



STUDY OF HYDRAULIC PARAMETERS IN LEACH MINING USING RADIOACTIVE TRACER

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Six radioactive tracer (^{131}I) experiments were carried out at in-situ leach mining site to study transit time of injected fluid from the injection wells to the production well along the dip, against the dip, along the diagonals and the strike. It was found that the dip of the host sandstone does not affect the movement of fluid as the same velocity as was found along the dip (0.23 m/h) and against the dip (0.22 m/h). Along the diagonals, the breakthrough times for 13.75 m and 16.25 m were 54 hours and 155 hours respectively yielding velocities of 0.26 m/h and 0.1 m/h. The higher velocity is not only due to shorter distance but also due to higher porosity / injection rate. Along the strike, the breakthrough time was 29 hours (very short) for 9.25 m distance and 147 hours for 16.25 m distance. The unexpectedly high velocity along the strike for shorter distance was also due to higher injection rate in the well as the other well was accepting only small fraction of the total injection. At higher injection/production rate or higher hydraulic gradient, the breakthrough time is shorter and also the dispersion of fluid is less, consequently the leach area would be relatively small. Fluctuations of activity in some cases show the presence of fractures/cracks at certain places in the strata. The estimated porosity and hydraulic conductivity of the aquifer are 28% and 1.23×10^{-5} m/s respectively.

Keywords: Mining, In-situ, Radioactive tracer, Leaching, Hydraulic parameters

1. Introduction

In-situ leach mining is relatively a new technique. It is applied when the most commonly used mining methods i.e. open pit mining and underground mining are not feasible. The Eagle Hill uranium ore deposit located at the southeastern part of the Bannu Basin in Lakki Marwat District is being mined by in-situ leaching because the ore deposit is deep (145-160 m) and the host rock is incompetent sandstone. Different leaching patterns like quadrilateral or hexagonal grids with the injection wells at the corners and production well in the center have been used. A mixture of leaching chemicals is introduced in the injection wells and pumped out in the form of leach liquor containing the metal ions from the production well. Leaching efficiency and recovery of the metal depend on the type of pattern and transit time of leaching chemicals from the injection wells to the production well. Transit time is further dependent on the distance between the injection wells and the production well and difference of hydraulic pressures in both types of wells.

For efficient leaching, transit time of the

leaching chemicals from injection wells to production well should be same. Due to the large angle of dip i.e. about 40° of the ore body, it was thought that under same difference of hydraulic heads, real velocity would be more along the dip as compared to that against the dip. In such situation, the distances of the injection wells from the production well in a particular pattern have to be adjusted/optimized so that the residence time is similar in both the cases.

To optimize the recovery of the metal and efficiency of method the project authorities were interested to know about the transit time of leaching chemicals from injection wells to production well moving along the dip, against the dip, along the strike and the diagonals. Radioactive tracer experiments were carried out to study transit time of fluid in different arrangements under particular hydraulic heads and aquifer parameters: hydraulic conductivity and effective porosity. As there was no actual leach mining activity at the experimental site, wells were drilled and a series of experiments were carried out by injecting radiotracer bearing water in the injection wells and pumping it from the production well. The present

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manuscript describes experimental details and results of six tests conducted to achieve the objectives.

2. Geology

The deposit is located at the southeastern part of the Bannu Basin. From the plate tectonic point of view, the position of geotectonic location belongs to the component part of folded thrust zone in northwest of the Indo-Pakistan Plate. Under the setting of tectonic movement, gradually the Himalayan Orogenic Zone and Chaman Shear Zone were formed. In the Early Middle Miocene, about 18 million years ago, the third episode of Himalayan tectonic movement occurred. A winding arc shaped long and narrow foredeep was formed along the northwest margin of Indo-Pakistan Plate. Then the Paleo-Indus River System began its development. As a result, a great amount of erosional weathering products from the emerging Himalayan Orogenic Zone were transported and deposited in the foredeep basin. This depositional episode formed the famous Siwalik continental detrital mollasse i.e. the Siwalik Group. The Siwalik continental detritus rocks host the major uranium bearing strata. The rocks are foredeep furrow deposits which are highly folded and thrust. The rocks of Siwalik group were exposed to erosion as a result of upward tectonic movement and epigenetic reformation by surface and ground water and the interlayered infiltration type sandstone Uranium deposit began to develop in the Bannu Basin. During the recent time, the geotectonic movement was featured by the repeatedly pulsative regional uplift movement. This uplift formed geomorphological expressions of multistage erosional surface along with changes of ground water level which registered several drops. This continuous change in groundwater table resulted in the leaching and reprecipitation of the uranium deposits several times before it finally occupied the present position [1].

Siwalik Group comprises of a set of continental detritus/sedimentary rocks which indicate rapid transportation and rapid deposition. The middle to upper part of this group i.e. Dhok Pathan Formation, was the strata of interest in this study. This sandstone is light grey to grey colored which contains fine-grained interlayering. It also contains certain amount of volcanic ash and organic matter and some rock fragments. It shows greater

variation in thickness i.e. 36.8 to 72.0 m with an average of 56.38 m [1].

