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ASSESSMENT OF REINJECTION TRIALS IN KIZILDERE GEOTHERMAL FIELD

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ABSTRACT

Kizildere Geothermal Field discovered in 1968 produces hot water and saturated steam from two hydraulically connected reservoirs. During fourteen years of operation of the power plant in the field, the production of about 80 million tons of water caused approximately 1 MPa drop in reservoir pressure. The estimated recharge rate of the field is about 550 tons of water per hour and is insufficient for maintaining the reservoir pressure and desired power generation.

Produced hot water has been discharged as waste into nearby Buyuk Menderes River from where the water is used for agricultural irrigation. The adverse effects of high boron content of geothermal water on agricultural activity has put a limitation on both the discharge and the production rates, and thus on power generation capacity. Reinjection of wastewater back into the reservoir seems to be the only viable method for both disposal and reservoir pressure maintenance.

Two reinjection pilot tests have been conducted to study the effects of reinjection on reservoir performance and to measure the injectivity index. The first test lasted for 29 weeks in 1976. The cooling effect of reinjection was felt at the bottom of the observation well. A heat flow model describing the non-isothermal fluid flow in naturally fractured reservoirs is applied and the temperature behavior in the observation well is predicted successfully. A sudden increase in injectivity after an initial decline in injectivity and a similar trend observed in pressure is attributed to the possible fracturing of the formation. The second test lasted for 40 days in 1995. Decline in injectivity is related to the possible plugging by scale deposition in the injector. Some change in the chloride content but no change in the temperature of the produced water is observed. The rise in water levels in observation wells gave good clues about the flow mechanism of the reservoir.

1. INTRODUCTION

The disposal of the waste hot water is classified as one of the major challenges in geothermal reservoir management. The most common method of disposal is reinjecting the waste hot water back into the reservoir. Reinjection does not serve only the purpose of hot water disposal but also supplemental heat extraction from the reservoir while maintaining its pressure.

The major difficulties encountered in reinjection applications are (1) the realization of constant injectivity rate in reinjection wells, (2) the determination of the flow direction of injected water, and (3) the confrontation of adverse changes in the produced water quality, as the injected water moves to the producing wells. An engineered design, prior to reinjection applications, is indispensable to overcome such difficulties.

Two preliminary reinjection applications, one in 1976 and the other in 1995, were conducted in Kizildere Field in Turkey. First, the high boron content of the produced water, that is disposed into nearby Buyuk Menders River, was severely detrimental to both the river biota and the large-scale agricultural activity in the area, since the river water is used for irrigation. Second, local decline in reservoir pressures up to 1 MPa was observed after about 80 million tons of water production over 14 years between 1984 and 1998. Such decline in reservoir pressure has caused the emergence of two phase fluid flow in the reservoir and thus, limited the electrical power generation capacity of the field power plant to some extent.

Therefore, the reinjection attempts in Kizildere field arose as a result of both the environmental and economical concerns.

2. KIZILDERE FIELD IN GENERAL

Kizildere Field, the largest geothermal field in Turkey, was discovered in 1968. As illustrated by Dominco (1974) in Figure 1, the field is located in a graben. Production is from two geothermal reservoirs in the upper part of the middle block of the graben bounded by two normal fault zones. The shallower limestone reservoir is separated from the underlying marble reservoir by a 200-m thick red shale. Both reservoirs about 150 to 200 m. Studies by Serpen and Gulgor (1995) and Serpen, et. al. (1998) showed the existence of hydraulic communication through a natural fracture system developed in between the two reservoirs. The fluids in both reservoirs contain dissolved carbon dioxide of 1.5 percent by weight. In-situ fluid temperatures in limestone and marble reservoirs of the middle block are in the range of 452 ^{o}K to 472 ^{o}K and 470 ^{o}K to 479 ^{o}K, respectively.

