Permeability Recovery and Enhancements in the Soda Lake Geothermal Field, Fallon, Nevada

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ABSTRACT

During the 1980s the apparently low permeability 77-29 and 84-33wells at the Soda Lake field were improved into useful long-term production or injection wells with standard perforation recompletions of cemented casings. In the early 1990s long term low pressure injection into well 81-33 either created or restored permeability that had not been recognized or had been damaged during drilling operations. Because of this historic response to stimulation, a technique that employs deflagration (the targeted ignition of a propellant to force a pressure wave into the surrounding formation) has been performed on 3 Soda Lake wells. In 2009 and 2010 relatively small charges had uncertain success in wells 45A-33 and 41B-33 due to the fact that other well modifications occurred at the same time. Charges 2.3 times larger became available in 2011 and three of these were used in the 25A-33 well. Immediately following the deflagration of the propellant charges, 5 days of low pressure (<150 psi) injection improved the injectivity by 20 fold from 30 gpm to over 600 gpm. Magma ignited the larger charges in three perforated sections of the well at 4153', 4575' and 4911'. Within two weeks of the stimulations using deflagrating materials the injection capacity of the well steadily increased from an initial 30 gpm to a steady flow over 600 gpm, with a maximum of about 750 gpm, all of this occurring at normal injection system pressures less than 150 psig.

Introduction

Soda Lake Geothermal field, located in Churchill County Nevada, six miles northwest of the City of Fallon has been in production since 1989 *(Figure 1)*. The two binary power plants, Soda Lake 1 and Soda Lake 2 have a combined nameplate capacity of 23.1 MW. A lack of sufficient production fluid and declining temperatures have kept the project from ever reaching full output in spite of a drilling history of 23 wells and 6 redrills *(Figure 2)*.

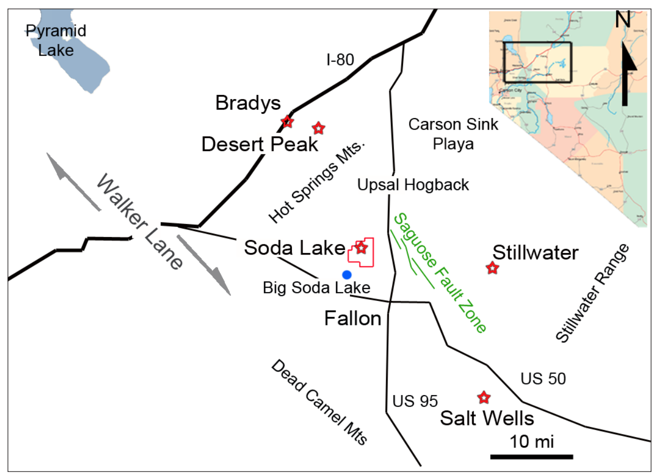

Figure 1. Regional location map, figure courtesy Jim Echols, Magma Energy (U.S.) Corp.

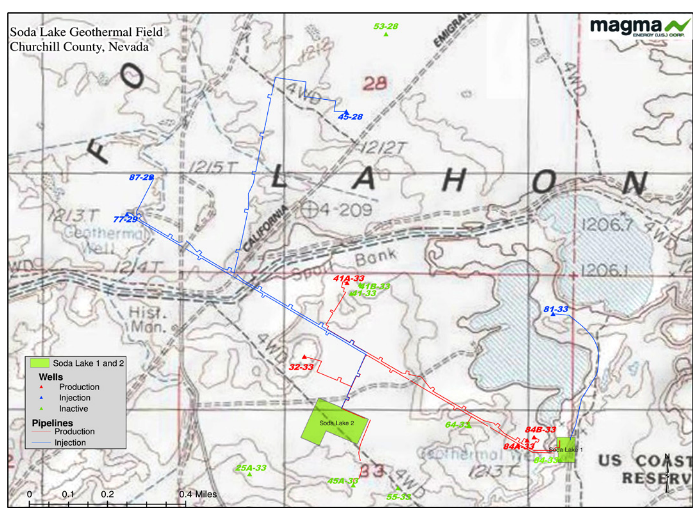

Figure 2. Soda Lake well field map.

