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Measurement of Velocity Profiles in Production Wells Using Wireline Spinner Surveys and Rhodamine WT Fluorescent Tracer; Coso Geothermal Field (California)

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ABSTRACT

Pressure-Temperature-Spinner surveys have been combined with water flow tracers to determine the flow characteristics of production wells and the optimum location in the well bore for placement of capillary tubing for scale inhibitor application. The combined techniques have determined the locations of thief zones, low velocity flow zones, fluid counterflow, fluid velocities and fluid flow rates.

INTRODUCTION

Pressure-Temperature-Spinner (PTS) surveys have been run in production wells to select calcium carbonate scale inhibitor injection depths and to diagnose production problems. Unusual survey results in some wells have been clarified using Rhodamine WT (RWT), a fluorescent dye water tracer. The observed flow profiles include low velocity flow zones, flow reversals, thief zones and surging. The results of PTS surveys and tracer tests explain some scale prevention difficulties experienced at Coso.

Coso production wells range from 400m (1300 feet) to 3200m (10,500 feet) in depth and are deviated up to 25° from vertical. Permeability is variable and flowing pressure drawdown (i.e., the difference between the shut-in pressure at a feed-point and the flowing pressure at that feed-point) ranges from negligible to 17 Mpa (~2500 psi). Production zone temperatures range from 200°-340°C (400°-650°F), and production zones can flow either single-phase liquid, single-phase steam or a two-phase mixture.

Frequent scale inhibition failure motivated the coupling of PTS surveys with liquid tracers. Coso reservoir fluids are saturated with calcium carbonate. Production-induced boiling causes supersaturation, and wellbore scaling often occurs if a liquid phase is present. Scale formation is prevented by injecting a scale inhibitor chemical through a capillary tube to a point below the flash depth in the well, as determined by a pressure-temperature survey. This method is generally effective. However, some wells continued to form scale above the inhibitor injection depth or required excessive chemical dose rates. Stagnant fluid at or below the flash depth was the suspected cause of scale inhibitor failures, so spinners were added to the pressure-temperature surveys to measure fluid velocity.

SPINNER SURVEYS

A spinner is a wireline tool used to measure wellbore fluid velocities. It has a propeller that spins when fluid flows past it while the tool counts the number of rotations in a fixed period. The counts are proportional to the velocity of fluid moving past the tool (above a threshold velocity), with a slight difference depending on direction of flow. The constant of proportionality, which varies for each tool, fluid and wellbore geometry, must be determined for each survey. A continuous spinner profile is produced with a moving survey tool, so the tool velocity must also be accounted for.

A multi-pass spinner interpretation method is necessary at Coso. Four passes over the interval of interest are made at different tool velocities and direction. A cross-plot of spinner counts and tool velocity is constructed to find a linear correlation of tool velocity to counts (Peebler, 1982). Multiple passes are useful for identifying spurious data and transient effects and are necessary when the direction of fluid motion is unknown because the spinner tool does not indicate direction, only magnitude. A computer program was written to automate the analysis of spinner surveys (Spielman, 1994). The program performs a cross-plot at each data point (approximately every meter on each pass), determines the constant of proportionality, and calculates the fluid velocity. Non-linear spinner response due to low velocities and direction changes is ignored because velocities are generally high in geothermal wells, and variations due to changes in hole size, fluid density, and flow regime are large. When the four passes agree, the calculated velocity profile is considered reliable. If there is a wide variation in velocities calculated from the four spinner passes, there is a problem in the interpretation, the tool, or the well, and the velocity profile may not be accurate.

