Well Bore Remediation Using Sonication

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Abstract

Sonication technology is being developed, under the sponsorship of the National Energy Technology Laboratory, for the remediation of well bore damage in underground natural gas storage wells. Two separate technologies, low-frequency sonication and underwater plasma, were developed and tested during the last 2 years. Although the underwater plasma technology showed great potential at removing scale and rust, there are several areas that require further research and development before field-testing can proceed. However, low-frequency sonication was very efficient at removing scale and rust in laboratory testing. A prototype-laboratory unit was developed and was modified for additional laboratory tests and field tests in an observation well at Nicor Gas' Pontiac Storage Field. The technology, project results, and accomplishments are discussed.

Introduction

Total underground natural gas storage capacity in the United States was about 8.2 Tcf in 2000, with approximately 3.9 Tcf of working gas capacity. The total number of storage facilities at the end of 2000 was 413. These facilities can provide a maximum deliverability of 80 Bcf/d from over 14,000 injection and withdrawal wells. Most storage wells decline in deliverability after several years of injection and withdrawal cycling, and they require remediation to re-establish deliverability. The gas storage industry spends approximately $80 to $100 million annually to revitalize existing wells[1], but current revitalization methods, such as mechanical cleaning, blowing/washing, acidizing, and re-perforating, often provide only limited temporary delivery restoration.

To gain a better understanding of the types of damage that affect gas storage wells, the National Energy Technology Laboratory (NETL), co-funded research with the Gas Technology Institute (GTI). The GTI/DOE co-funded project[2] completed research on 33 wells in 12 gas storage fields to identify the mechanisms responsible for losses in well deliverability, and established guidelines for use by storage field operators. The major causes of damage were inorganic precipitates (more commonly known as scale), hydrocarbons, organic residues, production chemicals, bacterial fouling, and particulate plugging.

The next step in this work is now underway: characterizing the geochemical conditions that promote damage and lead to decreased performance, and designing and successfully demonstrating practical and cost-effective remedial techniques. Three NETL projects have been initiated since January 2000 to address the characterization and remedial techniques. This paper discusses the results of the remediation project involving sonication NETL funded with Furness-Newburge, Inc., as the principal investigator.

Sonication Technology

The science of sonication has been studied for more than 200 years. Early experimentalists used tuning forks (frequency) to show how acoustic energy could cause ripples on the surface of water. They also noted the extreme reaction caused when a tuning fork came in contact with water. By the 1840's, materials had been 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. Magnetostrictive science developed slowly, being overshadowed by piezoelectricity, a rather inexpensive means of producing electricity or mechanical 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 using 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 fluid. The power available in today's generation of magnetostrictive sonication, 3,000-6,000 watts (2213-4425 foot-pounds per second), dwarfs what most researchers were using in the laboratory 4 years ago, i.e., units with 350-500 watts (258-369 foot-pounds per second). The tremendous increase in power, plus the much smaller size of the sonication unit, allows users to apply sonication technology to a number of situations at power levels previously unavailable. Thus, the technology can be used downhole with an intense amount of energy and can possibly provide the industry with a tool for economical remediation of natural gas storage wells, gas and oil stripper wells, and other applications.

Underwater Plasma Testing

The underwater plasma (UWAP) technology consists of a pulsed discharge of capacitor-stored electricity through a sparking device into a liquid medium. In the laboratory unit used at the Furness-Newburge facility, a distributor produces up to 8,000 volts of electrical power and feeds the electricity to the capacitor. When the capacitor reaches a selected level (nominally between 60%-80% of the available voltage), the electricity is discharged through a spark plug in approximately 4 microseconds. This pulsed wave of energy causes water to turn to steam at the discharge point, an expansion of approximately 1,800 times its volume. The expansion – an underwater combustion – creates a shock wave that rapidly moves out from the discharge point. The result is a release of a tremendous amount of energy to perform "work" and the creation of hydrogen and hydroxyl radicals, scavengers of organic materials.