The lithological data and observation on the samples from the area show that Dhok Pathan Formation consists of a set of light grey coloured continental detrital sedimentary formation. Because of the rapid transportation and accumulation, the rocks show lower maturity and loose cementation, while microcline, perthite, epidote, biotite and pyrite is also present in the core samples obtained from the site area [2]. Generally the fine-grained sandstone contains higher content of arkoses while the coarse sandstone contains more heavy minerals and rock fragments [3].

3. Experimental Procedure

3.1 Layout of the experimental wells

Schematic of the experimental wells is shown in Fig. 1. Six wells (EH-1 to EH-6) of 15 cm diameter were drilled to carry out tracer tests along the dip, against the dip, along the strike and along the diagonals with different distances. For each experiment, three wells in a line were used. After injecting radiotracer in one of the end wells, pumping was done from the central well (production well) and water was injected continuously in both the end wells (50% in each well) with the flow rate equivalent to the production rate (7 to 10 m³/hr). The following three sets were used for the experiments.

- a. EH-5 to EH-3 (along the dip) and EH-1 to EH-3 (against the dip). The distance of both the injection wells from the production well was 10 m but due to some deviation during drilling, the wells were shifted at the bottom and the distances of EH-5 and EH-1 from EH-3 (the production well) became 9.5 m and 9.9 m respectively.
- b. EH-2 to EH-3 and EH-6 to EH-3 (along the diagonals but with different distances i.e. 14 m and 18 m). Due to shift, the distances of EH-6 and EH-2 from EH-3 (the production well) became 16.25 m and 13.75 m respectively.
- c. EH-4 to EH-5 and EH-6 to EH-5 (both along the strike but with different distances i.e. 10 m and 15 m respectively). Due to deviation, the distances of EH-4 and EH-6 from EH-5 (the production well) became 9.25 m and 16.25 m respectively.

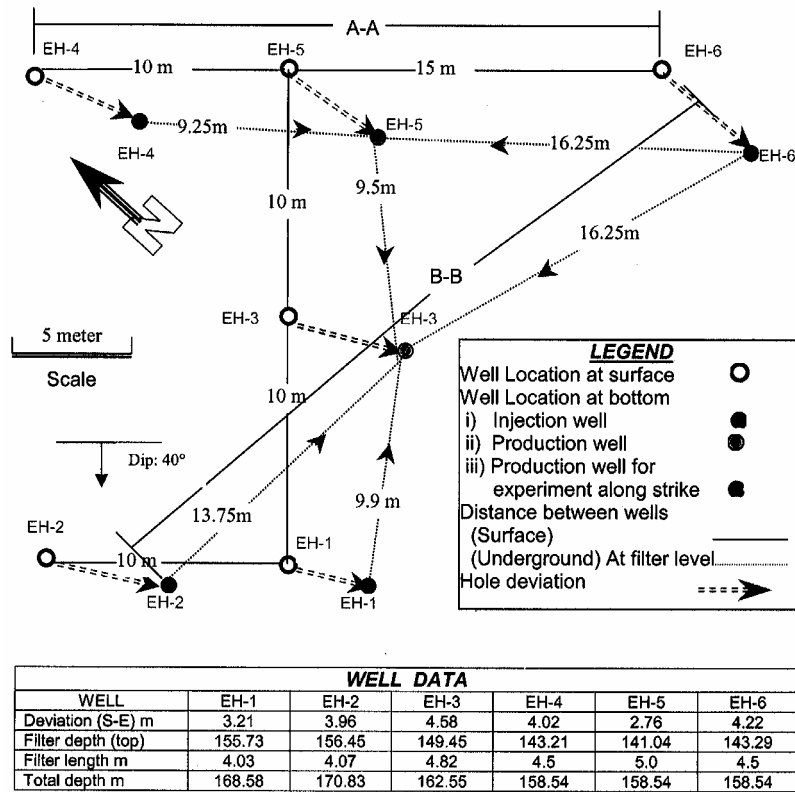


Figure 1. Schematic diagram of experimental wells

3.2. Selection of radioactive tracer and activity

Conventional tracers like fluorescent dye tracers do not work in the porous medium because they get absorbed. Therefore, a radioisotope is a best tracer for groundwater in porous medium but it has to fulfil certain criteria e.g. the half-life is compatible with the expected duration of the experiment; it is not lost in the medium due to physico-chemical processes (adsorption, precipitation, decomposition etc.); detectability under field conditions is reasonably high; it is easy and economical to produce and handle; the specific activity is high; and radiation hazards are minimum. Suitably selected gamma ray emitting anionic radioisotopes usually meet these conditions [4, 5]. For selection of proper radiotracer, ⁵¹Cr, ¹³¹I and ⁸⁶Rb were tested in a column using the sand collected from the strata under study. Some tracer experiments were performed in the laboratory with inactive K₂CrO₄ and radioactive ¹³¹I. It was found that chromate ions get absorbed by the sand when the pH is basic and it passes when the medium is acidic. In the present case, the tracer carrier was natural water and the pH was about 8.4. Hence, ⁵¹Cr was found unfit for the experiments. Being cation, ⁸⁶Rb

was also deemed unsuitable radiotracer for the basic medium. ¹³¹I gave good results and was not affected by pH of the medium. Due to the limitation of availability of only one radioactive tracer, multi-tracer tests were not possible and all the tests were conducted one by one using ¹³¹I. It emits eight gammas ranging from 0.005 to 0.724 MeV with the most abundant type of 0.365 MeV having 6.3 cm water half thickness (thickness of water which attenuates half of the gamma flux). Its half-life is 8.07 days [5], which was useful for expected duration of the experiments. The radiotracer was prepared at Pakistan Research Reactor-I (PARR-I), PINSTECH, Islamabad.

