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DAEDALEAN ASSOCIATES, Incorporated

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FINAL REPORT

THE DEVELOPMENT OF A CAVITATING
DESCALING TECHNIQUE FOR ON-LINE
GEOTHERMAL PIPE AND COMPONENT
CLEANING AND SCALE REMOVAL © ⁸⁴

Submitted to:

Department of Energy
Division of Geothermal Energy
20 Massachusetts Avenue, N.W.
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NOTATION

- I_e - intensity of erosion
- P_i - the impact pressure arising from bubble collapse
- P_o - free stream pressure
- P_v - vapor pressure of liquid
- R - the size of the bubble or jet
- Δt - time of erosion
- V_o - velocity of the free stream
- Δy - drilling depth of erosion
- A - area of cleaning
- ρ - density of liquid
- σ - cavitation number
- E - energy absorbed by the material removed
- ΔV - volume of material removed
- S - scale strength
- n - number of impacts per unit time
- C_v - coefficient of velocity

THE DEVELOPMENT OF A CAVITATING
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1.0 INTRODUCTION

The conversion of geothermal energy into useable electrical power has become increasingly important to the overall national energy needs and requirements. A major area of concern which has resulted from the initial development of geothermal power plants is the scale formations in downhole wells, piping systems, flash tanks, injection lines and other system components. The geothermal scale formation is a result of the high concentration of minerals in the geothermal fluid depositing on the pipe walls due to flashing. The scale initiates in the downhole geothermal well and continues throughout the system.

The current state-of-technology for removing scale from pipe and system components consists of a combination of acid soaking, waterblasting, sandblasting, and "pigging." With the exception of the "pig", a cylindrical device with wire brushes attached to its exterior which is utilized for cleaning of the injection line at the Niland facility, these cleaning methods require lengthy periods of facility shutdown and extensive disassembly of the pipe and components. Because the GLEF can operate about 1,000 hours before scale buildup necessitates shutdown, the required cleaning operation has become an important

factor in determining facility operating costs (approximately 25 percent of the total time is devoted to cleaning operations). The acid soak and sandblasting also produce a deterioration of the base materials which, in turn, reduces the useable life expectancy of pipes, fittings, valves, and other system components. The above described methods of scale removal have not proven to be satisfactory due to the excessive cost and downtime.

DAEDALEAN ASSOCIATES, Inc. (DAI) under contract to the Division of Geothermal Energy (DOE) has utilized the phenomenon of cavitation for cleaning and removing geothermal scale from pipes and system components. In this technique, water is pumped under high pressure through a properly designed pump/motor/nozzle system. The high speed jet emerging from the nozzle produces cavitation bubbles which collapse on the surface to be cleaned. The combination of cavitation and high velocity flow removes the hard scale in an effective manner. As the high pressure jet emerges from a nozzle with a properly defined pump and motor combination, a large number of cavitation bubbles are produced in the jet. These bubbles are carried by the jet to the hard mineral scale wherein they collapse with a predetermined intensity of erosion which can be tailored for the type of scales occurring in geothermal pipes and system components. The phenomenon of cavitation is discussed more fully in Appendix A.

The objectives of the initial phase of the program were to verify the technical feasibility for utilizing cavitation to

remove scale from the surface of geothermal pipes and tubes and to generate the necessary engineering data for optimizing the associated input parameters in order to establish the design of the CONCAVERTM cleaning system. The input parameters included the pump pressure, volume flow rate, nozzle design, jet velocity and associated cleaning rates under laboratory conditions. A prototype field demonstration cleaning system was designed, fabricated and tested during the second phase of the program. The prototype cleaning system was designed utilizing the engineering data generated under the initial phase. Laboratory testing of the system has been completed utilizing sections of pipe and valving containing geothermal scale which were supplied by the geothermal division of the Union Oil Company and San Diego Gas and Electric Company. During the second phase of the program, the field capabilities of the system were demonstrated at the Niland facility of the San Diego Gas and Electric Company. The results of the field demonstration indicated the following:

1. THE CONCAVER system will remove hard silica type scale without acid soaking normally required with commercial waterblasting techniques.
2. The cleaning rate accomplished with the CONCAVER system is at least ten times faster than commercial waterblasting in straight pipe sections.
3. The maximum system pressure required for the most difficult scale was 8,000 psi.

4. The CONCAVER will clean system components as efficiently as it cleans pipe.

The overall conclusion drawn from the results of the second program was that the CONCAVER system offers cleaning results superior to the methods currently employed in the geothermal energy industry.

2.0 PROGRAM PLAN

The goal of the third or current program was to provide a CONCAVER system for in-line cleaning in geothermal facilities. The objective of this program was to utilize the existing controlled cavitation cleaning technology for the specific purpose of cleaning and removing geothermal scale from the facility pipes and components without necessitating a facility shutdown. The goals of the program were to design, fabricate and test the integral and peripheral equipment and to demonstrate the cleaning capability of the controlled cavitation system and its components during a 1,000 hour operating cycle of the facility.

The specific goals of the program included:

1. design and fabrication of the system components;
2. modification of facility pipe sections and components;
3. selection of support equipment;
4. test and evaluation of overall system; and
5. field demonstration at SDG & E geothermal facility during a plant operating cycle.

3.0 BACKGROUND

One of the major sources of technical interest in attempting to develop facilities that are utilized for the conversion of geothermal energy into useable electrical power is the formation of scale on the interior portions of pipes, valves and other system components. This scale is caused by the deposition of mineral particles found in solution in the geothermal fluid. Since the operating efficiency of the geothermal facility is a function of the severity of scale formation, the removal of the scale in an efficient manner is of prime importance. It is also equally important for the scale to be removed without damage to the pipes and system components.

