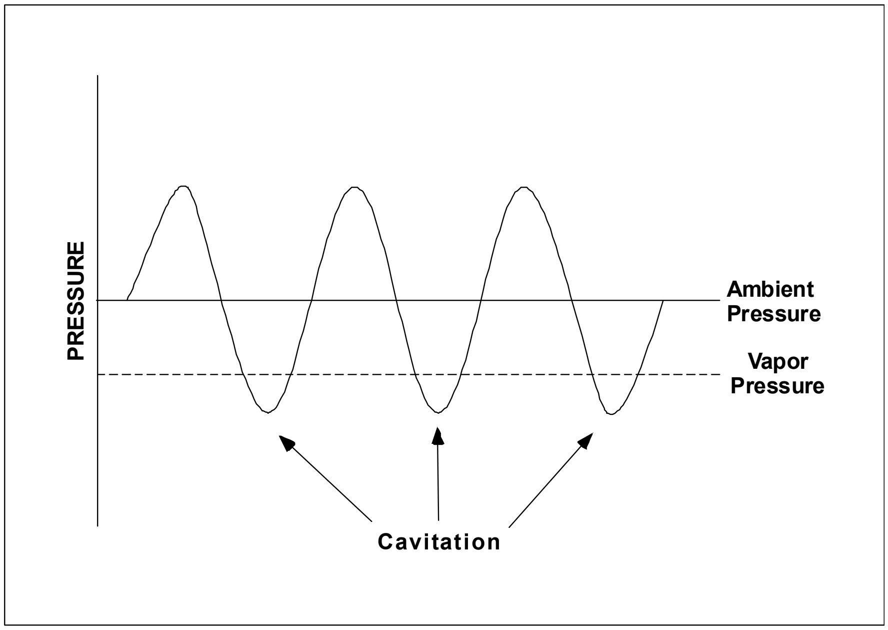



**Figure 4 Illustration of Pressure Drop Below Vapor Pressure of a Liquid Causing Cavitation**

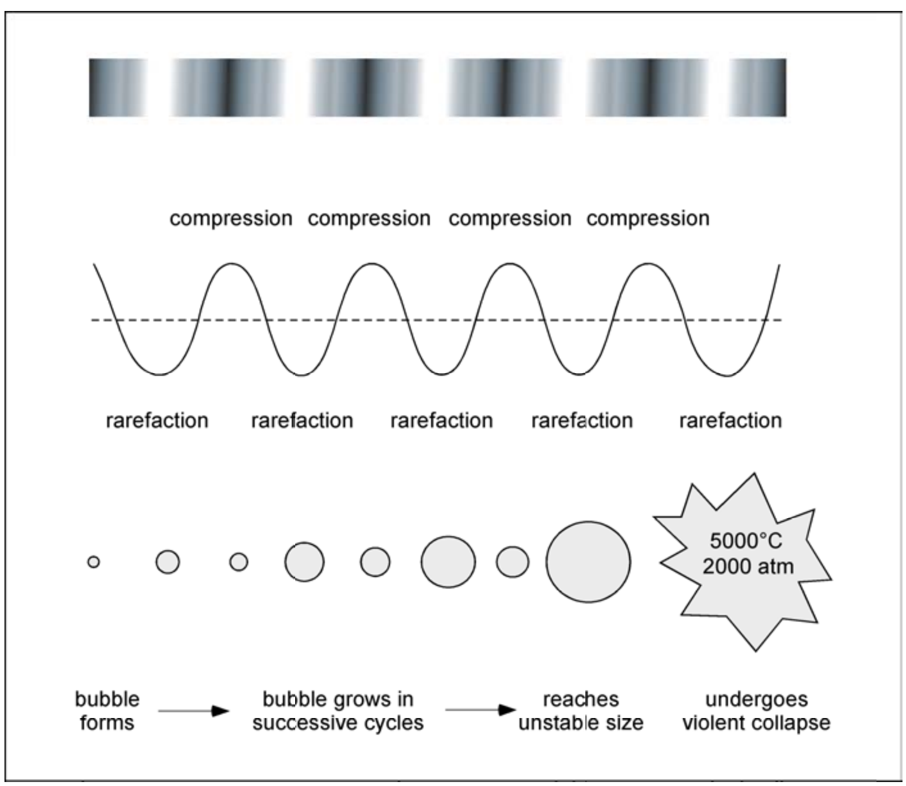



**Figure 5 Schematic Illustration of Bubble Growth and Collapse during Cavitation**

Energy released when cavitation bubbles collapse occurs in three forms. Temperatures on the order of 5,000 °K (8,500 °F) and pressures in excess of 1,000 atmospheres have been calculated to occur at the collapsing bubble interface during implosions (see Suslick, 1994). Furthermore, under some circumstances, light emissions also have been observed during sonication (sonoluminescence), which further indicates the release of intense energy from the cavitation process (Crum, Mason, Reisse, and Suslick, 1997; Beckett and Hua, 2001). It is also possible to generate strong, but small-scale shock waves within the sonicated fluid resulting from the sudden input/pulse of increased pressure when a bubble collapses. It must be remembered that all of these cavitation-related phenomena are on a very small scale and the energy dissipates very quickly in the immediate vicinity of the bubble. Consequently, the overall physical properties (e.g. temperature) of the ambient fluid tend to remain relatively unchanged. However, the very large amount of energy involved does have the capacity to produced dramatic, localized changes in the chemistry and physics of the sonicated medium (Mason and Lorimer, 2002; Mason and Peters, 2002).

In water, the reactions within and adjacent to a collapsing bubble result in the formation of hydroxyl (•OH) and hydrogen (H•) radicals. Although these chemical species are extremely short-lived, they are very reactive and effective in destroying organic compounds contained within the water. The intensity of cavity implosion and the nature of the reactions involved can be controlled by process parameters such as the sonic frequency, sonic intensity (power per unit volume of liquid), static pressure, temperature, and the addition of reactive oxidants such as hydrogen peroxide ($H_2O_2$), ozone ($O_3$), and metal catalysts. Cavitation reactions supplemented by these additives produce an advanced oxidation system that has many potential environmental and industrial applications.

## The Sonication Device

The sonication system consists of 1) an actuator or transducer, a device for converting electrical energy to mechanical energy; 2) a horn, a device for directing the mechanical energy into horizontally transmitted acoustic energy waves; and 3) an AC power source with a manual oscillator module.

The actuator used in this project was a modified version of an AA090J series model manufactured by ETREMA Products Inc. of Ames, Iowa. Information on the actuator is available on the ETREMA website, www.etrema-usa.com.

The horns were cut from 2" titanium bar stock according to a design pattern developed by Furness-Newburge, Inc. For this project, the space between the disks was approximately 2.5 cm (one inch). Related work had determined that this spacing works well when oil is the fluid medium for sonication. The upper end of the horn is threaded and connects with the base of the actuator.

The system's power is controlled by a Titan Series MAC-O1S mainframe AC power source manufactured by Compact Power Co. of Yorba Linda, California. The sonication system for this project was powered by two mainframe units, each capable of producing 1,000 watts of output power, that were connected in series to increase the voltage and available power. A Titan MOS-01 manual oscillator module with digital readout capability is connected to the mainframes. More information on and specifications for Titan series products are available at www.CompactPowerCo.com.

**Field Setup**

Two field tests were completed during this project. For each test, a field service company was put under contract to provide a wire-line truck and power. The wire-line truck contained a motorized cable reel that allowed the operator to determine the downhole depth to which the sonication device was lowered. A generator provided power. The power was sent to the Titan power source controls mounted on an equipment rack in the cab of the wire-line truck, and then connected by wires from the controls to leads in the wire-line cable. The cable was linked to the sonication system by a connector (Baker-Atlas AS4-0100) that transmitted the electrical current from the cable to the sonication system. A rigging crew was brought on site to handle the removal and reinsertion of pipe and tubing when necessary. For the first test, the rigging crew brought a backhoe for digging a pit to collect the produced oil. The pit was lined with rubber and a vacuum truck periodically emptied the pit of oil. For the second test, the oil was pumped directly to the oil storage tank for measurement and water separation. The well selected for the tests was the Rex Alman #3, located in the SE 1/4 of the NE 1/4 of Section 4 in Township 10 North, Range 3 West in the East Gilbertown Field, Choctau County, Alabama. The depth to the oil pay zone was 958 m (3143 ft) below grade; the pay zone was 3 m (10 ft) thick.

