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GEOTHERMAL WELL STIMULATION EXPERIMENTS IN THE UNITED STATES

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ABSTRACT

From 1979 through 1984 the U.S. Department of Energy (DOE) sponsored ten stimulation experiments in hydrothermal geothermal wells. The work included literature reviews, laboratory studies, field tests of hydraulic fractures and acidization treatments, explosive stimulation, and high energy gas fracturing. Hydraulic fractures can be economic in sedimentary rock with substantial matrix permeability. But what are now seen as the most typical hydrothermal wells, in naturally fractured reservoir zones, were not converted to useful wells in these experiments.

1. INTRODUCTION

The DOE Geothermal Reservoir Well Stimulation Program (GRWSP) extended petroleum industry stimulation technologies to geothermal wells. The goal was to improve geothermal economics by developing stimulation as a less expensive alternative to the normal practice of redrilling or replacing deficient wells. Republic Geothermal, Inc., led the GRWSP with Maurer Engineering, Petroleum Training and Technical Services, and Vetter Research as subcontractors. Most of that research was not reported in refereed journals. But it provided important results that affect the perceptions of many geothermists about the value of stimulation. It remains of value as baseline information for current attempts to enhance the productivity of hydrothermal wells. Much of the information about GRWSP reported here is from a summary report by Verity (1984).

In other DOE experiments Los Alamos National Laboratory (LANL) performed explosive stimulation of a well at The Geysers, and Sandia National Laboratories studied high energy gas fracturing.

General issues identified by Verity remain important and challenging today. In geothermal wells, stimulation must bring about much larger fluid production rates than in conventional oil and gas stimulations. It demands the creation of very high near-wellbore permeability and/or fractures with very high flow conductivities over long intervals. This normally dictates use of relatively large volumes and high flow rates. Behaviors of stimulation fluids, proppants, and equipment must be evaluated at high temperatures. Also, high temperature chemical compatibility between reservoir rocks and fluids and the stimulation materials must be verified.

GRWSP baseline research included reviews of conventional oil and gas stimulation technology, covering treatment design, evaluation techniques, stimulation materials performance, and mechanical equipment (Maurer Engineering, 1980a, 1980b). Laboratory data were gathered on high temperature behavior of stimulation materials. Proppants, fracturing fluids, and fracturing fluid additives were tested at temperatures to 260^{o}C. Polymer-based fracturing fluids were tested. Solubilities and reaction products of common formation materials and drilling mud clays in acetic, formic, hydrochl oric, and hydrofluoric acid were studied at 175^{o}C and 225^{o}C. Thermal stability of several calcium carbonate scale inhibit ors was studied (for preventing downhole scaling). Four co mputer codes were revised to provide field experiment desi gn and analysis capability.

2. GRWSP FIELD EXPERIMENTS

Wells in thoroughly studied proven reservoirs were favored for the field tests. In general, the experiments progressed from reservoirs of lower to higher temperature.

Stimulation Experiments 1 and 2 were done at Raft River, Idaho in 1979. This naturally fractured hard rock reservoir has a relatively low resource temperature, 143^{o}C. A revers e flow technique was used in Well RRGP-4, to intersect ne arby faults. It was designed to create a branched fracture p attern, which was probably not achieved. A borehole televi ewer and pressure buildup data indicated that a fracture 60 m high (vertical) at the wellbore and 100 m long (horizonta l) was created. Productivity was increased 5-fold, but at on ly 13 tonne/hr, the flow was still subcommercial.

In Experiment 2 well RRGP-5, near the intersection of two major faults, was stimulated with a conventional hydraulic fracture treatment in a 66 m openhole interval near the bott om of the well. Complications in the original well completion caused the fracture to channel upwards. The fl ow rate achieved was only about 50,000 kg/hr (about one fifth of that from a well that intersected a nearby fracture) a nd the produced fluid temperature was subcommercial.

Experiments 3 and 4 were done at East Mesa, California, in 1980. This Imperial Valley site produces from a sandstone and siltstone matrix, at moderate temperature (160-175^{o}C). Well 58-30 had been completed with a cemented, jet perfor ated liner, which made it inexpensive to isolate zones for tr eatment.

Experiment 3 was a planar-type hydraulic fracture of a 75 m low-permeability sandstone interval near the bottom of the well (about 2,000 m). This zone had permeability severely reduced by carbonate minerals. This fracture treatment was designed to create a high conductivity linear flow channel. After treatment, this zone was sanded back to allow stimulation in the upper part of the well.

Experiment 4 was a staged fracture treatment in a shallower 90 m interval of higher permeability. This zone, drilled with a bentonite mud, had good sands that showed permeability impairment near the wellbore. The treatment was designed to create multiple short fractures through the damaged zone around the wellbore.