A total of 20 wells, of which 2 are for reinjection and the rest are for production purposes, have been drilled in the field. The drilling of new reinjection wells at more desirable locations is still an ongoing process. An overlay illustration of several well locations on the map of the marble formation top in the field is shown in Figure 2. The wells designated by solid circles were completed into the limestone reservoir, and other wells directly penetrate into the marble reservoir. The limestone reservoir has limited aerial spread and dips in the similar direction with the marble reservoir. The wells, designated by plain circles in Figure 2, are drilled into the marble reservoir without encountering the limestone.

3. VINDICATION OF HOT WATER REINJECTION

Due to the following reasons an engineered reinjection of the produced wastewater back into the reservoir appears to be an inevitable necessity in Kizildere Field.

3.1. Decline in Reservoir Pressure

In the field a power plant with an installed capacity of 20.4 MW_e and an effective capacity of not more than 10 MW_e gross has been operating, since 1984. During fourteen years of operation at the effective capacity of the power plant, about 80 million tons of water was produced at an average rate of 1000 tones of water per hour, causing nearly 1 MPa drop in reservoir pressure. At separator conditions only 11-percent of 1000 tons/hr production rate was in the form of saturated steam and the rest was boron rich water.

3.2. Insufficient Natural Recharge of the Reservoir

Serpen and Gulgor (1995) estimated the natural recharge rate of the field to be about 550 tons of water per hour. Under the conditions of equal rates of total production and natural recharge without reinjection, the field power plant has a net power generation capability of 5 MW_e. Yet, it is believed that the power generation of 20.4 MW_e can be attained with the engineered production and reinjection operations carried out in a fully developed field.

3.3. Evolution of Free Gas Phase

When the total production rate exceeds the natural recharge rate of the field, the reservoir pressure undergoes a decline. Below the flash pressure, dissolved carbon dioxide (CO_2) gas starts evolving and forms free gas pockets. Serpen, et. al. (1995) proved the occurrence of free gas zone by the analysis of neutron and density logs recorded in well KD-22.

3.4. Calcite Precipitation

The liberation of CO_2 gas results in calcite precipitation, which causes plugging problems both in the reservoir and in the well bores. The further the pressure declines the farther away the calcite precipitation advances into the reservoir from the well. As a result, the production rate gradually declines and the producing wells are shut in and the power generation is terminated for the acid cleaning of the well bores and the removal of the calcite precipitate.

3.5. Restricted Waste Water Emission Into The River

The emission of boron rich produced water into the Buyuk Menderes River is the current practice for water disposal. Besides the adverse effects of boron content on river biota and agricultural products, such undesirable application also limits the power generation capacity of the power plant, up to a certain extent. During the arid months of spring and summer seasons, the flow rate in the river decreases because of the marginal water recharge and the increased water withdrawal for irrigation. At these low river flow rates the effects of boron content on the environment is felt even more. Thus, the wastewater emission into the river is decreased in those seasons and restricts the production rate and the power generation.

4. REINJECTION TESTS

Two reinjection pilot tests were attempted to examine the reservoir response and to measure the injectivity index.

4.1. Reinjection Test in Well KD-1A

In 1976, the water produced from well KD-15 was injected into well KD-1A at an average rate of about 85 tons/hr for 29 weeks. Injected water temperature varied from 313 ^oK to 353 ^oK. Well KD-1, which is 68 m away from KD-1A, was chosen as the observation well. Figure 3 illustrates the injection rate and wellhead pressure recordings at well KD-1A. For the first 5 weeks, the injection rate increases from 75 tons/hr to 90 tons/hr, and the wellhead pressure follows a similar trend by increasing from 0.7 MPa to 0.9 MPa. During the following two weeks the pressure remains constant, although injection rate increases slightly. In the mean time, as seen in Figure 4, both the temperature and the bottom hole pressure in the observation well KD-1 remain constant with some minor fluctuations.