**Experimental Protocol**

Originally, this project had scheduled three downhole field tests. The costs associated with the field service companies providing support for the first downhole test exceeded the amount budgeted. As a result, the project team requested, and was given, permission to modify the project scope into two downhole field tests, while still meeting all of the planned objectives for the three scheduled tests. The experimental protocols are presented for production data and for process parameter date.

**Production Data**

The primary overall objective of the project was to evaluate the use of acoustic energy to stimulate oil production from a stripper well. For the first test, conducted from October 13 through October 17, 2003, data were collected from two different approaches. First, daily production data were obtained from records collected by Field Management LLC and subsequently sent to the Alabama Oil and Gas Board, for the month preceding the field test of October 14-17, 2003 and the month following the test. In some cases the daily production totals were unavailable, because the production data from the test well had been combined with another well or wells.

Second, during the test, oil was collected in a container of known volume by inserting the container into the produced oil stream and collecting all of the oil flowing from the open casing until the container was full, while measuring the time to fill the container with a stopwatch.

These measurements were made periodically with no set schedule and not for statistical purposes, but to obtain data on flow rates in relation to changing frequency levels and power intensities. This method was used out of necessity because, for this test, the well was open and the oil was not being pumped or collected. No flow meter was available, thus no reliable method other than the one used was available.

For the second test, the measurement method had to be changed. Because the sonication system was placed downhole and the tubing reinstalled before the test began, all oil produced was collected and transported by an underground pipe to the oil water separator/oil storage area. Therefore, the container/time method could not be used. The project team was interested in knowing daily production rates for the test well. Since the beginning of 2004, production from the test well had been combined with production from two other wells and sent to the separator/storage area. Field Management, LLC, operator of the well field, agreed to isolate the production from the test well for 30 days before the scheduled field test and to maintain the isolation for 30 days following the test, allowing a more realistic evaluation of the effect of sonication on production.

**Process Parameter Data**

Another objective of this project was to develop data and know-how on methods and techniques of using a sonication system downhole. The goals of the field tests were to identify the optimum frequency level, power intensity, and output current during the first test, then to use this information in conducting the second test where the variable was time, i.e., to run a continuous downhole test for at least 40 hours.

This project was conducted in parallel with a major study funded by the U.S. Department of Energy's Small Business Innovative Research (SBIR) program. This study – SBIR Phase I and Phase II, titled "Acoustic Energy: An Innovative Technology for Stimulating Oil Wells" – is evaluating sonication technology as a means of lowering the viscosity of oil. This detailed laboratory testing study was conducted using a specially designed and fabricated multi-actuator reactor. The laboratory portion of the project was done with the assistance of the University of Alabama at Birmingham's Department of Civil and Environmental Engineering. The project involves the evaluation of sonication's impact on three oils: a light crude with an average API index of 35, a heavy crude with an API index of 18 and a very heavy crude with an API index of 8. The 18° heavy crude is from the formation in the East Gilbertown Field being tested in the Stripper Well Consortium (SWC) project.

The SBIR study is evaluating acoustic frequency levels, various horn configurations, chemical additives, and power intensities on the viscosity of the oils. Thus a great deal of information relative to the testing in the SWC project was known from preliminary results of this other project. For example, for the SWC project, frequency levels were placed into four categories based on information developed in the SBIR study: 1) Low: 950-1150 Hertz; 2) Intermediate: 1150-1350 Hertz; 3) Medium: 1350-1550 Hertz; and 4) Medium Plus: 1550-1750 Hertz. Varying the spacing between disks on the horn (see Photo 1 in Appendix C) was evaluated in terms of viscosity reduction, and the optimum power intensity range was narrowly defined. This information was used as input to the SWC project. In the SBIR study, sonication without the addition of chemicals reduced viscosity by 15-42% in the laboratory reactor. Chemicals used in the SBIR study reduced oil viscosity by 13-40%. Combining the two – chemicals and sonication – reduced the viscosity of the heaviest oil (API index of 8) by 80%. Chemicals were not used in the SWC study.

The primary methods for determining optimum frequency are listening to the sound of an actuator under load (a trained ear can recognize the harmonic sound), watching the formation and activity of cavitation bubbles, and observing oscilloscope patterns. Because the activity for this project was taking place more than 914 m (3000 ft) below the ground surface, oscilloscope patterns were used to identify optimum patterns with the realization that harmonics at various frequency levels could produce very similar patterns. Power intensities and the output current were controlled and monitored through the MAC-O1S power supply.

The first test was designed to identify an "optimum" frequency through oscilloscope pattern recognition, observe the impact on production, then modify the power intensity and output current while maintaining an "optimum" pattern and note any changes in production. After the first test was completed, the test plan had a six-week interval built into the schedule to allow for monitoring of production data and for evaluating and determining the optimized parameters for the next test. Once optimum conditions were identified, they were used as input parameters in test two, where conditions were run continuously, as opposed to the 7-8 hour runs of test one.

## RESULTS AND DISCUSSION

### Results

#### Field Test 1, October 13-17, 2003

Upon receipt of the actuators and power supplies and following fabrication of the horns, the system was assembled and tested in the Furness-Newburge, Inc. facility in Versailles, Kentucky. After completing several tests using water (initially) and then oil, the sonication system, consisting of the actuators, the power supplies, and the horns, was and shipped (via ground transportation) to the field test site in Alabama.

**October 13.** The project team tested the sonication system onsite for mechanical and electrical reliability prior to its being inserted downhole. A centering device and a sinker bar were attached to protect the actuator and horns each time they were sent downhole. The pump and tubing were pulled from the hole, and the hole was left open for insertion of the actuator.

**October 14.** The field service crew ran a Gamma Neutron Ray Log to identify the depth to the top of the pay zone (958 m, 3143 ft below grade) and the thickness of the zone (3 m, 10 ft). The project team had decided to use the intermediate frequency level category (1150-1350 Hertz), based on the SBIR study data, with an average power intensity of 67%, i.e., output power of 1340 watts (2000 watts x 67%) and an average output voltage of 548 volts rms (root-mean-square). The 3-m (10-ft) pay zone section was traversed by lowering the actuator 15 cm (6 in) every 40 minutes. The test was run for seven hours.

According to the well operator, the well had been producing approximately 0.95 $m^3$/day (six barrels per day) before the test. During the first day of the test, flow was measured by the container-stopwatch method at between 1.3 and 1.6 $m^3$/day (eight and ten barrels per day). The sonicator was operating in an open hole and oil was flowing out of the casing into the oil collection pit.

**October 15.** The frequency was increased to the medium frequency level category (1350-1550 Hertz) and the power intensity was raised to ±85%. Thus the output power was raised to 1700 watts (85% of 2000 available watts). The output voltage was raised to an average of 556 volts rms. For this test, the actuator was lowered to the bottom of the pay zone 961 m (3153 ft) and raised 15 cm (six inches) every twenty minutes. The test was run for seven hours.

Using the container-stopwatch approach, production was measured at between 1.6 and 1.9 $m^3$ (ten and twelve barrels) per day. Visual observations of the well by the project team indicated the presence of more gas in the well on this day compared to the previous day.

**October 16.** The frequency was lowered by 11%, putting the frequency level for this day's testing in the low category (950-1150 Hertz). For the next day's testing (October 17), the frequency would be raised from the medium category into the medium plus category. Although the project team believed that operating the frequency level in the intermediate and medium categories would result in the largest production increases, the team felt that obtaining "learning-curve" data (Project Objective 2) was critical to the overall success of the project. In addition, by operating in all four frequency categories, the project would successfully complete the work scope that required "sweeping" or changing frequencies while sonicating a specific pay zone. The power intensity was reduced to 55.2% or 1104 watts of output. The output voltage was limited to 524 volts rms. During the previous two days, when the output voltage was above 526 volts rms, a slight deformation in the sine wave was noted on the oscilloscope. This deformation or shoulder appeared just below the peak of the sine wave. Tests were run and the deformation disappeared when the output voltage was below 526 volts rms. The actuator was lowered to the 961-m (3153-ft) horizon and raised 15 cm (six inches) very twenty minutes. The test was run for seven hours.