For all the underwater plasma tests, the sparking device was fixed in position in the base of a 15-gallon, cone-shaped polypropylene tank. The power supply was in a large (3' x 3') case mounted, freestanding structure. Power levels were changed through a Variac potentiometer. The frequency of sparking is normally 72 times per minute. Two periods of testing were completed. In the first testing period, the power level and time of operation were held constant. The position of the pipe was then changed to evaluate the impact of energy parallel to the pipe versus perpendicular to the pipe, and a test was run to evaluate the impact of the underwater plasma on plugged perforations, which were simulated using spackling compound in drilled holes. In the second testing period, the power levels were varied, two types of sparking devices were compared, and the length of pipe was varied. The time of operation for tests in the second testing period was constant, but different from the time used in the first period of testing, allowing for a comparison.

The underwater plasma technology was very effective at removing scale/rust. It also removed almost all of the spackling compound from the holes drilled into the pipe to simulate plugged perforations (Figure 1). The angle at which the energy wave (shock waves) impacts the pipe wall may control the amount of work that is being accomplished. Energy perpendicular to the wall did little work; energy parallel to the wall did the most work. Thus, when operating downhole, vertical movement of the UWAP unit – up or down – will ensure maximum scale removal from the damaged zone.

Figure 1. Pipe Showing Complete Removal of Spackling Compound

The underwater plasma technology, while potentially superior to the sonication technology, needs further research, development, and testing to resolve technical issues prior to extensive field-testing. Many of the issues, such as (1) increasing the power to raise the efficiency of the process, (2) developing a two-wire electrode feed and automatic gapping mechanism, (3) using of a titanium parabolic shield to focus the energy, and (4) developing a high voltage, high current pulsed power supply to fit into a 2-7/8" pipe, were beyond the scope of this project.

Ultrasonic Laboratory Testing

Preliminary testing of high-frequency sonication was done on 2-foot sections of pipe supplied by Nicor Technologies from its Pontiac storage field. The testing, conducted at Argonne National Laboratory, used a Branson ultrasonics batch sonicator capable of providing 600 watts of output power at a fixed frequency of 20 kHz. Several trial runs were made to evaluate and optimize operating conditions by varying the power intensity from 12.4 to 50 w/cm^2 and the time of testing from 15 minutes through 120 minutes at 15-minute increments. The optimum conditions established for the fixed, high frequency sonicator were a power intensity of 35.8 w/cm^2 for a duration of 90 minutes. Using these parameters, a final test was run. An 8-inch section of pipe, with a diameter of 2 7/8 inches, was weighed before and after testing. The material removed by sonication was decanted and collected on a filter paper and weighed. The pipe was then scraped with a steel brush to remove any remaining rust/scale. This material was also collected on filter paper and weighed. The formula for presenting the scale removal efficiency was defined as the weight of the rust/scale removed by sonication divided by the total material removed by sonication and brushing. The solid material removed was acidized (nitric acid, pH <2) and analyzed.

The results confirmed the results of earlier testing, namely that ultrasonics or high-frequency sonication was not very effective at removing scale. The optimized test had a removal efficiency of 3.7% using the formula discussed above. The analytical results of the acidified solids (51.8 mg/L of calcium (6.7%), 1.8 mg/L of magnesium (0.2%), and 719.7 mg/L of iron (93.1%), with almost no barium) indicated that the majority of the solid material removed from the pipe was rust with a small amount a calcium compound, probably calcium carbonate.

Low-Frequency Sonication Laboratory Testing

The work at the Furness-Newburge, Inc. (FNI), facility was done with sonicators providing energy through actuators using magnetostrictive technology materials. These materials, solid-state crystal alloys of rare earth materials terbium and dysprosium plus iron, convert (transduce) a changing magnetic field into mechanical energy extremely quickly and with high force. The power package allows the operator to select or optimize the frequency for the specific task, modulating the frequency either manually or automatically. The energy is dispersed from the transducer via a titanium horn. Two actuators were used in the FNI tests, one with approximately 325 watts of maximum continuous power, and the other with close to 500 watts of power. The frequency range on these units was 0-15 kHz. Two types of horn design were used, finned, and plain. (Figure 2).