An important and previously unpublished part of this extensive drilling history has involved post-completion stimulation of apparently low permeability wells that has enabled some of them to be placed into long-term service as production or injection wells. This paper reviews the history and evolution of successful post-completion stimulation techniques at Soda Lake. The most recent and unquestionably successful stimulation used a patented propellant deflagration technique to improve a new and essentially impermeable well into a well capable of accepting 600 to 700 gallons per minute (gpm) at normal Soda Lake power plant injection pressures.

Well 77-29 Recompletion

Well 77-29 was drilled in 1974 to a depth of 4403' by Phillips Petroleum and Chevron. This well drilled through a 332°F shallow lateral outflow plume in poorly consolidated Quaternary alluvium with its maximum temperatures between depths of 760' and 880'. During drilling there was a partial loss of returns at a depth of 954' that was easily cured by tripping out of the hole and mixing new mud. Drilling then continued to 1025' with full returns. During the running of 13⅜" casing to a depth of 1008' there was a full loss of returns when the casing became stuck and had to be removed. A cement plug healed the wellbore and circulation was regained for the casing to be run and cemented into place. No deeper permeability was encountered in well 77-29. In 1975 the well was abandoned below a depth of 991' and the 13⅜" casing was perforated from 791' to 980' with two ½" shots per foot (spf). The well was not successfully flow tested until 1981 when it was easily kicked off and produced 460 gpm of 332°F water. Since 1989 the 77-29 well has been an important large-volume injector accepting up to 2200 gpm but this injectivity was not evident during the drilling.

Well 84-33 Recompletion

Well 84-33 was drilled in 1981 to a depth of 8489' by Phillips Petroleum and Chevron. A lost circulation zone was encountered between 3340' and 3378' in Tertiary volcanic rocks which accepted about 1000 barrels (bbl) of mud. This zone was easily cured with 2 pills of gel and lost circulation material totaling 165 bbl. The well was then drilled to 4989' with no additional losses and 9⅝" casing was cemented in place with good cement returns to surface noted by the driller. Later static temperature profiles showed abnormally rapid re-warming of the well near depths of 3400' and 3900'. The 9⅝" casing was perforated between 3252' and 3498' with 4 spf and the well flowed 510 gpm during testing. After a second perforation the well artesian flowed from this zone at 580 gpm.

The perforations and flow testing of wells 77-29 and 84-33 opened the door for geothermal development at Soda Lake as these were the initial production and injection wells for the Soda Lake 1 plant. These two wells provided the first hints that permeability in Soda Lake wells was either easily damaged during drilling or could be easily re-accessed following casing cementing operations. In neither of these cases was the lost circulation so large or obvious that either well was initially believed or suspected to have commercial permeability.

Well 81-33 Stimulation

Well 81-33 was drilled in 1991 to a depth of 7350' by Ormat. During drilling small mud losses of about 7 bbl/hr began at a depth of 3354'. The drilling records are vague as to how long this mud loss continued, but it may have continued for a few days to a depth of 5445'. This lost circulation zone was not put behind pipe and when flow tested the open hole bridged. After the bridge(s) were cleaned out, a slotted 9⅝" liner was installed with slots from 3375-3809', and an acid job was performed. However, the well would not sustain flow so injection activities commenced and the injection rate gradually increased from 450 to over 1000 gpm in about 6 months. It is still in use, continuously accepting about 1500 gpm. Temperature and spinner logs run during injection in 2009 showed that most of the injectate exited through slots in the 9⅝" liner between 3340 and 3700' and that the remainder exited through a previously unknown and unrecognized zone at 4990'. This marked the first unintentional stimulation or improvement of permeability of a Soda Lake well through continuous injection at normal power plant injection conditions of < 200 psi. It was not stimulated by short-term high pressure injection.