Sensitivity of the best available detection system at Radiation and Isotope Application Division (with 3"x3" NaI crystal) for ¹³¹I in water was previously assessed and the following relationship of detector response in counts per second (cps) with tracer concentration in nano Curie per liter (nCi/l) was determined [6].

$$\text{Count Rate} = 920 \times \text{Conc.} + 36 \quad (1)$$

In order to have count rate in thousands cps (say 10,000 cps) and maximum possible diluting

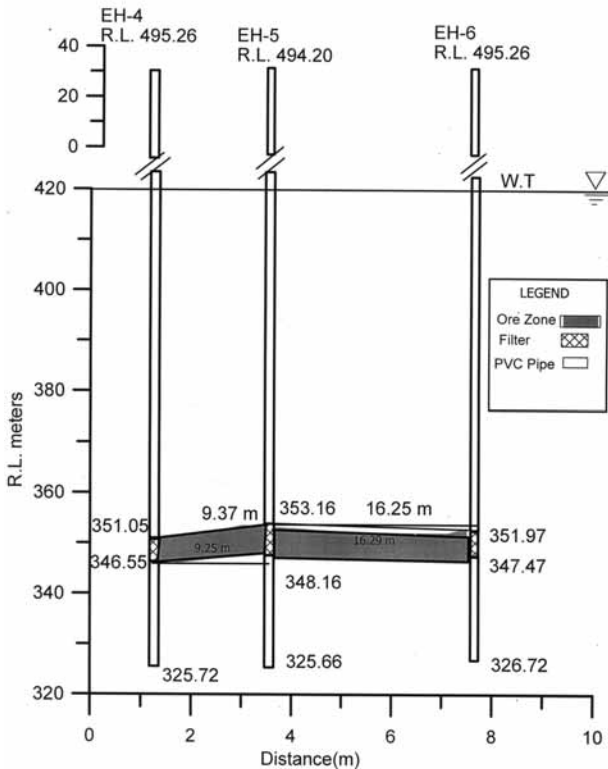


Figure 1a Section A-A of Fig. 1 showing position of filter and ore zone.

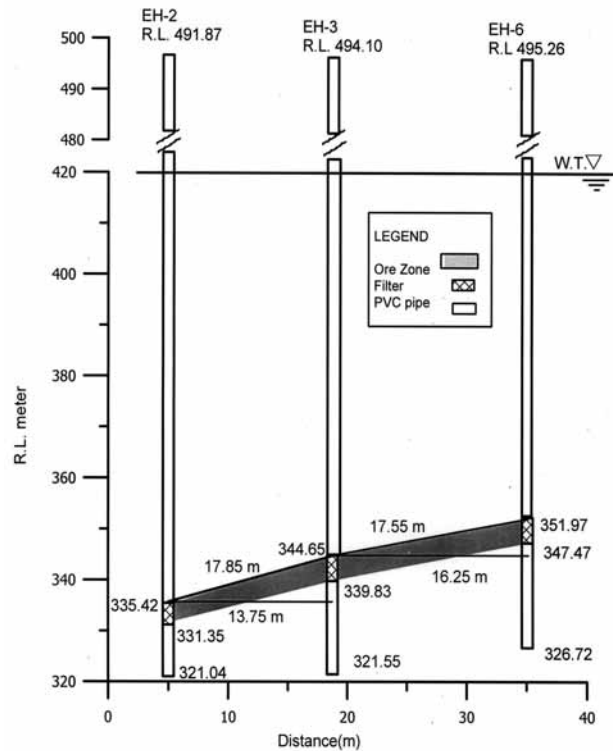


Figure 1b. Section B-B of Fig. 1. Showing filter position and ore zone.

volume of water (cylindrical volume around the production well having radius equal to the maximum distance upto the injection well, and height about double the length of filter tube), the total activity was calculated as 30 mCi. To be on the safe side and compensate any absorption, it was decided to inject few hundreds mCi activity of ¹³¹I for each test.

3.3. Injection and detection of radioactive tracer

The locally fabricated injection system to release tracer in a well was simply a G.I pipe of 6.5 cm diameter and 2m length with a perforated disc fitted at the bottom. A special plastic pipe of 2 cm in diameter was connected to the bottom of G.I pipe. The whole system was lowered in the well after adjusting the length of plastic pipe to keep its lower end in front of the screen of the well and the upper part of the G.I pipe outside the well. The glass ampoule containing radiotracer was placed at the perforated disc of the G.I pipe through a funnel and broken by hammering. The tracer was flushed by water and brought down in front of the screen of the well. Hydraulic gradient towards gradient well was created by continuous injection of water in the injection well and pumping from the

production well. As a result the radiotracer moved from injection well towards the production well.

