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Geothermal Reservoir Well Stimulation Program

Final Program Summary Report

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I. SUMMARY

Republic Geothermal, Inc., and its subcontractors have planned and executed eight experimental stimulation treatments under the U.S. Department of Energy-funded Geothermal Reservoir Well Stimulation Program. The program, begun in February 1979, has concentrated on extending petroleum industry stimulation technology for use by the geothermal industry. This report describes the eight field experiments and the associated theoretical and laboratory work performed to develop the stimulation technology.

Two stimulation experiments were performed at Raft River, Idaho, in late 1979. This is a naturally fractured, hard rock reservoir with a relatively low geothermal resource temperature (290°F). A planar hydraulic fracture job was performed in Well RRGP-5 and a dendritic, or reverse flow, technique was utilized in Well RRGP-4.

In mid-1980, two stimulation experiments were performed at East Mesa, California. The stimulation of Well 58-30 provided the first geothermal well fracturing experience in a moderate temperature (350°F) reservoir with matrix-type rock properties. The two treatments consisted of a hydraulic fracture of a deep, low-permeability zone and a dendritic fracture treatment of a shallow, high-permeability mud/cement-damaged zone in the same well.

In January 1981, an acid etching stimulation treatment was performed in the Ottoboni State 22 well located in The Geysers geothermal area of California. The resource is a 460°F naturally fractured dry steam reservoir. The treatment involved the injection of a 10% HF-5% HCl acid solution behind a slug of high viscosity crosslinked gel fluid. This technique was intended to take advantage of the fluid mobility differences to etch discrete flow channels in the fracture faces.

A 7,600 bbl hydraulic fracture treatment was also performed in early 1981 in the Baca 23 well of the Redondo Creek area of New Mexico. The stimulation interval was in the upper part of the Bandelier Tuff, a 450°F interval in which the well had not encountered productive natural fractures. This treatment utilized a large cooling water prepad, a high viscosity frac fluid, and temperature resistant proppants, i.e., sintered bauxite and resin-coated sand.

The seventh field experiment was conducted in Baca 20 on October 5, 1981, again utilizing a large cooling water prepad followed by a high viscosity frac fluid carrying only sintered bauxite as the proppant. The large hydraulic fracture job was performed in a deep interval with a temperature of about 520°F, which gave Baca 20 the distinction of being the hottest well to be fracture stimulated with the use of proppants in the United States to date. A follow-up HCl acid job was done to remove calcium carbonate particles introduced as a fluid loss additive in the fracturing treatment.

The last field experiment, the Beowawe Field chemical stimulation treatment, was designed for the Rossi 21-19 well as a two-stage acid job to remove near-wellbore restricted permeability. HCl acid solution was pumped in the first stage and followed by the second stage consisting of a HCl-HF acid solution. The treatment was confined to the slotted liner interval below 4,369 feet with an average reservoir temperature of about 400°F. The acid solutions were intended to increase the permeability in existing reservoir flow channels by reacting with secondary mineralization, dispersing drilling mud residue, and/or etching the fracture faces.

A discussion of the pre-stimulation and post-stimulation data and their evaluation is provided for each experiment in this report. Overall results have shown that stimulation is viable where adequate reservoirs are penetrated by wells encountering formation damage or locally tight formation zones. Seven of the eight stimulation experiments were at least technically successful in stimulating the wells. The two fracture treatments in East Mesa 58-30 more than doubled the producing rate of the previously marginal producer. The two fracture treatments at Raft River and the two at Baca were all successful in obtaining significant production from previously nonproductive intervals. However, these treatments failed to establish commercial production due to deficiencies in either fluid temperature or reservoir transmissivity. The Beowawe chemical stimulation treatment appears to have significantly improved the well's injectivity, but production data were not obtained because of well mechanical problems. The acid etching treatment in the well at The Geysers did not have any material effect on producing rate. Evaluations of the field experiments to date have suggested improvements in treatment design and treatment interval selection which offer substantial encouragement for future stimulation work.

The individual activities of the Program subcontractors, Maurer Engineering Inc., Vetter Research, Petroleum Training and Technical Services, and Terra Tek, Inc., are also summarized herein. The Phase I theoretical and laboratory studies were performed to provide the basic stimulation technology needed to design and evaluate geothermal well stimulation treatments. The Phase II site-specific laboratory and design work required for each field experiment was performed as needed by Maurer Engineering, Vetter Research, and Terra Tek.

Phase I and Phase II activities produced a number of important technical innovations and accomplishments. These were principally in the areas of data and software for stimulation design and new methods for well data acquisition and laboratory analyses.

II. INTRODUCTION

The U.S. Department of Energy (DOE)-sponsored Geothermal Reservoir Well Stimulation Program (GRWSP) was initiated in February 1979 to pursue industry interest in geothermal well stimulation work by extending the petroleum industry's stimulation technology for use in geothermal wells. The stimulation of geothermal wells has presented some new and challenging problems. The behavior of stimulation fluids, fracture proppants, and downhole equipment at elevated temperatures must be carefully evaluated before a treatment can be properly designed and executed. In order to avoid possible damage to the producing formations, high temperature chemical compatibility between the reservoir rocks and fluids and the stimulation materials must be verified. Perhaps most significant of all, in geothermal wells the stimulation treatment must bring about very large fluid production rates. This requirement for high flow rates represents a significant departure from conventional petroleum well stimulation and demands the creation of very high near-wellbore permeability and/or fractures with very high flow conductivities over long intervals. These factors, combined with high natural formation permeabilities relative to most oil and gas reservoirs, normally dictate relatively large volume, high rate treatments.

The principal aim of the GRWSP has been to improve geothermal development economics by developing stimulation as a viable, less expensive alternative to the normal practice of redrilling or replacing deficient wells. Candidate wells for the GRWSP field experiments fell into one or more of the three following categories: (1) Wells that failed to intersect major productive natural fractures in the reservoir; (2) wells that suffered man-made damage during drilling, completion, or workover operations, including mud or cement invasion; and (3) wells in matrix-type reservoirs that can benefit from the establishment of high conductivity, linear flow channels to improve flow capacity from surrounding localized regions of low permeability formation.