3.1 Summary of Previous Programs

DAI has conducted extensive research and engineering for the removal of geothermal scale utilizing a controlled cavitation erosion, CONCAVER, system. To date, the feasibility of utilizing the CONCAVER system for removal of geothermal scale has been demonstrated under laboratory conditions and under field conditions at the San Diego Gas and Electric (SDG & E) Company's Niland geothermal facility. Test results in the laboratory and in the field on scaled geothermal pipes and valves have produced rapid scale removal and have also verified the removal of the scale without damage to the pipe material or system components. The test results have indicated that this technique can readily remove the scale formation and, therefore, can

reduce facility downtime for both cleaning and maintenance in order to provide an overall improvement in facility efficiency. The feasibility and technique for the CONCAVER cleaning technology has been established and successfully demonstrated. A prototype system which was used to clean the scale formation between the third and fourth stage flash tanks of the SDG & E facility was developed and demonstrated. The cleaning technology has been determined technically feasible and the initial technology base has been established under previous programs.

3.2 Current Program Summary

The intent of the current program was to focus on the utilization of the CONCAVER technology and technique in order to engineer and field test a descaling system for in-line cleaning of a geothermal energy facility. Using the Niland facility of the SDG & E Company, components and pipe sections were selected and modified for installation of rigidly mounted and rotating cleaning heads for in-line cleaning during a typical 1,000 hour operational cycle of the facility. The cleaning heads were engineered to withstand the in-pipe environmental conditions encountered during operation of the facility.

Scale buildup in the pipe and components occurred as the geothermal fluid traveled throughout the facility. The methods employed for overall scale removal (acid soaking, waterblasting, and sandblasting) were time consuming, costly, and cause system deterioration with each use. The CONCAVER technology provided

a cleaning technique that was more cost effective and eliminated the need for acid soaking and sandblasting, thus eliminating system deterioration caused by these methods. The CONCAVER technique also removed the scale from several components inserted in a test loop at the GLEF.

This program utilized existing CONCAVER cleaning technology and adapted the technology and associated equipment to a system which was engineered to function under the environmental conditions encountered in an operating facility "on-line."

The system design consisted of cleaning heads, power supply, hose assemblies and quick disconnect couplings.

The basic cleaning heads were engineered such that this cleaning system could be incorporated into any new facility construction with minimum cost and could also be incorporated into the technical areas of existing geothermal facilities. After completion of the component design, the system was fabricated and subjected to extensive testing and evaluation to demonstrate the cleaning capability. At the completion of the laboratory test program, the equipment was transported to the Niland geothermal facility location for the nominal 1,000 hour field demonstration. The output from this program provided the geothermal industry with a cleaning system capable of removing scale without interruption to production and operation. The technology would also provide significantly reduced maintenance downtime and costs for cleaning.

4.0 PRELIMINARY FIELD TEST

A preliminary field test was scheduled at the Niland GLEF to obtain base line data that was extremely beneficial in the design process. It was necessary to obtain information on how frequently the nozzles should be cycled in order to prevent them from scaling completely closed. Also, additional information would be obtained on the scale accumulation on the nozzles in stagnant and dynamic regions of the piping system. The preliminary field test provided an opportunity to test hardware that had already gone through the modification process. This included a modified 10 inch gate valve (150 lb. rating). Data would be obtained on the first generation designs during this field test. In the event a design was weak in any area, corrective measures could be taken in this area before the next field exercise.

4.1 Preliminary Field Test Plan

This test called for the inclusion of a 10 inch modified gate valve, and two 10 inch flanges, each flange incorporating an array of 16 nozzles, into a test loop (Figure 1) located between the first and second stage brine flash tanks in train A. Additionally, this test was being conducted to yield information on the effects of running the high pressure pumping system using the clarified brine, from the pilot clarifier, as the pumping fluid. An objective was to determine if the clarified brine would affect the pump or any of its related systems in a deleterious manner.

Two nozzle assemblies were installed in the loop; one on the upstream end and one on the downstream end of the test section. Two nozzle sizes were used on each assembly. The nozzle assemblies were cycled to yield information on the length of time that a nozzle could remain idle in a geothermal environment before being completely closed due to the scale buildup. The nozzles were supplied with high pressure water after remaining idle for various time increments. A set of nozzles were activated every first, second, fourth, eighth, tenth, twelfth, fourteenth, sixteenth, and twentieth day.

The modified 10 inch gate valve was cycled once a week throughout the test period. This valve was modified to incorporate cavitating nozzles into the seats. Additional nozzles were located in the sides of the valve to remove the scale that would accumulate in the depressed area between the seats at the bottom of the valve body.

All nozzles were designed to be cycled at a pressure of 5,000 psi.

4.2 Nozzle Assemblies

Two nozzle assemblies were installed in the test loop. One was installed at the upstream end of the loop, and the other was positioned at the downstream end of the loop. Each nozzle assembly consisted of an array of 16 nozzles mounted on a 10 inch blind flange (Figure 2). The nozzles were divided into two groups based on the nozzle diameter. Group A consisted of

eight 0.023 inch nozzles. Group B contained eight 0.060 inch nozzles. These two nozzle diameters were chosen based on results of initial investigations of nozzle effectiveness conducted in DAI's laboratory.

Within each specific nozzle diameter group on the flange, there were two sizes of high pressure tubing nipples on which the nozzles were mounted. This was done to determine if there was any variation on the scaling rate of the nozzles when they were in a stagnant or dynamic region of the flow. The large nipples were 22 inches long, and the shorter ones were 6 inches.

Each face of the blind flange was drilled and tapped with 1/4 inch NPT thread to allow for the nozzle assemblies to be mounted. On the exterior of the flange, 16 short nipples that had 1/4 inch quick disconnect female couplings were positioned. The high pressure water supply hose was connected to these couplings which in turn supplied water to the nozzles.

4.3 Modified Gate Valve

A Walworth 5202-F ten inch gate valve was modified to accept several of the cavitating cleaning nozzles (Figure 3). This valve was similar in design to those in use at the GLEF. The cavitating nozzles were installed to remove scale from areas of the valve that were considered to be of critical importance in maintaining proper valve operation. The seating surfaces of the valve were of prime importance. Therefore, the seats were modified to accept several cavitating nozzles. Each

seat contained eight nozzles. The nozzles were 0.026 inches in diameter. The nozzles were positioned such that the cavitating jet would impact the opposing seat, and remove any scale which had accumulated on the seating surface. Additionally, scale would be removed from the gate as it was being closed because the cavitating jets emanating from the seats would impact the gate as it was being lowered.