From 7th to 12th weeks, the injector wellhead pressure drops down to 0.8 MPa, while the injection rate oscillates about 90 tons/hr. In the observation well, however, both the pressure and temperature at the depth of 530 m drop 0.2 MPa and 4.8 ^oK, respectively, while the temperature at 500-m depth drops only 1 ^oK. Such a temperature response at the observation well confirms the existence of the already detected fracture at the depth of 530 m in the observer. Thus the cooling effect of the injected water is felt more at the depth of 530 m compared to that at 500 m, in the observer. In addition, the cooling effect is felt at the observer 6 weeks after the start of injection.

After the 12th week, the injection rate exhibits a rather sharp drop to 75 tons/hr, until the 15th week. In the mean time, the wellhead pressure increases to 1.1 MPa. As expected, the pressure at the observer follows the same trend and increases to 5.9 MPa, indicating a good hydraulic communication in between the two wells. The temperature at KD-1 increases about 2 ^oK via the conductive heating of the rock, since the delivery of cooler water toward the observation well is mitigated with the rapidly decreasing injection rate. An idea for the cause of such rapid drop in injection rate and increase in wellhead pressure was the plugging of the bottom hole of the injector with silica, precipitated out of the injection water. The idea was based on the detection of about 2 to 4-mm thick silica scale on the inner walls of the wellhead, when it was removed after the operation. On the other hand, the injection water had to be stripped of much of its silica during its passage through the settling sections of the open flow conduit, between the Well KD-15 and the KD-1A pond. The intermittent seasonal rains led the injection water temperature decrease to a level between 313 ^oK and 353 ^oK, which provides the means for an increase in silica separation at the surface.

If any sorts of solids precipitation took place in the reservoir, then the injector KD-1A had to experience a rise in pressure much earlier than did the observer KD-1. Yet, such response is not seen in Figures 3 and 4. Based on these facts, the actual reason for the rapid drop in injection rate is thought to be the filling up of the reservoir with the cumulative water injected by that time. Thus, the attempt of forcing more water into the already filled up reservoir back pressured the reinjection well.

As seen in Figure 3, the injection rate suddenly increases and reaches 85-tons/hr level, as the wellhead pressure remains constant, between the 15th and 16th weeks. Such behavior is likely to be the initiation of hydraulic fracturing of the rock of a pressured up formation. It is well known fact that once the formation breaks down, it does not take much pressure to progress the fracture. Thus, the injection pressure in Figure 3 starts increasing up to 1.3 MPa until the 17th week, then remains constant for six weeks. Injection rate also remains constant for six weeks. Another evidence for the probable fracturing of the formation may be deduced from the pressure behavior at the observation well in Figure 4. The observation well begins to sense the slow progressing fracturing action at the 17th week. The pressure at the observer jumps up and down 0.3 MPa until the 21st week, when the fracture progress is completed. Steady increase of the temperature at the depth of 530 m in the observation well indicates that the fracture was not formed at that direction and depth. According to the calculations, based on fracture gradient of the field, a pressure of 7.45 MPa was required to create a hydraulic fracture at the depth of 530 m. However, the fracture mentioned here was created at the pressure of 6.17 MPa, which was enough to break down the formation at a shallower depth of about 440-m. It should not be a coincidence that at 17th week the temperature at 500-m depth in the observation well had a disturbance of 1 ^{o}K.

After the completion of fracture progress at the 21st week, the injection rate declines slightly, and the pressure also declines with two-week delay, as illustrated in Figure 3. As expected, the temperature in the observer KD-1 increases slowly but steadily by conductive heating of the rock and the pressure remains almost constant, as seen in Figure 4. Such response implies that the injected fluid moves into a different direction from the observer KD-1, possibly toward the newly formed fracture system. Note that the reinjection operation was stopped between 23rd and 25th weeks, for some reason.