A series of tests were conducted to evaluate low and mid-range frequencies, and the power of the sonicator. The first test was conducted at a high frequency using the plain horn in order to

Figure 2. Finned and Plain Horns for Sonication Tool

duplicate the testing at Argonne. All other tests were conducted using the finned horn, and were run for 15 minutes. Table 1 shows the results of the sonication testing at FNI. The first test confirmed the results at Argonne, i.e., high-frequency sonication is not efficient at removing rust/scale. Tests 2 and 3 had a removal efficiency of nearly 81% using a 325-watt actuator. When the power was increased to a 500-watt actuator in Tests 4 and 5, the efficiency dropped. However, the results of all tests must be compared somewhat qualitatively since not all the pipe segments contained the same degree of scale and rust deposits, and the method of removing "all" the scale/rust, i.e., by a steel brush, could not assure consistent results. However, the huge jump in efficiency did show that low to mid-range sonication was quite efficient at removing rust and scale.

Tool Redesign

The project team (FNI, TSI, Nicor Technologies, and Baker Atlas) established a series of field design parameters for the sonication tool. The laboratory sonication tool just fit within 2-7/8" (inside diameter) pipe. In order to have sufficient room to waterproof and harden the encased tool, the sonicator had to be re-designed with a maximum outer diameter of 1-11/16". Concerns over the power output with a smaller sized actuator resulted in the manufacture of a new, thinner, low frequency actuator. The redesigned tool was sent to Baker Atlas for waterproofing and hardening, including the ability of the unit to withstand temperatures of 300 °F-350 °F and pressures up to 2,000 psia. The new system included a newly designed and re-configured titanium horn, a power supply (500-1000 watts) plus a receiver, a transmitter and cable, a digital oscilloscope, a suspension cable and/or hook-up to the cable system for lowering the unit into the well, and a portable generator.

The prototype unit was taken to Baker Atlas' wireline testing facility. Drawings of the cable head attachment to which the tool would be mated had been exchanged between Baker Atlas and FNI to select the cable head attachment and facilitate fabrication of the attachment coupling. A series of tests to investigate the affect of various power levels and operating frequency conditions was run in a controlled laboratory setting. The well bore was simulated using a 5-inch Plexiglas tube into which a 2-7/8" steel pipe had been inserted, centered, cemented, and dried. Prior to the test, the cement and pipe had been removed and eight 1-inch diameter holes simulating perforations had been drilled, filled with spackling compound, and dried.

Tests were run from 15 to 60 minutes. The material filling the holes began to be ejected at the 7-minute mark; the holes were cleaned within 15 minutes. The tests were monitored on a digital oscilloscope. Both sine wave and square-wave functions were used. For both waveforms, the wave patterns changed from their normally smooth forms to a saw-toothed form that eventually evolved back to the smooth form. The interpretation of this wave activity was that the energy (wave) encountered scale on the pipe wall, removed it (saw-tooth pattern), and then returned to the smooth waveform, representing a "cleaned" pipe wall. Thus, a potential mechanism for monitoring downhole

Table 1. Summary of Low-Frequency Sonication Tests

Experiment Number	Scale/Rust Removed by Sonication (g)	Scale/Rust Removed by Brushing (g)	Frequency (kHz)	Horn	Actuator (Watts)	Efficiency (%)
1	.02	--	14.91	Plain	325	3.42
2	2.12	0.50	6.43	Finned	325	80.92
3	0.62	0.15	1.64	Finned	325	80.50
4	1.19	0.45	1.94	Finned	500	72.56
5	0.52	0.51	1.94	Finned	500	50.49

remediation activity was available. The sonication unit was operated at the same power levels scheduled to be used in the field. The team then agreed that the unit was ready for the field demonstration.