Using the container-stopwatch approach, production was measured at 1.1 to 1.3 $m^3$ (seven to eight barrels) per day.

**October 17.** The frequency was raised from the medium category (1350-1550 Hertz), to the medium plus category (1550-1750 Hertz). The power intensity was raised to 87.4% or 1748 watts of output. The output voltage was 522 volts rms. The actuator was lowered to the 961-m (3153-ft) horizon and raised 30.5 cm (one foot) every twenty minutes. The test was run for three and one-half hours.

Using the container-stopwatch approach, production was measured at 1.2 $m^3$ (7.75 barrels) of oil per day.

Following Field Test 1, production data were monitored for six weeks. A comparison of production data before and after the test shows the following. For the eighteen days from September 13, 2003 (approximately one month before the field test began) until September 30, 2003 (the last day the well was individually monitored), the Rex Alman #3 well averaged 1.15 $m^3$ (7.22 barrels of oil) produced per day. From October 1 until October 12 production data were combined with production data from one or two other wells. The well had no recorded production from October 12 through October 17, as the well was disconnected from the oil production piping system during the field test. Following the test, from October 18 through October 25, the well's production was combined with the production from one or two other wells. Starting October 26 and continuing through all of November, the well's production was individually monitored.

For the period from October 26 through October 31, coinciding with the end of the second week following completion of the field test, production was averaging 1.5 $m^3$/day (9.5 barrels/day). A week later the production had dropped to an average of 1.3 $m^3$ (8.1 barrels) per day for the three weeks following the field test. After four weeks the total production after the field test had dropped to an average of 1.22 $m^3$ (7.7 barrels) per day. The production rate continued to drop to an average of 1.19 $m^3$ (7.5 barrels) by the end of week five and 1.18 $m^3$ (7.4 barrels) at the end of week six.

In terms of the increase in oil produced expressed as a percent increased, the well was producing 31.5% more oil at the end of the second week after the test than before the test. After the third week, the increase had dropped to 12% and continued downward to 6.6% at the end of week four, 3.8% at the end of week five and 2.2% at the end of week six. Thus a definite increase in production was noted after sonication, but the increase gradually reverted back to pre-sonication production levels.

The project team reviewed the results of Field Test 1 and concluded that a method had to be devised whereby the well could be sonicated and produced (pumped) at the same time. Designing and implementing such a system became a goal for Field Test 2.

The field test and production data from Field Test 1 are included as Appendix A.

**Field Test 2, June 28-July 1, 2004**

The objective of this field test was to run the sonication system in the optimized mode (as determined from the first field test) for a "continuous" period of time. In the first field test, the system was operated for approximately seven hours per day, then removed from the well. In this test, the tool was to be left downhole, with the goal being to operate the system continually for 40 hours. The well's production would be monitored for 30 days preceding the test and for 30 days following sonication to evaluate the sonication system's ability to increase production. The project team's goal was to increase production by 15%.

A series of discussions was held during the three months preceding the field test to develop an agreed-upon concept and procedure that would allow the sonication unit to be deployed downhole, left in place downhole, and operated after all the tubing and pumping equipment was put back into the well and pumping restarted. In this type of system the well could be stimulated and pumped at the same time. Initially, the project team had hoped to insert the sonication unit through the 7.3 cm (2 7/8 in.) tubing down to the zone to be stimulated. In the well used in the test, the tubing extended 457 m (1500 ft) downhole while the oil was in a formation producing via a perforated zone between 958 m and 961 m (3143 ft and 3153 ft) downhole. The 503 m (1650 ft) between the bottom of the tubing/pump and the oil zone necessitated a tight seal in the tubing/pump to ensure an efficient operation, allowing the pump to bring the oil to the surface. Unfortunately, the power cable was 10 mm (25/64 in. thick (0.39") and precluded a tight seal and efficient vacuum. The idea of inserting the sonication system downhole through the tubing was not possible in this well.

A second approach was presented, whereby the sonication unit would be inserted into the well (after the tubing/pump had been removed), pulled to one side, then the tubing/pump would be reinstalled in the well. The well had no packer between the tubing and the casing, so this option was technically feasible. However, concern was raised that the power cable to the sonicator might be smashed, severed, or made inoperable as it swung "freely" in the casing. Some of the team felt that the cable might wrap around the tubing, eliminating the possibility of raising or lowering the sonication system to do work downhole. A solution was finally reached the week before the test was scheduled. A "pupjoint", a section of tubing much smaller than the normal 15.2-m (50-ft) lengths used in downhole operations would be attached to the end of the tubing and a slot roughly 6.4 cm (2.5 in.) wide and 10.2 cm (4 in.) long cut into the 2.4 m (8 ft) long pupjoint. While still on the land surface, the power cable would be inserted through the slot and connected to the actuator. The sonication unit would be enclosed in a cage to protect the horns at the base of the unit as it was sent downhole. A sinker bar would be added to help stabilize and center the sonication unit as the unit was lowered down to the 958-m (3143-ft) level. Then the tubing, with the pipe joint attached, would be carefully reinserted in the casing. Finally, the pump and sucker rods would be reinserted in the tubing.

**June 28.** The project team arrived at the site and began working to ensure that everyone - the project team, the site operator, and the field service crew – understood how the system would be assembled and put downhole. The field service crew returned to their facility to prepare the pupjoint and the project team tested the sonication system – power supply, actuator and horns – to ensure its operability.

**June 29.** At 6:00 am the team assembled on site, and the unit was placed downhole. The tubing (with the pupjoint) and the pump/rods were reinserted in the well. At 7:30 am the sonication unit was started and the power was slowly increased according to a preset schedule. By 7:45 am the unit was operating flawlessly at the optimized parameters. Based on the data from Field Test 1, the project team decided to start this test with the frequency in the intermediate frequency level category (1150-1350 Hertz). The power intensity was set at 79%, thus the output current was 1580 watts; the output voltage was 422 volts rms. The actuator was positioned at the 959-m (3145-ft) level, approximately 0.6 m (2 ft) below the top of the pay zone.

The entire project team left the site late in the afternoon; the system was left operating. One member of the field service crew returned during the night to refill the portable generator with gasoline.

**June 30.** The unit continued to operate throughout the day. At 8:30 am the project team raised the frequency level to the medium frequency level category (1350-1550 Hertz). The first field test had maximum oil production at the intermediate and medium frequency levels. The project team had decided to initiate operations at the intermediate level and, after 24 hours, switch to the medium level. The power intensity was lowered slightly, to 74.3% or 1486 watts of output current, and the output voltage was 464 volts rms. The actuator was lowered to the 960-m (3150-ft) level, approximately 0.9 m (3 ft) above the base of the pay zone.

The entire project team left the site late in the afternoon and the system was left operating as during the previous night. A member of the field service crew refilled the gas tank on the generator an hour before midnight and reported that the unit was functioning normally.

**July 1.** Upon arrival at the site, the system was found to be not functioning properly. The output current was down to 29% and the amperage, normally at 2.2-2.3 amps, was down to 1.0 amps. After a series of tests, it was apparent that there was a short circuit, probably a broken wire, in the field-service power unit. The unit had been operating continuously for more than 40 hours until a wire in the field-service power assembly failed early on the morning of July 1. By knowing the amount of gasoline used per hour and by observing the read-out indicator on how much gasoline remained in the generator gas tank, the field service crew was able to back-calculate to determine that the wire bringing power to the actuator failed around 2:30 am Thursday morning. Therefore the project team assumes the unit ran approximately 42.5 hours before the problem occurred.

The sonication system was removed by mid-morning and the tubing/pump reinstalled by the early afternoon

Upon returning home, the sonication unit was tested and functioned properly. Had the power wire not broken, the system most likely would have continued to operate. However, the project team believes that this test was the longest, continuously operated, downhole test of a magnetostrictive sonication system that has been conducted to date.