The first of the above situations is probably the most common and five of the eight GRWSP field experiments were performed in candidates of this type. Even in well developed, productive fields, new wells often fail to encounter sufficiently productive fractures. Redrilling in an attempt to encounter better fractures is common industry practice in such cases. The GRWSP tested both acid stimulation and hydraulic fracturing as methods of creating high conductivity fractures to connect with major productive natural fractures in the reservoir. Hydraulic fracturing with proppants was favored where large fractures with radii of the order of hundreds of feet were believed necessary to reach major productive fractures in the formation.

Formation damage by invasion of drilling mud, cement, etc., is relatively common in both fractured and matrix-type reservoirs. Because the damage is normally confined to the near-wellbore area, fracturing or chemical stimulation can be applied. However, selection of the treatment method depends on site-specific considerations. Two of the GRWSP field experiments were done in formation-damaged wells.

One experiment was done to stimulate a low permeability region of a matrix-type reservoir. This category, being less common, received less attention, but offers opportunities for significant economic benefit by enhancing the productivity of marginal or subcommercial wells.

Some major concerns to which the GRWSP addressed itself, are as follows:

A. Hydraulic Fracturing

1. Hydraulic fractures may parallel the predominant natural fractures in the formation and fail to effectively connect with them.

2. Rapid thermal degradation of polymer frac fluids could prevent the effective growth and propping of hydraulic fractures.

3. Conventional downhole mechanical equipment may be inadequate for fracturing in high temperature wells.

4. Available proppants may degrade in high temperature, chemically reactive environments.

5. The possibility of excessive fluid leak-off, especially in naturally fractured formations, could result in an early termination of hydraulic fracture growth.

B. Acid Stimulation

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. Could fracture acidizing treatments provide adequate fracture conductivity for successful stimulation?

The Phase I and II activities described below have provided satisfactory answers to most of these concerns.

III. PHASE I

Phase I was the necessary predecessor to the planned Phase II field experiments. These laboratory investigations, literature studies, and computer software development activities accomplished the following:

A. Technology Transfer

Conventional oil and gas stimulation technology was reviewed for applicability to geothermal conditions. Literature and current unpublished work on stimulation treatment design, evaluation techniques, stimulation materials performance, and mechanical equipment were reviewed and applicable portions were documented in GRWSP reports.

B. Numerical Modeling

Four existing computer codes were modified and upgraded to provide field experiment design and analysis capability. Three of the codes involved were available from other DOE projects.

C. Laboratory Work

A large body of data on high temperature behavior of stimulation materials was gathered and documented for the program. These results constitute a valuable data base for any high temperature well stimulation work. Proppants, frac fluids, and frac fluid additives were tested at temperatures to 500°F to establish their performance limitations in the geothermal reservoir environment.

A large amount of data on performance of fracture proppants is available in the literature, but only for relatively low temperatures. For the GRWSP, data were obtained using a specially constructed proppant tester to evaluate proppants at elevated temperatures up to 500°F. The tests identified several proppants which are suitable for geothermal well fracturing.

Polymer-based frac fluids were tested to characterize by chemical methods their degradation behavior as a function of temperature and time. This study required development of new analytical procedures. Results helped to guide selection of frac fluids for field experiments and the same analyses were later applied to residual frac fluids produced from the field experiment wells for interpretation of experiment results.

Solubilities and reaction products of common formation materials and drilling mud clays in acetic, formic, hydrochloric, and hydrofluoric acids were studied at elevated temperatures of 347°F and 437°F. Such data on high temperature acid reactions are scarce and difficult to obtain, but are important to good treatment design.

Hydrothermal stability of several commercially available scale inhibitors (for calcium carbonate) was also studied in the laboratory. Interest in scale inhibition was centered on maintaining productivity in wells subject to downhole scale deposition. This work showed that 500°F thermal stability of commercial acidic inhibitors is improved by neutralizing the inhibitor.

D. Reservoir Selection

Criteria were established for selecting fields and wells as stimulation candidates for GRWSP field experiments. Wells in thoroughly studied proven reservoirs were favored because: (1) Reservoir data are essential to stimulation design and are time consuming and expensive to obtain; and (2) in order for stimulation to be viable, a productive reservoir must exist.

In selecting candidate reservoirs and wells, the program was influenced by many contributing factors. In addition to the obvious technical considerations, the program evaluated cost-sharing arrangements provided by the well owner and the potential impact that effective stimulation could have on the future commercial development of the field. This latter consideration played a strong role in the selection of the Raft River and Baca Project areas for performing four hydraulic fracturing experiments. Raft River was selected at the request of DOE Headquarters to support brine production activities required for the 5 MW geothermal power plant. Although Baca was of tremendous technical importance to the program because of its very high reservoir temperature, the fact that it was part of a DOE/Union/PNM Demonstration Plant Project considerably enhanced its priority status. The importance of The Geysers as the world's largest commercial electric generating geothermal field, along with the cost-sharing benefits offered by Union Geothermal Inc., was also instrumental in its selection for a well stimulation treatment. While each of these sites proved to be an excellent choice from a technical standpoint, it did result in six of the eight field stimulation treatments being performed in fracture dominated reservoirs. Only the two treatments at East Mesa addressed the very significant problems associated with matrix-type producing formations, including well skin damage resulting from drilling and completion operations.

GRWSP reports documenting the Phase I work are listed in Table 1. Published papers by the program participants are listed in Table 2. Republic and subcontractors Maurer Engineering, Petroleum Training and Technical Services (PTTS), Terra Tek, Inc., and Vetter Research were responsible for the Phase I investigations and documentation. Maurer Engineering and Vetter Research performed literature studies and laboratory investigations on stimulation methods, design, and materials, with Maurer Engineering concentrating on mechanical aspects and Vetter Research on the chemistry. PTTS was responsible for documentation of technology transfer, for converting and modifying the necessary computer codes, and for the Program's 1980 symposium on geothermal stimulation. Terra Tek, Inc. performed site-specific laboratory experiments in support of the stimulation treatment design efforts beginning in 1981. Republic coordinated the subcontractor studies and performed the reservoir selection task.