Field Test

The field test was conducted in August 2001 at Nicor Gas' underground aquifer storage facility located near Pontiac, Illinois. The well chosen for the demonstration was the Bashore #1 observation well. Bashore #1 was drilled in 1965 and completed with 5-1/2" J-55 casing set at 3,443 feet. The well was perforated from 3224' to 3236' with 4 shots per foot. The water level response to gas inventory for this well periodically becomes dampened (Figure 3). Nicor Gas suspects that dampening is caused by material obstructing the perforations. Nicor re-perforated and swabbed on July 10, 1990, from 3276' to 3286' (4 shots per foot) and December 13, 1996, from 3181' to 3206' (6 shots per foot). Both times the well responded by tracking gas inventory. Since the water level response on Bashore #1 has decreased significantly again, it was decided that Bashore #1 would be a good candidate for testing the sonic tool.

Prior to the field demonstration, preliminary background data was obtained for use as a baseline for comparing pre- and post-demonstration data. These data included the water level, a downhole video, the water chemistry, a segmented bond log, and a gamma ray/neutron log.

On August 13, 2001, the Baker Atlas crew attached the sonic tool to the end of the seven-line wireline feed and the entire device - sonic tool, sinker bars, and centering device - was lowered into the hole to the lowest set of perforations. Once the tool was in this position, the power to the tool was turned on and was swept through several frequencies to assure the project team that it was operational. The sine-wave function was observed on the analog oscilloscope located in the instrumented area of the Baker Atlas truck. The saw-tooth pattern indicating that sonication was doing "work," i.e., remediating the well (removing scale), was present but not as discernible as when the digital oscilloscope was used in the laboratory.

The test procedures for the demonstration were as follows:

- Raise the sonic tool to a new depth (normally in 5' increments).
- Set optimum power for the selected frequency.
- Monitor saw-tooth pattern.
- When pattern begins to smooth out into a fluid sine curve:
  - Sweep through several frequencies to find new saw-tooth patterns.
  - Optimize power.
  - Repeat until all swept frequencies attain smooth pattern.
- When all frequencies produce smooth sine curves, raise the tool to a new depth.

The sonicator was activated at 15 locations over a 40-foot section of perforations during a 3-hour period. The sonic tool began to show a

