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KLAMATH FALLS:
HIGH-POWER ACOUSTIC WELL STIMULATION TECHNOLOGY

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ABSTRACT

Acoustic well stimulation (AWS) technology uses high-power sonic waves from specific frequency spectra in an attempt to stimulate production in a damaged or low-production wellbore. The high-power ultrasound can potentially minimize skin damage, break-down oil viscosity, and increase wellbore permeability in treated zones. AWS technology is one of the most promising technologies in the oil and gas industry, but it has proven difficult for the industry to develop an effective downhole prototype. Klamath Falls Inc. and the Rocky Mountain Oilfield Testing Center (RMOTC) collaborated to conduct a series of tests using high-power ultrasonic tools to stimulate oil and gas production. The first phase of testing proved that the tool could transmit a stable ultrasonic signal, the required power threshold could be generated and transmitted without signal attenuation or excessive heat buildup, and that the tool could achieve a radial pattern of ultrasonic irradiation. The second phase of testing included two tests that demonstrated the ability of the AWS tools to increase production in damaged and low producing wells. Test 1 analyzed the pressure and fluid level variation before and after the AWS tools were deployed. Results showed that fluid levels and pressures built up to higher levels after the AWS deployment at quicker rates than before AWS stimulation. Test 2 looked at production output in a single well before and during the AWS stimulation. The AWS stimulation was run in a small interval over a course of 20 days while the well was pumping. Production output during the AWS stimulation had an incremental increase of approximately 700 percent gross production and over 1000 percent incremental increase in oil production, when compared to the historical 20-day average over a 21-month period.

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EXECUTIVE SUMMARY

Klamath Falls, Inc. contracted with Rocky Mountain Oilfield Testing Center (RMOTC) to conduct a series of tests of high-power ultrasonic tools designed to restore formation permeability, treat skin damaged oil wells, and to mobilize heavy and high-paraffin oil. This testing took place in two phases: Phase I, conducted onsite at RMOTC and Phase II, conducted at a field site near Roosevelt, Utah.

Phase I testing was designed and implemented to verify tool functionality, power requirements, and capacity of high-power acoustic well stimulation (AWS) tools developed by Klamath Falls Inc. During Phase I testing, two different AWS units were tested; a 42 mm (1.67 inches) diameter tool, designed to pass through tubing, and a 100 mm (3.97 inches) diameter unit that passes through the casing. The technical characteristics of both AWS units were confirmed in relation to their capacity to generate and transmit stable signals and in maintaining a high efficiency while transmitting through a 2000 m long Rochester type 7-H-464K geophysical cable (20–35 kHz and 30–50 kW/m^2). The AWS tool's operational capacity was demonstrated during one- to two-hour working periods. This time period represents the time expected for the normal treatment of a zone in a damaged well. The system proved to generate a stable signal with no attenuation, heat or other problems. The requirements for the downhole deployment and positioning of the AWS tools were determined. The effectiveness of the irradiation radial pattern and the application of high-power ultrasound transmission in both continuous and pulse mode were verified. The energy consumption of the AWS tools was measured. Only 10 kWh (380 V, 50 Hz) of electricity was consumed during the test.

A test to demonstrate the potential of the application of high-power ultrasound directly into the formation was performed by applying high-power ultrasound to a sheet of aluminum placed between the tool and the steel tubing. The foil, which represented formation damage in the wellbore, was observed to degrade within only a few seconds of application. This experiment illustrated the intensity of power delivered. The test also confirmed the effectiveness of the AWS tool irradiation pattern.

Phase II testing was implemented in a declining commercial oil field near the town of Roosevelt, Utah. The purpose of Phase II testing was to validate the production response of wells with marginal production rates to AWS stimulation and to capture and identify any changes in the downhole environment after tool deployment.

The AWS tools were deployed and tested in 3 wells. In the first two wells (wells A and B) the 42 mm diameter tool was deployed by wireline inside the tubing using Rochester 7-H-472 K geophysical cable. The zone was stimulated for one hour. Following stimulation, the tool was raised two feet and the processed was repeated until the entire perforated interval was treated.