The combined PTS survey solved the problem of locating the correct scale inhibitor injection depth in most wells. Where there was stagnant fluid in the bottom of the well the scale inhibitor had to be injected above the deepest inflow, which in some wells was very close to, or at, the flash depth. The depth of stagnant flow could not be determined by pressure-temperature surveys but was easily determined using the fluid velocity profile calculated from the spinner. However, some PTS surveys provided more questions than answers. There were several types of unusual velocity profiles: short, low velocity intervals at the flash depth, long, low velocity intervals above higher velocity intervals, large down-flow intervals, and widely variable velocities. Almost all of the wells had a short, low velocity zone at the flash depth; the exceptions were wells with high velocities below the flash depth. The short, low velocity intervals and long, low velocity intervals were thought to be due to hole washout or thief zones and the down-flow intervals were thought to be due to cross-flow into thief zones. Widely variable velocities were thought to be due to surging flow when they corresponded to surging flow at the surface. However, it is also possible that the spinner surveys were misleading and that none of the effects were real. Down-flow intervals disappeared when thief zones were cemented off in two wells, confirming the theory of cross-flow to a thief zone. The occurrence of a short, low velocity zone at the flash depth inside casing, and movement of the short, low velocity zone with the flash depth indicated that liquid hold-up could be the cause (liquid hold-up refers to the difference between liquid velocity and gas velocity in two-phase flow). The spinner tool lies in the slower moving liquid on the low side of the wellbore while the small amount of steam flows along the high side of the wellbore at a higher velocity. An independent measurement of the flow profile was needed that was quick and inexpensive. Tracer, injected downhole and detected at the surface, was the solution.

TRACER TESTS

The concept of using a fluorescent dye to trace scale inhibitor chemical flow was proposed by Thermochem, Inc., an analytical services contractor to California Energy Company. RWT was selected because it is relatively non-toxic, inexpensive, easily analyzed, and is sufficiently stable in geothermal conditions (M. Adams, pers. comm.). RWT is a bright red, fluorescent, liquid dye developed for water tracing (Crompton and Knowles Corporation, 1991). It is easily detectable to 1 ppb using a filter fluorometer, and visually detectable at ~1 ppm in a 100 ml sample.

Two variations of the test are used. The tracer is pumped downhole through the stationary capillary tubing normally used for scale inhibitor application <u>or</u> through a capillary tube while that tube is raised or lowered in the well bore. The former method has been employed most often due to rapidity and low expense. A 0.8 wt.% solution of RWT is pumped at a rate sufficient for a final (estimated) concentration in the surface liquid phase of 1-3 ppm. This concentration is high relative to the analytical detection limit, but allows visual detection of the tracer at the sample source. Samples collected at the wellhead, using a cyclone separator, are analyzed in the Coso laboratory. Prior to downhole application, RWT is injected at the production wellhead and sampled downstream to establish a liquid flow rate in surface piping for baseline comparison.

CASE HISTORIES

Well A - Normal Flow

The PTS survey for Well A is typical of surveys run in Coso production wells. The flash depth is close to the deepest entry, and there is an apparent low velocity zone just above the flash depth (Figure 1). The flash depth is represented by a decline in the pressure gradient above 1190m. The fluid velocity calculated from the spinner is zero below 1270m, above which it increases to 1 m/sec. Above the flash depth at 1190m the velocity drops off again, reaching zero at 1135m, then increases above 1080m. This is most likely a liquid hold-up circulation zone and is seen in many of the Coso production wells just above the flash depth.