The upper zone was tested first. Its average flow was 60 tonne/hr. The permeability-thickness (kh) product had increased 108 percent in this zone. The sand was then removed from the lower frac zone. The entire wellbore achieved a flow of 90 tonne/hr, an increase of 114 percent. This was the best commercial success of the GRWSP.

Experiment 5 was done in Union's Baca well 23 in north-central New Mexico in 1981. A nonproductive, 70 m interval in the upper portion of the reservoir was isolated using an experimental high temperature Otis packer with EDPM elastomer elements. Post-stimulation tests indicated a fracture had been successfully created and propped, but the production rates declined to noncommercial levels because of apparent low permeability in the formation surrounding the fracture. Microseismic measurements by LANL indicated activity in a zone roughly 700 m long, 200 m wide, and 400 m high, suggesting that rock failure had happened in a broad zone. However, a single fracture 100 m high and about 160 m long might have been created.

Experiment 6 was done at The Geysers, California, dry steam field in January 1981. An HCl etching treatment was done in Union's Ottoboni State 22 well, to etch discrete flow channels in the fracture faces. However, results indicated that the acid probably was dissipated in natural microfractures over a long 200 m openhole interval. There was no effect on the productivity of the well.

Experiment 7 was conducted in Baca well 20 in 1981. This test used a high viscosity fracturing fluid carrying only sintered bauxite as the proppant. To try to improve on the Baca 23 results, a larger size proppant was used and a deeper, hotter interval was selected. An 80 m interval at 1,600 m, which had produced only a small part of the well's 25 tonne/hr total flow, was isolated. The temperature of this interval (282^{o}C) made Baca 20 the hottest well to be fractured in the GRWSP work. The high temperature packer was again successful. Tests indicated a highly conductive fracture was achieved with a length of over 100 m. However, the productivity of the well was poor.

Finely ground calcium carbonate used as a fluid-loss additive during the fracture treatment was suspected in this job to result in some formation plugging. However, Experiment 7A, a follow-up acid treatment in Baca 20 designed to remove this material, did not improve the well's productivity. Pre-fracturing injection test data from the well showed that half of the fluid entered a non-productive fractured zone below about 1500 m whereas the primary production zone is at 1200 m (Riney and Garg, 1982).

Experiment 8 was done at the Beowawe, Nevada field in Chevron's Rossi 21-19 well in 1983. The Beowawe reservoir is a fractured volcanic sequence with temperatures of 180-215^{o}C. The Rossi well was noncommercial, even though it was known to intersect a high-temperature fluid zone. Test results showed that it was limited by restricted near-wellbore permeability. All the remaining Chevron wells had been tested with production rates measured of 100 to 145 tonne/hr. Hydraulic connectivity existed between all the wells. The treatment was a 227,000 liter, two-stage (first HCl, then HF) acid treatment. The treatment was done in the slotted liner interval below 1,330 m. The HCl stage was used only to avoid precipitation of CaF in the formation during the HF stage. Injectivity increased 2.3-fold. Mechanical problems with the well prevented an adequate production test. While the theoretical effectiveness of this treatment has to be scored "unknown," the experiment must be graded a failure due to the inability to complete tests.

Data on the eight GRWSP field experiments are summarized in Table 1. Table 2 summarizes some of the main results of the eight experiments.

3. OTHER STIMULATION WORK

3.1 Explosive Fracturing Test

LANL managed an explosive stimulation of Unocal's Geysers well FL-30 by Physics International Company in 1981 (Mumma, 1982). An initial test using 364 kg of HITEX II liquid explosive at 2,256 m showed that the explosive was safe after 48 hours in the well at temperatures up to 260^{o}C. The second test used 5000 kg of explosive, held in a 190 m long aluminum tube, at a depth of 1,697 m. Tests suggested that near-wellbore skin factor was reduced. However, the two treatments resulted in a 35% reduction in permeability-thickness (kh) product and steam flow rate, attributed by the researchers to a possible blockage of two deep steam entry zones by rubble from the first explosion. These results are consistent with the conventional wisdom that explosive stimulation tends to create near-wellbore damage.

3.2 High Energy Gas Fracturing

Realizing that explosives generally act so fast that they mainly pulverize and compress rock, Sandia scientists pursued the development and use of propellants that burn more slowly as a means to force fractures at least some distance from wellbores. This was called "high energy gas fracturing" (HGEF).