The flow of water from production well was diverted through a flow cell housing a detector. The detection system comprised 3"x3" NaI(Tl) detector with essential electronics: preamplifier, amplifier, single channel analyzer (SCA), ratemeter, counter, timer, and chart recorder. In order to calibrate the detection system in the working medium, the flow cell was filled with water of production well with inlet/outlet closed and an activity of few μ Ci was introduced in the flow cell. The counting window was selected and set properly to count the pulses of 0.321 MeV gamma rays of ¹³¹I. The detection of the tracer was carried out on hourly basis or more frequently.

3.4. Radiation protection

In order to protect the staff and the general population from radiation dose, radioactivity level was monitored starting from the Hot Cell of the Reactor (PARR-I) throughout transportation and injection. About 0.5 Ci activity of radiotracer was transported in a cylindrical lead container of 4 cm wall thickness and the dose rate at its surface was well below the maximum permissible level (MPL) of

Table 1. Results of the tracer tests

Test No.	Wells Involved	Distance (m)	Breakthrough Time (hr)	Breakthrough Velocity (m/hr)	Mean Residence Time (hours)	Average Velocity (m/hr)	Remarks
Test-1	EH-5 to EH-3	9.5	41	0.23	95	0.10	Along dip
Test-2	EH-1 to EH-3	9.9	46	0.22	107	0.09	Against dip
Test-3	EH-2 to EH-3	13.75	54	0.26	111	0.12	Diagonal along dip
Test-4	EH-6 to EH-3	16.25	155	0.10	270	0.06	Diagonal against dip
Test-5	EH-4 to EH-5	9.25	29	0.32	107	0.09	Along strike NW→SE
Test-6	EH-6 to EH-5	16.25	147	0.11	---	---	Along strike SE→NW

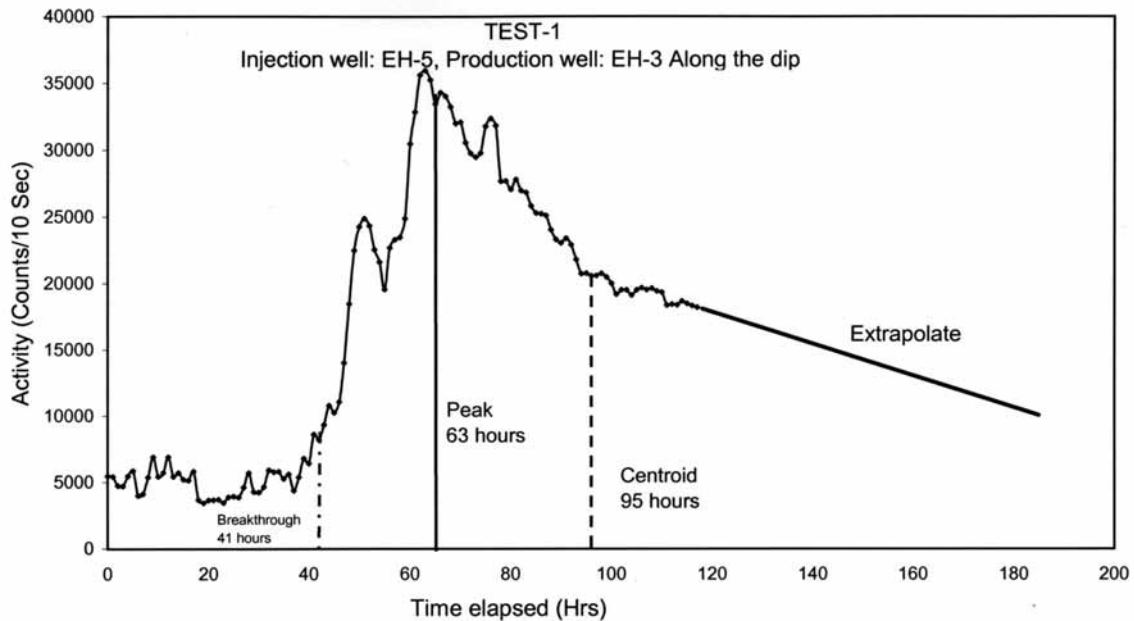


Figure 2. Breakthrough curve of radioactive tracer test from well EH-5 to EH-3.

2 mSv/h [7]. Radiation dose was recorded for the field workers by thermoluminescent dosimeters (TLD). Pocket dosimeters were also worn by the individuals to keep eye on the radiation dose being received in the field. TLD results show that the maximum dose to any individual was a small fraction of the maximum permissible dose i.e. 0.4 mSv per week [7].

4. Results and Discussion

4.1 Transit time

Data were obtained from the detection system in the form of counts taken for 10 seconds after

every hour. Breakthrough curves were obtained by plotting response of the detection system in the form of activity versus time elapsed after injection of radiotracer and are depicted in Figures 2 to 7. The summary of the results is given in Table 1.