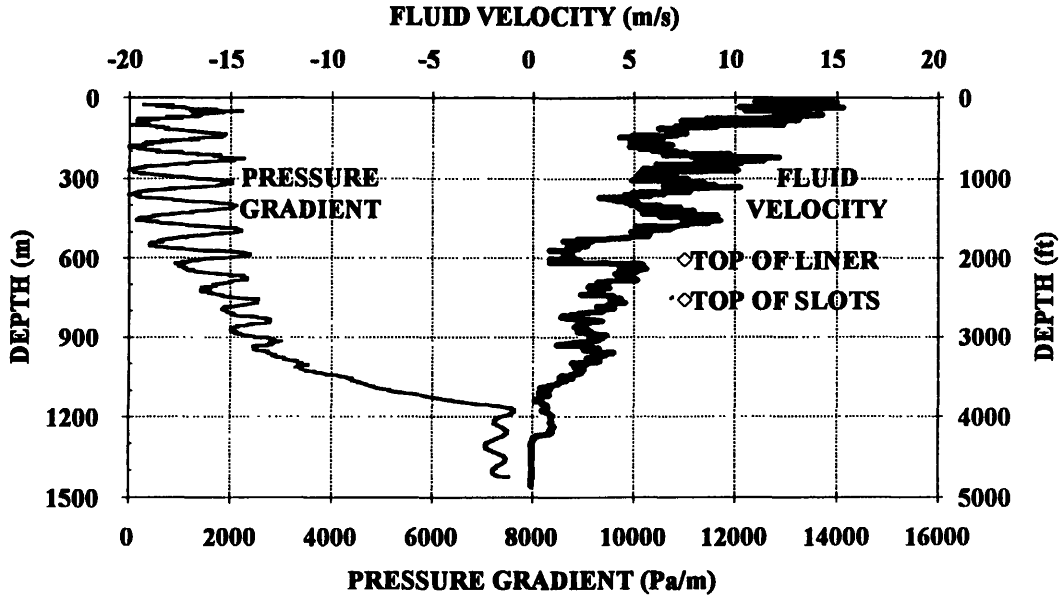

Figure 1 - Well A Flowing Spinner Survey

Scale was cleaned out of this well as deep as 1270m, so the inhibitor injection tube was set at 1280m where the spinner indicates no flow. A tracer test was necessary to make sure the inhibitor was moving up hole.

RWT was injected at the wellhead at a rate of 500 ml/min for 30 minutes and sampled downstream every 3 minutes. It was then pumped down the capillary tube, fixed at a depth of 1280m, at a pump rate that stabilized at 694 ml/min. RWT was pumped for one hour, followed by water for another hour. By pumping water after the tracer, the fluid travel-time up the well-bore can be determined. This cannot be accomplished by stopping the tracer pump because the tracer will continue to drain from the capillary tube at an unknown rate.

The surface-pumped RWT concentration averages 1.45 ppm (Figure 2). The downhole-pumped concentration, after normalizing the tracer pump rate to the surface-pumped rate and eliminating the first three non-equilibrated samples, averages 1.46 ppm. A 101% tracer recovery is indicated. The RWT concentration declined rapidly 23 minutes after the downhole tracer was switched to water, indicating the measured travel time for the tracer down the tube and back up the well.

The measured travel time is evaluated by comparison with a calculated travel time. The calculated travel time is the sum of the tubing travel time and the well-bore travel time. The problematic variable for determining tubing travel time, effective tubing volume, has been empirically determined to be 1 liter/100m for 0.635 cm O.D. stainless steel capillary tubing, which is significantly less than the true volume. The well-bore travel time is determined from the spinner-calculated fluid velocities. The calculated travel time for this test is 22 minutes and the measured travel time is 23 minutes, indicating no stagnant or slow flow zones in this well.

Well B - Depth Traverse Over a Thief Zone

Well B has an unusual fluid velocity profile that is similar to several other Coso production wells that have low flowing wellhead pressure. The fluid velocity calculated from the spinner is zero from total depth up to 1400m (Figure 3). The flash depth is represented by a decrease in the pressure gradient above 1280m. The velocity above 1280m is erratic, going below zero in several places. The low velocities from 1280m to 910m could be due to well bore washout or a thief zone. A tracer test was conducted to determine the cause of the low and negative fluid velocities indicated by the spinner.