A 0.060 inch nozzle was located on either side of the lower valve body. These nozzles were positioned to remove the scale from the depressed area at the bottom of the valve between the seats. This would allow the seat to be completely lowered, thereby, shutting off all flow.

Two additional 0.060 inch nozzles were installed in the valve bonnet to remove any scale that had accumulated on the valve stem.

High pressure water was supplied to all of the nozzles through shut-off type quick disconnects and high pressure stainless steel nipples screwed into the nozzle assemblies.

4.4 High Pressure Pumping System

The high pressure pumping system utilized during the preliminary field trial consisted of a trailer mounted 75 hp diesel powered triplex plunger pump. This particular pump unit was equipped with the 3/4 inch diameter plungers. With these plungers and the 75 hp drive motor, the pump was able to attain a maximum pressure and flow of 10,000 psi and 10 gpm.

The pump was driven by an oil lubricated automotive type crankshaft and connecting rods. The 3/4 inch plungers were constructed of a ceramic material. These plungers were water lubricated.

The system reservoir had a capacity of 80 gallons and was rated for pressures of up to 100 psi. The supply water from the reservoir was fed to a suction manifold through individual cylinder filters and into the pump cylinders. The high pressure discharge was then fed into a manifold and from there via high pressure hose to the cleaning device being utilized.

4.5 Results of Preliminary Field Test

4.5.1 In-line Equipment

The preliminary field test occurred during the months of August and September of 1978. The Magmamax 1 production well was used for this test. All of the equipment was located in a test section positioned between the first and second stage brine flash tanks.

The flange-nozzle assemblies were cycled to yield information on the maximum length of time that a nozzle could remain idle before being rendered inoperable due to a scale buildup over the nozzle orifice. Nozzles were cycled at a pressure of 5,000 psi. The nozzles were supplied with high pressure water after remaining idle for various time increments. It was determined that the maximum length of time a nozzle could remain idle and still be successfully activated was sixteen days. This

meant that for any nozzle that was installed in the geothermal system, it must be cycled at least once each sixteen days to prevent the scale from rendering the nozzle inoperable. It was also determined that there was no significant difference in the scale buildup between nozzles exposed to the flow and those that resided in the stagnant flow region (Figure 4).

The ten inch gate valve was cycled once a week during the test. Cavitating nozzles were incorporated into the seats of this valve. The nozzles were designed to remove the scale from the gate as well as any scale that had accumulated on the opposite seat. A sealing problem between the valve seat-nozzle assembly and the valve body prevented operating at pressures greater than 1,000 psi. The optimum design pressure for these nozzles was 5,000 psi.

However, even though the design pressure was not achieved, the test results for the valve were promising. For the duration of the testing, the modified valve was able to shut off the flow completely. Additionally, the valve was able to be operated and closed manually without having to use a spanner or "cheater bar" as an aid.

4.5.2 Triplex Pump Performance

The final area that was investigated was the performance of the high pressure triplex pump utilizing geothermal brine as the pumping fluid. Several days testing was conducted with the brine as the pumping fluid. This geothermal fluid had first passed

through the pilot clarifier at the facility before being supplied to the pump. The pump performed well utilizing the clarified brine and no difficulties were encountered. Correct pressure and flow was maintained throughout the test using the brine feed. Subsequent to the field trial, the pump was disassembled, and inspected for signs of unusual wear. All of the internal parts (pistons, valves, seals, etc.) were in very good condition. The pistons were slightly discolored as a result of using the clarified brine, but no unusual signs of wear were noted.

5.0 GLEF IN-PLANT FIELD DEMONSTRATION

The CONCAVER cleaning system was transported to the Niland GLEF during the last week in December. The evaluation would occur during the 1,000 hour operating cycle of the plant that was scheduled to begin in early January. All of the modified equipment was designed to be operated while the plant was on-line. The equipment that was installed in the test loop included two modified ten inch gate valves, a thermowell assembly, and an in-line rotating cleaning assembly. Additionally, an attempt would be made to remove the scale from one of the production lines by incorporating the cleaning nozzle with a continuous coiled tubing unit leased from the Nitrogen Oil Well Service Company (NOWSCO).

5.1 Test Plan

The test plan utilized during this field trial specified that the equipment be cycled daily. The initial pressure setting for the nozzles was 2,000 psi. After the high pressure supply hose was connected to the nozzles, the pressure was increased to the specified level. This pressure was maintained for a period of sixty seconds.

Arrangements were made with San Diego Gas and Electric personnel to periodically open and inspect the test loops during the 1,000 hour test. This inspection allowed on-site personnel to verify that the nozzle parameters were correct and that the scale was being successfully removed. Suitable corrections to the nozzle systems would be made at this time if required.

5.2 High Pressure Water Pumping System

Figure 5 is a schematic representation of the high pressure pumping system. The operating characteristics of the system were variable through a range of 40 gpm at 5,000 psi (the maximum flow capability) to 12 gpm at 20,000 psi (the maximum pressure capability). The flexibility in operating characteristics of the pumping system provided the capability for selection of the optimum nozzle configuration of the pumping system is shown in a photograph of the actual equipment in Figure 6. The pumping system was powered by a diesel engine which delivered 175 horsepower at 1,800 rpm. The complete drive system consisted of the diesel engine, a five speed transmission and a speed reducer. This drive train allowed the water pump to be operated through the entire required speed range (220 rpm to 560 rpm) while operating the engine at an optimum 1,800 rpm.

The high pressure water pump selected for this application was a triplex plunger pump having displacement and an operating pressure range of 20,000 psi. As a safety feature, the pump housing was rated at 80,000 psi burst pressure. The pump was driven by an oil lubricated, automotive type crankshaft and connecting rods. The pump was equipped with three water lubricated ceramic plungers sealed by chevron packings. Each of the three cylinders was protected by a suction line filter. The pump design is shown in Figure 7A.