In the third well (well C), a 130 mm tool was deployed. This tool was attached to the tubing and energized by a conventional three-conductor cable (normally used with the submersible pump) strapped to the outside of the tubing in the annular space. In this well, two different techniques were used to achieve different results. The first technique was set up to stimulate and clean the entire perforated interval. The zone was treated by using a workover rig to move the tubing and the attached AWS tool through the perforated interval in a process similar to what was done in wells A and B. The second technique involved placing the AWS tool at the optimum depth within the perforated interval and energizing the crude oil in the formation, thereby reducing the viscosity of the oil and allowing it to become more mobile.

Results showed that all three wells exhibited rapid buildup rates of fluid levels and pressure immediately after stimulation. Two of the three wells showed increases in wellbore pressure from pre-treatment levels within 48 hours of running the AWS tools. In Well C, the productive response of the well during 20 days of continuous AWS treatment was compared to production during a similar time period immediately prior to the AWS treatment. As a result of the AWS stimulation, total fluid produced from the well showed an incremental increase of 3,684 percent over the 20 days of production immediately preceding the test. Oil production showed an incremental increase of 2,357 percent. Using a more conservative 20-day average over the 21-month time period immediately prior to testing, the AWS tool accounted for a 699 percent increase in total fluids produced and a 1,010 percent increase in oil production. The results of phase II testing validated the ability of the AWS tool to both clean the well, restoring the effective wellbore permeability to pre-damage conditions, and to increase the mobility of the oil by decreasing the viscosity of the oil.

INTRODUCTION

Klamath Falls, Inc., a BVI Corporation, contracted with Rocky Mountain Oilfield Testing Center (RMOTC) to conduct a series of tests of high-power ultrasonic tools designed to restore formation permeability, treat skin damaged oil wells, and to mobilize heavy and high-paraffin oil. This testing took place in two phases: Phase I, run at RMOTC to verify tool functionality, power requirements, and capacity; and Phase II, run off-site in an oil field near Roosevelt, Utah to test the technology in commercial oil wells.

The use of ultrasound to stimulate production through the irradiation of elastic waves has the potential of significantly increasing recovery rates in declining oil fields throughout the world. The technology uses high-power sound waves to loosen or break-up skin buildup surrounding the wellbore within a producing interval. Once developed commercially, ultrasound technology or acoustic well stimulation (AWS) could provide the oil industry with an environmentally-friendly and cost-effective alternative to mechanical and chemical well stimulation techniques. Conventional well stimulation treatments are often invasive and involve pumping of specialized fluids such as acids and hydraulic frac proppants through the completed wellbore intervals and into the targeted formation (Wong *et al.*[1]). It is possible to use AWS technology as a means of well stimulation for removing hydrate plugs, paraffins, and asphaltenes within wellbore completion intervals (Champion *et al.*[2] and van der Bas *et al.*[3]).

Although this is one of the most promising new technologies in the oil and gas industry, there is a lot of skepticism surrounding the concept of acoustic well stimulation. This skepticism is based on the fact that the application of ultrasound at an industrial scale was something that, up until this test, has been difficult to achieve. In the past, there have been problems associated with taking ultrasound technology from the laboratory and developing it into a functioning, commercial oil field tool that could be deployed downhole into a well (Wong *et al.*[1]). Klamath Falls Inc. solved the technical aspects that prevented the commercialization of the technology and developed environmentally-friendly tools that could be deployed downhole using both wireline and tubing.

The downhole AWS tools, developed by Klamath Falls, create controlled, high-intensity vibrations that are radiated in a specific frequency spectrum. This is done by using high-performance transducers along with special magnetostrictive materials that allow for high-amplitude displacement of acoustic waves within the necessary power range for the dowhhole equipment. A mode transformation system is used to generate an effective radial stimulation pattern for treatment of reservoir rocks surrounding the wellbore.