IV. PHASE II

Phase II of the program consisted of eight field experiments with associated site-specific laboratory studies. Responsibilities for the various Phase II tasks are outlined in Table 3. In general, the experiments progressed from reservoirs of lower to higher temperature.

A. Raft River

The first two stimulation experiments were performed at Raft River, Idaho in late 1979. This is a naturally fractured, hard rock reservoir with a relatively low geothermal resource temperature (290°F). A conventional planar hydraulic fracture treatment was performed in Well RRGP-5 and a dendritic, or reverse flow, technique was utilized in Well RRGP-4. The fracturing process used in RRGP-4 is covered by U.S. Patent No. 3,933,205. This technique, designed to create a branched fracture pattern, was used in RRGP-4 to enhance the chances of intersecting major natural fractures paralleling the nearby Narrows fault. Analysis of the treatment pressure history indicated that dendritic fracturing was probably not achieved. Post-treatment evaluation using the the USGS borehole televiewer and pressure buildup data indicated that a fracture 195 feet high at the wellbore and 335 feet in length was created. The well productivity was increased five-fold, but the producing rate achieved was still subcommercial. RRGP-5, situated near the intersection of two major faults, was stimulated with a conventional hydraulic fracture treatment in a 216-foot openhole interval near the bottom of the well. The treatment was designed to obtain commercial production rates from a higher temperature portion of the well. Complications in the well mechanical condition, stemming from the original drilling, interfered with the treatment and caused the hydraulically created fracture to channel upwards into a cooler interval. Although a high well flow rate was achieved after stimulation, the produced fluid temperature was subcommercial.

B. East Mesa

In mid-1980, two cost-shared stimulation experiments were performed at East Mesa, California. Stimulation of Well East Mesa 58-30 provide the first geothermal well fracturing experience in a moderate-temperature (350°F) reservoir with matrix-type rock properties. The two experiments consisted of a hydraulic fracture treatment of a deep, low permeability zone and a dendritic fracture treatment of a shallow, high permeability mud/cement damaged zone in the same well. Both treatments were technically and economically successful and together more than doubled the producing rate of the previously marginal producer.

C. The Geysers

In January 1981, an acid etching stimulation treatment was performed in Union's Ottoboni State 22 well located in The Geysers geothermal field of California. This experiment was also cost-shared with the operator. The treatment involved the injection of 20,000 gallons of 10% HF-5% HCl acid behind a 20,000 gallon slug of high viscosity crosslinked gel polymer fluid. This technique was intended to take advantage of the fluid mobility differences to etch discrete flow channels, or fingers, in the fracture faces. The relatively low injection pressures experienced during the treatment combined with post-treatment temperature and R/A tracer logs indicated that the acid probably was dissipated in natural microfractures over a relatively long (650-foot) openhole interval instead of creating a single, large fracture as planned. This broad vertical distribution of the acid resulted in relatively shallow penetration of the formation and the treatment had no effect on the productivity of the well.

D. Baca

Also in 1981, hydraulic fracture treatments were performed on two wells located in Union's Baca project area in north-central New Mexico. Both experiments were cost-shared with Union. The treatment in Baca 23 was conducted in March utilizing a cooling water prepad followed by a high viscosity frac fluid carrying a mixture of sintered bauxite and resin-coated sand as the proppant. A nonproductive, 231-foot interval in the upper portion of the Baca reservoir was isolated for the treatment. An experimental high temperature Otis packer, using EPDM elastomer elements developed by another DOE program, was used successfully in this job. The same packer was used again in the post-stimulation evaluation testing. For this, a drillstem test method was devised by Republic to acquire downhole transient pressure data under the Baca reservoir conditions of high temperature and subhydrostatic pressure. Post-stimulation surveys and production tests indicated a fracture had been successfully created and propped; however, the production rates declined to noncommercial levels because of several factors, including the relatively low temperature of the interval selected, apparent low permeability in the formation surrounding the fracture, and reduced relative permeability caused by two-phase flow effects in the formation.

During the fracture treatment, Los Alamos National Laboratory (LANL) performed a fracture mapping experiment using Baca 6 as an observation well. A triaxial geophone system was placed in the well and, using techniques developed for the Hot Dry Rock Project, microseismic activity caused by the fracture job was mapped. The 14 discrete seismic events indicated northeast trending activity in a zone roughly 2,300 feet long, 650 feet wide, and 1,300 feet high. Calculations of the theoretical fracture length were made assuming a 300-foot high fracture. The results suggest a fracture wing of 430 to 580 feet in length may have been created, depending on the assumptions utilized for the frac fluid, fluid efficiency, and fracture width.

The second Baca experiment was conducted in Baca 20 in October 1981, again utilizing a cooling water prepad followed by a high viscosity frac fluid carrying only sintered bauxite as the proppant. In order to maximize fracture conductivity and improve on the Baca 23 results, a larger size proppant was used and a deeper, hotter interval was selected. A 240-foot interval from 4,880 feet to 5,120 feet was isolated for the job. The temperature in this interval (520°F) gave Baca 20 the distinction of being the hottest well to be fracture stimulated with the use of proppants in the United States to date. The Otis high temperature packer and special drillstem test method were used again successfully in Baca 20. In addition, a special instrument carrier was designed by Republic to house Amerada-type pressure instruments downhole during the fracture treatment and the data acquired enhanced the interpretation of the job.

Post-stimulation tests and analyses indicated a highly conductive fracture was created with a length of over 340 feet. LANL was successful again in measuring microseismic activity caused by the fracture job. However, the productivity of the well was poor, probably because of the low permeability formation surrounding the highly conductive propped fracture. Finely ground calcium carbonate introduced as a fluid-loss additive during the fracture treatment was suspected in this job and others to result in some formation plugging. However, a follow-up acid treatment in Baca 20 designed to remove this material did not improve the well's productivity. Although the results were disappointing, this follow-up acid clean out was successful in dispelling long standing concerns about the selection and application of solid fluid-loss additives.