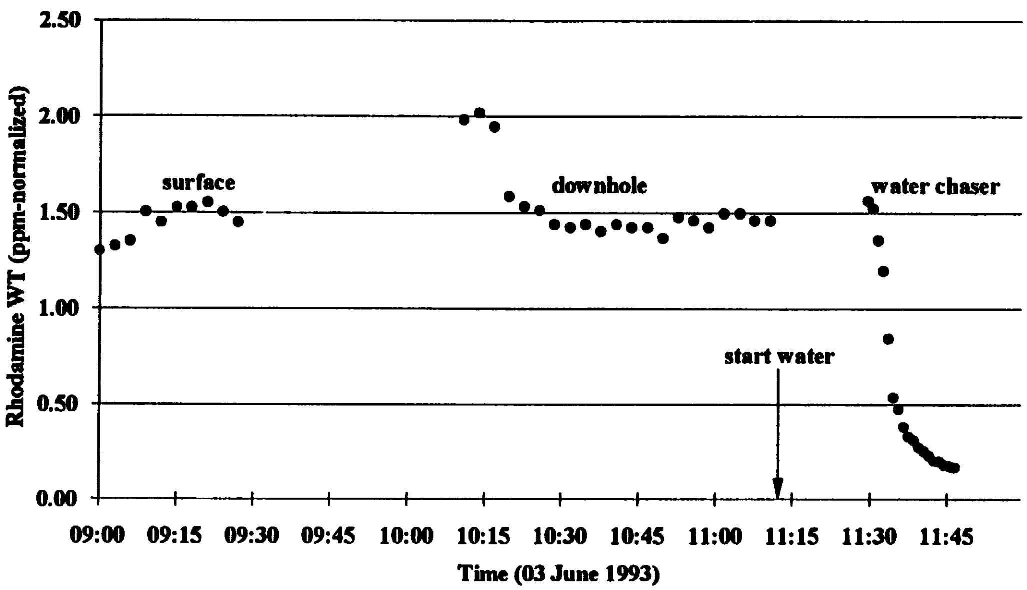

Figure 2 - Well A Tracer Response

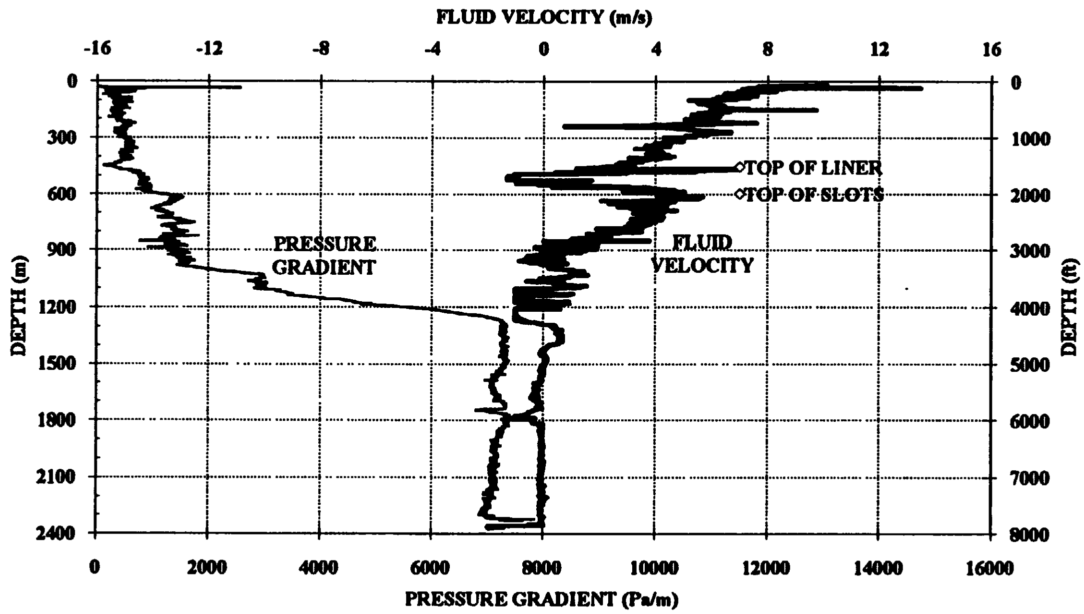

Figure 3 - Well B Flowing Spinner Survey

A capillary tube was lowered from 910m to 1400m at 3 m/min while tracer was pumped at a continuous rate. The sample concentration varied from 2.9-3.4 ppm from 914-1036m, then dropped to 2.0-2.5 ppm below 1036m (Figure 4). Excursions from these general trends are probably due to perturbations in tracer flow during verification of pump rate (e.g., 930m, 990m, 1045m).