METHODOLOGY AND RESULTS

In order to test the technology, a two-phase testing program was developed. The first phase was designed to verify the functionality of the prototype tools and determine the capability of the tools to deliver high-power ultrasound in a downhole environment. Specifically, the purpose of the first phase (Phase I) was to verify the capacity of the prototype tools to meet the following objectives:

1) Test the functionality of a 42 mm (1.67 inches) diameter tool (designed to be run inside of tubing) and of a 100 mm (3.97 inches) diameter tool (designed to be run inside of casing
2) Generate and transmit stable ultrasonic signals for a two hour period of continuous operation.
3) Reach the required power threshold of 30–50 kW/m^2 at 20–35 kHz.
4) Verify the absence of operational problems such as signal attenuation, heat buildup.
5) Achieve an effective radial irradiation pattern.
6) Analyze tool functionality in both continuous and pulse modes of operation
7) Validate marginal electric energy consumption.

Phase II testing was implemented to test the effect of the tools on oil production in producing wells in a declining oil field. The purpose of Phase II testing was to validate the effects of deploying the AWS tools downhole in wells with economically marginal production rates and to capture and identify any changes in the downhole environment after tool deployment by the following objectives:

1) Collect and record bottom-hole pressure data in each well before and after AWS treatment.

2) Collect and record fluid levels in each well before and after AWS treatment.

3) Collect and record production output of each well before and after AWS treatment.

4) Analyze data collected to determine tool effectiveness.

Phase I Methodology

Phase I testing consisted of connecting the AWS system with elements to be used during field application and irradiating a wellbore model with different ultrasonic fields. Figure 1 shows the set up of this test. The materials used in this test consisted of the following components:

1) Electric generator

2) Control system

3) Cooling system

4) ROCHESTER Type 7-H-464 K geophysical cable

5) Pulley and tension

6) Well with steel casing

7) AWS prototype tools

8) Aluminum foil

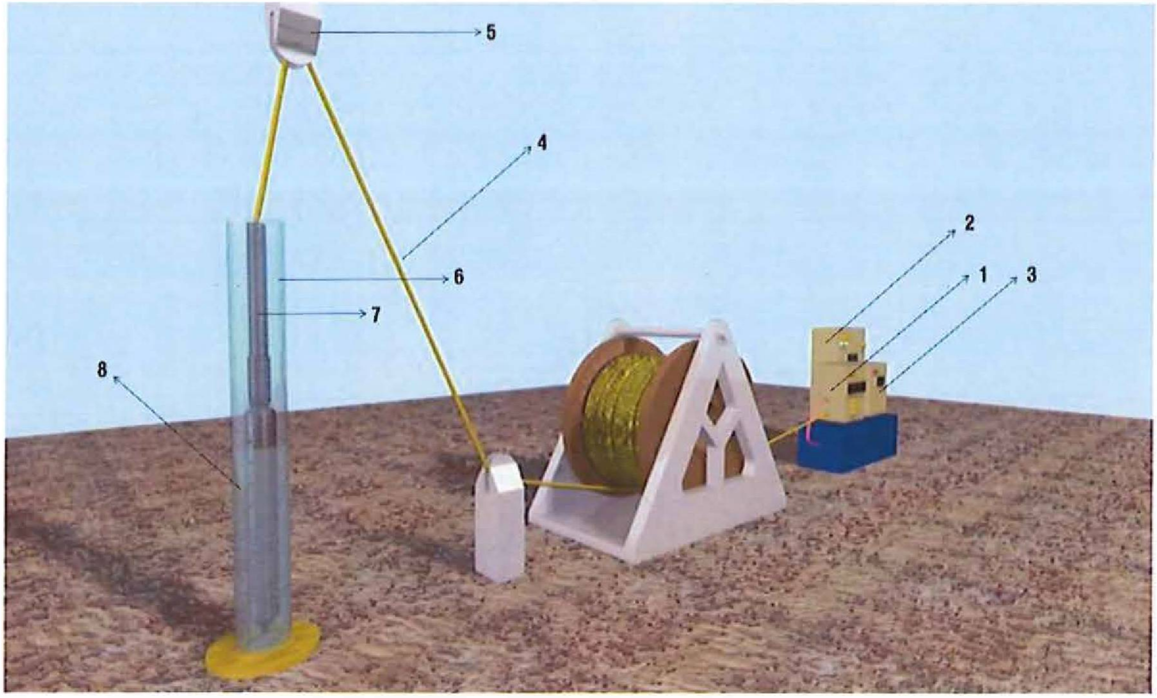

Figure 1. Illustration showing the setup of Phase I testing at RMOTC

The generator supplying the required power of 380 V and 50 Hz was connected to the AWS tools by 2000 meters of geophysical cable and lowered into a steel cased well using a pulley system. In order to verify the frequency spectrum of power needed to deliver a specific irradiation pattern caused by ultrasonic energy emitted by the AWS prototypes, a sheet of aluminum was placed between the steel tubing and the AWS tool housing submerged in water. This experiment was designed to verify the disintegration of the aluminum. The aluminum was placed in a parallel position to the axis of the tool so that only radial irradiation could disintegrate the sheet.

Phase I Test Results

Klamath Falls Inc. successfully exhibited their laboratory work and test results to RMOTC as follows:

1. Two different AWS units were tested; a 42 mm (1.67 in) diameter tool designed to pass through tubing, and a 100 mm (3.97 in) diameter unit that passes through the casing.

2. The technical characteristics of both AWS units were confirmed in relation to their capacity to generate and transmit stable signals and in maintaining a high efficiency while transmitting through a 2000 m long Rochester type 7-H-464K Geophysical cable (20–35 kHz and 30–50 kW/m^2).

3. The AWS tool's operational capacity was demonstrated during one- to two-hour working periods. This time period represents the time expected for the normal treatment of a zone in a damaged well. The system proved to be robust with no signal instability, attenuation, heat or other problems.

4. The requirements for the downhole deployment and positioning of the AWS tools were determined.

5. The effectiveness of the irradiation radial pattern was verified.

6. The application of high-power ultrasound in both continuous and pulse mode was verified.

7. A test to demonstrate the potential of the application of high-power ultrasound directly into the formation was performed by applying high-power ultrasound to a sheet of aluminum placed between the tool and the steel tubing. The foil, which represented formation damage in the wellbore, was observed to degrade within only a few seconds of application. This experiment illustrated the intensity of power delivered. The test also confirmed the effectiveness of the AWS tool irradiation pattern.

8. The energy consumption was measured. A nominal 10 kWh electric consumption was verified (380 V, 50 Hz).

Conclusions of Phase I Testing

The technology tested at RMOTC (developed by Klamath Falls) was confirmed in its main features and capacities to deliver High-power Ultrasound in a real wellbore. This demonstrated that the technical barriers to bringing the technology from the laboratory to a commercial application have been successfully overcome.

The ultrasonic signals demonstrated during this phase were verified to be within the necessary range of frequency to generate results similar to those observed in the laboratory. The device successfully overcame the threshold of power by applying up to

50 kW/m^2 of ultrasonic energy directly into the formation. This energy was applied with a radial pattern of irradiation (perpendicular to the axis of the borehole).

The positive results from Phase I testing, demonstrated that commercial testing of the AWS tools (Phase II) of the High-power Ultrasound over damaged wells (Skin Factor) needed to be initiated.

Phase II Methodology

Phase II testing was set up in a productive oil field near Roosevelt, Utah. The conditions of the oil field represented a typical stripper field, i.e. a field with declining production caused by depleted or damaged oil wells. In order to validate the effects of the AWS tools, bottomhole pressures, fluid levels, and production data were collected from each well prior to running the tool downhole and again, collected after the tool was deployed. It was very important to understand the ambient pre-test conditions of each well in order to quantify and isolate the effects of the ultrasonic stimulation.

Bottomhole pressure data were collected by Delsco North West Inc. using a Pressure & Temperature Survey after the wells had been shut in for a known period of time. Fluid levels were also collected by Delsco North West Inc. prior to deploying the ultrasonic tools downhole using an echometer.