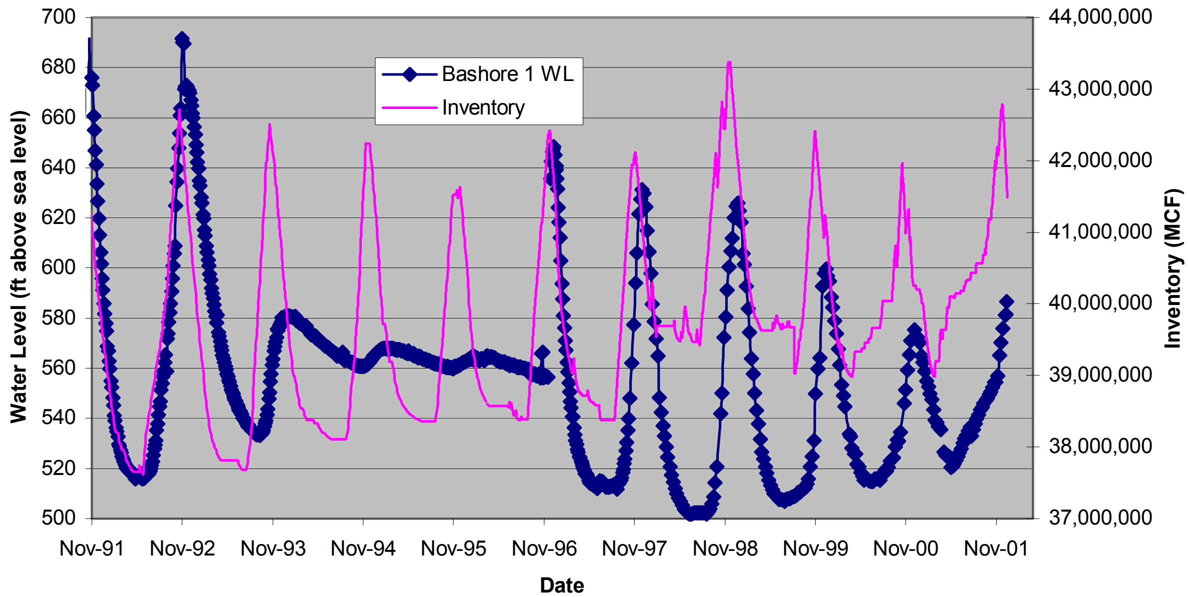

Figure 3. Water Level vs. Inventory for Bashore #1 Observation Well

problem in the area of the connection to the wireline and a second tool was attached. While attaching the tool to the sinker bar, the electrical wire assembly was snapped. Testing ceased. Because the delay in obtaining another tool would be more than a few days, the team decided to end the field test by collecting the post-demonstration data.

Results of the Field Test

The downhole video data collected in the preliminary testing period was unusable due to poor visibility, probably because of the high presence of iron compounds near the base of the well. Hence, a post-sonication video was not run. A comparison of the pre- and post-sonication segmented bond log showed that operating the sonication tool caused no damage to the cement bond in the well. Similarly, the gamma ray/neutron log showed no change to the gas storage bubble, indicating that there was no apparent damage to the formation.

Reviewing the water level data shown in Figure 3 indicates that although the water level increased above the December 2000 peak, the gas inventory volume also increased. Thus, the data to date are inconclusive for making any definitive statement. Collecting and analyzing additional water level data will be necessary before any correlation can be made between water levels and inventories as a result of operating the sonicator.

The water chemistry data turned out to be the most valuable in the absence of being able to flow the well or conduct pressure transient tests. Should sonication remove any scale, the data would show a change in the post-demonstration water chemistry. An analysis of the key constituents found in the water is shown in Table 2.

The sharp rise of calcium and the nominal rise of magnesium in the water indicate that the sonic tool is removing scale from the casing and/or perforations and placing it in solution. The dramatic shift in pH is indicative of the calcium carbonate type scale being removed and

Table 2. Water Chemistry Data

Parameter	Units	Before Range	After Range
pH	Standard	3.11 to 3.25	8.23 to 8.45
Alkalinity	mg/L as $CaCO_3$		50 to 56
Conductivity	MS	58.5 to 61.6	59.4 to 61.2
Calcium	mg/L as Ca	1755 to 1984	3400 to 4028
Magnesium	mg/L as Mg	285 to 296	461 to 480.2
Iron	mg/L as Fe	63 to 76	39.38 to 253.2
Barium	mg/L as Ba	1 to 2.1	0.36 to 0.52
Chloride	mg/L as Cl	27117 to 28116	26992 to 27242
Nitrates	mg/L as NO_3	43 to 45	46.5 to 47.3
Sulfates	mg/L as SO_4	1029 to 1132	1095 to 1128
Total Solids			
Dissolved		60280 to 65680	50328 to 52968
Suspended		130 to 240	240 to 1472

put into suspension, thus providing a buffering situation, holding the pH in this very tight range of 8.23 to 8.45. The increase in suspended solids indicates that some of the removed scale is in fine particles and is not dissolving. The decrease in dissolved solids is probably related to the change in pH. A review of all the above data documents the fact that the application of low-frequency sonication technology, operated for only a few hours, definitely removes scale.

Conclusions

Two separate technologies, low-frequency sonication and underwater plasma, were developed and tested during the last 2 years. Although the underwater plasma technology showed great potential at removing scale and rust, there are several areas that require further research and development before field-testing can proceed. However, low-frequency sonication was very efficient at removing scale and rust in laboratory testing. Since a prototype-laboratory unit was available, it was modified for additional laboratory tests and field tests in an observation well at Nicor Gas' Pontiac Storage Field. Comparison of pre- and post-sonication water chemistry data indicate that the sonic tool is removing scale. The post-sonication segmented bond log showed that operating the sonic tool caused no damage to the cement bond in the well.

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