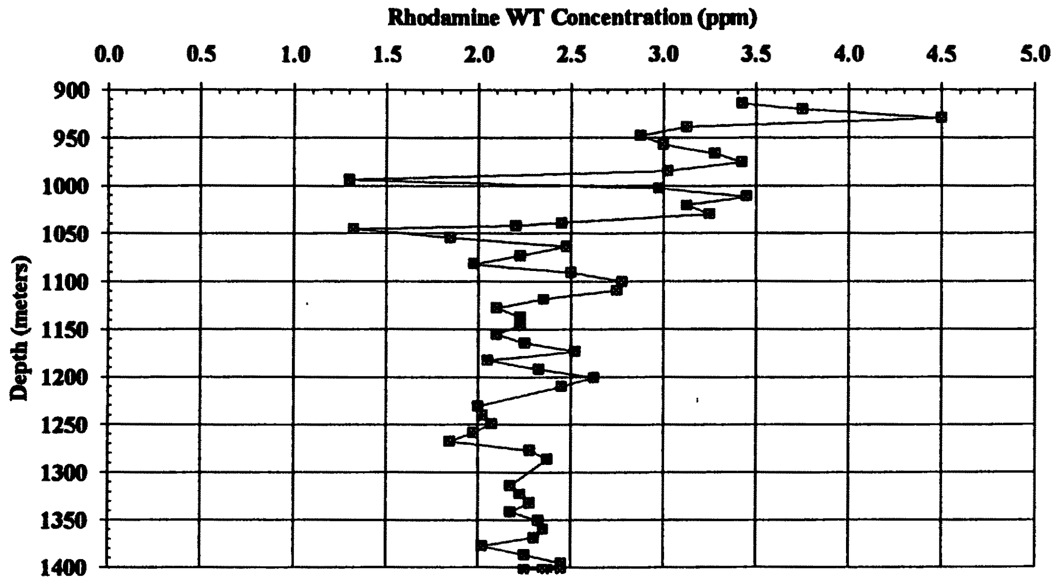

Figure 4 - Well B Tracer Response

The drop in concentration represents a 30% loss in tracer return to the surface. The PTS survey indicates that boiling is initiated at 1280m. A single-phase liquid or two-phase fluid entry is indicated at 1036m, which correlates with a drilling break at that depth. The tracer loss may be occurring at 1036m, or it may be occurring at greater depth due to counterflow of the traced liquid down the well. Counterflow provides a good explanation for calculated fluid velocities fluctuating near zero from 910-1280m.

To determine fluid velocity, water was pumped after the tracer at 1400m, then tracer was pumped after the water at 914m. The measured travel time for tracer travelling down the tubing and back to the surface from 1400m was 96 minutes, and from 914m it was 56 minutes. The fluid pump rate and, therefore, the residence time of tracer (or water) in the capillary tubing, was nearly the same for both events. Therefore, the time difference of 40 minutes represents the wellbore liquid travel time from 1400m to 914m depth, or an average velocity of 0.2 m/sec (40 feet/min).

Well C - Low Velocity Flow Zone

Well C has low velocities in the bottom of the well that could cause problems for scale inhibition. The velocity may be insufficient to carry the inhibitor chemical up the well, or degradation of inhibitor may occur due to the length of time the inhibitor is exposed to high temperatures.

The flash depth is represented by a decrease in the pressure gradient above 1160m (Figure 5). The spinner survey response was erratic, with poor agreement between passes, from total depth up to 1250m, and indicated low velocities from 1250m up to 760m. The velocity then increases rapidly from 760m to 600m. The inhibitor injection tube was installed at 1370m, and a tracer test was conducted to determine if the inhibitor was returning to the surface.

The method used in this test is similar to that describe for Well A. Tracer was injected at the wellhead and sampled downstream to determine baseline tracer concentration. Subsequently, the tracer was pumped down the in-place capillary tubing set at 1370m. The pump rate stabilized quickly, allowing determination of wellbore liquid travel time by noting that the first return of tracer to the surface occurred after 59 minutes. Subtraction of the calculated residence time of the tracer in the capillary tubing (11 minutes) yields a wellbore travel time of 48 minutes. Tracer concentration increased slowly, fortunately reaching 100% recovery just before the test was terminated (Figure 6).