Deflagration of Propellant for Well Stimulation

The stimulation technique which involves the deflagration of propellant at targeted depths uses a patented system developed by Dale Seekford of Precise Propellants. This technique was employed in 2010 at two Soda Lake wells with uncertain results. The theory behind deflagration of material as a well stimulation technique is to create a pressure wave via formation of a gas bubble at a fast enough rate that the gas is forced into the near wellbore formation. The major gases formed during the deflagration are H_2O, H_2, HCL, CO_2, CO and N_2. There is a substantial amount of hydrochloric acid (HCL) formed, which is a typical acid job component. The formation of HCL would be anticipated to have only a minor beneficial effect as the volume is very small compared to a normal acid job.

Though several systems for propellant deflagration below ground have been developed since the early 1980s the Precise Propellant technique is the current state of the art for geothermal applications because it is designed to withstand temperatures up to 400°F and not prematurely detonate, thus enabling precise targeting of the propellant. The technology was originally developed for natural gas well stimulation in well bores that are typically much smaller than the conventional geothermal well completion.

Well 45A-33 Recompletion and Stimulation

Well 45A-33 was drilled in 2009 to a depth of 4468' by Magma Energy (U.S.) Corp. This well encountered a total loss of circulation at a depth of 4168' during drilling. It was drilled from 4168' to 4468' with no returns putting about 9 cubic yards of cuttings into the fracture plus 1.3 million gallons of fluid including a significant amount of gel used during drilling. After the well reached total depth a 9⅝" slotted liner was run to the bottom of the well.

The first nitrogen assisted flow test of the well was run immediately after the well was completed and failed to result in sustainable flow. A month later a second flow test resulted in a 300 gpm flow rate with nitrogen assist but the flash point was 3000' deep. The slotted liner was then easily pulled and rerun but another nitrogen lift showed no improvement. An injection test was then performed at rates as high as 1300 gpm and wellhead pressures as high as 300 psig reconfirming the low permeability of the well as completed. In late 2009 plans were made to remove the slotted liner as a possible impediment to flow and to also use the deflagration of propellant in the well. The initial intention was to remove the liner, test the well, and then deflagrate the charges, but a fishing job at the start of the liner pulling and the coldest temperatures in 20 years resulted in performing the stimulation immediately following the liner removal. Two propellant treatments were applied conveyed by wireline to a depth of 4170'. Both applications were in open hole with the fluid level at, or close to surface.

Flow testing following the liner removal and use of the propellants showed a 600 gpm sustainable rate with a flash point at a depth of 1500'. Unfortunately, the two changes were essentially simultaneous so it is not possible to ascribe any percentage improvement to just the propellant deflagration. This was the first known use of propellant deflagration in a geothermal well.

Well 41B-33 Recompletion and Stimulation

Well 41B-33 was drilled in 2009 to a depth of 8995' by Magma Energy (U.S.) Corp. This well encountered massive losses of circulation below a depth of 775' that were put behind 13⅜" casing. Below the 13⅜" casing no fluid losses were detected during drilling but static temperature logs showed a sharp temperature maximum of 382°F at a depth of 3880 to 3890' that clearly showed nearby thermal fluid movement. This uncemented 9⅝" liner was perforated from 3836 to 3920' and deflagrated with 3 charges identical to those utilized in well 45A-33. Injection testing performed between and following the 3 deflagrations showed little or no improvement in the permeability. The real improvement to the production capacity of 41B-33 came from the perforation of the original lost circulation zone encountered during drilling above 1000'. This zone was perforated with .41" holes 5 per foot at 910-950' and 960-980' in September 2010. One deflagration was performed in the upper perforated zone, but it is uncertain as to how much of the well's improvement resulted from the deflagration. A new and lower fluid level resulting from the perforations between 910' and 980' made it unsafe to perform a second deflagration. The well was lifted with nitrogen after the perforations, but would not sustain flow without assistance. More perforations were shot in the shallow part of the well in December 2010 from 964-974' and 988-1008' and a pumped flow test with a submersible pump began in later in the month. The well produced an average of 700 gpm at 336°F, with the likelihood that the majority of this flow came from the shallow zone. It is uncertain as to how much of the improvement resulted from the deflagration.

Well 25A-33

Well 25A-33 represents the most successful and best documented example of deflagration improving well performance at Soda Lake and is therefore elaborated on in considerably more detail than the other wells.