The distances between injection well and production well for Test No. 1 (EH-5 to EH-3), along the dip and Test No. 2 (EH-1 to EH-3), against the dip are almost similar i.e. 9.5 m and 9.9 m respectively. These two tests were meant to study the effect of dip angle on the movement of fluid from the injection wells to the production well. The response curves for both the tests (Figs. 2 and

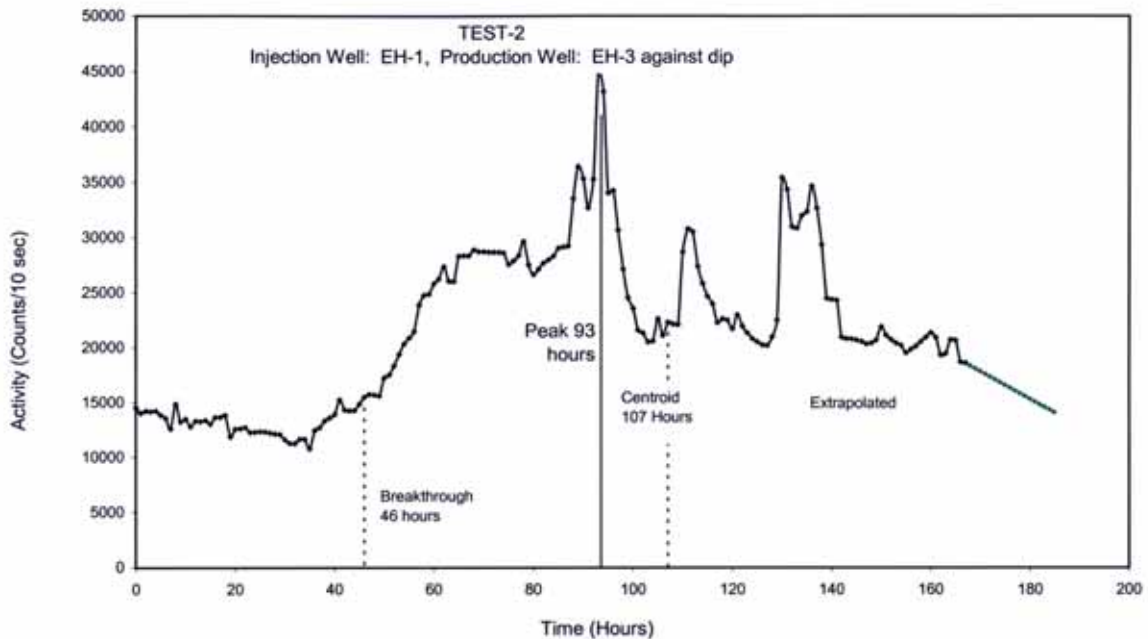


Figure 3. Breakthrough curve of tracer test from Well No. EH-1 to Well No. EH-3.

3) show that the breakthrough times along the dip and against the dip are 41 hours and 46 hours respectively. Real velocity of moving front of plume comes out to be 0.23 and 0.22 m/hr for both the cases. The shapes of the curves are different in these cases and peaks appeared at different times. The highest peak is after 63 hours in Test No. 1, while it is after 93 hours in Test No. 2. In the first case, the residence time distribution curve is relatively more regular as compared to that in the second case. This might happen due to the heterogeneity of the strata. Moreover, the power failed during the second test for few hours. In both the cases, the average velocities (0.1 m/hr and 0.09 m/hr) calculated using the mean residence times (i.e. 95 hours and 110 hours) corresponding to the centroids of the areas under the curves are also similar. It confirms that the average velocities of the fluid moving against the dip and along the dip are similar under similar conditions.

The next experiments i.e. Test No. 3 (EH-2 to EH-3) and Test No. 4 (EH-6 to EH-3) were along the diagonals with different distances of 13.75 m and 16.25 m respectively. Response curve of Test No. 3 (Fig. 4) indicates the breakthrough time of 54 hours, while the maximum activity reached after 79 hours. Velocity of the moving front of tracer was found to be 0.26 m/h, while the average velocity was calculated as 0.12 m/h using mean residence

time of 111 hours. In spite of the longer distance, the velocity in this test is slightly more as compared to that from first two tests, which might be due to higher hydraulic gradient resulting from higher injection rate. During Test No. 3 & 4, Well No. 2 and Well No. 6 were used for water injection and Well No. 3 as production well. In the fourth test, the tracer could not breakthrough in about four days, it was realized that Well No. 6 did not intake significant quantity of the injected water. Actually, Well No. 6 was accepting a small fraction of the total injection rate due to some blockage in its filter. This disparity was not noticed in the third test. Hence, Well No. 6 was cleaned on 12 July 2000 from 1120 hours to 1800 hours. Even after cleaning, the situation was not improved significantly. Anyhow monitoring was again started and some activity was found reaching the production well which was slightly decreasing with time. It was the activity which might have reached near the well before cleaning. The breakthrough time was 155 hours and the maximum activity reached after 270 hours giving a broad spectrum (Fig. 5). The average velocity was determined as 0.06 m/hr according to the mean residence time of 270 hours. The results of this set are not reliable as the hydraulic regime was changing during the experiment.