Figure 7B is a general layout of the system plumbing. The plumbing was arranged for connection to an external water supply having a capacity of 40 gpm at a minimum 20 psi. The reservoir had a capacity of 80 gallons and was rated for inlet water pressures of up to 100 psi. The supply water was fed, by system reservoir pressure, to a suction manifold, through individual cylinder filters and into the pump cylinders. The discharge from the pump (high pressure) was fed from each individual cylinder into the discharge manifold and from there to the cleaning device being utilized. To prevent pump damage due to line blockage or low water supply, the system was equipped with high and low pressure and low water level shutoff systems. Pressure guages were installed for the operator to read pump suction and discharge pressures and reservoir pressure. An additional safety device was a throttle control which automatically returns the diesel engine to an idle condition when high pressure water was not being supplied.

5.3 Modified Walworth Gate Valve

Two of the modified Walworth 5202-F gate valves were included in the test equipment installed in the test loop (Figure 8). The design of these valves was very similar to the design of the valve that was included in the preliminary field test. The only difference occurred in the number and size of the nozzles located in the seats and in the absence of the nozzles in the bonnet. The nozzles in the seats were decreased in size to 0.020 inches,

and increased in number from eight in the original design to twelve. The increase in number of the nozzles was done to insure an adequate overlap of the spray from each nozzle assembly.

5.4 Rotating In-line Cleaning Mechanism

One-half of a 12 foot long straight spool section in the test loop was cleaned by utilizing a rotating cleaning mechanism (Figure 9). This mechanism was mounted on a flange that was positioned at the upstream end of the test loop (Figure 10). The flange had a stuffing box pressed into it. The stuffing box allowed a section of 9/16 outside diameter high pressure tubing to enter into the test section without allowing any geothermal fluid to escape.

Affixed to the outside of the flange was the mechanism that advanced and rotated the high pressure cleaning lance (Figure 11). This mechanism consisted of an eight foot aluminum channel frame and a small carriage which was driven by a small gearmotor. Rotation of the high pressure tube was accomplished by means of a helical gear that was attached to the high pressure tube was designed to rotate twice for each revolution of the carriage's drive gear.

The DC gearmotor drive was controlled by a variable speed power supply. The power supply adjusted the speed of the carriage from zero to a maximum speed of approximately one foot per second. This converted to a maximum rotation of the cleaning lance of 460 rpm.

Connected to the cleaning lance on the inside of the test loop was a multi-nozzle cleaning head (Figure 12). The cleaning head would accept four nozzles, and could be fitted with various lengths of tubing to allow for the nozzles to be positioned at their optimum standoff distance from the inside pipe wall. Two types of nozzles were used on this cleaning head, a fan spray inducing nozzle, and a conical spray nozzle.

5.5 Thermowell Nozzle Installation

A thermowell assembly was installed in the downstream end of the test loop (Figure 13). The thermowell assembly was approximately eight inches long, and one inch in diameter. Two cavitating nozzles were installed in short pipe nipples located at the outside of the test loop ten inch diameter pipe. These nozzles were positioned in such a manner that the water jet from the nozzle would impact the thermowell surface one and one half inches from its bottom. This would keep enough of the thermowell surface scale free so that an accurate temperature would be registering throughout the test. Figure 14 is an exterior view of the thermowell assembly showing the high pressure supply hose connected to one of the CONCAVER nozzle assemblies.

5.6 Control Valve

A six inch Dexurik v-port ball control valve was equipped with two nozzle assemblies (Figure 15). These nozzles were 0.060 inches in diameter and were positioned inside the valve. The cavitating jets would impact the ball seating surface, thereby

removing any accumulated scale and insuring the trouble free operation of the valve. The specified operating pressure for these nozzles was 6,500 psi. The jets from the two nozzles were designed to overlap approximately $3/4$ inches. In this manner, when the ball was rotated inside the valve, the spray from the two nozzles would extend from one edge of the ball to the other and clean the entire surface.

The ball valve was unable to be installed into the test loop for the plant cycle that began in January. An extension was granted that allowed the valve to be installed and cycled during the plant operating cycle that started in May.

5.7 Field Test Results

The GLEF operating cycle began on January 18. The test equipment was cycled daily (Figure 16) on February 1, the GLEF reinjection pump malfunctioned and the plant was shut down. At this time, the test loop was opened for inspection. The straight ten inch diameter spool piece that was under test by the rotary head had approximately 0.065 inch accumulation of scale. It was impossible to visually inspect the gate valves at this time, but, immediately prior to shutdown, the valves were closing completely. The valve stem was in the completely closed position. Throughout the remainder of the test, this was used as one means of gauging whether the valve seated completely. It was decided to raise the pressure on the in-line cleaning head to 4,000 psi when the plant restarted on February 6.

The plant shut down again on March 6. The test loop was taken apart and inspected. The straight spool section had a 0.175 buildup of scale on the section cleaned by the rotary head. The thermowell, just prior to shutdown, was registering 20°F hotter than a standard thermowell positioned before the test loop. With the exception of two spots on either side of the thermowell that had been impinged upon by the cleaning nozzles, the thermowell was covered by scale. The two areas on the sides of the thermowell that had been impinged upon by the water jets produced by the nozzles were reasonably clean. Within these areas, several small spots of scale were still intact and had not been removed. The ten inch gate valves were still able to be closed completely. When the valves were shut tightly, the stems were at the same height as when the valves were first installed in the test loop.

The insufficient cleaning of the straight spool piece and the spotty accumulation of scale on the thermowell indicated that the nozzle pressures should be raised to produce a greater intensity of erosion since the erosion strength of the scale was greater than originally anticipated. For the remainder of the testing, the nozzle pressures were raised to 6,000 psi.