The first well on the 25-33 pad location (25-33) was drilled to a depth of 2908' in 1991. Well 25-33 had a bottom hole temperature of 305°F and a bottom hole temperature gradient of 7.7°F/100', suggesting a temperature of ±390°F could be present as shallow as a depth of 4000' *(Figure 3)*. A 2010 reevaluation of all the data from the Soda Lake field confirmed that the 25-33 well was completed too shallow to intercept the geothermal resource, but that it was located close to the hottest part of the field below 3500'. These numbers were instrumental to the decision to drill deeper on the 25-33 pad. At the time of site selection for well 25A-33 there was little or no direct geological or structural evidence with which to target a well to intersect a particular fault or stratigraphic unit at a predictable depth.

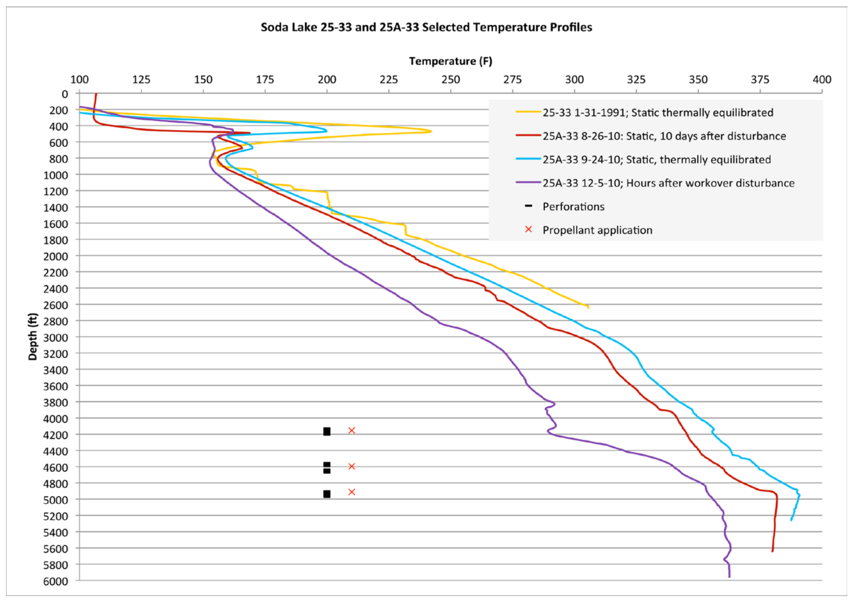

Figure 3. Selected temperature profiles from well 25-33 and 25A-33.

The two hottest producing wells in the field prior to the drilling of 25A-33 are 45A-33 with a maximum measured production temperature of 394°F and well 32-33 with an initial production temperature of 382°F. The 25A-33 surface location is situated south of 32-33 by 1600' and 950' west of the bottom-hole location of 45A-33 *(Figure 2)*. Well 45A-33 intersects the top of the reservoir at about 4125' true vertical depth and 32-33 at about 3910'. The geothermal reservoir was also expected to be encountered in 25A-33 near 4000'. Both 45A-33 and 32-33 encountered total lost circulation upon entering the reservoir and that same behavior was expected in the 25A-33 well. Wells 45A-33 and 32-33 did not encounter any significant drilling difficulties above the production zone depth.

Drilling

Well 25A-33 was drilled to a total depth of 6000'; about 1500' deeper than originally planned. Only one lost circulation zone was encountered at a depth of 4188', which was suspiciously identical to the 4168' depth of the main fluid entry zone are in well 45A-33. An attempt to protect this zone by sanding back above the lost circulation zone at 4188' so that a liner could be installed and cemented without damaging the zone was unsuccessful. A supposedly drillable packer was set to protect the lost circulation zone. The packer was not drillable once the liner was set, requiring a sidetrack around the packer from a depth of 3905'. It was surprising when no lost circulation was encountered in the sidetrack. A temperature survey showed that there was still a high temperature gradient below 4800'. The sidetrack was drilled to a depth of 6000' without lost circulation. A 2⅞" tubing string was hung from the surface to the bottom of the hole to ensure equilibrated temperature logs could be obtained in the open hole from 3905' to 6000'. The bottom joint of the tubing was slotted to obtain pressure data from inside the tubing.