The wellbore travel time is estimated to be 4 minutes, plus an indeterminate time traversing the

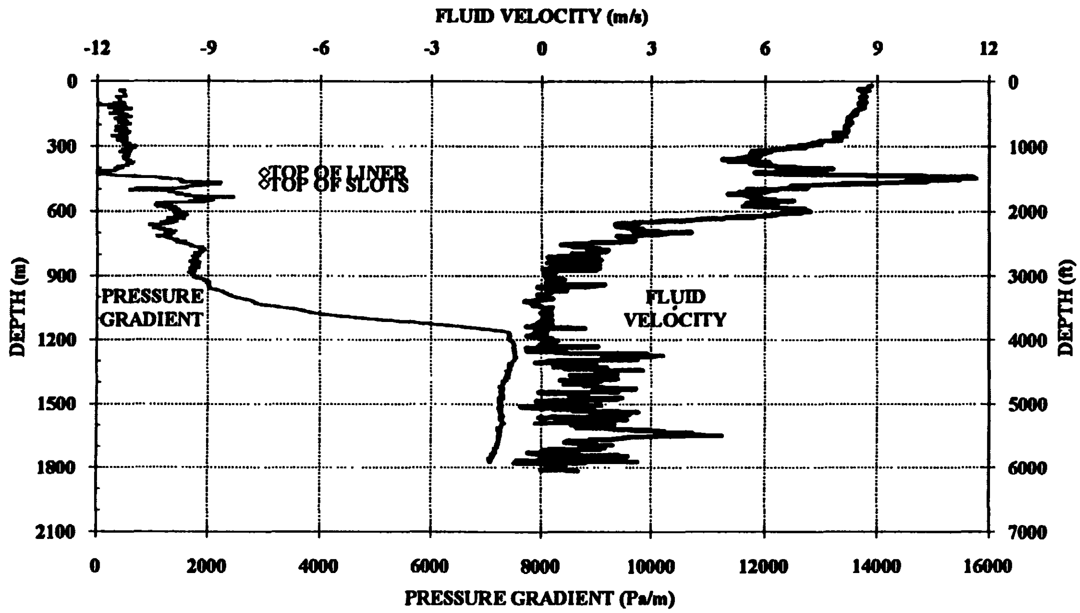

Figure 5 - Well C Flowing Spinner Survey

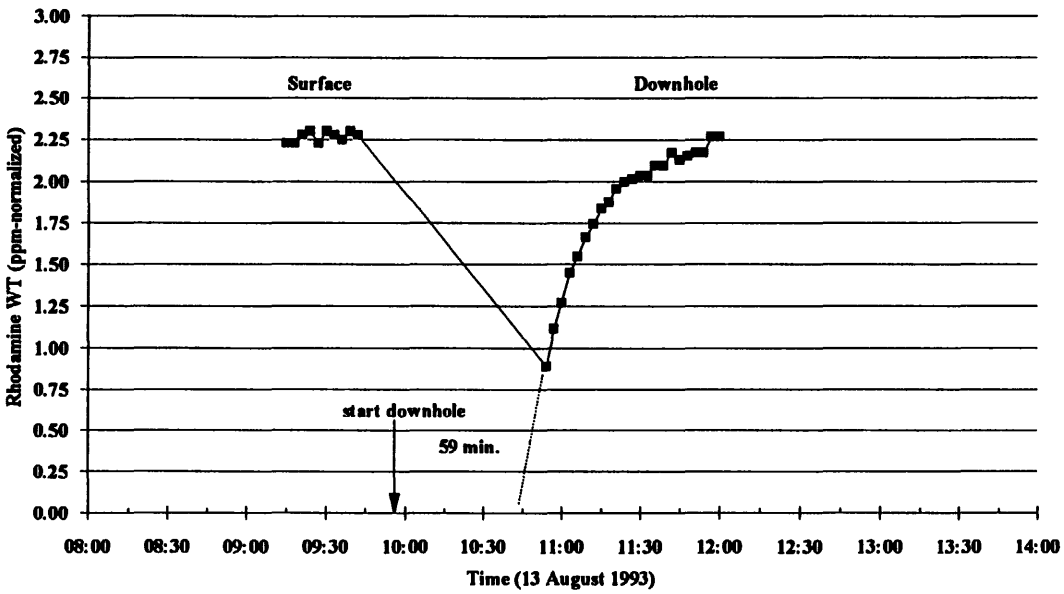

Figure 6 - Well C Tracer Response

410m slow zone. The calculated time of 4 minutes compared to the measured time of 48 minutes suggests a travel time of 44 minutes in the 410m low velocity zone, or an average velocity of 0.15 m/sec (31 feet/min). This velocity was considered unacceptable for effective scale inhibitor application, so the tube was raised to a depth of 1280 m.