E. <u>Beowawe</u>

The Beowawe, Nevada field experiment, the eighth of the GRWSP, was performed in Chevron's Rossi 21-19 well in August 1983. The experiment was cost-shared with Chevron Resources Company. The Beowawe reservoir is a fractured volcanic sequence with temperatures of 360-420°F. The Rossi 21-19 well was noncommercial even though it did intersect a high-temperature fluid zone. Chevron's reservoir test results showed that it was limited by near-wellbore, restricted permeability. The stimulation experiment was a

60,000-gallon, two-stage acid treatment designed to enhance productivity of the natural fractures and to remove drilling mud residue and secondary mineralization.

The treatment was confined to the slotted liner interval below 4,369 feet. A pre-stimulation injection profile survey indicated that about 80 percent of the injected fluid was entering the formation below a restriction in the liner at 5,480 feet. This restriction prevented logging to find the exact injection interval. The first treatment stage consisted of 500 bbl of a 14.5 percent HCl acid solution displaced by 2,446 bbl of water. The second stage consisted of 982 bbl of a 12 percent HCl-3 percent HF acid solution displaced by 3,019 bbl of water. Laboratory tests on drill cuttings from Rossi 21-19 had indicated average formation solubilities of 14 percent in HCl and 53 percent in HCl-HF. The hydrochloric acid stage did not by itself produce any measurable stimulation effect, but was necessary to prevent formation of insoluble calcium fluoride precipitate in the formation during the second stage. Injectivity tests performed during the experiment indicated a 2.2-fold increase in the well's injectivity index resulting from the second stage treatment. A planned production test to further evaluate the results was not accomplished because of a mechanical problem with the well.

Sandia National Laboratories and LANL both participated in the Beowawe experiment by testing fracture mapping methods and providing data on the direction of fluid movement in the reservoir during the treatment. Sandia applied its surface electrical potential system (SEPS) to map the movement of the treatment fluids in the reservoir. The SEPS was shown to be highly sensitive to the chemical treatment and was also responsive to fluid-filled fractures in the reservoir before any acid injection. Major acid flow paths were observed along the Malpais fault line (60°/225°) and along a 15°/195° path. LANL was able to detect and map microseismic events during fluid injection operations using the triaxial geophone instrument in the neighboring well Ginn 1-13. Seismic activity occurred along the direction of the Malpais fault and along an east-west trend. This was especially significant in that the treatment was carried out at pressures below fracturing pressure.

Data on the eight field experiments are summarized in Table 4 and the results are summarized in Table 5. The field experiments have been documented in GRWSP reports listed in Table 1. Published technical papers by the program participants are listed in Table 2.

V. SUBCONTRACTORS

The subcontractors involved in the program have changed during the course of the work as the emphasis of the program shifted from the Phase I theoretical and laboratory studies to the Phase II field experiments. Originally, Maurer Engineering Inc., Vetter Research, and Petroleum Training and Technical Services comprised the subcontractor team. With the modification of the contract in July 1981, Terra Tek, Inc. was added as a subcontractor for the laboratory flow test work required to support the design of field experiments. The following sections detail the specific activities of the subcontractors. It should be noted that all of the subcontractors were involved in varying degrees in the field experiments, as well as their individual tasks, and that these efforts represent a considerable part of the GRWSP accomplishments to date.

A. Maurer Engineering Inc.

1. Field Experiments

Maurer Engineering was directly involved in the planning, supervision, execution, and evaluation of all the field experiments. Its primary functions were to design and help supervise the hydraulic fracturing treatments, and also provide an ongoing link with the service companies and stimulation materials suppliers participating in the field experiments. These tasks were a significant part of the overall program and allowed the utilization of the most advanced stimulation technology available.

2. Laboratory Studies

Maurer Engineering was also responsible for several tasks of the Phase I portion of the program to develop new technology for geothermal well stimulation. Laboratory studies were performed on proppants, frac fluids, and additives to evaluate the limits on each material's potential for use in a geothermal environment.

Available data in the literature on proppants give only properties and strengths under triaxial stress at low temperatures. Data were obtained using a proppant tester constructed for this program, to evaluate proppant materials at elevated temperatures up to 500°F. Both short-term and long-term test results showed that most proppants are temperature sensitive. Sand was found to degrade severely if subjected to both closure stress and temperature above 300°F. These results were reported in "Geothermal Fracture Stimulation Technology - Fracturing Proppants and Their Properties," Volume I, July 1980, "Geothermal Fracture Stimulation Technology - High-Temperature Proppant Testing," Volume II, July 1980, and "Geothermal Fracture Stimulation Technology - Proppant Analysis at Geothermal Conditions," Volume IV, January 1981.

Physical strength and crush measurements were carried out on many potential geothermal proppant materials. Proppant materials with desirable properties at elevated temperature include: aluminum oxide, garnet, resin-coated materials (sand, bauxite, etc.), and sintered bauxite. While there are limits to the use of these proppants, they are generally resistant to the crushing loads and geothermal waters at geothermal temperatures.

Fluid-loss additives (e.g., silica flour, sand, calcium carbonate, etc.) were evaluated at high-temperature under static test conditions. These materials work by bridging and plugging the exposed formation to enhance frac fluid efficiency and fracture growth. No significant differences in results were found in these tests for the different materials; however, calcium carbonate was easily dissolved in low pH fluids, and therefore was a preferred choice in several of the field experiments to avoid possible permeability damage to the propped fracture.

Fracturing fluids were compared and evaluated with several different laboratory tests which include: polymer degradation in Baroid test cells at high-temperature, apparent viscosity measurements in high-temperature FANN viscometers, and proppant carrying capacity in a high-temperature falling ball viscometer. These results are reported in "Geothermal Fracture Stimulation Technology - Geothermal Fracture Fluids," Volume III, January 1981. Degradation of even the best polymer solutions starts around 300°F. This degradation continues at higher temperatures with time, even if stabilizers or other high-temperature additives are included. The physical properties of these fluids, especially the crosslinked polymer systems, are quite complex since they depend on temperature, time, shear rate, shear history, and concentration. In the higher temperature environment, frac fluid stability problems can be overcome by utilizing special treatment procedures (e.g., high injection rates, pre-cooling the formation, etc.).