Experiments done on five boreholes at the DOE Nevada Test Site demonstrated that multiple fractures could be created to link a water-filled borehole with other fractures. The region fractured was mined out to determine the direction and length of the fractures (Chu et al., 1987). One finding that remains very interesting today was that fractures could be made in perpendicular directions, when a slotted liner was set up to do this. This offers at least some hope of forcing fractures to be parallel to the least principal stress in rocks, and thereby break through to pre-existing fractures. Any pre-existing fractures are generally expected to be perpendicular to the least principal stress. The hope should be somewhat guarded however, since the fractures formed in that direction were shorter (0.5 to 3 m) than those perpendicular to them (one of which was about 6 m). A model developed to predict the formation of fractures in these experiments was generally useful (Taylor, et al. 1984). An HGEF stimulation tried at The Geysers in the early 1980s failed because the propellant ignited prematurely. Nevertheless, HGEF should be useful to remediate at least near-wellbore damage.

3.3 Later Experience

U.S. firms have continued to study hydrofracturing in geothermal wells, but not intensively. Three hydrofracs done in the 1990s have been described to the author, but not in great detail. A working consensus seems to be that injectivity can be improved a lot in some circumstances, but that enhancement of production rates is still elusive.

4. GENERAL FINDINGS

Verity (1984) noted some major concerns about hydraulic fracturing that were addressed by the GRWSP. Our current (1999) interpretation of the GRWSP findings are in italics. (1) Hydraulic fractures in fractured formations may merely parallel the predominant natural fractures in the reservoir and fail to effectively connect with them. *The results of the GRWSP work remain consistent with this concept*. (2) Rapid thermal degradation of polymer frac fluids could prevent the effective growth and propping of hydraulic fractures. *Propping appeared to work in at least the East Mesa experiments, and perhaps at Baca*. (3) Conventional downhole mechanical equipment may be inadequate for fracturing in high temperature wells. *This concern seem to have been allayed successfully by running pretreatments ("prepads") of cool water*. (4) Available proppants may degrade in the high temperature, saline environment. *The field work seemed not to have studied this issue, e.g., with long-term tests of productivity from stimulated wells*. (5) The possibility of excessive fluid leakoff, especially in naturally fractured formations, could result in an early termination of hydraulic fracture growth. *Some of the GRWSP results, e.g., at Raft River, were interpreted to be consistent with this idea*.

The decision to confine fracture treatments to relatively short, nonproductive intervals of the wellbore at Baca and Raft River was based on the premises that: (1) petroleum industry fracture design technology is applicable to creating new fractures in unfractured rock; and (2) the fracture height at the wellbore face must be limited by zone isolation in order to achieve the desired fracture width (aperture) and horizontal fracture extension. This approach necessitated recompletion of these wells to exclude about 90 percent of the original open interval. Because reliable methods did not exist to temporarily isolate intervals for hydraulic fracturing in the open wellbore, virtually 100 percent of the well's pre-stimulation production was sacrificed. For the experiments, these limited interval treatments reduced the risk of a complete job failure and simplified interpretation of the results. However, in terms of the level of productivity achieved, the Raft River and Baca experiments were handicapped by the exclusion of previously productive intervals. *In 1999, we note that this factor should be considered to work against scoring these experiments as complete failures in the commercial sense.* Today, metal-based packers could likely be used to isolate zones in similar wells.

Concerns about acid stimulation were: (1) Acid reaction rates with formation materials at high temperatures were not well known. (2) Data on the solubility of formation rocks in acids and the resulting products of reaction were needed for treatment design. (3) Some concern existed regarding whether or not fracture acidizing could provide adequate fracture conductivity for successful stimulation. *Concerns (1) and (2) were met using laboratory measurements. It appears to the current author that not enough positive cases resulted from the various acid treatment experiments to be able to get good field-based answers to concern (3)*.

Overall it was shown that both hydraulic fracturing and acidizing can, if properly applied, be effective remedies for near-wellbore formation damage and for enhancing productivity of a well penetrating a local region of low reservoir permeability.

5. CONCLUSIONS

The fracture treatments in Raft River and those in Baca succeeded in getting significant production from previously nonproductive intervals. However, the four treatments failed to establish commercial production rates due to deficiencies in either well fluid temperature or flow rate or both. These results have contributed, historically, to the working concept that hydrofracturing of wells in fractured geothermal zones does not "rescue" poor producers. Italian experience at Lardarello has been similar. It is believed that although new fractures are created or reopened, they run parallel to existing permeable fractures and do not connect to them (Cappetti, 1998).

Many have noted that these experiments were done on wells with very low flow rates, and that the negative conclusion above might not apply to wells where the initial flow rate was moderate, rather than very low. However, detailed theory for why this might work on a practical basis remains to be worked out. It seems probable that the more productive the completed interval is, the less likely that the fracturing fluid would have any effect in enhancing near-bore permeability, because the fluid will tend to simply run off into the f ormation. Also, a number of the stimulated wells had completion problems that affected either what was attempted or the results of the stimulation.