The AWS tools were deployed and tested in 3 wells. In the first two wells (wells A and B) the 42 mm diameter tool was deployed by wireline inside the tubing using Rochester 7-H-472 K geophysical cable. Each zone was stimulated for one hour. Following stimulation, the tool was raised two feet and the process was repeated until the entire perforated interval was treated.

In the third well (well C), a 130 mm tool was deployed. This tool was attached to the tubing and energized by a conventional three-conductor cable (normally used with a submersible pump) strapped to the outside of the tubing in the annular space. In this well, two different techniques were used to achieve different results. The first technique was set up to stimulate and clean the entire perforated interval. The zone was treated by using a workover rig to move the tubing and the attached AWS tool through the perforated interval in a process similar to what was done in wells 1 and 2. The second technique involved placing the AWS tool at the optimum depth within the perforated interval and energizing the crude oil in the formation, thereby reducing the viscosity of the oil and allowing it to become more mobile.

Phase II Results:

The results of phase II testing validated the ability of the AWS tool to both clean the well, restoring the effective wellbore permeability to pre-damage conditions, and to increase the mobility of the oil by decreasing the fluid viscosity. These testing procedures and results of each well are shown below.

Well A: Naturally Fractured, Low Producer

Well A was shut in on September 30, 2005. After 27 days fluid levels were recorded showing a level of 4,075 feet from the surface. Pressure readings showed a wellhead pressure of 35 PSI. The bottomhole pressure was calculated to be 572 PSI (lower perforated level, located at 5,384 feet depth).

After treating the well with the AWS tool, the well was swabbed. After only 48 hours, the fluid level had built up to 4,142 feet from the surface. The bottomhole pressure was calculated to be 541 PSI [4]. Figure 2 shows a comparison between the pre-test and post-test bottomhole pressures and measured fluid levels.

Well (A): Naturally fractured - low producer.

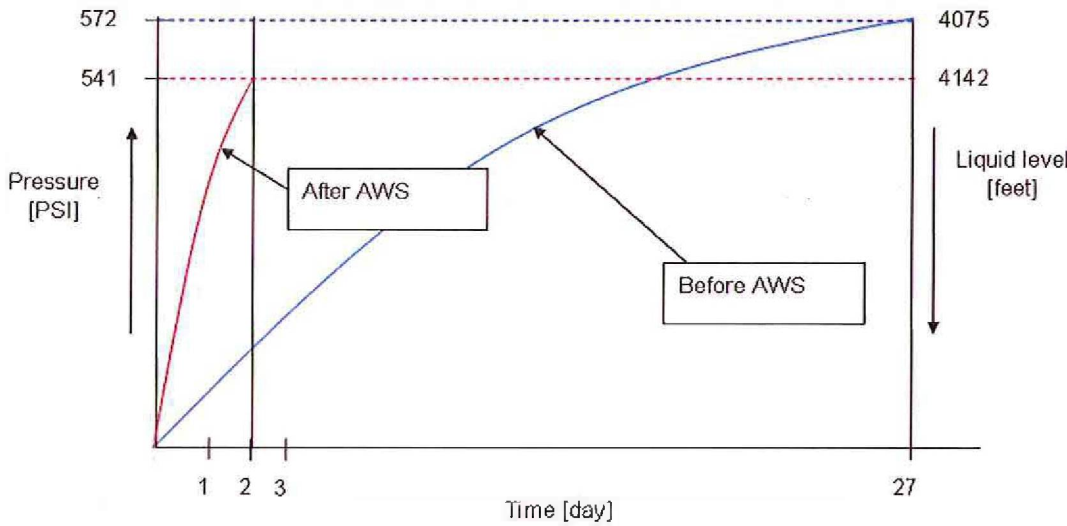

Figure 2. Well A bottomhole pressure and fluid level comparisons before and after AWS treatment.