4.2. Application of An Analytical Heat Model

An analytical heat model, developed by Satman (1988) to describe the non-isothermal fluid flow in naturally fractured reservoirs, is applied to predict the temperature behavior at well KD-1. The model assumes a reservoir embodying lateral repetitive elements of fracture and matrix pairs. The early and late time solutions for the dimensionless temperature behavior in the matrix, T_{mD}, and the fracture, T_{fD}, are given separately. The early time solutions for T_{mD}, and T_{fD}. are found to be identical to those given by Bodvarsson (1972). Expressions describing the heat extraction from hot matrix by re-injected water are incorporated with the model and used. The derived equations and the usage of the model are also explained.

The total amount of heat, which can be extracted by water during a temperature reduction from T_o to T_i, is divided by the number of repetitive elements and designated as, Q_R. T_o and T_i indicates the initial temperatures of reservoir and injection water, respectively. The rate of heat extraction, Q_q, by water is determined for the temperature reduction from T_f in the fracture to T_i. Then, the cumulative heat extracted by injected water, Q_w, in a time frame of "*t*", may be calculated from

$$Q_w = \int_0^t Q_q \, dt$$

The extracted fraction of the initial heat content of the rock by water can, then, be obtained from the expression of "Q_W/Q_R".

The model is applied to the decreasing temperature behavior at the depth of 530 m in the observation well KD-1, as shown in Figure 4. The heat extraction of water from the rock takes place as water flows from well KD-1A toward the observer through the fracture system, as explained previously. The rate of injection, into a 140-m thick formation, is considered to be 85 tons/hr. As seen in Figure 4, the reservoir temperature at the 6th and 11th weeks of the operation are 471 ^{o}K and 467 ^{o}K, respectively. The ratio of the specific heat capacities, $\rho\, C$, of the fracture and matrix is assumed to be unity, and the thermal conductivity of the rock, *k*, is considered to be 2.0 W/m K. Figure 5 illustrates the calculated temperature distributions for three different numbers of fractures, assumed to exist in the rock, and for two different water reinjection temperatures. The observed temperature behavior is also plotted on the same graph. A reasonably good agreement between the actual and predicted behavior was obtained for 12 fractures assumed to occur between the injection and observation wells. At the first glance, though, the agreement between the actual and the predicted behavior of temperatures seems to be poor. Yet, as mentioned earlier, the temperature of the injection water had varied between 313 ^{o}K and 353 ^{o}K at the bottom of the injector. It is probable that the injected water temperature decreased for a while during the operation and then recovered back to its initial level. Considering the complexity and the number of unknowns of a fractured reservoir system, the applicability of the model is proven for all practical purposes. One can tune the model to a particular reservoir in hand and design a reinjection operation.

4.3. Reinjection Test in Well KD-7

In the summer of 1995, the water produced from KD-20 was injected into well KD-7 by gravity. The wellhead injection temperature was 373 ^{o}K during the 45-day operation. Pressure was monitored at the depth of 600 m in the 667-m deep injector. Recorded pressures and injection rates are shown in Figure 6. The producer KD-20 also served as an observation well for monitoring the produced water temperature and chloride (Cl^-) concentration. In Figure 6, only the change in Cl^- concentration is provided since no cooling was detected in produced water at KD-20.

The major problem encountered in the reinjection operation was the continuous drop in injectivity. As seen in Figure 6, 125-tons/hr rate of injection early in the operation decreases down to an average of 35 tons/hr by the end of the test. The problem of injectivity is attributed to the possible plugging of both the formation and the injector. It is likely that some calcite precipitation within the formation and the bottom hole occurred due to the rise in the temperature of the calcite saturated injection water, during its downward flow from surface to bottom hole in KD-7. The other supplemental reasons for plugging could be the silica deposition during reinjection, back flow and accumulation of the corrosion products formed previously in the flow lines, and the 30 to 40-m high debris that was known to exist at the bottom hole. Note that the well KD-7 was normally a producer and not prepared for a reinjection operation. Due to the limitations in technical conveniences at that time the actual reasons of plugging difficulty have never been revealed.