The highest static temperature measured in well 25A-33 is 390.8°F at 4943' and is the highest static temperature measured in the field above a depth of 7000' (Figure 3). Below 4943' the gradient was slightly negative in the fully developed thermal profile.

Testing

One air lift was performed in the original hole before beginning the sidetrack. The well did not sustain flow, even with the air assistance. A very low pressure water injection test consisting of simply pouring water into the open wellhead amounted to only about 15 gpm. Another low pressure injection test when the well reached its total depth resulted in a similar rate. This low injection rate cancelled plans for a completion flow test.

In September 2010 a higher pressure injection test through the 2⅞" tubing was performed with pumps capable of injecting at pressures up to 400 psi. The well would take no fluid through the 2⅞" tubing or from the wing valve injecting outside of the tubing. In October 2010 the 2⅞" tubing was removed and the slotted bottom joint was found to be plugged with mud and pipe dope, explaining the inability to inject through the tubing. Injection directly into the well was then attempted again, but the well still took no fluid. Shortly thereafter a bridge in the open hole section of the well was discovered at a depth of 4864'. In early December a workover rig cleaned out the open hole from 3925' to 5989'. A 7" perforated and blank liner was set on the bottom, between depths of 3857' and 5989'. The well accepted about 150 gpm at a wellhead pressure of 400 psi during an injection test at the time of the workover.

Perforated intervals in the 7" liner (4129-4201'; 4555-4594'; 4633-4672'; and 4901-4979') were based on inflections in the temperature surveys, which indicate localized fluid movement in or near the well. The most prominent inflection is the temperature maximum at 4950' *(Figure 4)*. The depth where lost circulation was encountered in the original hole was also perforated. As Soda Lake is a pumped binary plant there is no particular advantage to trying to maximize the produced temperature from the well, greater mass flow is more important, especially for an underperforming plant. Injection was again attempted during the clean out and after the installation of the 7" liner, but the well was able to accept only about 7 gpm under the plant injection system pressure of about 140 psi in both cases. Through this testing it became obvious that without some increase in permeability this well could not be used as either a production well as was intended or an injection well, despite being one of the two hottest wells in the field. Redrilling options were considered, but deemed to be premature, because there was not a defined nearby permeability target.

Since the previous use of the propellant deflagration technique earlier in 2009 and 2010 on wells 45A-33 and 41B-33, the maximum size of the charges had been increased 2.3 times. The bigger charges send a larger pressure wave out into the formation and burn for 700 milliseconds as opposed to 20 millisecond burns with the smaller charges. The prior propellant deflagration in Soda Lake wells 45A-33 and 41B-33 released approximately 5.52 MSCF of gas per stimulation. The new size more than doubles this gas volume to 12.66 MSCF per stimulation. The larger charge requires a higher water column for safety purposes above the deflagration depth. The low injectivity of well 25A-33 at that time allowed the maximum possible downhole pressure with the wellbore full to the surface. On February 1, 2011 three shots at depths of 4142'-4150'; 4568'-4576'; and 4902'-4910' were burned in 3 of the 4 perforated intervals of 25A-33. Each of the three charges released a total energy of 31.2 million calories as opposed to 13.6 million calories released from the smaller charges.

Immediately after the propellant treatment, injection testing at wellhead pressures of 120 to 150 psig resumed. Within two weeks the injection flow steadily increased from an initial 30 gpm to a consistent flow over 600 gpm, with a maximum of about 750 gpm *(Figure 5)*. Injection was terminated due to a permitted injection test time limit. The propellant deflagration technique applied in the three 10' long zones increased 25A-33 injection capacity performance by about 2 orders of magnitude.