The tracer test was repeated at the 1280m tube depth five days later. Well flow conditions were nearly identical to the previous test. Thus, the wellbore travel time in this case was again estimated to be 4 minutes plus an indeterminate time traversing the slow zone, which was reduced to 320m. The first return of tracer to the surface yields a measured wellbore travel time of 7 minutes; water pumped after the tracer indicates 12 minutes. Assuming an intermediate value of 9 minutes, the wellbore travel time was reduced by 39 minutes from the previous test.

From this data several flow parameters can be determined. The slow zone interval in the second test was reduced to 320m where the tracer residence time was 5 minutes, indicating an average velocity of 1.1 m/sec (210 feet/min). Travel time was decreased by 39 minutes by raising the tube 91m, indicating an average fluid velocity of 0.04 m/sec (7.7 feet/min) in that 91-m interval. In that interval the well was drilled with a 12.25-inch bit and cased with 9.625-inch slotted liner. Experience at the Coso field has shown that fluid flow tends to utilize the entire drilled diameter. Therefore, we calculate a flow rate of 3.0 l/sec (24,000 lb/hr) from below 1280m depth.

Well D - Surging Flow

The spinner survey on this well was baffling. It indicated that the fluid flow direction was down, despite the fact that the well was producing steam at the surface. This might be blamed on tool failure but a spinner survey performed three and a half months earlier produced the same result.

The fluid velocity calculated from four spinner passes is negative to a depth of 700m, indicating that the flow direction is downward (Figure 7). Stagnant liquid below 700m is represented by zero fluid velocity and a 8000 Pa/m (0.35 psi/ft) pressure gradient. At 700m the pressure gradient drops off rapidly, indicating a steam entry. The pressure gradient is 1000 Pa/m (0.05 psi/ft) over most of the wellbore, indicating a two-phase mixture, but drops to zero above 60m. The measured enthalpy for this well was 1776 kJ/kg, indicating an average liquid/mass fraction of about 50% at the surface. A tracer test was conducted to see what might be causing the unusual spinner surveys.