Figure 6 illustrates the chloride (Cl^-) concentration increase, from an initial 135 ppm to 146 ppm, in the water produced from well KD-20, after 25 days of reinjection. Then the Cl^- concentration keeps decreasing with decreasing injection rate. The increase in Cl^- concentration is due to the movement of the hydraulic front from KD-7 to KD-20. A material balance calculation, based on the cumulative injected water and Cl^- content in both injection and produced waters, has shown that about 40 percent of the injected water, with 135-ppm Cl^- content, arrived at well KD-20. It is known that the thermal front is as slower than the hydraulic front as "1.5 x porosity" in Kizildere reservoir. For instance, if it took 25 days for the hydraulic front to arrive at KD-20 and if the formation porosity is 0.10, then at constant injection rate it would take 167 days for the thermal front to arrive at KD-20. Note that the positive effect of molecular diffusion on ion movement within the hydraulic front is not yet taken into account in this estimation. Otherwise, the travel time of the thermal front would turn out to be much longer.

After 25-day reinjection in KD-7, the water levels in wells KD-8 and KD-1A, which were completed in the limestone reservoir, were observed to rise somewhat as is shown in Figure 7. Although the injection was into the marble reservoir, the rise of water levels in both observers is another evidence of good hydraulic communication between the limestone and marble reservoirs within the middle block of the graben.

As shown in Figure 8, though, the bottom hole pressure in KD-9 did not show any appreciable response, and the small down-peak anomaly seems to be the result of a local disturbance in pressure. Thus, it can be stated that the southern fault zone behaves as a flow barrier down to a depth of about 1000-m below sea level.

5. CONCLUSIONS

The assessment of the reinjection pilot trials in wells KD-1A and KD-7 in Kizildere Field indicates that the reinjection of produced water back into the geothermal reservoir would provide the benefits of (1) supplemental heat recovery from the reservoir, (2) pressure maintenance against insufficient natural recharge of reservoir, (3) better comprehension of reservoir flow mechanism, and (4) environmental protection of biota within and without the Buyuk Menderes River.

Adequate engineering design is the vital factor for the success of reinjection applications. The selection and preparation of reinjection wells has paramount importance in achieving desirable injection rates and trouble-free operations.

The application of the heat flow model developed by Satman (1988) may be helpful in designing the reinjection operations.

The limestone and marble reservoirs in Kizildere Field are in hydraulic communication within the middle block of the graben. The southern fault zone acts as a permeability barrier in between the middle and lower blocks down to the depth of about 1000-m below the sea level.

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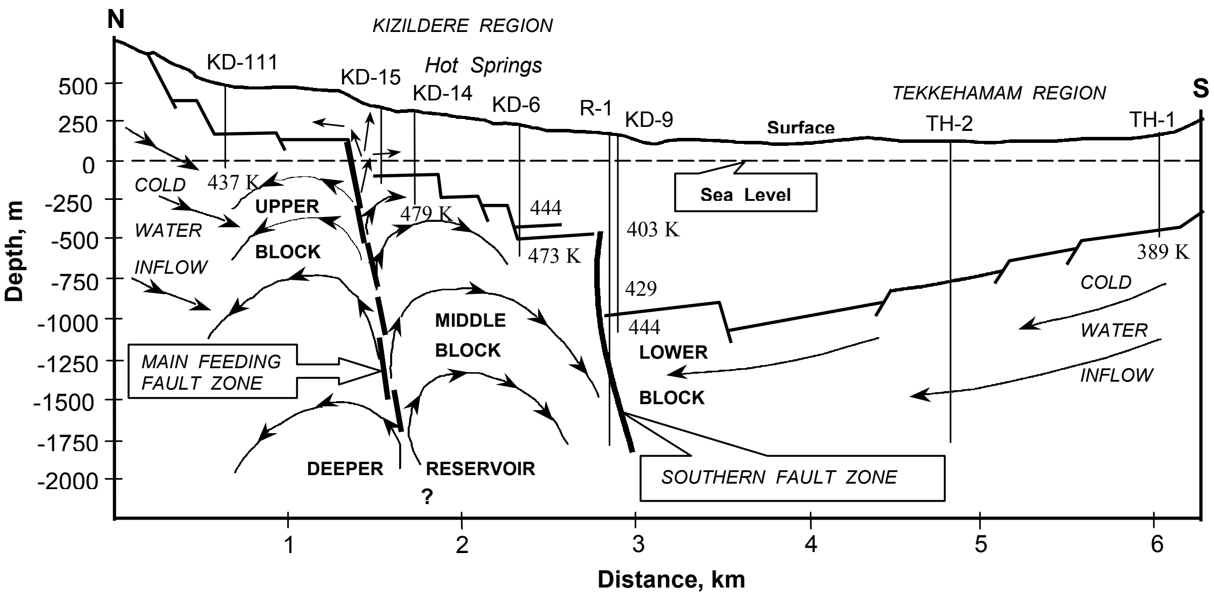