The day prior to the plant shutdown, field personnel were able to isolate the test loop using just the modified gate valves to shut off the flow. The unmodified standard gate valves, that were used in series with the modified valves, would not seal

completely due to the scale accumulation on the seating surfaces. The test loop was isolated to allow for the repair of a malfunctioning quick disconnect on one of the nozzles.

On March 19 at 8:00 a.m., final shutdown on the GLEF occurred. The test equipment was cycled one final time before disassembling the loop. This was done to eliminate the scale which had built up during the 22 hour period the plant had run since the equipment was last cycled. The loop was drained and then disassembled. The straight spool piece was completely free of any scale in the area that was cleaned daily (Figure 17). The uncleaned section of the spool had a 5/8 to 3/4 of an inch scale accumulation (Figure 18). The thermowell was registering 25°F hotter than the uncleaned thermowell positioned immediately before the test loop. The cleaned thermowell registered the same temperature at the end of the test that it had registered at the beginning. The ten inch gate valves were able to seal completely. Figures 19 and 20 show the left and right side seating surfaces of one of the gate valves. The seating areas of the valve were maintained relatively scale free. The interior portions of the valve that were not subjected to the cavitation cleaning accumulated a coating of scale. This is seen in the figures along with the clean seating surfaces.

5.7.1 Ball Valve Test Results

The ball control valve was operated during the plant cycle that began during May. The valve was originally installed in

Train B which was being supplied from the Woolsey production well. After the Woolsey well began experiencing problems it was decided to shut down both the Woolsey well and Train B of the GLEF. This necessitated the relocation of the valve to Train A which was being supplied by the Magmamax well.

The contract extension period ended on July 31. During the operating period from late May through July 31, the ball valve was exposed to the geothermal environment for approximately 500 hours. The valve was cycled every other day.

The valve was able to be operated manually during the entire 500 hour exposure period. However, the scale was only removed completely from two 1-inch wide strips on the ball. The remainder of the ball had about $1/32$ of an inch of scale accumulation. It was felt the reason only two strips were cleaned completely was because the brine flow through the valve did not allow the jets to expand over as wide an area as the original design specified. Therefore, it is now apparent that nozzles with a much wider spray pattern must be added to the valve and the spacing between the nozzles must be adjusted such that the jets sufficiently overlap to remove the scale from the entire ball surface.

6.0 PRODUCTION LINE CLEANING TRIAL

Two cleaning tests incorporating a coiled tubing unit, leased from NOWSCO, with the high pressure pump and cavitation cleaning head system were undertaken. One test took place on February 15 and the other occurred on March 15. These tests were an attempt to determine if the cleaning heads could be adapted to an existing piece of oil field service equipment and be used successfully to remove the geothermal scale from one of the production lines at the GLEF. A 165 foot long straight section of the Magmamax #1 supply line was used during both tests. The Magmamax supply line was not flowing during the test. This allowed the test results to be verified immediately. However, the line was filled with water before the testing commenced.

6.1 Equipment

The equipment utilized during this test consisted of a NOWSCO coiled tubing unit, a high pressure pumping system, a 16 nozzle cleaning head, and a centering device for positioning the cleaning head inside the supply line.

6.1.1 Coiled Tubing Unit

The coiled tubing unit (Figure 22) consisted of an eight foot in diameter reel that was mounted on a ten wheeled transporter. The reel contained 6,000 feet of one inch O.D. steel tubing. This tubing had a theoretical burst pressure of 11,350 psi. However, the operating pressure was limited to 4,000 psi by NOWSCO in order to maintain an adequate safety factor.

Mounted on a lifting arm on the rear of the transporter was a hydraulically powered injector head. The injector head (Figure 23) fed the tubing into the production line and controlled the injection speed. Maximum injection speeds of one hundred feet per minute were available with this injector head. The coiled tubing unit was used as the method of advancing the cleaning head through the production line as well as the means of supplying the high pressure water to the nozzles in the cleaning head.

6.1.2 Cleaning Head Assembly

The cleaning head assembly consisted of a sixteen nozzle cleaning head and a centering device-adaptor piece that was connected to the coiled tubing. The sixteen nozzle cleaning head had eight nozzles angled 45° from vertical pointing in a forward direction and eight nozzles at a 45° angle from vertical pointing rearward. The rear eight nozzles were positioned such that the jets of water from these nozzles would fall in the area that was not overlapped by the jets from two adjacent front nozzles. Sixteen 0.031 inch conical spray nozzles were used in this cleaning head. The centering device was utilized in an attempt to maintain the cleaning head position in the center of the test section. This was done in order for all of the nozzles to be at the same distance from the pipe wall, and therefore, operating within their optimum intensity range.

6.2 Cleaning Test #1

At the beginning of the first cleaning test, the nine inch rigid centering device on the cleaning head would not go through

the nonstandard flange that was on the end of the ten inch diameter Magmamax line. This nonstandard flange had an eight inch opening. Therefore, a modified centering device was devised and utilized during the first test. The NOWSCO unit was pushing the cleaning head through the ten inch production line at a speed of 24 feet per minute. This was the slowest speed that could be attained with their control system. Five passes were made at a pressure of 4,000 psi. The pipe was inspected at the end of the fifth pass, and it appeared that the centering device allowed the cleaning head to be positioned too far off center. The scale was removed from about 30 percent of the circumference of the pipe wall.

The results of the first test are as follows:

1. Nozzle designs could successfully be incorporated with the NOWSCO tubing unit.
2. The need for a centering device with a more universal application that can overcome the problem that has been made apparent.
3. With the centering device that was utilized, only limited success in removing the scale was realized.
4. The nozzle head needed to be more accurately centered in the pipe to be within each nozzle's optimum intensity range.