Production data was reviewed for all of 2004 prior to the test date. Field Management LLC, operator of the entire well field, agreed to separate the production data from the project test well at least one month prior to the scheduled field test date. The well's production data had been combined with production data from two other wells from January 27, 2004 through May 15, 2004. Beginning on May 16, the well was monitored individually. Production averaged 1.0 $m^3$ (6.3 barrels) per day from May 16 through June 27, 2004. On June 28, the well was opened and the tubing and pump/rods were removed. On June 29, following the downhole installation of the sonication unit, the tubing and pump/rods were reinstalled in the well and pumping began at 9:30 am. On June 30, 1.3 $m^3$ (eight barrels) of oil production were recorded. On July 1, following the wire break and loss of power to the sonication unit, the tubing and pump/rods were removed from the well so that the sonication unit could be removed. The tubing and pump were reinstalled in the well and production resumed. From July 2 through August 6, 2004, the well averaged 1.2 m3 (7.3 barrels) per day, an increase of 15.87%. Thus the objective of a 15% increase in production for Field Test 2 was met

The field test data and associated production data from Field Test 2 are included in Appendix B of this report.

## Discussion

Data were analyzed relative to the objectives of the project, i. e., increased production, system operation, and first-cut economics.

### Increased Production

The primary objective of the project was “to evaluate the use of sonication to stimulate oil production in stripper wells”.

In mid-April of 2003, TechSavants, Inc. and Furness-Newburge, Inc. conducted a sonication stimulation test for a private client in California. Production increased by 30% and held for a period of several months. A second well may have been indirectly stimulated, adding to the recorded increase in production. The test included use of a chemical to induce chemical viscosity change in addition to the physical velocity change due to sonication.

In October 2003, the first field test was conducted under this Stripper Well Consortium project. The test well – Rex Alman 3 – had been producing 1.15 $m^3$ (7.22 barrels) of oil per day up to two weeks before the test. No data on the well’s production was available for the two-week period immediately preceding the test, as the production had been combined with production from one or two other wells. During the test, oil production was recorded by a container-stopwatch method, with production on the first day of testing being between 1.3 and 1.6 $m^3$ (8 and 10 barrels). The second day's production averaged between 1.6 and 1.9 $m^3$ (10 and 12 barrels). For the last two days, production averaged 1.1 to 1.3 $m^3$ (7 to 8 barrels) per day. Following the test, the field crew reconnected the well to combine its production with one or two other wells, as had been done as normal operations. After eight days, the well's production finally was isolated. For the next six days the production level averaged 1.5 m3 (9.5 barrels) a day, an increase of 31.5% more than pre-testing levels. Since the production levels slowly decreased over the next four weeks, one might surmise that the production levels might have been even greater during the eight days for which no individual production data could be recorded. Over the next four weeks, average daily production as computed from cumulative weekly production, gradually decreased with values of 1.29, 1.22, 1.19, and 1.18 $m^3$ (8.1, 7.7, 7.5, and 7.4 barrels) of oil per day.

For the second field test, the well's production was isolated. Daily production averaged 1.0 $m^3$ (6.3 barrels) of oil per day for the month before sonication and 1.2 $m^3$ (7.3 barrels) for a month after sonication, an increase of 15.87%.

The goal of the project team was to increase production by 15%; the data indicate that the goal was met overall and in each of the tests.

As to why production increased, several mechanisms are proposed. While this list is not exhaustive, the likelihood is that a combination of the proposed mechanisms, perhaps not all operating at the same time, accounts for the observed increase in production. Beresnev and Johnson (1994) provide an excellent review of work (especially Russian studies) on elastic wave stimulation and oil production.

The proposed mechanisms for increasing production are:

1. Viscosity change. In parallel with the current project, TechSavants, Furness-Newburge and an oil industry consultant have been working with the University of Alabama at Birmingham on a U.S. Department of Energy Small Business Innovation Research (SBIR) project (SBIR I and II) to evaluate the impact of sonication and selected sonication system parameters – power intensity, horn spacing, frequency levels, time, and chemical additives – on changing the viscosity in three oils with differing API index numbers. One of the oils is from the East Gilbertown Field in Alabama. The SBIR studies gave the project team insights relative to that oil on horn spacing, power intensity and optimum frequency range. Viscosity reductions of 21-24% were measured for the East Gilbertown oil (15-42% for heavier oil) in the SBIR II study, almost entirely due to acoustic energy, as the actuators were not in direct contact with the oil thereby negating any effect of actuator-generated heat on the results. In downhole applications, the heat from the actuators will be dissipated into fluids in the formation (increasing viscosity reduction) and in the casing, as long as the downhole temperature is less than the heat released by the actuator. Viscosity reduction leads to better, more mobile flow, and increasing production.

2. Screen clogging. In many wells, production is inhibited by a buildup of accumulated petroleum-related products, especially asphaltene deposits, on the screens used in an attempt to keep sand and other debris from entering the well and being pumped to the surface. These types of deposits can also reduce the effectiveness of casing perforations. In studies conducted for three industrial clients, TechSavants and Furness-Newburge cleaned metal mesh screens and slotted pipe of buildup, increasing the flow rate in the system. Thus the initial pulse of production might be related in some part to screen or perforation cleaning. A longer-term study would help determine the role of screen cleaning on production.

3. Film removal. Similarly, sonication has the ability to remove organic scale and films from pore spaces, thus increasing the formation's ability to transmit fluids from and through pore spaces. If there is a very thin layer of water between the film and the host rock, the film can be readily broken away from the rock. If there is a layer of oil between the film and the host rock, the task is much more difficult.

4. Gas bubbles. As the formation is sonicated, gas bubbles can form within interstitial/pore liquids. The gases may be a) carbon dioxide, related to the destruction of oil-eating bacteria; b) hydrogen, related to cavitation and the breakdown of formation water; and/or c) organic gases related to chemical reactions between the oil and the acoustic energy of sonication.

5. Change in frictional forces. In many cases the oil might not flow because it is held (at the microscopic level) by capillary forces within the pore spaces in the formation. The acoustic energy put into the formation by sonication may be enough to overcome the adhesive forces of capillary attraction and break the physical bonds between the oil and the formation. If a very thin layer of water exists between the oil and the host rock, the bond is easier to break than if the oil is directly attached to the rock.

While these mechanisms may all have had a role in the increase in production (as may other mechanisms), it was not the design nor intent of this study to identify production-increasing mechanisms. However, at some point, a cause-and-effect study needs to be done to identify and quantify the mechanisms by which acoustic energy increases production. Only then will a truly optimized and targeted sonication system be able to be designed, built, and implemented.

This study answered the original problem statement "Does the use of sonication increase oil production in stripper wells?" with a positive "yes". What is left to answer is the question of "how".

**System Operation**

The secondary objective of the project was "to develop learning curve data and know-how on methods and techniques of employing a sonication system downhole in an active well".

The following discussion will focus on the sonication system and then on the downhole operation.

**Sonication system.** The sonication system performed quite well. The project team was concerned about power levels, as running the system at higher levels increases internal wear on the equipment and increases the cost of operating the system. From earlier laboratory and field work, the project team knew that the optimized power range was between 75 and 90%. The first field test was operated at a wide range of power levels to gain experience on interpreting the relationship between power and system performance. For the second test, the power was kept in a limited range, 74-79%.

Output voltage had to be controlled, as too large of a value resulted in distortions to the sine wave on the oscilloscope. Oil production was maximized when the frequency was in the medium category; slightly less production resulted when the frequency levels were in the intermediate category.

For the first test, the equipment was removed from the well at the end of each day's activities and examined for wear. The equipment was housed in a cage to protect it while being inserted downhole and when brought back to the land surface. On one occasion the cage was damaged, and as a result, one of the horns was bent. A modified cage design was developed that appeared to resolve the problem.

In the first test, since each day's activity was done as a separate event, the project team was limited in the amount of time the sonication system could be continuously operated. In addition, because the oil was not collected under on-line pumping conditions, an accurate characterization of the short-term impact of sonication on increased production was difficult to obtain. The second test, therefore, needed to be conducted under conditions where sonication and pumping were occurring at the same time. The project team's activity planned for the second test was "to run a lengthy, continuous test using the conditions that maximized oil production…". The project team set a goal of 40 hours of continuous operation. Even though the test ended when a wire in the power cable/connection system broke, the system had been running for 42.5 hours, thus the goal was met. Had the wire not broken, the unit would have continued to function. However, to the best of the project team's knowledge, this test was the longest, continuous operation of a magnetostrictive sonication system in a pressurized, operating well that has been completed to date.