Figure 1 – Hydrogeological model for Kizildere Field, after Dominco (1974.)

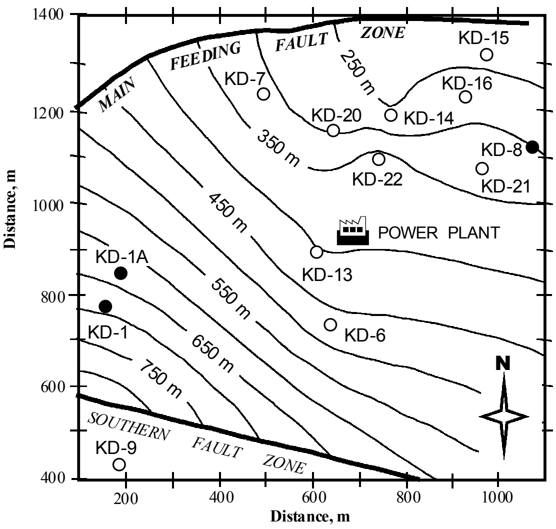


Figure 2 - Well locations projected over the contour map of top of the marble reservoir (elevations are subsurface).

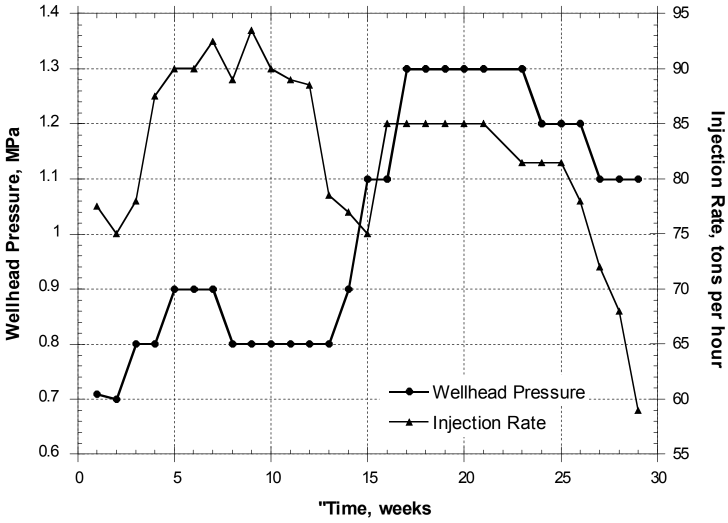


Figure 3 - Injection rate and wellhead pressure behavior during the reinjection operation in the well KD-1A.