The rapid change in the height of the fluid column after the AWS treatment indicates the removal of skin damage and an increase in effective permeability surrounding the wellbore.

Well B: Drill Mud Damaged, Low Producer

Well B was shut in on October 15, 2005. After 18 days the measured fluid level was recorded at a level of 5,097 feet measured depth. The wellhead pressure was measured at 46 PSI with a bottomhole pressure calculated to be 594 PSI (lower perforated level, located at 6,433 feet depth).

After the AWS treatment, the well was swabbed. Fluid level and wellbore pressure data were collected. After only 48 hours, Well B fluid levels were measured at 3,534 feet measured depth. The bottomhole pressure was calculated to be 1,188 PSI [4]. Figure 3 shows a comparison between the pre-test and post-test bottomhole pressures and measured fluid levels.

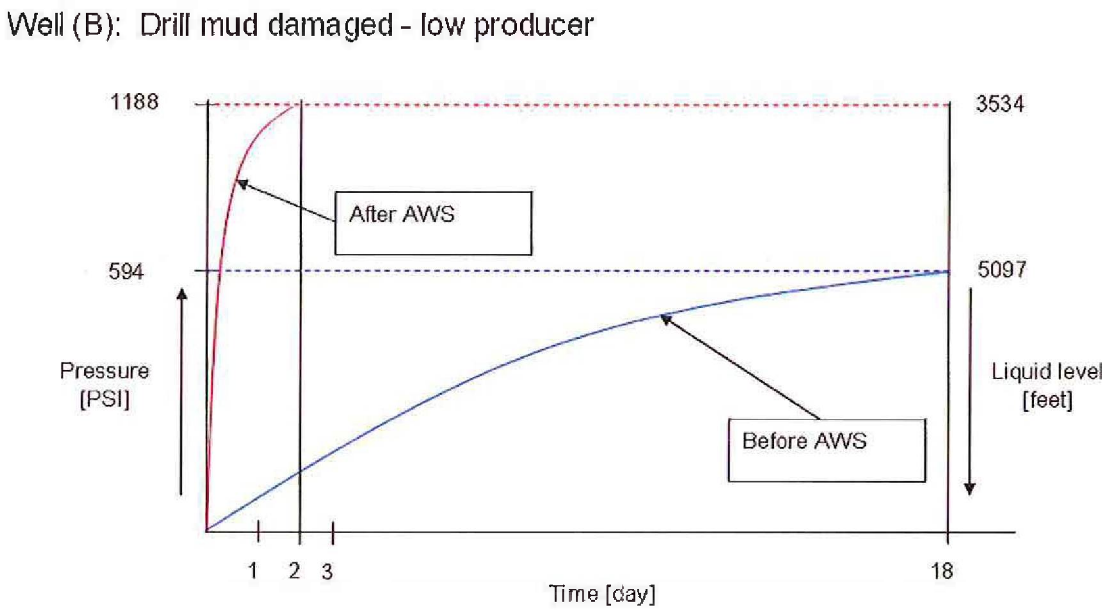

Figure 3. Well B bottomhole pressure and fluid level comparisons before and after AWS treatment.

The rapid change in the height of the fluid column after the AWS deployment indicates the removal of skin damage and an increase in effective permeability surrounding the wellbore. This change is attributed to the ultrasonic treatment.

Well C: High Paraffin Content, Low Producer

In Well C, a 130 mm diameter AWS tool was deployed via tubing. This well was used in two separate tests. The first test, or *Test 1*, was designed and implemented to verify the capability of the tool to restore the effective permeability of the formation surrounding the wellbore by cleaning the perforated interval and removing any skin damage. The second test, or *Test 2*, was executed to validate the ability of the tool to increase the mobility of the high-paraffin oil and to monitor effects to fluid production during AWS stimulation.

Test 1 Results.

Well C was shut in on October 31, 2005. After 30 days of shut in time, the fluid level was measured at a level of 7,006 feet measured depth, and showed a 0 PSI wellhead pressure. Bottomhole pressure was calculated to be 305 PSI (lower perforated level, located at 7,751 feet depth).