Test No. 5 (EH-4 to EH-5) and Test No. 6 (EH-6 to EH-5) were carried out along the strike with

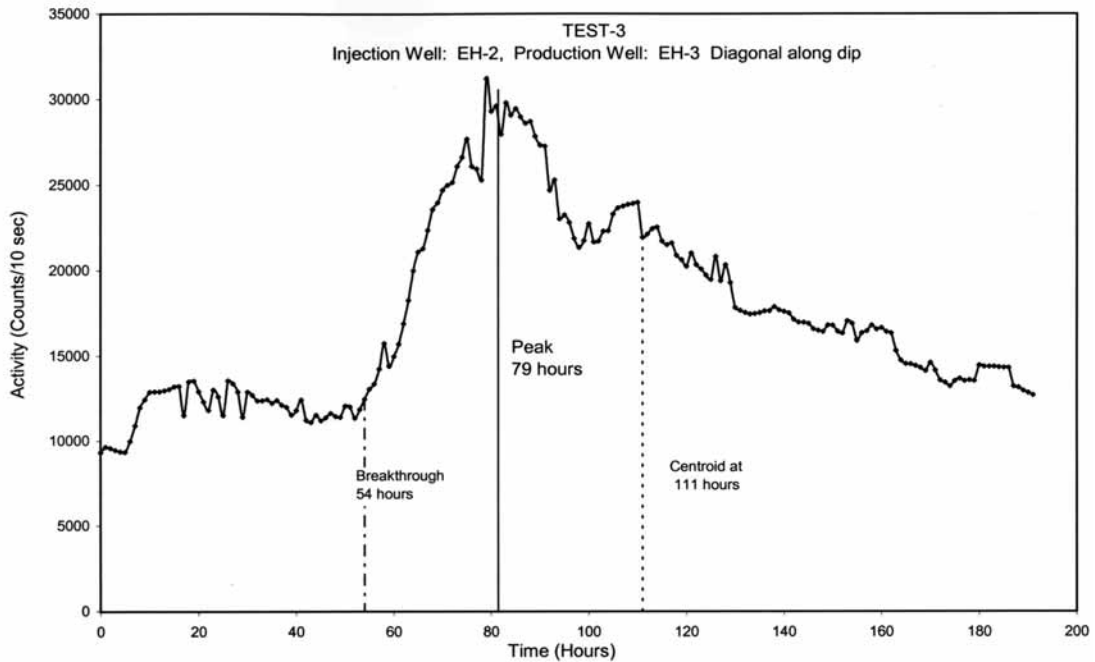


Figure 4. Breakthrough curve of tracer test from Well No. EH-2 to Well No. EH-3.

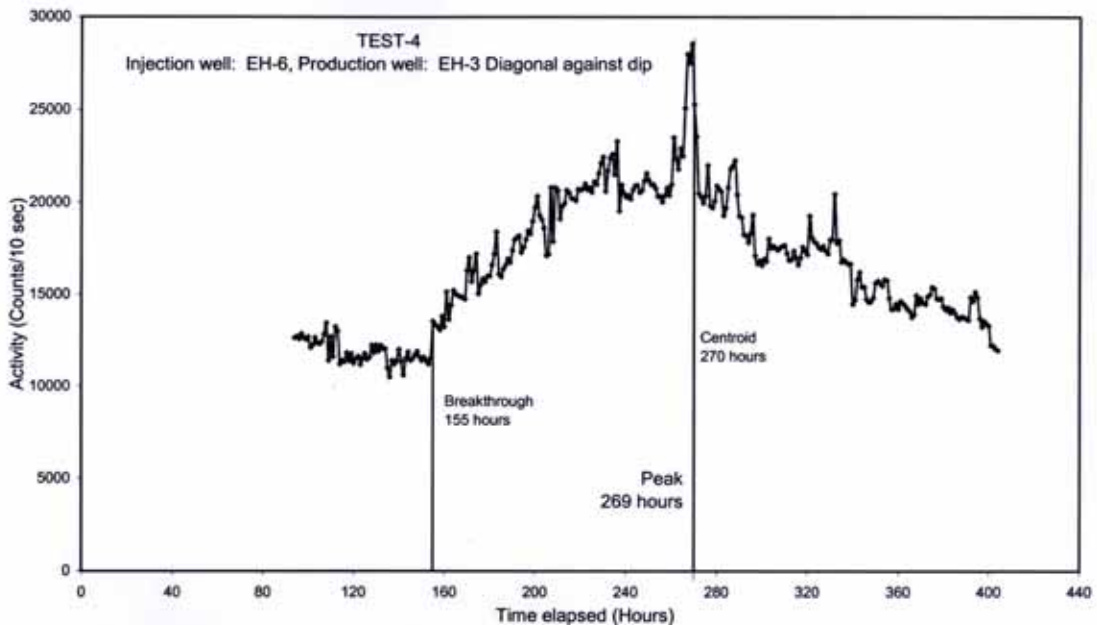


Figure 5. Breakthrough curve of tracer test from Well No. EH-6 to Well No. EH-3.

varying distances i.e. 9.25 m and 16.25 m respectively. Responses for both the tests are given in Figs. 6 and 7. The breakthrough was very quick (29 hours) in Test No. 5 as compared to that in Test No. 6 (146 hours). Therefore, the velocity was much higher (0.32 m/hr) for shorter distance than that for longer distance (0.11 m/hr). Short breakthrough time in this case is not only due to

less distance but also due to much higher injection rate in EH-4 as compared to that in EH-6. Even after cleaning, EH-6 was not accepting the given (half) injection rate. As a result, the hydraulic gradient for EH-4 to EH-5 must be much higher than EH-6 to EH-5 and also that in first two tests (i.e. EH-5 to EH-3 and EH-1 to EH-3). The breakthrough time and velocity for the tests: EH-6