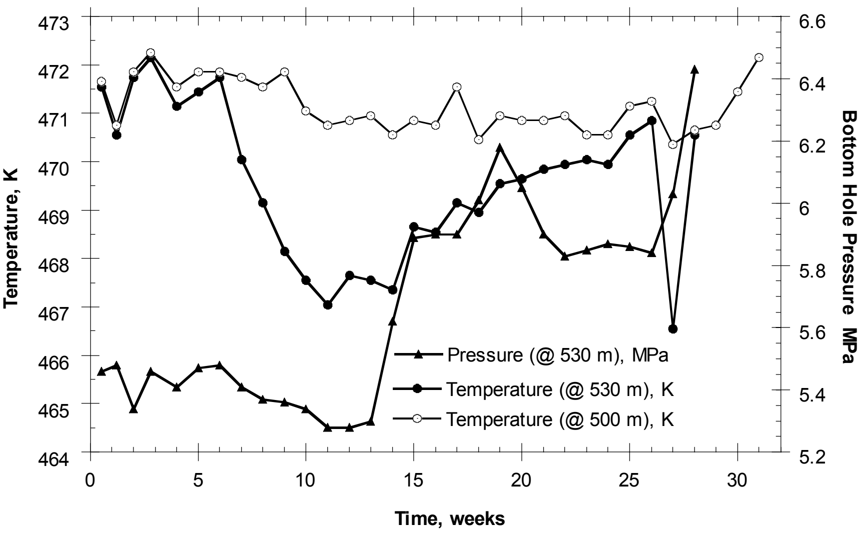
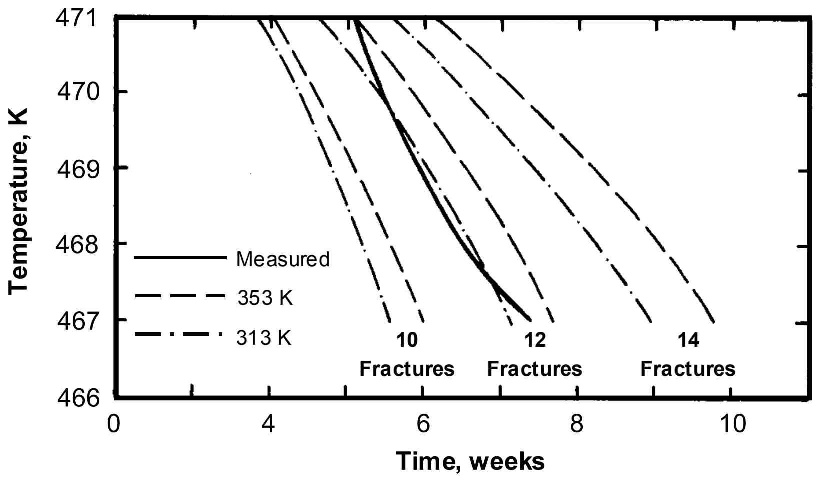


Figure 4 - Pressure and temperature observations in Well KD-1 during the reinjection test conducted in Well KD-1A.

Figure 5 - The prediciton of the observed temperatures at the depth of 530 m in Well KD-1 with the analytical heat-flow model, after Satman (1988.)