After the AWS treatment, the well was swabbed. Fluid level and wellbore pressure data were collected. After only 48 hours, Well C fluid levels built up to a level of 4,991 feet measured depth. The wellhead pressure was measured at 8 PSI, and the bottomhole pressure was calculated to be 1,140 PSI [4]. Figure 4 shows a comparison between the pre-test and post-test bottomhole pressures and measured fluid levels.

Well (C): Heavy oil (waxy, 60 % paraffin content, 65 °C), very low producer (17 API).

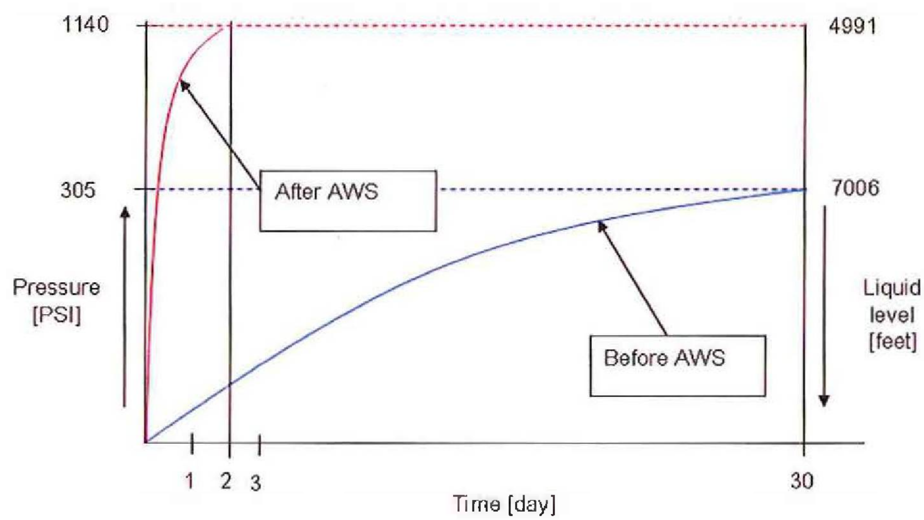

Figure 4. Well C bottomhole pressure and fluid level comparisons before and after AWS treatment.

The rapid change in the height of the fluid column after the AWS deployment indicates the removal of skin damage and an increase in effective permeability surrounding the wellbore. This change is attributed to the ultrasonic treatment.

A pressure and temperature survey was executed by Delsco North West Inc. to verify pressure gradients changes in the perforated interval of the well both before (November 29, 2005) and after treatment (December 1, 2005).

Table 1 shows a comparison of the pressure readings taken before and after the AWS treatment for Well C. The AWS treatment created a 112% increase in wellbore pressure. This increase in wellbore pressure seen after the treatment supports the claim that skin damage was removed and that reservoir permeability was enhanced.

	Before	After	Change
Pressure	416.2 PSI	881.4 PSI	465.2 PSI

Table 1. Comparison of pressure data collected prior to and after the AWS treatment for Well C.

Test 2 Results.

The second test in Well C involved positioning the tubing-emplaced AWS tool at a specific depth (7,729 measured depth) within the perforated interval. The tool was energized for a period of 20 days, during which time the well was on production. The productive response of the well during the 20 days of AWS treatment was compared to the production during a similar time period immediately prior to AWS treatment in October, 2005. The productive response during the 20-day AWS treatment was also compared to the cumulative production for an average 20-day interval using a 21-month period from January 2004 through October. The results of these comparisons are outlined below. In analyzing these results, it is important to bear in mind that the AWS tool (working through its radial irradiation pattern) was stimulating only 12% of the perforated zone (6 of the 52 feet).

The gross liquid production in the well recorded for the last 20 days of production prior to shutting in the well was 38 bbls. Of those produced fluids, 32 bbls were oil and 6 bbls were water (Table 2). The average historical production from Well C, over a 20-day period between January 2004 and October 2005 was calculated to be 180 bbls of total fluid, including 76 bbls of oil and 104 bbls of produced water (Table 3). The amount of produced fluid increased drastically during the 20-day period while the AWS tool was running in the fixed interval. During these 20 days, gross production of total liquids was measured at 1,439 bbls. This included 844 bbls of oil (Table 4).