6.3 Cleaning Test #2

The second NOWSCO test occurred on March 15. For this demonstration, a spring-loaded centering device (Figure 24), was designed and proved to be much more effective. The cleaning head was held relatively close to the centerline of the pipe. The NOWSCO unit advanced the cleaning head at a slower rate during this test. Through judicious use of their control system, NOWSCO was able to slow the rate to 15 feet per minute. More of the scale was removed, but, approximately 50 percent of the pipe surface remained covered with scale. It was apparent from this second test that a pressure in excess of 4,000 psi, the maximum allowable working pressure of the NOWSCO tubing, was needed before the scale could be removed completely from the pipe wall. Subsequent experience derived from the in-plant test loop experiment has shown that 6,000 psi is the minimum pressure that will completely remove the geothermal scale. Also, much better coverage of the interior pipe wall could have been obtained through the use of some type of rotating cleaning head. There appeared to be an insufficient overlap between adjacent nozzles of the stationary cleaning head.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The successful completion of the tasks of this program have yielded sufficient information to justify the following conclusions.

7.1 Conclusions

1. On-line cavitation cleaning of geothermal in-plant equipment during facility operating cycles is a technically feasible and economically attractive technique for maintaining peak plant efficiency.
2. The 0.060 and 0.023 cavitating nozzles have been successfully activated after having remained idle in the geothermal environment for a full 400 hours.
3. The high pressure pumping systems utilized during this program performed well. They did not suffer any deleterious effects after having used the clarified brine as the pumping fluid.
4. From the experience gained at the in-plant test loop, the pressure that was required to effectively remove the geothermal scale was only 6,000 psi. Any pressure below 6,000 psi did not allow for the complete removal of all the scale deposits.

5. The straight spool section in the test loop was completely cleaned of all of the geothermal scale. The rotating cleaning apparatus was operated without having to disassemble the loop and while the plant was on-line. The uncleaned portion of the loop had an accumulation of 5/8 to 3/4 of an inch of scale.
6. The ten inch gate valves that had been modified to contain the CONCAVER cleaning nozzles were able to completely shut off all flow to the loop. These gate valves were able to be operated manually and also close completely for the entire plant operating cycle.
7. The thermowell in the test loop that was subjected to the CONCAVER nozzle cleaning exhibited a much more accurate temperature reading than a similar uncleaned thermowell positioned immediately before the loop. The temperature on the DAI cleaned thermowell was 25°F hotter than the uncleaned thermowell.
8. The Magmamax production line cleaning demonstration utilizing the DAI cleaning head and the NOWSCO coiled tubing unit demonstrated the feasibility of marrying the two pieces of equipment for use on the straight runs of the production line

pipe. However, working pressure limitations of 4,000 psi on the particular tubing that was used prevented the complete removal of the scale. The in-plant testing yielded the fact that 6,000 psi was the minimum pressure that could be utilized to completely remove the scale from the pipe wall. The use of tubing with a slightly higher pressure rating would alleviate the problem.

7.2 Recommendations

1. Equipment modified to accept CONCAVER nozzles should be utilized in the geothermal industry to insure longer and more trouble free operation of geothermal facilities.
2. The CONCAVER nozzles should be operated at a pressure no less than 6,000 psi in order to effectively remove the silica type geothermal scale.
3. The production line cleaning technique utilizing the NOWSCO coiled tubing unit should be investigated further. Future tests utilizing tubing with at least a 6,000 psi working pressure should be conducted.

7.3 Additional Developments

A subsequent program undertaken by DAI sponsored by the Department of Energy deals with removing the scale that was accumulated inside geothermal well casings. An integral part of this

program was to locate or develop a coiled tubing capable of operating at 11,000 psi.

A heavy wall tubing of 1 inch outside diameter capable of withstanding an 11,000 psi operating pressure has been located. This tubing is being utilized by Otis Engineering Company on their newest series of coiled tubing units.

With the availability of this new series of tubing, the pressure limitation problem that prevented the complete removal of the scale from the production line has been alleviated.

FIGURE 1 SCHEMATIC DRAWING OF INITIAL TEST LOOP INSTALLATION AT GEOTHERMAL PILOT PLANT

FIGURE 2 MULTI NOZZLE FLANGE BEFORE INSERTION IN LOOP

FIGURE 3 MODIFICATION SCHEMATIC OF 10" GATE VALVE SHOWING
RELATIVE POSITION OF CONCAVER NOZZLES

FIGURE 4 SCALE BUILD UP ON MULTI NOZZLE FLANGE AFTER APPROXIMATELY
1000 HOURS EXPOSURE TO THE GEOTHERMAL ENVIRONMENT

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FIGURE 5 SCHEMATIC REPRESENTATION OF HIGH PRESSURE PUMPING SYSTEM UTILIZED DURING THE GLEF ON LINE CLEANING TEST

FIGURE 6 PHOTOGRAPHIC REPRESENTATION OF HIGH PRESSURE PUMPING UNIT

1. LUBRICATION	8. DISCHARGE MANIFOLD
2. PLUNGER PACKING	9. SUCTION MANIFOLD
3. PLUNGER	10. FILTER
4. SUCTION VALVE	11. EXTENSION ROD
5. DISCHARGE VALVE	12. EXTENSION ROD SEAL
6. SECTIONALIZE FLUID HEAD	13. CONNECTING ROD
7. VALVE COVER	14. CRANKSHAFT

Fluid Area

FIGURE 7-A SCHEMATIC OF HIGH PRESSURE WATER
PUMP UTILIZED DURING FIELD TRIALS

FIGURE 7-B WATER PUMPING SYSTEM SCHEMATIC FOR PROTOTYPE CONCAVER FIELD UNIT

FIGURE 8 SCHEMATIC DRAWING OF TEST LOOP AT GEOTHERMAL PILOT PLANT UTILIZED DURING IN PLANT CLEANING TEST

FIGURE 9 CLEANING MECHANISM INSTALLED ON TEST LOOP STRAIGHT SPOOL SECTION

FIGURE 10 CLEANING MECHANISM MOUNTED TO FLANGE IN TEST LOOP

FIGURE 11 UNDERSIDE VIEW OF ON LINE CLEANING MECHANISM SHOWING DRIVE GEAR, GUIDE SYSTEM, AND NOZZLE/TUBING ROTATOR GEARS

FIGURE 12 FOUR NOZZLE CLEANING HEAD AND CENTERING DEVICE BEFORE
INSERTION INTO TEST LOOP STRAIGHT SPOOL SECTION

LOCATE (2) IN TEST
SPOOL - FIELD ORIENT

1"-3000# THD'D
HALF CPLG

DISCO. 385H

W/7½" "U" DIM.