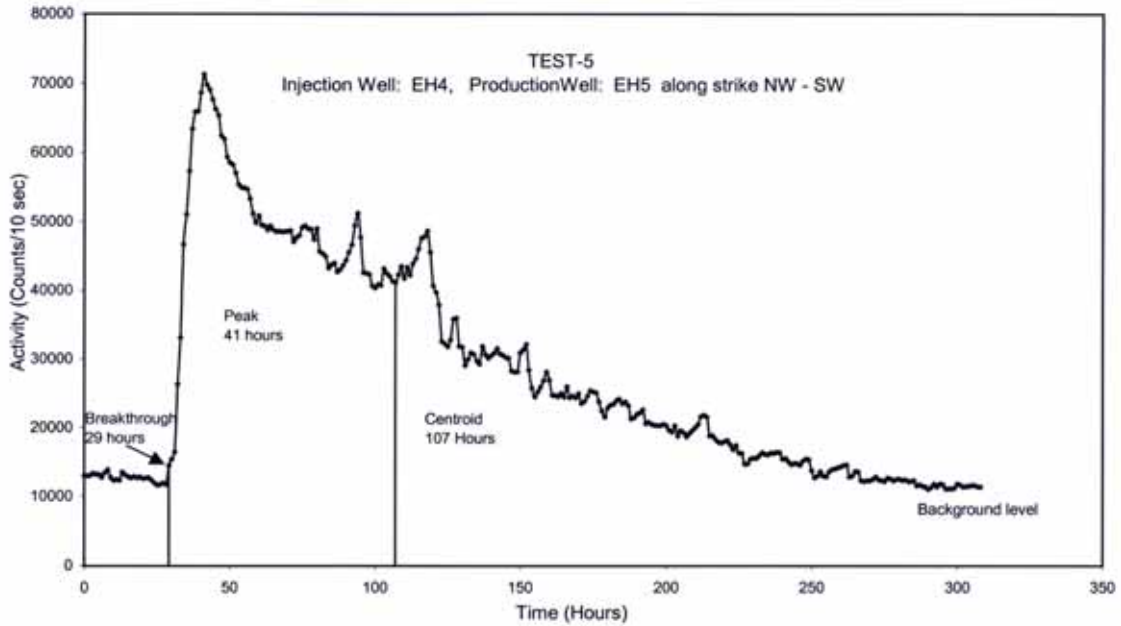


Figure 6. Breakthrough curve of tracer test from Well No. EH-4 to Well No. EH-5.

to EH-5 and EH-6 to EH-3 are almost similar as the distances and injection rates were similar. The residence time distribution curve for Test No. 5 shows that after quick breakthrough, the maximum activity reached shortly (41 hours lapse time), while the recession took longer time with some fluctuations (Fig. 6). From this behaviour, one can conclude that by increasing the injection rate/hydraulic gradient, most of the injected fluid reaches the production well in relatively short period. As mentioned above, the Well No. 6 was not accepting half of the injection rate which resulted in less hydraulic gradient. Therefore, the breakthrough time for Test No. 6 was quite long (147 hours). After breakthrough, the flat plateau indicates that almost uniform concentration of activity was reaching the production well which might be due to big dispersed plume having uniform activity. It indicates that at lower injection rate/hydraulic gradient, dispersion is higher and swept area is more.

4.2 Porosity

Porosity, p of a porous medium is defined as:

$$p = (V_v / V_o) \cdot 100 \quad (\%) \quad (2)$$

Where V_o is the given volume of the porous medium and V_v is that of the voids.

In the present case, the first test (EH-5 to EH-3) has been used to estimate the effective porosity because both the injection wells were almost at the same distance from the production well and also had the same injection rate. It is assumed that the main flow was from two quarters (EH-5 and EH-1) of cylindrical volume due to hydraulic gradient resulting from injection and production of water. From the other two quarters, the flow was only due to hydraulic gradient induced by production well. During the breakthrough time, the swept volume would be roughly the sum of the volume of two quarters having water injection (i.e. 50% of the cylinder volume) and half of the volume of rest two quarters (25% of the cylinder volume). In this way, V_o would be about 75% of the cylindrical volume ($\pi (R)^2 \cdot H$) [5].

$$V_o = 0.75 \pi (R)^2 \cdot H \quad (3)$$

Where R is radius of the cylinder, which is the distance of EH-3 from EH-5 (i.e. $9.5/\cos 41.83^\circ = 12.75\text{m}$ and EH-1 (i.e. $9.9/\cos 39^\circ = 12.74\text{m}$) along the slope. In this case, its value (average) is 12.745m & H is the height of the cylinder obtained by converting the length of the filters (thickness of the ore body: about $5\text{m} \times \cos 40 = 3.83\text{m}$).