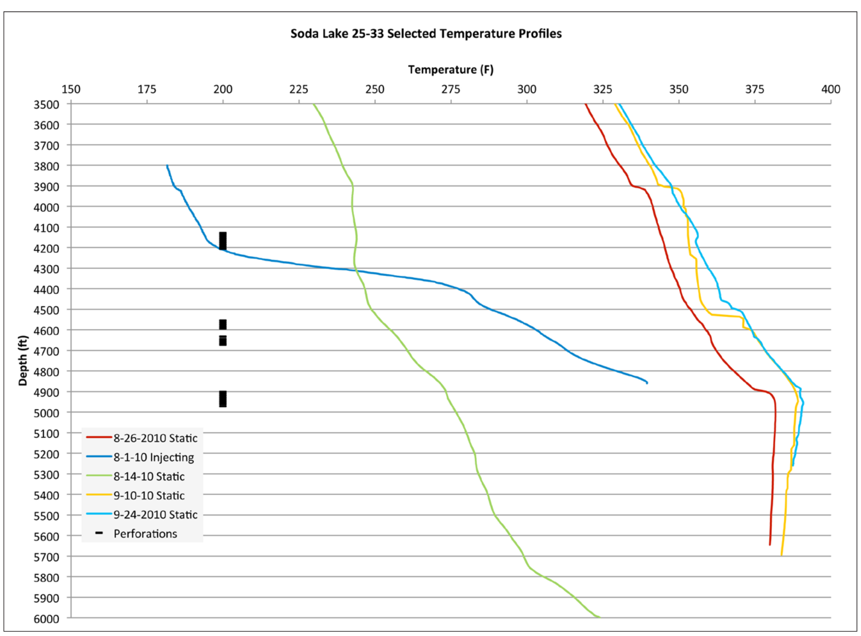

Figure 4. Soda Lake well 25A-33 temperature surveys used to select perforation locations with the perforation locations.

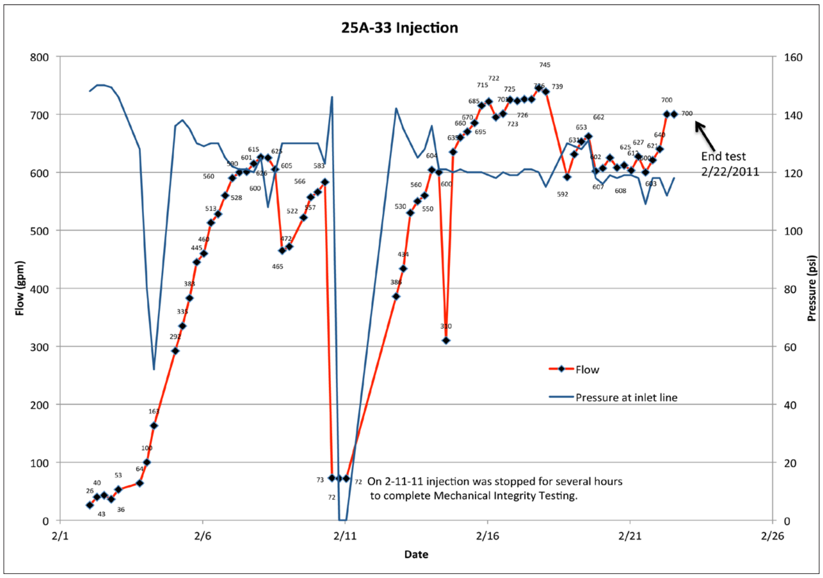

Figure 5. Injection testing results after deflagration February 2010.