B. Vetter Research

Under the terms of the GRWSP contract, the services supplied by Vetter Research (VR) as a subcontractor fell under two general categories. The areas were field experiments and laboratory studies.

1. Field Experiments

In five of the stimulation experiments, Vetter Research personnel were directly involved in the treatment design and at the field site with quality control and sampling of injected and produced fluids. For all the jobs, Vetter Research supplied the quantitative chemical analyses needed by the program. In particular, the analytical work applied to tracer materials, both radioactive and chemical, which were used in the stimulation experiments to help in the post-stimulation diagnostics. As part of the tracer studies, laboratory techniques were developed which allowed the polymer material in the fracture fluid to be used as an effective tracer. In addition, other chemical tracers, such as alcohol and Tinopal CBS-X®, were shown to be useful in monitoring fluid behavior in the geothermal environment.

2. Laboratory Studies

The laboratory efforts on the chemical aspects of the GRWSP consisted of three parts: fracturing fluid evaluation, acid work, and scale inhibitor tests. The object of the fracturing fluid evaluation was to characterize by chemical methods, the temperature/time degradation behavior of polymer-based fluids that may be used in stimulating geothermal wells. The organic polymers tested were hydroxypropyl guar, hydroxyethylcellulose, carboxymethylcellulose, and xanthan gum. Also, two commercially available crosslinked hydroxypropyl guar systems were investigated.

The report titled "Fracturing Fluid Evaluation (Laboratory Work)," GRWSP, January 1982 presents the development of analytical techniques for characterizing the polymers and the results of static and dynamic high-temperature aging of the polymers in various salt water environments. The fluids were tested at 302, 392 and 482°F. Also covered are the implications of these results based on the time/temperature degradation of the polymers and the relative ease of flushing the degraded polymer from a sandpack.

The report "Acidification of Geothermal Wells - Laboratory Experiments," GRWSP, January 1982, contains the results of the acid studies and scale inhibitor tests. In particular, this report describes the laboratory testing of the reactions of acetic, formic, hydrochloric, and hydrofluoric acids with calcium carbonate, kaolin, sepiolite, and two formation rocks at temperatures of 347 and 437°F.

A test procedure was developed which provided information regarding the relative reactivities of selected minerals or formation materials with three of the four acids investigated. Tests with hydrochloric acid were complicated by reactions of the acid with the test vessel materials and, therefore, only limited work could be done with this acid at the desired temperatures. In spite of these difficulties, information regarding the amount of soluble material in the various acids was obtained. From this information, an approximate value for the percent dissolution of the minerals under the different reaction conditions was calculated. Additional information regarding the formation of solid secondary reaction products upon cooling of the reacted acid was also obtained. The implications of the mineral reactivities with the different acids and the formation of secondary solids on geothermal acidizing operations were discussed.

The report on the acidification also contained data on the hydrothermal stability of several commercially available scale inhibitors (for calcium carbonate). Their efficiency in inhibiting the formation of calcium carbonate scale before and after aging at 500°F was measured. The significant conclusion reached, as a result of this laboratory work, was that all commercially available scale inhibitors are thermally unstable (as a function of time) at 500°F in their acidic forms. If the inhibitor is acidic, then it should be neutralized for better thermal stability.

C. Petroleum Training and Technical Services

Under the initial two-year GRWSP contract, PTTS was assigned specific tasks and responsibilities summarized below. In addition, PTTS assisted in the planning and evaluation of the first four field experiments in the GRWSP Phase II effort. PTTS was primarily involved in three tasks:

1. Technology Transfer - The objective of this task was to assess the stimulation technology developed for the oil and gas industry and to evaluate it as to applicability to the geothermal industry. A

detailed analysis was made in the following areas: (a) stimulation process variables, (b) frac fluid interactions, (c) fracturing problems, (d) temperature effects in fracture design, (e) fracture evaluation, and (f) stimulation case histories.

An integral part of the analysis involved a breakdown of each stimulation report to quantify the efficiency of various treatments and design criteria in a more objective fashion to provide an ordered ranking according to productivity increase. The results of this phase are summarized in a final report "Technology Transfer." Volume I and II, May 1980.

2. Numerical Modeling - PTTS was involved in the development and/or modification of the following five computer codes for use by the GRWSP:

   a. Interactive Fracture Design Program: This hydraulic fracture design program was developed by combining the functional elements: WELTEM - a wellbore temperature model and GERTSM - a fracture parameter and fracture fluid temperature model.

   b. WELTEM: This code is a wellbore fluid temperature model.

   c. GEOTEMP: This code simulates heat flow in and around the wellbore.

   d. DIFFUS: This program is a comprehensive reservoir model capable of three-dimensional flow simulation within a fractured system.

   e. SHAFT78: This reservoir simulation code could not be made operational and work was terminated on its conversion.

3. Symposium on Geothermal Stimulation - PTTS assisted Republic in the organization and delivery of a symposium on Geothermal Reservoir Well Stimulation to facilitate the interchange of information on geothermal well stimulation technology. This symposium took place in San Francisco on February 7, 1980 and the Proceedings of the conference were published as a GRWSP report.

D. Terra Tek, Inc.

As part of the GRWSP contract modification of 1981, Terra Tek, Inc. was added as a subcontractor and assigned the task of performing laboratory flow tests to provide design and evaluation data for the stimulation experiments. Terra Tek has assisted in the work associated with Experiment Nos. 7 and 8.

Because of the extremely hostile reservoir conditions at Baca 20, a laboratory test was performed to evaluate the effectiveness of the frac fluid under in-situ conditions. This test utilized the actual Baca formation material (Bandelier Tuff), the frac fluid (crosslinked HP guar polymer), and the 16/20 sintered bauxite proppant in a synthetic Baca brine to determine the possible damage to the proppant pack caused by the thermal degradation of the polymer. By measuring fluid conductivity prior to and immediately after the flow of the frac fluid through a vertically fractured core under the simulated in-situ conditions of the Baca reservoir, the extent of conductivity impairment was quantitatively obtained. The test results indicated that the frac fluid would not cause conductivity damage because of polymer residue or proppant embedment; therefore, the hydraulic fracture treatment of Baca 20 was performed as designed.