**Downhole operation.** Operating the sonication system downhole while pumping/producing oil required developing a unique method for running the system. For this type of well, without a downhole packer, a pupjoint could be attached to the tubing to serve as a guide for centering and controlling the actuator and centering bar. The bar was needed to add weight to the system to help lower the actuator through any oil and water in the well casing. The slot cut into the pupjoint also helped eliminate concerns about the actuator cable wrapping itself around the tubing, thus making raising and lowering of the actuator, as well as precise positioning of the actuator at the desired depth in the pay zone, impossible. Other methods of operation may be required in different downhole situations.

A second downhole issue was the use of a generator to provide power. In situations where electric power is available, the sonication unit should be powered in this manner, rather than using a generator, thereby eliminating the need for someone to stay on site or return to the site to monitor and service the generator. Where power is not available, a generator will be needed.

Another issue that was resolved pertained to positioning the actuator in the pay zone. For the second field test, the system was operating at a depth of 959 m (3145 ft), i.e., the upper half of the pay zone. The project team felt that operating near the top of the pay zone would remove petroliferous material adhering to the perforations, allowing any oil trapped beyond or within the perforations to flow into the well and be pumped to the surface. In addition, the team assumed that the oil would migrate upward in the pay zone, thus the team believed that opening up the perforations near the top of the oil-bearing section would allow more oil to flow into the well, whether water driven or because of viscosity reduction. The test plan called for lowering the sonication device to near the base of the pay zone for days two and three to change the viscosity in the lower half of the formation, allowing the oil to move upward in the section and/or into the well bore. Late on day three and from that point in time throughout the rest of the field test, the unit would be raised back to the upper half of the pay zone to keep the perforations open, the viscosity lowered, and the oil flowing. With the broken wire occurring near the end of day two, the plan was not followed. However, the project team believes the approach of opening the top of the pay zone, then attacking the lower part(s) of the pay zone, and finally returning to the top of the pay zone will maximize production in acoustically stimulated wells.

**Economics**

The third objective of this study was "to collect first-cut data on economics of the process". Because this was primarily a research study, many of the costs were first-time costs. In addition, because one of the objectives of this study was to obtain data on operating parameters, a comparison of the project's actual costs with projected future costs (in a non-research mode) is required. Labor support was the largest cost. Extensive costs were realized during the first test, as a result of having a field operating crew and a wireline truck/field service crew on site for the duration of the test. For the second test, the on-site manpower was reduced in number and in the time present on site.

The project team projects the following costs to install a downhole sonication system where the actuator will be left downhole and operated as needed:

Length of time = two days. Depth = 915-1219 m (3000-4000 feet).

| | |
|---|---|
| Labor: field crew and wireline truck/crew | $ 5,000 |
| Cost of sonication unit plus backup unit | $ 24,000 |
| Installation cost (manpower and expenses) | $ 7,000 |
| Total | $ 36,000 |

These costs may be lowered as the number of units sold increases.

With the price of a barrel of oil rising and the uncertainty therein, one can assume that the following payback scenarios are speculative.  If production is increased two barrels a day, and the amount received by the well owner is $20 per barrel, payback is achieved (just on the increase in production) in 900 days or approximately 30 months.  At $30/barrel, payback takes 20 months; and at $40/barrel, 15 months.  If production is increased by 3 barrels/day, payback goes down to 20 months for $20 oil, 13 months for $30 oil, and 10 months for $40 oil.

## CONCLUSIONS

This project evaluated the impacts of the use of sonication to stimulate oil production in the East Gilbertown Field, West-Central Alabama. The project's primary objective was to determine and document if downhole sonic (acoustic) stimulation resulted in increased oil production. Related objectives were to develop information and know-how on deploying a sonication system downhole and to develop first-cut economic data. All of the project's objectives were accomplished.

The following conclusions were reached:

1. Sonic (acoustic) stimulation increased production in each of the two field tests by a minimum of 15% to as large as 30% for an initial period, then production returned to levels slightly higher than original levels within a few weeks. The data showed that sonication did have an impact on production, but the impact was related to operating the sonication system. When sonication was stopped, the impact on increased production gradually abated.

2. The sonication system (power source, actuator, and horn) was operated continuously for more than 40 hours. This period of time was the longest, continuously run test to date and demonstrated that the actuator and horn could be left downhole to operate for extended periods of time. This fact is critical to the future commercial development of oil well stimulation by sonication, as the field tests made it apparent that the wells would have to be stimulated at selected intervals (periodically to continuously) by an actuator left downhole.

3. A method was devised and successfully employed that allowed sonication and fluid production by pumping to occur simultaneously. Development of this method also was critical to the future commercial success of the technology, as the flexibility of periodic sonication with continuous pumping maximizes oil production while minimizing the cost of field operations.

4. Data on optimum frequency levels and power intensities were developed. While these data are useful as guidelines for applying sonication technology in a certain type of sandstone lithology, more data are necessary from other types of geologic conditions before optimization of a sonication system can be achieved.

5. Very preliminary data on the economics of the system indicate that payback of the system's cost is relatively quick. Depending on the number of cubic meters or barrels of oil per day of increased production, plus the price the well owner gets for the oil, payback times for a deployed sonication system could range from 30 to as little as 10 months, if just 0.32-0.48 additional m3 (2-3 additional barrels) of oil are produced per day.

The following recommendations are made with the idea of rapidly commercializing the technology:

## RECOMMENDATIONS

1. The tests run to date have been of limited duration. Although the technology and methodology have now been developed and demonstrated to the point where both sonication and pumping can be operated simultaneously, it is now time for a series of long-duration field tests. At a minimum, tests should be run for periods of two, four, and six weeks, with simultaneous, continuous sonicating and pumping.

2. A second series of tests should be run where the sonication system is operated intermittently while pumping is continuous, for a period of six weeks. Special concern should be taken to monitor production levels related to the intermittent use of the sonication system.

3. A series of tests should be run using chemical additives in conjunction with sonication to reduce the viscosity of the oil as another means to increase production in stripper wells. Based on data from the DOE funded SBIR II study "Acoustic Energy: An Innovative Technology for Stimulating Oil Wells" being conducted by two members of the project team (TechSavants, Inc., and Furness-Newburge, Inc.) plus the University of Alabama at Birmingham and Aarmco, an oil industry consulting group, the chemicals used in the study reduced the viscosity of API 8° oil from 13-40% in addition to the 15-42% reduction related to sonication. The effects of using chemicals plus sonication to increase oil production from stripper wells needs to be evaluated in closely monitored field tests.

4. New instrumentation and equipment need to be developed to increase the efficiency and performance of the sonication system. The next generation of actuators needs to be developed specifically for downhole use, i.e., for operating in high-temperature, high-pressure, corrosive environments. The power of the actuators must be increased, the broadband frequency capabilities expanded, and a higher efficiency method for directing and transferring the acoustic energy into the oil-bearing formation must be developed.

5. Data collection needs to be enhanced through the development of accurate, robust, and reliable sensors. New passive photonic sensors need to be developed and integrated with the actuator into a downhole package to measure pressure waves (pressure levels and gradients), temperatures, and flow rates of fluids of various densities.

6. One of the critical factors in evaluating the effectiveness of acoustic stimulation on stripper well production is a determination of the lateral extent of the input stimulus. Ultra-low frequency sound (20-100 Hertz) is known to travel laterally for several miles. What is unknown is how far the impacts of sonication – the acoustic wave – extend before becoming ineffective, at the frequencies necessary to increase oil production. If it can be shown that an acoustic wave has enough energy to impact (increase production) in nearby wells, the value of the technology dramatically increases and the operating costs to produce a barrel of oil decrease dramatically.

Deploying geophones downhole alongside passive wave sensors (recommendation 5) needs to be integrated into the long-term field tests recommended in items 1-3 above.