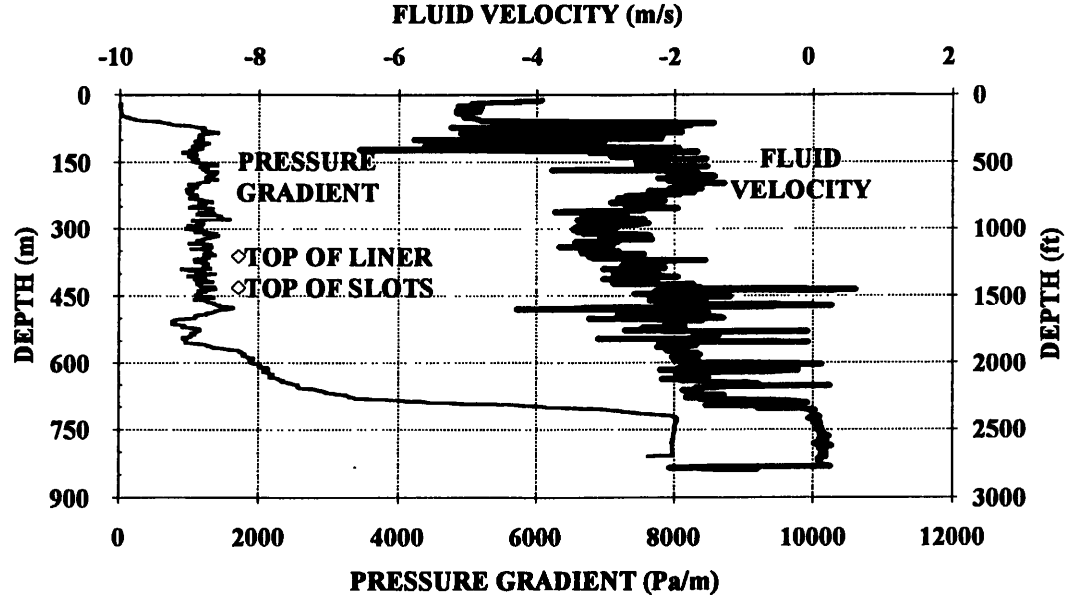

Figure 7 - Well D Flowing Spinner Survey

The 8000 ppm solution of RWT tracer was injected at the wellhead at a rate of 500 ml/min for nearly one hour. Samples collected downstream show highly variable concentrations ranging from 10.6 ppm to 935 ppm (Figure 8; note logarithmic RWT scale), indicating a liquid flow rate variation of 0.07 l/sec to 12.6 l/sec (600-100,000 lb/hr). The surge cycle duration is 25-30 minutes, with a wellhead pressure variation of only 0.024 MPa (3.5 psi).

Tracer injected downhole to a depth of 745m returned to the surface at increasingly higher concentrations with each surge cycle. Peak concentrations appear to be approaching a plateau near 30 ppm when the test was terminated. The peak concentration at the first cycle to return tracer was 4.2 ppm, followed by 21.2 ppm, 25.5 ppm and 28.5 ppm in successive cycles. The first return of

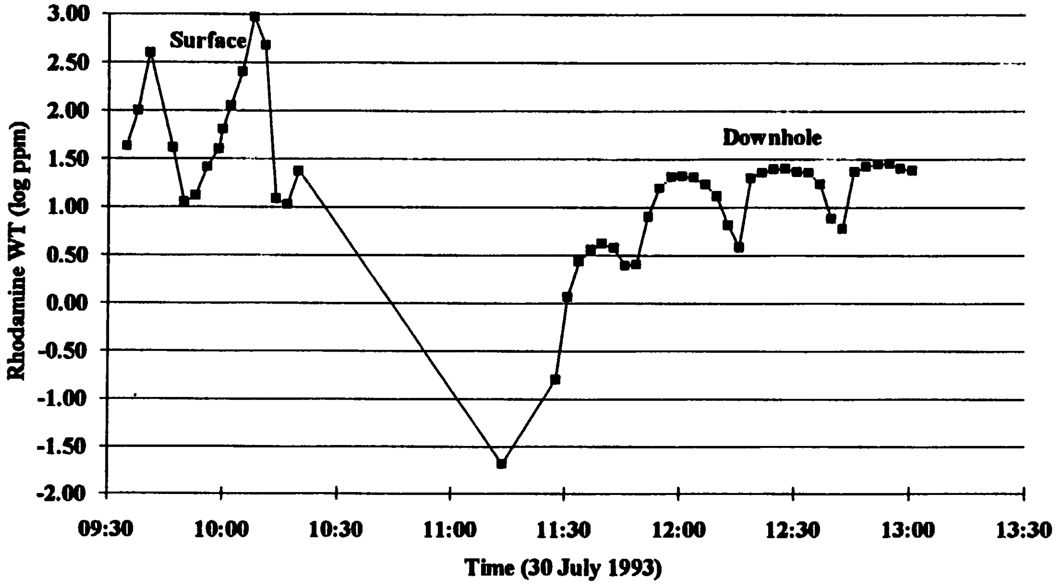

Figure 8 - Well D Tracer Response

tracer to the surface occurred 45 minutes after thetracer reached the bottom of the hole, suggesting that fluid velocities at 745m are very low. However, the slow return time may also be due to liquid counterflow in the wellbore, as is implied by the spinner survey. Peak concentrations for tracer injected downhole are 300 times lower than for surface injection, indicating that only a fraction of the downhole tracer, and the liquid into which it was injected, is reaching the surface. Liquid flowing up from the stagnant bottomhole, and counterflow liquid from above, may be exiting the wellbore at 709m.

SUMMARY

The primary use of downhole tracer investigations at the Coso field has been clarification of spinner survey results for optimum scale inhibitor injection tubing placement. This, in turn, has allowed a more thorough understanding of wellbore hydraulics for all Coso wells. Tracer studies are capable of determining liquid velocities, flow rates, and the existence and location of thief zones.

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