In addition, Terra Tek performed laboratory tests designed to provide general information on geothermal reservoir acidizing programs. The testing work included laboratory tests to determine the effectiveness of acid treatments in restoring the permeability of formation materials infiltrated with hydrothermally altered drilling muds. Furthermore, autoclave tests were performed to determine the degree of hydrothermal alteration and the effects of acid digestion on drilling muds and drill cuttings from two geothermal reservoirs. The results are provided in the report "Final Report - A Laboratory Study of Acid Stimulation of Drilling Mud-Damaged Geothermal Reservoir Materials," May 1983.

VI. TECHNICAL INNOVATIONS AND ACCOMPLISHMENTS OF THE GRWSP

In addition to the major conclusions of the GRWSP (discussed in the following section), there were a number of other technical innovations and accomplishments by Republic and the Program subcontractors which are worthy of note. These are listed below with appropriate references. The GRWSP reports are listed, by number, in Table 1 and technical papers are listed in Table 2.

1. Created a comprehensive data base on performance of stimulation materials at high temperatures.

   GRWSP Reports: 14 (Volumes I-IV), 20
   Technical Papers: 3, 5, 6, 13

2. Devised a new method of analysis for characterization by chemical methods of the temperature/time degradation of polymer-based fluids.

   GRWSP Reports: 20
   Technical Papers: 1, 3, 5

3. Developed software for high-temperature fracture treatment design.

   GRWSP Reports: 7, 8, 27

4. Devised a novel geothermal well drillstem test method to acquire downhole pressure data for interpretations of fracture length, fracture conductivity, and formation productivity.

   GRWSP Reports: 17 and 27
   Technical Papers: 8, 10, 14

5. Devised a novel method of measuring downhole pressure during a fracture treatment.

   GRWSP Reports: 27
   Technical Papers: 7

6. Provided an opportunity for testing high-temperature packer elastomers, fracture mapping techniques and logging tools developed by other DOE-funded programs.

   GRWSP Reports: 17 and 27
   Technical Papers: 5, 8, 10, 14

7. Encouraged continued development by private industry of treating fluids, packers, and logging tools for high-temperature wells.

   This was a continuing effort within the Program, but was not reported, per se, in any of the references. The following specific examples are illustrative of such development efforts.

   At the initiation of the program the well stimulation team visited Halliburton, Dowell, B. J. Hughes, and Western to inform the stimulation service companies of the needs and objectives of the stimulation program.

Proprietary fluids and materials were tested by the well stimulation subcontractors to determine their performance under geothermal conditions. Proprietary agreements were signed and, although the data could not be published, materials that performed satisfactorily could be recommended for commercial use.

The Western Company introduced a new high-temperature fracturing fluid with greater stability and viscosity under severe geothermal conditions. This fluid was successfully used to place the sintered bauxite proppants in Baca Well 20. The Western Company made a television commercial and an industry journal advertisement based on this fracturing treatment. It was the highest temperature fracturing treatment using proppants ever performed in the United States and possibly in the world.

OTIS Engineering manufactured a high-temperature casing packer making use of the L'Garde-developed Y-267 EPDM elastomeric seal. This new packer design performed flawlessly in repeated applications in the extreme environment of the Baca wells.

A newly developed Baker Production Services high-temperature pressure logging tool was used to log the Rossi well during the Beowawe field experiment. This operation could not have been performed with conventional electronic pressure logging tools.

8. Gained substantial industry support for field experiments through cost sharing.

GRWSP Reports: 15, 16, 17, 27, 28

VII. CONCLUSIONS AND FUTURE DIRECTION

The two fracture treatments in Raft River and the two in Baca were successful in obtaining significant production from previously nonproductive intervals. Highly conductive propped fractures were created; however, the four treatments failed to establish commercial production due to deficiencies in well fluid temperature or reservoir transmissivity or both.

The two stimulation treatments in a matrix-type formation at East Mesa 58-30 more than doubled production from the well and constituted an economic and technical success. The lower zone treatment stimulated production from a tight sandstone formation. The upper zone treatment successfully stimulated mud and cement-damaged, high-permeability sands around the wellbore.

The acid etching treatment of the Ottoboni State 22 well in The Geysers failed to increase production. It is believed likely that the treatment fluids were dissipated into formation microfractures and, therefore, failed to penetrate deep enough into the formation to enhance communication with major natural fractures.

The Beowawe acidizing experiment produced a 2.2-fold increase in injectivity in a well which apparently penetrated a local region of low permeability and which may also have suffered formation damage during drilling.

With few exceptions, commercially available fluids, proppants, and equipment performed satisfactorily in the eight stimulation experiments. In many cases, special techniques such as precooling the wellbore and formation were employed to accommodate limitations of available materials and equipment. 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. However, in three of the four hydraulic fracture treatments at Raft River and Baca, extensive, highly conductive fractures were created and propped which failed to establish commercial productivity from marginal resources.

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 was conservative in that it utilized proven fracture design technology, but necessitated recompletion of the Baca and Raft River wells to exclude about 90 percent of the original open interval. Because reliable methods do not exist to temporarily isolate intervals for hydraulic fracturing in the open wellbore, virtually 100 percent of the wells' pre-stimulation production was sacrificed. For the sake of experimentation, 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.

At least two solutions appear possible. One is to perform a series of short-interval treatments in each well, thereby creating a long stimulated interval. However, this approach is inherently expensive and, as mentioned previously, a suitable method of zone isolation for most well designs does not exist. A second and more promising approach is to focus on stimulating existing productive fractures. Observations during the field experiments and well testing activities indicate that fractures can widen and increase in flow capacity under fluid injection conditions. This has led to a new concept of widening and propping natural fractures near the wellbore to enhance their fluid conductivity.

This proposed new approach takes advantage of the phenomenon of "fracture compliance" which has been observed in field experiments and which has been studied and described on a laboratory scale in the technical literature. Natural fractures are known to dilate during fluid injection and to constrict during production with a corresponding loss in productivity. For a sufficiently elastic, or compliant, fracture system, it is theoretically possible to prop fractures in the dilated state, thus retaining a higher fluid conductivity under production conditions. Successful stimulation of this type could increase geothermal well productivity by several-fold. Relative to other technology development work sponsored by DOE, such stimulation offers one of the greatest potential opportunities for enhancing the economics of geothermal power production.