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# APPENDIX A

# FIELD TEST 1 DATA

## APPENDIX A

**Table A-1 Test Data for October 14, 2003**

| Depth (ft) | Start | End | Duration | Frequency | Output % | Volts |
|---|---|---|---|---|---|---|
| 3,142.0 | 8:17 | 8:22 | Warm-up | Intermediate | 20.3 | 222 |
| 3,142.0 | 8:22 | 9:00 | Warm-up | Intermediate | 64.1 | 540 |
| **Depth (ft)** | **Start** | **End** | **Duration** | **Frequency** | **Output %** | **Volts** |
| 3,143.0 | 9:00 | 9:23 | 0:23 | Intermediate | 66.4 | 546 |
| 3,143.5 | 9:23 | 9:43 | 0:20 | Intermediate | 66.8 | 548 |
| 3,144.0 | 9:43 | 10:02 | 0:19 | Intermediate | 66.7 | 546 |
| 3,144.5 | 10:02 | 10:22 | 0:20 | Intermediate | 66.9 | 546 |
| 3,145.1 | 10:22 | 10:42 | 0:20 | Intermediate | 67.1 | 546 |
| 3,145.4 | 10:42 | 11:02 | 0:20 | Intermediate | 67.2 | 546 |
| 3,146.0 | 11:02 | 11:21 | 0:19 | Intermediate | 67.3 | 548 |
| 3,146.5 | 11:21 | 11:41 | 0:20 | Intermediate | 67.3 | 548 |
| 3,147.0 | 11:41 | 12:01 | 0:20 | Intermediate | 67.4 | 548 |
| 3,147.5 | 12:01 | 12:20 | 0:19 | Intermediate | 67.5 | 548 |
| 3,147.9 | 12:20 | 12:40 | 0:20 | Intermediate | 67.5 | 548 |
| 3,148.4 | 12:40 | 12:59 | 0:19 | Intermediate | 67.5 | 548 |
| 3,149.0 | 12:59 | 13:19 | 0:20 | Intermediate | 67.5 | 548 |
| 3,149.4 | 13:19 | 13:40 | 0:21 | Intermediate | 67.4 | 548 |
| 3,150.0 | 13:40 | 14:00 | 0:20 | Intermediate | 67.3 | 548 |
| 3,150.5 | 14:00 | 14:20 | 0:20 | Intermediate | 67.2 | 548 |
| 3,151.0 | 14:20 | 14:40 | 0:20 | Intermediate | 67.2 | 548 |
| 3,151.5 | 14:40 | 14:59 | 0:19 | Intermediate | 67.1 | 548 |
| 3,152.0 | 14:59 | 15:19 | 0:20 | Intermediate | 67.0 | 548 |
| 3,152.5 | 15:19 | 15:39 | 0:20 | Intermediate | 67.2 | 548 |
| 3,153.0 | 15:39 | 16:00 | 0:21 | Intermediate | 67.3 | 548 |

NOTE: Output Current = Output % multiplied by 2000 watts. To convert depth in feet to depth in meters, multiply by 0.3048.

**Table A-2  Test Data for October 15, 2003**

| Depth (ft) | Start | End | Duration | Frequency | Output % | Volts |
|---|---|---|---|---|---|---|
| 3153.0 | 7:36 | 7:45 | Warm-up | Low | 15.2 | 204 |
| 3153.0 | 7:45 | 7:54 | Warm-up | Low | 58.2 | 542 |
| 3153.0 | 7:54 | 8:00 | Warm-up | Medium | 81.0 | 548 |
| **Depth (ft)** | **Start** | **End** | **Duration** | **Frequency** | **Output %** | **Volts** |
| 3153.0 | 8:00 | 8:20 | 0:20 | Medium | 82.8 | 550 |
| 3152.5 | 8:20 | 8:41 | 0:21 | Medium | 82.7 | 552 |
| 3152.0 | 8:41 | 9:00 | 0:19 | Medium | 83.1 | 550 |
| 3151.5 | 9:00 | 9:22 | 0:22 | Medium | 83.6 | 554 |
| 3151.0 | 9:22 | 9:40 | 0:18 | Medium | 84.2 | 556 |
| 3150.4 | 9:40 | 10:00 | 0:20 | Medium | 84.7 | 556 |
| 3149.5 | 10:00 | 10:20 | 0:20 | Medium | 84.7 | 556 |
| 3149.0 | 10:20 | 10:40 | 0:20 | Medium | 84.8 | 556 |
| 3148.5 | 10:40 | 11:01 | 0:21 | Medium | 85.0 | 556 |
| 3147.9 | 11:01 | 11:21 | 0:20 | Medium | 85.2 | 556 |
| 3147.3 | 11:21 | 11:40 | 0:19 | Medium | 85.3 | 558 |
| 3147.0 | 11:40 | 12:00 | 0:20 | Medium | 85.4 | 558 |
| 3146.4 | 12:00 | 12:20 | 0:20 | Medium | 85.5 | 558 |
| 3146.0 | 12:20 | 12:40 | 0:20 | Medium | 85.6 | 558 |
| 3145.5 | 12:40 | 13:00 | 0:20 | Medium | 85.7 | 558 |
| 3145.0 | 13:00 | 13:20 | 0:20 | Medium | 85.5 | 558 |
| 3144.4 | 13:20 | 13:40 | 0:20 | Medium | 85.4 | 558 |
| 3144.0 | 13:40 | 14:00 | 0:20 | Medium | 85.3 | 558 |
| 3143.5 | 14:00 | 14:21 | 0:21 | Medium | 84.8 | 556 |
| 3143.0 | 14:21 | 14:40 | 0:19 | Medium | 84.8 | 556 |
| 3142.5 | 14:40 | 15:00 | 0:20 | Medium | 84.7 | 556 |

NOTE: Output Current = Output % multiplied by 2000 watts.  To convert depth in feet to depth in meters, multiply by 0.3048.

**Table A-3  Test Data for October 16, 2003**

| Depth (ft) | Start | End | Duration | Frequency | Output % | Volts |
|---|---|---|---|---|---|---|
| 3153.0 | 7:50 | 7:55 | Warm-up | Low | 15.2 | 212 |
| 3153.0 | 7:55 | 8:00 | Warm-up | Low | 36.7 | 520 |
| **Depth (ft)** | **Start** | **End** | **Duration** | **Frequency** | **Output %** | **Volts** |
| 3153.0 | 8:00 | 8:30 | 0:30 | Low | 54.6 | 526 |
| 3152.5 | 8:30 | 9:00 | 0:30 | Low | 54.6 | 526 |
| 3152.0 | 9:00 | 9:20 | 0:20 | Low | 54.5 | 522 |
| 3151.5 | 9:20 | 9:40 | 0:20 | Low | 54.7 | 524 |
| 3151.0 | 9:40 | 10:00 | 0:20 | Low | 54.8 | 524 |
| 3150.5 | 10:00 | 10:20 | 0:20 | Low | 55.0 | 524 |
| 3150.0 | 10:20 | 10:40 | 0:20 | Low | 55.4 | 524 |
| 3149.6 | 10:40 | 11:01 | 0:21 | Low | 55.4 | 524 |
| 3149.1 | 11:01 | 11:20 | 0:19 | Low | 55.5 | 524 |
| 3148.5 | 11:20 | 11:40 | 0:20 | Low | 55.6 | 524 |
| 3148.0 | 11:40 | 12:00 | 0:20 | Low | 55.8 | 524 |
| 3147.5 | 12:00 | 12:20 | 0:20 | Low | 55.7 | 524 |
| 3147.0 | 12:20 | 12:40 | 0:20 | Low | 55.3 | 524 |
| 3146.5 | 12:40 | 13:00 | 0:20 | Low | 55.3 | 524 |
| 3146.0 | 13:00 | 13:20 | 0:20 | Low | 55.2 | 524 |
| 3145.5 | 13:20 | 13:40 | 0:20 | Low | 55.2 | 524 |
| 3145.0 | 13:40 | 14:00 | 0:20 | Low | 55.2 | 524 |
| 3144.5 | 14:00 | 14:20 | 0:20 | Low | 55.3 | 524 |
| 3144.0 | 14:20 | 14:40 | 0:20 | Low | 55.2 | 524 |
| 3143.4 | 14:40 | 15:00 | 0:20 | Low | 55.3 | 524 |
| 3143.0 | 15:00 | 15:20 | 0:20 | Low | 55.3 | 524 |

NOTE: Output Current = Output % multiplied by 2000 watts.  To convert depth in feet to depth in meters, multiply by 0.3048.