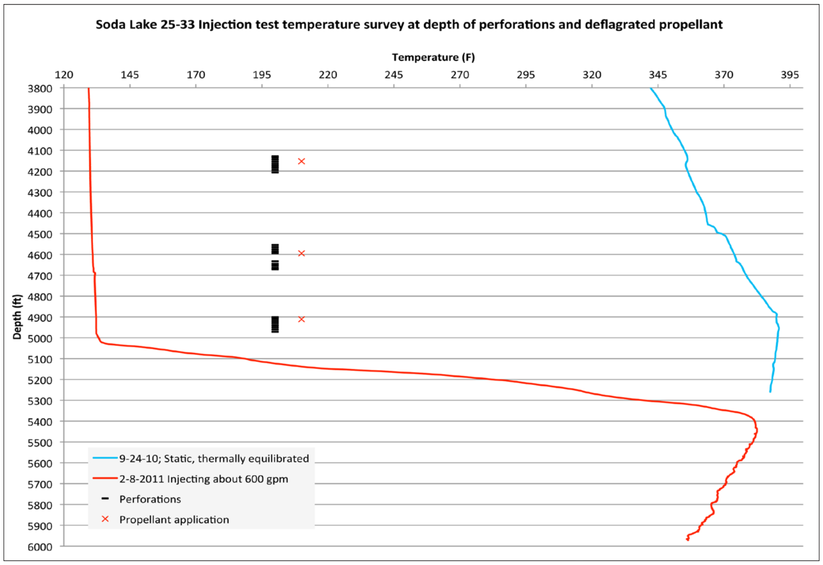

Figure 6. Temperature survey run during injection testing on February 8, 2011.

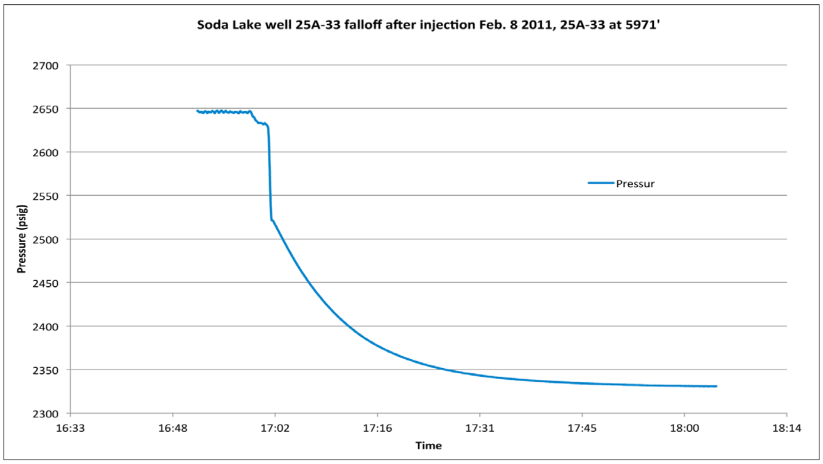

Figure 7. Pressure fall off in well 25A-33 after injection stopped on February 8, 2011.

An injecting temperature survey run on Feb. 5, 2011 during injection of ± 600 gpm of 125°F shows virtually all of the injectate exiting the wellbore just below a depth of 5018' (*Figure 6*) which is below the deepest perforations. Apparently the injectate exits the lowest perforations and then flows down outside of the uncemented liner another 38' before leaving the wellbore. No injectate flowed below a depth of about 5430' in the wellbore as those temperatures are identical with the thermally equilibrated log. The deflagration therefore did not create permeability outside of the deepest perforations in the hottest part of the well. It created permeability below the deepest perforations in a slightly cooler portion of the well.

The pressure falloff after injection ceased *(Figure 7)* shows that the well almost reached equilibrium after about 1 hour. The top of the log is uneven due to the time it took for the valve to be closed and the last of the injecting fluid got to the bottom of the well, but the actual falloff curve is typical.

Conclusion

The permeability of Soda Lake wells may not be easily recognizable or be easily damaged during drilling operations. Some intervals, even those not initially recognized during drilling, can be responsive to stimulation and become commercial producers or injectors. In some of the older wells permeability was recovered through standard perforating techniques. The injectivity of well 81-33 improved over a period of months with continuous low pressure injection. Relatively small propellant charges were deflagrated in wells 45A-33 and 41B-33, but it is difficult to tell what improvements are attributable to the propellant because two actions were taken at one time in these wells. Larger propellant charges allowed 25A-33 to initially accept modest amounts of injectate. Five days of continuous injection following the deflagration of the propellant increased the permeability of 25A-33 by about 2 orders of magnitude.

Acknowledgements

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References

Primary references are internal Magma Energy (U.S.) Corp. reports and data.

Precise Propellant website: www.precisepropellant.com.