Stimulation field experiments are expensive and risk prone, but offer high potential for significant economic impact on the geothermal industry. Field experiments are clearly necessary to develop technology of use to the industry. The geothermal industry retains a strong interest in well stimulation and the related development of tools and techniques for well and reservoir data acquisition.

TABLE 1

GRWSP REPORTS

1. Part I - Contract Proposal - Geothermal Reservoir Well Stimulation Program Management - EW-78--32-0114

   Part II - Technical Proposal

   Part III - Cost Proposal

2. Management Plan for Geothermal Reservoir Well Stimulation Program Management, March 22, 1979

3. Proposal for Producing Well Hydraulic Fracture Stimulation - Raft River Field, GRWSP, June 1979

4. Geothermal Reservoir Well Stimulation Project - Reservoir Selection Task, November 1979

5. Geothermal Reservoir Well Stimulation Program - First-Year Progress Report, February 1980

6. Proposal for Producing Well Hydraulic Fracture Stimulation Treatments - East Mesa Field, GRWSP, April 1980

7. Modification and Implementation of the M.E.T.C. Simpac Program, May 1980

8. Interactive Fracture Design Model, May 1980

9. Volume I - Geothermal Reservoir Well Stimulation Program - Technology Transfer, May 1980

   Volume II - Geothermal Reservoir Well Stimulation Program - Technology Transfer, May 1980

   Volume III - Geothermal Reservoir Well Stimulation Program - Technology Transfer, May 1980

   Volume IV - Geothermal Reservoir Well Stimulation Program - Technology Transfer, May 1980

10. Proposal for Producing Well Hydraulic Fracture Stimulation Treatment - Baca Project Area, GRWSP, November 1980

11. Raft River Well Stimulation Experiments, GRWSP, August 1980

Table 1 (continued)

12. Proceedings of the Geothermal Reservoir Well Stimulation Symposium, February 7, 1980

13. Proposal for Producing Well Chemical Stimulation Treatment - The Geysers, GRWSP, December 1980

14. Volume I - Geothermal Fracture Stimulation Technology-Fracturing Proppants and Their Properties, July 1980

    Volume II - Geothermal Fracture Stimulation Technology - High Temperature Proppant Testing, July 1980

    Volume III - Geothermal Fracture Stimulation Technology - Geothermal Fracture Fluids, January 1980

    Volume IV - Geothermal Fracture Stimulation Technology - Proppant Analysis at Geothermal Conditions, January 1981

15. Chemical Stimulation Treatment - The Geysers - Ottoboni State 22, Geothermal Reservoir Well Stimulation Program, February 1981

16. Hydraulic Fracture Stimulation Treatments at East Mesa 58-30, Geothermal Reservoir Well Stimulation Program, February 1981

17. Hydraulic Fracture Stimulation Treatment of Well Baca 23, GRWSP, June 1981

18. Technical Proposal - Geothermal Reservoir Well Stimulation Program Extension, June 1981

    Cost Proposal - Geothermal Reservoir Well Stimulation Program Extension, June 1981

19. Proposal for Producing Well Hydraulic Fracture Stimulation Treatment - Baca Project Area - Experiment No. 7, GRWSP, August 1981.

20. Fracturing Fluid Evaluation (Laboratory Work), GRWSP, January 1982

21. Acidification of Geothermal Wells - Laboratory Experiments, GRWSP, January 1982

22. A Review of Surface Equipment Requirements for Geothermal Well Stimulation, February 1982

23. Geothermal Reservoir Well Stimulation Program - Program Status Report, May 1982

24. Requirements for Downhole Equipment Used for Geothermal Well Stimulation, GRWSP, August 1982

Table 1 (continued)

25. Proposal for Producing Well Chemical Stimulation Treatment - Beowawe Geothermal Field - Experiment No. 8, GRWSP, May 1983

26. Final Report - A Laboratory Study of Acid Stimulation of Drilling Mud-Damaged Geothermal Reservoir Materials, May 1983

27. Hydraulic Fracture Stimulation Treatment of Well Baca 20, GRWSP, July 1983

28. Chemical Stimulation Treatment of the Rossi 21-19 Well - Beowawe Geothermal Field, GRWSP, January 1984

29. GRWSP Final Program Summary Report, January 1984

Note: Copies of the published GRWSP reports may be obtained from:

U.S. Department of Energy
Technical Information Center
P.O. Box 62
Oak Ridge, Tenn. 37830

TABLE 2

PUBLISHED TECHNICAL PAPERS ON GRWSP EXPERIMENTS

1. Caenn, R., Tyssee, D. A., and Vetter, O. J.: "Degradation of Polymer Used in Geothermal Fracturing," Geothermal Resources Council, Transactions, Vol. 4, September 1980.

2. Campbell, D. A., Morris, C. W., and Verity, R. V.: "Geothermal Well Stimulation Experiments and Evaluation," paper SPE 10316 presented at SPE 56th Annual Technical Conference and Exhibition, San Antonio, October 5-7, 1981.

3. Campbell, D. A., Sinclair, A. R., Hanold, R. J., and Vetter, O. J.: "A Review of the Geothermal Reservoir Well Stimulation Program," presented at the International Conference on Geothermal Drilling and Completion Technology, Albuquerque, January 21-23, 1981.

4. Hanold, R. J.: "Geothermal Well Stimulation Treatments," presented at the National Conference on Renewable Energy Technologies, Honolulu, December 7, 1980.

5. Hanold, R. J., and Morris, C. W.: "Induced Fractures - Well Stimulation Through Fracturing," Fractures in Geothermal Reservoirs - A Workshop, Honolulu, August 27, 1982.

6. Hanold, R. J., Campbell, D. A., and Sinclair, A. R.: "The DOE Geothermal Well Stimulation Program," Proceedings of the Second DOE-ENEL Workshop for Companies in Geothermal Energy, Berkeley, October 1980.