**Table A-4 Test Data for October 17, 2003**

| Depth (ft) | Start | End | Duration | Frequency | Output % | Volts |
|---|---|---|---|---|---|---|
| 3153.0 | 7:23 | 7:35 | Warm-up | Medium + | 14.8 | 142 |
| **Depth (ft)** | **Start** | **End** | **Duration** | **Frequency** | **Output %** | **Volts** |
| 3153.0 | 7:35 | 8:00 | 0:25 | Medium + | 85.0 | 518 |
| 3152.0 | 8:00 | 8:20 | 0:20 | Medium + | 86.7 | 522 |
| 3150.9 | 8:20 | 8:40 | 0:20 | Medium + | 86.8 | 522 |
| 3149.9 | 8:40 | 9:00 | 0:20 | Medium + | 87.2 | 522 |
| 3148.9 | 9:00 | 9:20 | 0:20 | Medium + | 87.7 | 522 |
| 3147.9 | 9:20 | 9:40 | 0:20 | Medium + | 87.7 | 522 |
| 3146.9 | 9:40 | 10:00 | 0:20 | Medium + | 88.0 | 522 |
| 3146.0 | 10:00 | 10:20 | 0:20 | Medium + | 88.1 | 522 |
| 3145.0 | 10:20 | 10:40 | 0:20 | Medium + | 88.3 | 524 |
| 3144.0 | 10:40 | 11:00 | 0:20 | Medium + | 88.4 | 524 |

NOTE: Output Current = Output % multiplied by 2000 watts. To convert depth in feet to depth in meters, multiply by 0.3048.

**Table A-5 Production Data Associated with Test 1**

| Production Source | Date | Production (barrels/day) |
|---|---|---|
| Rex Alman #3 | 9/13/2003 | 2 |
| ¨ | 9/14/2003 | 3 |
| ¨ | 9/15/2003 | 6 |
| ¨ | 9/16/2003 | 5 |
| ¨ | 9/17/2003 | 7 |
| ¨ | 9/18/2003 | 6 |
| ¨ | 9/19/2003 | 8 |
| ¨ | 9/20/2003 | 8 |
| ¨ | 9/21/2003 | 8 |
| ¨ | 9/22/2003 | 8 |
| ¨ | 9/23/2003 | 8 |
| ¨ | 9/24/2003 | 8 |
| ¨ | 9/25/2003 | 9 |

| Production Source | Date | Production (barrels/day) |
|---|---|---|
| Rex Alman #3 | 9/26/2003 | 9 |
| ¨ | 9/27/2003 | 9 |
| ¨ | 9/28/2003 | 9 |
| ¨ | 9/29/2003 | 8 |
| ¨ | 9/30/2003 | 9 |
| Combined with Hubert Mosley#3 | 10/1/2003 | 27 |
| ¨ | 10/2/2003 | 33 |
| ¨ | 10/3/2003 | 37 |
| ¨ | 10/4/2003 | 37 |
| ¨ | 10/5/2003 | 30 |
| ¨ | 10/6/2003 | 40 |
| ¨ | 10/7/2003 | 32 |
| ¨ | 10/8/2003 | 30 |
| ¨ | 10/9/2003 | 28 |
| ¨ | 10/10/2003 | 32 |
| ¨ | 10/11/2003 | 23 |
| Test Well Shut Down | 10/12/2003 | Down – Test Period |
| ¨ | 10/13/2003 | Down – Test Period |
| ¨ | 10/14/2003 | Down – Test Period |
| ¨ | 10/15/2003 | Down – Test Period |
| ¨ | 10/16/2003 | Down – Test Period |
| ¨ | 10/17/2003 | Down – Test Period |
| Combined with Hubert Mosley#3 | 10/18/2003 | 60 |
| ¨ | 10/19/2003 | 28 |
| ¨ | 10/20/2003 | 27 |
| ¨ | 10/21/2003 | 28 |
| ¨ | 10/22/2003 | 28 |
| ¨ | 10/23/2003 | 28 |
| ¨ | 10/24/2003 | 28 |
| ¨ | 10/25/2003 | 13 |

| Production Source | Date | Production (barrels/day) |
|---|---|---|
| Rex Alman #3 | 10/26/2003 | 9 |
| ·· | 10/27/2003 | 9 |
| ·· | 10/28/2003 | 9 |
| ·· | 10/29/2003 | 10 |
| ·· | 10/30/2003 | 10 |
| ·· | 10/31/2003 | 10 |
| ·· | 11/1/2003 | 3 |
| ·· | 11/2/2003 | 8 |
| ·· | 11/3/2003 | 7 |
| ·· | 11/4/2003 | 7 |
| ·· | 11/5/2003 | 9 |
| ·· | 11/6/2003 | 7 |
| ·· | 11/7/2003 | 7 |
| ·· | 11/8/2003 | 7 |
| ·· | 11/9/2003 | 7 |
| ·· | 11/10/2003 | 7 |
| ·· | 11/11/2003 | 8 |
| ·· | 11/12/2003 | 6 |
| ·· | 11/13/2003 | 8 |
| ·· | 11/14/2003 | 6 |
| ·· | 11/15/2003 | 8 |
| ·· | 11/16/2003 | 7 |
| ·· | 11/17/2003 | 7 |
| ·· | 11/18/2003 | 8 |
| ·· | 11/19/2003 | 5 |
| ·· | 11/20/2003 | 7 |
| ·· | 11/21/2003 | 7 |
| ·· | 11/22/2003 | 7 |
| ·· | 11/23/2003 | 7 |
| ·· | 11/24/2003 | 7 |

| Production Source | Date | Production (barrels/day) |
|---|---|---|
| ¨ | 11/25/2003 | 7 |
| ¨ | 11/26/2003 | 7 |
| ¨ | 11/27/2003 | 7 |
| ¨ | 11/28/2003 | 6 |
| ¨ | 11/29/2003 | 7 |
| ¨ | 11/30/2003 | 6 |

NOTE: To convert from barrels of oil per day (barrels/day) to cubic meters per day ($m^3$/day) multiply by 0.1589.

## APPENDIX B

## FIELD TEST 2 DATA

## APPENDIX B

**Table B-1  Test Data for June 29 – July 1, 2004**

| Depth (ft) | Time | Frequency | Output % | Volts |
|---|---|---|---|---|
| June 29, 2004 | | | | |
| 3144.9 | 7:30 | Intermediate | 65.7 | 352 |
| 3144.9 | 8:00 | Intermediate | 80.2 | 420 |
| 3149.0 | 9:10 | Intermediate | 79.8 | 422 |
| 3147.0 | 10:30 | Intermediate | 79.9 | 422 |
| 3144.9 | 10:45 | Intermediate | 79.8 | 422 |
| 3144.9 | 11:30 | Intermediate | 79.8 | 422 |
| 3144.9 | 12:00 | Intermediate | 79.1 | 422 |
| 3144.9 | 12:30 | Intermediate | 79.0 | 422 |
| 3144.9 | 13:00 | Intermediate | 79.2 | 422 |
| 3144.9 | 13:30 | Intermediate | 79.0 | 422 |
| 3144.9 | 14:00 | Intermediate | 79.1 | 422 |
| 3144.9 | 14:30 | Intermediate | 79.1 | 422 |
| 3144.9 | 15:00 | Intermediate | 79.1 | 424 |
| Test ran continuously through the night. | | | | |
| June 30, 2004 | | | | |
| 3144.9 | 7:00 | Intermediate | 78.0 | 424 |
| 3144.9 | 7:30 | Intermediate | 78.9 | 424 |
| 3144.9 | 8:00 | Intermediate | 77.7 | 424 |
| 3144.9 | 8:30 | Medium | 75.8 | 476 |
| 3150.0 | 9:00 | Medium | 73.8 | 464 |
| 3150.0 | 9:30 | Medium | 73.9 | 464 |
| 3150.0 | 10:00 | Medium | 73.6 | 464 |
| 3150.0 | 10:30 | Medium | 73.5 | 464 |
| 3150.0 | 11:00 | Medium | 73.5 | 464 |
| 3150.0 | 11:30 | Medium | 76.0 | 464 |
| 3150.0 | 12:00 | Medium | 76.0 | 464 |
| 3150.0 | 12:30 | Medium | 73.3 | 464 |
| 3150.0 | 13:00 | Medium | 73.1 | 464 |

| Depth (ft) | Time | Frequency | Output % | Volts |
|---|---|---|---|---|
| 3150.0 | 13:30 | Medium | 73.2 | 464 |
| 3150.0 | 14:00 | Medium | 74.9 | 464 |
| 3150.0 | 14:30 | Medium | 75.5 | 464 |
| Power Supply wire broke at 2:30 (estimated). | | | | |
| July 1, 2004 | | | | |
| 3150.0 | 8:00 | Medium | 29.0 | 464 |

NOTE: Output Current = Output % multiplied by 2000 watts. To convert depth in feet to depth in meters, multiply by 0.3048.