DECKER INSTRUMENT SUPPLY CO.

(213) 272-0131

¼" NPT DRILL
& TAP FOR HEX.
NOZZLE, BODY M'T'G
(TYP.)

FIGURE 13 MODIFICATION OF GEOTHERMAL THERMOWELL
FOR INSTALLATION OF FIXED CLEANING NOZZLES

FIGURE 14 EXTERIOR VIEW OF THERMOWELL ASSEMBLY SHOWING HIGH PRESSURE SUPPLY HOSE CONNECTED TO ONE OF THE CONCAVER NOZZLE ASSEMBLIES

FIGURE 15 MODIFIED V PORT BALL VALVE

FIGURE 16 HIGH PRESSURE WATER HOSE BEING CONNECTED TO VALVE SEAT NOZZLE SUPPLY ASSEMBLY

FIGURE 17 STRAIGHT SPOOL PIECE AFTER PLANT CYCLE SHOWING EFFECTIVENESS OF IN-LINE CLEANING TECHNIQUE. (VIEW SHOWS CLEANED AREA IN THE FOREGROUND)

FIGURE 18 STRAIGHT SPOOL PIECE AFTER PLANT CYCLE SHOWING EFFECTIVENESS OF IN-LINE CLEANING TECHNIQUE. (VIEW SHOWS SCALED AREA IN FOREGROUND)

FIGURE 19 MODIFIED WALWORTH GATE VALVE AFTER 900 HOUR EXPOSURE.
VIEW SHOWS THE LEFT SIDE SEATING SURFACE

FIGURE 20 MODIFIED WALWORTH 10" GATE VALVE AFTER 900 HOUR EXPOSURE. VIEW IS OF RIGHT SEATING SURFACE. SEATING SURFACES OF THE VALVE WERE MAINTAINED IN A RELATIVELY SCALE FREE CONDITION ENABLING VALVE TO FUNCTION THROUGHOUT THE TEST

FIGURE 21 COILED TUBING UNIT AND HIGH PRESSURE PUMPING SYSTEM AT
NILAND TEST SITE

FIGURE 22 PHOTOGRAPH OF NOWSCO COILED TUBING UNIT UTILIZED DURING PRODUCTION LINE CLEANING ATTEMPT

FIGURE 23 VARIABLE SPEED INJECTOR HEAD ON NOWSCO UNIT

FIGURE 24 MULTI-NOZZLE CLEANING HEAD ASSEMBLY WITH SPRING LOADED CENTERING DEVICE USED IN PRODUCTION LINE CLEANING ATTEMPT

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APPENDIX A

DESCRIPTION OF CAVITATION PHENOMENA

In most engineering contexts, cavitation is defined as the process of formation of the vapor phase of a liquid when it is subjected to reduced pressures at constant ambient temperature. In general, a liquid is said to cavitate when vapor bubbles are observed to form and grow as a consequence of pressure reduction. When the phase transition is a result of pressure change by hydrodynamic means, a two-phase flow composed of a liquid and its vapor is called a cavitating flow. While these definitions imply a distinction between phase transitions associated with reduction of pressure, on the one hand, and addition of heat (i.e. boiling), on the other, heat-transfer effects may play an important role in many cases of cavitating liquids. Such effects are especially of importance in liquids near their boiling points. From a purely physical-chemical point of view, of course, no distinction need be made between boiling and cavitation, at least insofar as the question of inception is concerned, and many of the basic physical ideas regarding inception, vapor mass transfer, and condensation apply equally.

As cavitation just begins, tiny vapor bubbles form in rapid succession at the point of lowest pressure and are carried downstream by the flow into a zone of higher pressure, where they immediately collapse as the vapor within them condenses. The process of formation and collapse is so nearly instantaneous that with

the naked eye only a continuous opaque blur can be distinguished. However, as each of the countless individual bubbles collapse, the resulting impact of opposing masses of liquid produces an extremely great local pressure which is transmitted radially outward with the speed of sound, followed by a negative pressure wave which may lead to one or more repetitions of the vaporization-condensation cycle. Boundary materials in the immediate vicinity are therefore subject to rapidly repeated stress reversals and may eventually fail through fatigue, the first sign of which is cavitation erosion.

An increase in the velocity of flow beyond that required for incipient cavitation can produce no further reduction in pressure at the point of cavitation, but merely an elongation of the zone over which the vapor limit prevails. At the same time, the size of the vapor bubbles increases until at advanced stages a more or less stable vapor pocket is formed, which is very similar in shape to the zone of separation next to an unstreamlined boundary. Since the formation of such a pocket must result in a change of the surrounding flow pattern, it is to be expected that the pressure distribution will change accordingly, the pressure necessarily remaining at its vapor limit throughout the length of the cavitation pocket.

For the purposes of this program, the phenomena of cavitation is the formation, growth and collapse of vapor cavities formed from nuclei. Water will provide the continuous media for the

cavitation process. As the vapor cavities form in the vicinity of the cavity envelope, the scale is removed from the surface (Figure A-1). Figure A-2 is a photographic representation of the cavity envelope during which the cavitation process is developed. The process is initiated from a nuclei which forms, grows to critical size and collapses.

CAVITATION INCEPTION PARAMETER

A useful index for the cavitation phenomenon is formulated by introducing for the symbol P in the pressure parameter its minimum value P_v , the result being called the cavitation number:

$$\sigma = \frac{P_o - P_v}{\frac{1}{2}\rho V_o^2} \quad [1]$$

where: P_o = free stream pressure

P_v = vapor pressure of liquid

V_o = free stream velocity

ρ = density of liquid

So long as σ has an appreciably greater numerical value than the minimum ordinate on the dimensionless pressure-distribution curve for a body of given form, the occurrence of cavitation is not to be expected at any point on the boundary. Once σ becomes approximately equal in absolute magnitude to the minimum ordinate, on the other hand, conditions of incipient cavitation should prevail, and at values of σ below this critical limit σ_i a marked effect upon the pressure distribution is to be expected.