$$V_o = 0.75 \pi (12.745)^2 \times 3.83 = 1466.5\text{m}^3$$

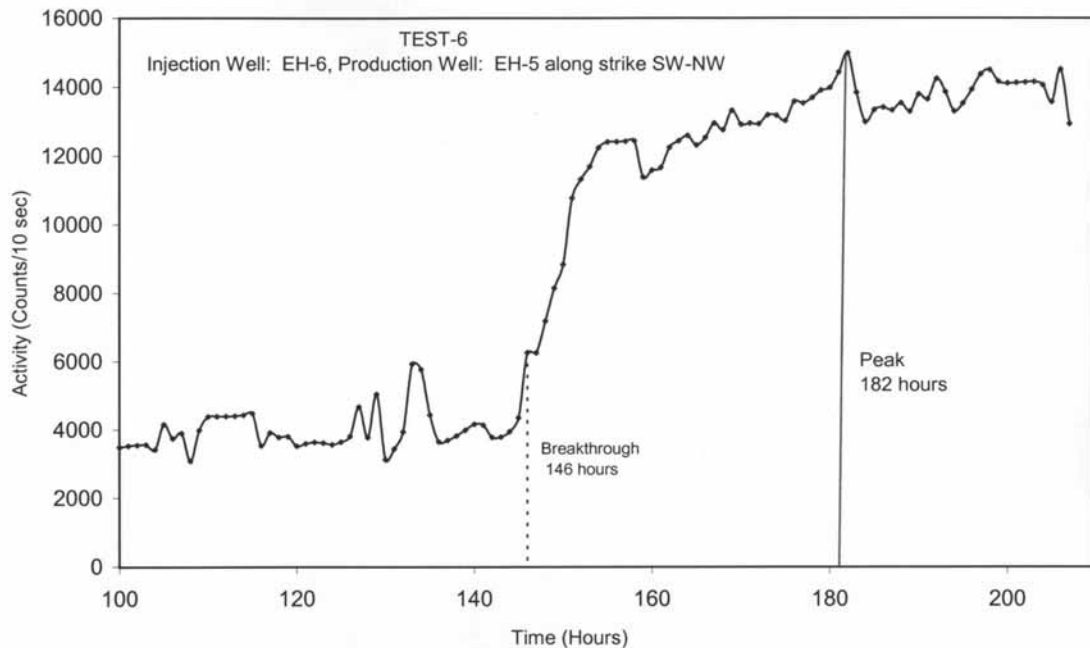


Figure 7. Breakthrough curve of tracer test from Well No. EH-6 to Well No. EH-5.

V_v may be taken as the volume of the water pumped during the breakthrough time.

$$V_v = Q \cdot T \quad (4)$$

Where Q is the production rate and T is the breakthrough time of the tracer.

$$V_v = 10 \times 41 = 410 \text{ m}^3$$

Substituting the values of V_v and V_o in Eq. 2, the porosity is calculated as:

$$\rho = (410 / 1467.6) \cdot 100 = 28 \%$$

The calculated porosity falls in the range for sandstone (i.e. 5-29%) given in ref. [8].

4.3. Hydraulic conductivity

The hydraulic conductivity, K , depends on the properties of the fluid and the characteristics of the medium and is given by the Darcy's Law [8]:

$$K = v_f / I \quad (5)$$

Where v_f is Darcy velocity or filtration velocity and I is hydraulic gradient.

$$v_f = v_r \cdot \rho \quad (6)$$

Where v_r is real velocity or mean pore velocity. Data of the first and second tests can be used for determination of hydraulic conductivity as there was no disturbance in these tests. But hydraulic heads could not be measured in the first test, so only the choice of second test (EH-1 to EH-3) was left. Substituting $v_r = 0.22$ m/h or 5.28 m/day (breakthrough velocity in the second test) and $\rho = 0.28$ (as determined above) in Eq. 6, we get :

$$v_f = 5.28 \times 0.28 = 1.48 \text{ m/day}$$

Hydraulic gradient (I) is calculated from the hydraulic heads of the injection well (h_{EH-1}) and the production well (h_{EH-3}) and the horizontal distance (d) between these wells.

$$I = (h_{EH-1} - h_{EH-3}) / d \quad (7)$$

$$I = (422.829 - 409.002) / 9.9 = 1.4$$

Putting the values of ' v_f ' and ' I ' (calculated as above) in Eq. 5.

$$K = 1.48 / 1.4 = 1.06 \text{ m/day} = 1.23 \times 10^{-5} \text{ m/s}$$

The value of hydraulic conductivity for sandstone given in ref. [8] is in the range of 10^{-10} to 2×10^{-6} m/s approximately. Higher value of hydraulic conductivity might be due to presence of fractures and cracks in the sandstone.

5. Conclusions

Breakthrough times and velocities determined in different radiotracer tests are mentioned in Table 1. However, the following main conclusions are drawn.

- a. Breakthrough time and velocity along the dip and against the dip are almost the same under the similar hydraulic conditions.
- b. At higher injection/production rate or higher hydraulic gradient, the breakthrough time is shorter and the dispersion of fluid is less. Consequently, the leach area would be relatively less.
- c. Fluctuations of activity in some cases show the presence of fractures/cracks in the strata.
- d. The estimated porosity and hydraulic conductivity of the aquifer are 28% and 1.06 m/day.

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