**Table B-2 Production Data Associated with Test 2**

| Production Source | Date | Production (barrels/day) |
|---|---|---|
| Rex Alman #3 | 5/16/2004 | 8 |
| ¨ | 5/17/2004 | 5 |
| ¨ | 5/18/2004 | 8 |
| ¨ | 5/19/2004 | 5 |
| ¨ | 5/20/2004 | 8 |
| ¨ | 5/21/2004 | 7 |
| ¨ | 5/22/2004 | 8 |
| ¨ | 5/23/2004 | 5 |
| ¨ | 5/24/2004 | 7 |
| ¨ | 5/25/2004 | 8 |
| ¨ | 5/26/2004 | 7 |
| ¨ | 5/27/2004 | 5 |
| ¨ | 5/28/2004 | 7 |
| ¨ | 5/29/2004 | 8 |
| ¨ | 5/30/2004 | 8 |
| ¨ | 5/31/2004 | 7 |
| ¨ | 6/1/2004 | 2 |
| Well Not Producing | 6/2/2004 | 0 |
| Rex Alman #3 | 6/3/2004 | 5 |

| Production Source | Date | Production (barrels/day) |
|---|---|---|
| Rex Alman #3 | 6/4/2004 | 5 |
| ¨ | 6/5/2004 | 7 |
| ¨ | 6/6/2004 | 8 |
| ¨ | 6/7/2004 | 5 |
| ¨ | 6/8/2004 | 3 |
| ¨ | 6/9/2004 | 5 |
| ¨ | 6/10/2004 | 7 |
| ¨ | 6/11/2004 | 7 |
| Pump Equipment Problem | 6/12/2004 | 3 |
| Rex Alman #3 | 6/13/2004 | 5 |
| ¨ | 6/14/2004 | 5 |
| ¨ | 6/15/2004 | 7 |
| ¨ | 6/16/2004 | 7 |
| ¨ | 6/17/2004 | 5 |
| ¨ | 6/18/2004 | 2 |
| ¨ | 6/19/2004 | 2 |
| ¨ | 6/20/2004 | 7 |
| ¨ | 6/21/2004 | 10 |
| ¨ | 6/22/2004 | 8 |
| ¨ | 6/23/2004 | 7 |
| ¨ | 6/24/2004 | 8 |
| ¨ | 6/25/2004 | 8 |
| ¨ | 6/26/2004 | 10 |
| ¨ | 6/27/2004 | 8 |
| Well Shut Down<br>Preparation for Test | 6/28/2004 | 0 |
| Tool Placed in Well | 6/29/2004 | 0 |
| Production | 6/30/2004 | 8 |
| Tool Removed from Well<br>Production Restarted | 7/1/2004 | 0 |
| Rex Alman #3 | 7/2/2004 | 7 |

| Production Source | Date | Production (barrels/day) |
|---|---|---|
| Rex Alman #3 | 7/3/2004 | 10 |
| ¨ | 7/4/2004 | 10 |
| ¨ | 7/5/2004 | 7 |
| ¨ | 7/6/2004 | 8 |
| ¨ | 7/7/2004 | 7 |
| ¨ | 7/8/2004 | 7 |
| ¨ | 7/9/2004 | 8 |
| ¨ | 7/10/2004 | 10 |
| ¨ | 7/11/2004 | 8 |
| ¨ | 7/12/2004 | 7 |
| ¨ | 7/13/2004 | 7 |
| ¨ | 7/14/2004 | 7 |
| ¨ | 7/15/2004 | 5 |
| ¨ | 7/16/2004 | 7 |
| Well Down – Electrical Problem | 7/17/2004 | 0 |
| Rex Alman #3 | 7/18/2004 | 5 |
| ¨ | 7/19/2004 | 8 |
| ¨ | 7/20/2004 | 5 |
| Well Down – Line Problem | 7/21/2004 | 3 |
| Rex Alman #3 | 7/22/2004 | 10 |
| ¨ | 7/23/2004 | 7 |
| ¨ | 7/24/2004 | 7 |
| ¨ | 7/25/2004 | 7 |
| ¨ | 7/26/2004 | 5 |
| ¨ | 7/27/2004 | 8 |
| ¨ | 7/28/2004 | 8 |
| ¨ | 7/29/2004 | 8 |
| ¨ | 7/30/2004 | 8 |
| ¨ | 7/31/2004 | 8 |
| ¨ | 8/1/2004 | 7 |

| Production Source | Date | Production (barrels/day) |
|---|---|---|
| Rex Alman #3 | 8/2/2004 | 7 |
| ¨ | 8/3/2004 | 5 |
| ¨ | 8/4/2004 | 8 |
| ¨ | 8/5/2004 | 10 |
| ¨ | 8/6/2004 | 7 |
| ¨ | 8/7/2004 | 3 |

NOTE: To convert from barrels of oil per day (barrels/day) to cubic meters per day ($m^3$/day) multiply by 0.1589.

## APPENDIX C

## PHOTOGRAPHS

**Photo 1  Horn Design used in Field Tests.  The Lower Portion of the Actuator is also Shown.**

**Photo 2 Horn, Actuator, Connector, Centering Device and Bottom of Sinker Bar Before Inserting into a Test Well in Gilbertown, Alabama**

**Photo 3 Tool Being Lowered into Well for First Test on October 14, 2003.**

**Photo 4 Examining Tool for any Signs of Wear or Damage Immediately after the Completion of the First Day of Testing on October 14, 2003.**

**Photo 5 No Wear or Damage to the Sonic Tool Observed after the Completion of Testing on October 14, 2003.**

**Photo 6  One of the Bars of the Lower Centralizer was Bent during October 15, 2003 Testing.**

**Photo 7  Two Screws Holding One Bar to the Top Centralizer Came Loose during October 15, 2003 Testing.**

**Photo 8  Note that the Upper Fin was Slightly Bent during Testing on October 15, 2003.**

**Photo 9  One of the Four Quadrants of the Upper Fin was Slightly Bent during the Testing on October 15, 2003.**

**Photo 10  Bubbles in Oil during October 15, 2003 Testing.**

**Photo 11  Oil Flowing from Wellhead during Testing on October 15, 2003.**

**Photo 12 Sonication Tool Being Lowered into Well the Morning of October 16, 2003**

**Photo 13  Cedarhill Operating Company's Oil Pit and Service Truck.**

**Photo 14  Cedarhill's Oil Pit Near the Wellhead.**

**Photo 15  The Cage Protecting the Sonication Tool was Modified for the Second Field Test.  Here the Cage is being Attached to the Actuator-Horn Apparatus.**

**Photo 16  Power Supplies Connected in Series to Control Electrical Power Supplied to Downhole Tool.**


**Photo 17 Pup Joint Showing Slot that was Cut to Allow Insertion of Wires Connecting to the Sonication Tool.**

**Photo 18 Inserting Pump into Tubing Within the Well Used for Field Test 2.**

**Photo 19 Pup Joint after Removal from the Well at the Conclusion of Field Test 2.**