In the case of body forms which result in separation, it is to be noted that cavitation will generally begin within the fine-scale eddies formed at the separation surface long before the boundary pressure attains its vapor limit. As a result, it is then not

possible to predict the magnitude of σ_i either by analytical means or by actual measurement of the pressure distribution in flow without cavitation. On the other hand, not only are boundary forms which properly guide the flow most subject to analytical determination, but they are also those least subject to cavitation. The process of streamlining, in other words, simultaneously lowers the magnitude of σ_i (i.e., the tendency toward cavitation) and makes it more accurately predictable by analytical means.

The cavitation inception parameter is to be experimentally determined in order to evaluate the optimum operating parameters and the efficiency of cleaning by the cavitating jet technique.

CAVITATING JET CLEANING TECHNIQUE

Cavitation cleaning is caused by the collapse of bubbles at or near the solid boundaries guiding high speed flow. Since the early cavitation experiences were encountered on ship propellers in a highly corrosive medium (seawater), there were some controversies as to whether the mechanism was corrosion or mechanical removal. However, it is now generally accepted that the high pressures caused by the collapse of bubbles produce mechanical removal of material. During the process of cavitation a certain volume of material is removed from the surface as a result of the work done by the bubble collapse forces. The energy absorbed by the material is given by:

$$E = \Delta V \cdot S \quad [2]$$

where: E = energy absorbed by the material removed

ΔV = volume of material removed

S = scale strength which represents the energy absorbing capacity of the material per unit volume under the action of the forces

The intensity of cavitation is then defined as the power absorbed by the material per unit area and given by:

$$I = \frac{\Delta V \cdot S}{A \cdot \Delta t} \quad [3]$$

or
$$I = \frac{\Delta y}{\Delta t} (S) \quad [4]$$

where: A = area of cleaning

$$\Delta y = \text{mean depth of scale} = \frac{\Delta V}{A}$$

Δt = exposure time

This is the output intensity of cleaning as seen by the material; similarly one can derive an expression for the bubble collapse intensity which is the input to the cleaning process.

$$\left(\frac{\Delta y}{\Delta t} \right) \cdot (S) \propto (P_i) \cdot (R) \cdot (n)$$

where: P_i = impact pressure

R = size of the bubble or jet

n = number of impacts per unit time

These ideas have been incorporated into a master chart for cavitation cleaning as shown in Figure A-3. In this chart, the intensity of erosion is plotted against the rate of mean depth of erosion for various materials ranging from soft lead to very highly resistant stellites. The range of intensities typical of practical machines varies from 10^3 - 10^4 in. - lb/year-in.². (The screening tests such as the vibratory test and rotating test operate at intensity levels on the order of 10^5 in. - lb/year-in.² (1 watt/m²) . The depth of erosion is generally in the range of a fraction on an inch per year. Chemical corrosion rates on steels are in the range

of 10^{-3} - 10^{-2} in. per year (ipy). Erosion rates on the order of 1 ipy represent serious erosion which may warrant operational limitation or redesign.

The level of threshold intensities for various metals are on the order of 10^{-1} w/m² at the most. Elimination of cavitation by the substitution of one metal for another is possible only up to this level of intensity. For this reason, the usefulness of cathodic protection also seems to be limited at this level. If one is prepared to tolerate some erosion and periodic maintenance, then the materials selected coupled with cathodic protection can possibly extend the allowable intensity levels up to 1 w/m². However, if the intensity levels are higher than these values, then the foregoing protection methods may not work. In such cases, hydrodynamic redesign, air injection, and specifying limits for operation are the alternate remedial possibilities.

Another tool for the benefit of designers and operators is a multipurpose nomogram as shown in Figure A-4. It provides a visual idea of the range of intensities encountered in actual practice within the range of the depth of cavitation material used and time of operation. It also provides a quick and easy method of estimating the intensity of cavitation for a given field installation. Lastly, the selection of better materials, if available, is easily made.

From such tools as the master chart and the nomogram, it is possible to estimate the intensity of cavitation required to remove

the geothermal scale most efficiently at the optimum rate of cleaning without damage to the pipe surfaces underneath. For example, to remove a scale thickness of 0.5 inches in a time of one hour, a cavitation intensity of approximately 20 watts/m² is required. To remove this thickness of scale in a shorter time, the intensity of cavitation must be increased.

The intensity of cavitation utilized during the inplant operation was approximately 12,000 watts/m². Operation at this cavitation intensity produced a near instantaneous scale removal as the scale was impinged upon by the jet. Yet, this operating level was significantly below the intensity level that would produce erosion of the steel pipe.

The specific advantages of utilizing cavitation jet cleaning for scale removal are as follows:

1. Cavitating water jet cleaning method is relatively simple and reliable.
2. Power requirements are reduced because of the cavitation phenomenon.
3. The possibility of damaging the pipe material that exists when using other mechanical methods of cleaning, including acids, is eliminated.

FIGURE A-1 PRINCIPLE OF CONTROLLED CAVITATION EROSION TECHNIQUE AS APPLIED TO REMOVAL OF GEOTHERMAL SCALE

FIGURE A-2 PHOTOGRAPHIC REPRESENTATION OF THE CAVITATING ENVELOPE DURING WHICH TIME THE BUBBLES FORM A NUCLEI, GROW TO CRITICAL SIZE AND COLLAPSE IN THE CONTINUOUS CAVITATION PROCESS

RANGE OF VELOCITIES (75-150 FPS)

FIGURE A-3 MASTER CHART FOR CAVITATION EROSION

THIRUVENGADAM'S EROSION-STRENGTH ESTIMATOR

FIGURE A-4 EROSION INTENSITY ESTIMATOR