7. Morris, C. W., and Bunyak, M. J.: "Fracture Stimulation Experiments at the Baca Project Area," Proceedings Seventh Workshop Geothermal Reservoir Engineering, Stanford, December 1981.

8. Morris, C. W., and Hanold, R. J.: "Fracture Stimulation Experiments," Final Report of the Department of Energy Review Team for the Baca Geothermal Demonstration Power Plant Project, Berkeley, California, March 1982.

9. Morris, C. W., and Sinclair, A. R.: "Evaluation of Bottomhole Treatment Pressure for Geothermal Well Hydraulic Fracture Stimulation," paper SPE 11157 presented at SPE 57th Annual Technical Conference and Exhibition, New Orleans, September 26-29, 1983.

10. Morris, C. W., Verity, R. V., and Ritz, C. L.: "Fracture Stimulation Experiment in Baca 20," Geothermal Resources Council, Transactions, Vol. 6, October 1982.

Table 2 (continued)

11. Morris, C. W., Verity, R. V., and Sinclair, A. R.: "Raft River Well Stimulation Experiments," Geothermal Resources Council, Transactions, Vol. 4, September 1980.

12. Nicholson, R. W., Hanold, R. J., Vetter, O. J., and Verity, R. V.: "Technology for Geothermal Well Stimulation," Geothermal Resources Council, Transactions, Vol. 3, September 1979.

13. Sinclair, A. R., Pittard, F. J., and Hanold, R. J.: "Geothermal Well Stimulation," Geothermal Resources Council, Transactions, Vol. 4, September 1980.

14. Verity, R. V.: "Geothermal Well Stimulation - Program Summary and the Beowawe Field Experiment," Proceedings of the Geothermal Program Review II, CONF-8310177, U.S. Department of Energy, Washington, D.C., October 11-13, 1983.

15. Verity, R. V., and Morris, C. W.: "Fracture Stimulation of Union's Baca Well 23," Geothermal Resources Council, Transactions, Vol. 5, October 1981.

TABLE 3

PHASE II TASKS

Republic Geothermal, Inc. (prime contractor)

Overall program management
Solicitation of geothermal operators and selection of experiment candidates
Field experiment planning and design
Field experiment execution
Field experiment reporting

Maurer Engineering (subcontractor)

Stimulation treatment design
Job-specific laboratory testing of proposed stimulation materials
Field supervision of stimulation service companies
Continuing literature review and liaison with service companies to maintain awareness of new developments
Reporting on stimulation treatment execution

Petroleum Training and Technical Services (subcontractor)

Numerical modeling for design of field experiments
Seminar in February 1980 for technology transfer

Vetter Research (subcontractor)

Job-specific laboratory testing of proposed stimulation materials
Planning, execution, and interpretation of chemical and R/A tracer studies
Chemical analysis of fluids injected and produced during field experiment stimulation and production testing.

Terra Tek (subcontractor, beginning in 1981)

Laboratory testing for acid stimulation of mud-damaged formations

TABLE 4

SUMMARY OF GRWSP FIELD EXPERIMENTS

Experiment	Location and Well	Reservoir Temperature (°F)	Reservoir Formation	Stimulation Treatment Type	Treatment Interval Height (ft)	Fluid	Proppant
1	Raft River, ID RRGP-4	290	Fractured metamorphic and intrusive rocks	Dendritic hydraulic fracture	195	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	Fractured metamorphic and intrusive rocks	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	Deltaic sandstone and shale sequence	Hydraulic fracture	247	2800 bbl 60 lb HP Guar (crosslinked gel)/ 1000 gal	Sand 44,500 lb 100-mesh 59,200 lb 20/40-mesh Resin-Coated Sand 60,000 lb 20/40-mesh
4	East Mesa, CA 58-30	320	Deltaic sandstone and shale sequence	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 B-23	450	Fractured Bandelier Tuff	Large hydraulic fracture	231	3600 bbl water prepad 4000 bbl 60 lb HP Guar (Crosslinked gel)/ 1000 gal	Sand 42,000 lb 100-mesh Resin-Coated Sand 81,500 lb 24/40-mesh Bauxite 98,500 lb 20/40-mesh
6	The Geysers, CA OS-22	460	Fractured Franciscan graywacke and greenstone	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	520	Fractured Bandelier Tuff	Large hydraulic fracture	240	3000 bbl water prepad 5600 bbls 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	520	Fractured Bandelier Tuff	Acid treatment to dissolve calcium carbonate fluid-loss additive	240	1045 bbl 11.9% HCl	None

TABLE 5

SUMMARY OF GRWSP EXPERIMENT RESULTS

		Pre-Stimulation			Post-Stimulation			Production Rate Increase		
Well	Field	Rate (lb/hr)	Wellhead Pressure (psig)	Interval (ft)	Rate (lb/hr)	Wellhead Pressure (psig)	Interval (ft)	lb/hr	Percentage	Type of Treatment
RRGP-4	Raft River	4,700	0	1,589	28,300	17	195	23,600	500	Hydraulic fractures in short, nonproductive intervals
RRGP-5	Raft River	90,000±	17	1,517	94,300	17	216	0	0	
EM 58-30	East Mesa	90,000	50	1,383	180,000	30	1,383	90,000*	100*	Hydraulic fracture of 247' low permeability interval Hydraulic fracture of 304' damaged interval
Baca 23	Baca	0	0	2,643	73,000	37	231	73,000	-	Hydraulic fracture in a short, nonproductive interval
OS-22	Geysers	46,000	127	3,760	44,100	130	3,760	0	0	Acid frac of 1,000' interval
Baca 20	Baca	56,100	116	3,307	50,000	25	240	*	*	Hydraulic fracture in a short, nonproductive interval
Rossi 21-19	Beowawe	319,200 (injection)	555.1**	1,111+	317,100 (injection)	247.3**	1,111+	-	123***	Acid stimulation of long interval in fractured formation

* Rates are not directly comparable because wellhead pressures are not equal.

** ΔP = (injection pressure at 5,000 feet) - (static reservoir pressure at 5,000 feet)

*** Percentage increase in injectivity.

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