Using the last 20 days of Well C production immediately prior to the AWS treatment, the AWS tool accounted for a 3,684 percent increase in total fluids produced.

$$\text{Incremental Increase} = \frac{(1{,}439bbls - 38bbls)}{38bbls} \times 100 = 3684\%$$

Equation 1. Incremental Produced Fluid Increase.

The AWS tool accounted for a 2537 percent increase in oil produced.

$$\text{Incremental Increase} = \frac{(844bbls - 32bbls)}{32bbls} \times 100 = 2537\%$$

Equation 2. Incremental Produced Oil Increase.

Using a more conservative 21-month average for a 20-day production history of gross liquid production, the AWS tool accounted for a 699 percent increase in total fluids produced.

$$\text{Incremental Increase} = \frac{(1{,}439\,bbls - 180\,bbls)}{180\,bbls} \times 100 = 699.4\%$$

Equation 3. 21 Month Average Liquid Production Increase

Oil production increased from an average 20-day cycle of 76 bbls (averaged over the 21-months of production prior to treatment) to the AWS treatment production of 844 bbls during 20 days of continuous stimulation. This change in oil production represents a 1,010 percent increase over the 21-month average.

$$\text{Incremental Increase} = \frac{(844\,bbls - 76\,bbls)}{76\,bbls} \times 100 = 1010\%$$

Equation 4. 21 Month Average Oil Production Increase

Fluid Type	Cumulative production for 20 days	Average daily production over 20-day period
Water	6 bbls	0.3 bbls/day
Oil	32 bbls	1.6 bbls/day
Gross Liquids	38 bbls	1.9 bbls/day

Table 2. Production history for 20–day period immediately prior to AWS stimulation.

Fluid Type	Average Cumulative production for	Average daily production over 20-day period
Water	104 bbls	5.2 bbls/day
Oil	76 bbls	3.8 bbls/day
Gross Liquids	180 bbls	9.0 bbls/day

Table 3. Average production for a 20–day period from January 2004-October 2005.

Fluid Type	Cumulative production for 20 days	Average daily production over 20-day period
Water	595 bbls	29.8 bbls/day
Oil	844 bbls	42.2 bbls/day
Gross Liquids	1,439 bbls	72.0 bbls/day

Table 4. Production history for 20–day period during AWS stimulation.

Conclusions of Phase II Testing

The AWS technology applied in the Green River Formation by Klamath Falls Inc. showed very positive short-term results. The dramatic increases of pressure and fluid levels immediately after AWS stimulation demonstrated the effectiveness of the tools to remove skin damage and increase fluid mobility.

CONCLUSION

The high-power ultrasonic prototype tools designed and built by Klamath Falls Inc, demonstrated that AWS technology can be applied downhole in oil and gas wells to remove skin damage and stimulate production. The technology also demonstrated an ability to mobilize high-paraffin crude by reducing the effective viscosity. In one well during the field test, the AWS tools demonstrated the ability to increase total gross production 7 fold and oil production was increased 10 fold through continuous ultrasonic stimulation.

This project demonstrated that AWS technology can be deployed using wireline equipped with standard geophysical cable or on tubing. It also proved that the technology can continuously stimulate a zone of interest while the pump in running, eliminating down time in a well. By developing and proving AWS technology, Klamath Falls Inc. has made it possible for oil and gas operators to dramatically increase the recovery factor of damaged wells and wells with heavy or waxy oil. The results of the testing illustrate the potential of AWS technology to significantly enhance recovery rates within existing oil and gas wells. If the technology becomes widely adapted in the United States and throughout the oil and gas industry, there may be a large increase in production of hydrocarbon fluids. The resulting increase in domestic production could decrease the dependency of the United States on foreign oil.

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