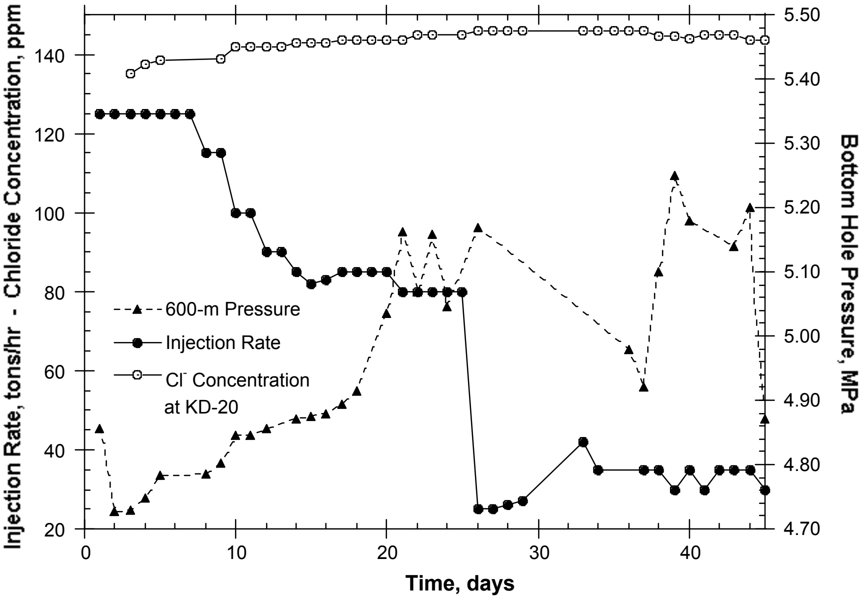
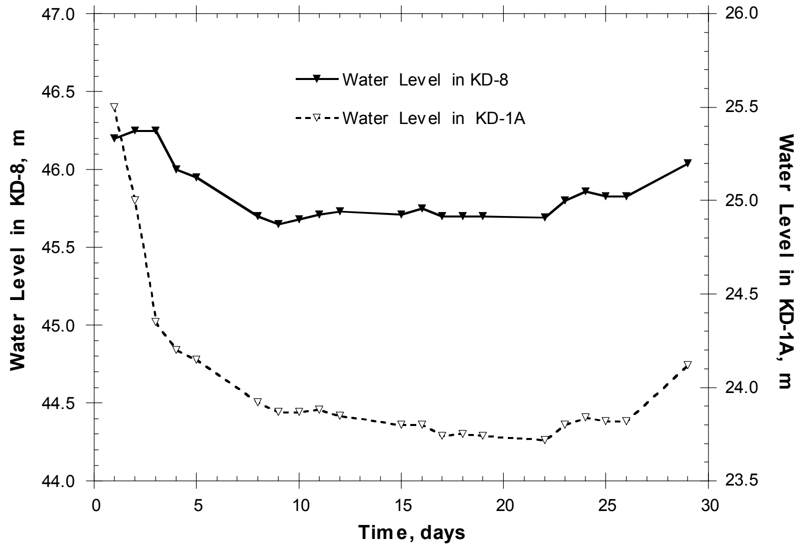


Figure 6 - The variation of pressure and injection rate in Well KD-7 in comparison with the chloride concentration in the KD-20 produced water, during the reinjection trial in KD-7.

Figure 7 - Change in water levels (measured from wellhead) in the observation Wells KD-8 and KD-1A during the reinjection trial in Well KD-7.



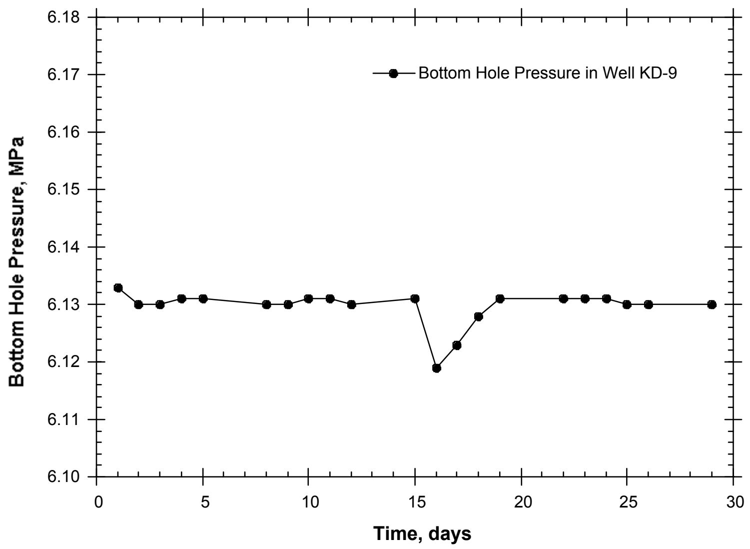


Figure 8 - Monitored bottom hole pressures in the observation Well KD-9 during the reinjection trial in Well KD-7.