It seems clear that the more productive and intact a well is, the less likely that the owner would risk possible damage to it by stimulation attempts. The next round of experiments should most likely be focussed on producers that already have modest rather than minimal flows, and thus are of marginal economic value in their unstimulated state.

In 1984 Verity noted that at both Raft River and Baca, the knowledge of the reservoirs and the geometries of the created fractures were too limited to establish for certain the proximity of productive natural fractures to the wellbore and whether or not the pattern of natural fractures is such that a hydraulic fracture can intercept them effectively. He anticipated new methods of fracture mapping that could eliminate much of this uncertainty in natural fracture treatments. In 1999, such methods for hydrothermal systems are still "anticipated" rather than a reality, and remain a critical need for successful stimulation work.

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Table 1. SUMMARY OF GRWSP EXPERIMENTS

Exper. No.	Location and well	Reservoir Temp. (°F)	Stimulation Treatment	Treatment Interval Height (ft)	Fluid	Proppant	
1	Raft River,ID RRGP-4	290	Dendritic hydraulic fracture	196	7900 bbl 10 lb HP Guar/1000 gal 2 lb XC Polymer/1000 gal	Sand	50,400 lb 100-mesh 58,000 lb 20/40-mesh
2	Raft River,ID RRGP-5	290	Large hydraulic fracture	216	7600 bbl 30 lb HP Guar/1000 gal	Sand	84,000 lb 100-mesh 347,000 lb 20/40-mesh
3	East Mesa,CA 58-30	350	Hydraulic fracture	247	2800 bbl 60 lb HP Guar (Crosslinked gel)/1000 gal	Sand RCS	44,500 lb 100-mesh 59,200 lb 20/40-mesh 60,000 lb 20/40-Mesh [c]
4	East Mesa,CA 58-30	320	Dendritic hydraulic fracture	304	10,300 bbl 10 lb HP Guar/1000 gal 2 lb XC Polymer/1000 gal	Sand	44,000 lb 100-mesh
5	Baca,NM 8-23	450	Large hydraulic fracture	231	3600 bbl water prepad 4000 bbl 60 lb HP Guar (Crosslinked gel)/1000 gal	Sand RCS Bauxite	42,000 lb 100-mesh 81,5000 lb 24/40-mesh 98,500 lb 2O/40-mesh
6	The Geysers,CA OS-22	460	Acid etching	1000	476 bbl prepad 15 lb HP Guar/1000 gal 476 bbl pad 60 lb HP Guar (Crosslinked gel)/1000 gal 476 bbl 5% HCl-10% HF 445 bbl displacement 15 lb HP Guar/1000 gal	None	
7	Baca, NM B-20	540	Large hydraulic fracture	240	3000 bbl water prepad 5600 bbl 60 lb HP Guar (Crosslinked gel)/1000 gal	Bauxite	119,700 lb 16/20-mesh 119,700 lb 12/20-mesh
7A	Baca, NM B-20		Acid treatment [a]	240	1045 bbl 11.9% HCl	None	
8	Beowawe, NV Rossi 21-19		Acid etching [b]	1111+	Stage 1: 500 bbl 14.5% HCl 2446 bbl water displacement Stage 2: 982 bbl 12% HCl-3% HF 3019 bbl water displacement	None	

Notes:

[a] To dissolve calcium carbonate fluid-loss additive

[b] To remove formation damage

[c] "RCS" is resin coated sand

Table 2. Summary of Results of Stimulation Experiments					
Experiment & Well	Formation Type	Treatment Goal	Stimulation successful?	Well Fixed?	Conclusions
1. Raft River RRGP-4	Fractured	Dendritic fracture	Yes, but long fracture	No	Flow rate too low
2. Raft River RRGP-5	Fractured	Long fracture	Partially	No	Flow rate low & fluid too cool
3. East Mesa 58-30	Sedimentary	Long fracture	Yes	Yes	Hydrofrac worked
4. East Mesa 58-30	Sedimentary	Long fracture	Yes	Yes	Hydrofrac worked
5. Baca B-23	Fractured	Fracture	Yes	No	Impermeable formation
6. Geysers OS-22	Fractured	Acidize	No	No	Fractures too short
7a. Baca B-20	Fractured	Long fracture	Yes. Fracture created.	No	Impermeable formation
7b. Baca B-20	Fractured	Acidize	Unknown	No	Permeability not increased
8. Beowawe R21-19	Fractured	Acidize	Probably	Partial	Injectivity increased 2.3 fold.