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# DOWNHOLE HEAT EXCHANGE

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## ABSTRACT

In an earlier paper in this conference series Pan et al. (1981) outlined a laboratory and full scale experimental investigation of the downhole heat exchanger. In this paper, further experimental work is presented against which a computer programme is tested. It is concluded that the biggest unknown in modelling the downhole heat exchanger (DHE) is the mechanism of establishing the convection cell within the well when the DHE is running. At present a mixing ratio is used which has to be linked to reservoir parameters such as permeability. That link has not been defined in detail; however, data is presented demonstrating its effect on DHE output. Conclusions are drawn from the computer analysis and results which lead to a better understanding of the heat transfer and flaw mechanism involved.

## 1 INTRODUCTION

The principle of heat recovery from a downhole heat exchanger has been discusred elsewhere (Culver and Reistad, 1978; Anderson and Lund, 1979; Bloomquist et al., 1980). However, a detailed understanding of the fluid mechanics and heat transfer processes involved has still to be published. The fundamental work of Culver and Reistad (1978) has done much to aid this understanding. In particular, the effects of geometric parametere and reservoir temperature on the DHE output has been demonstrated by using a computer programme and carrying out a parametric study about a typical well installation. The concept of mixing ratio was introduced in an attempt to include the interaction of reservoir and well fluids. This was only partially successful, and the need for modelling more correctly the reservoir crossflow and well natural convection cell was realiaed.

The work of Culver and Reistad (1978) established that a DHE fitted in a cased well gave a greater output than when fitted in an uncased well. This was found to be due to a strong convection cell circulating in the annulus between the casing and well bore and the central casing. Work by Allis and James (1979) demonstrated that a cell could be generated by a 'promoter' tube installed inside the well and slotted at the top and bottom, the direction of circulation being a function of the ratio of tube to well diameter.

Further work by Allis (1981) showed that in order to obtain 10 kW continuously for 24 hours (peak 20-30 kW) to supply a household from a 20 cm diameter well 50 m deep in a reservoir where the hydraulic gradient was 1%, a permeability of about 50 darcies is necessary. Above 50 darcies a promoter can be utilised; below, a small pump will be necessary. This was based on studies of the Moana, Reno, USA, reservoir which has low permeability. Unfortunately, reliable data on permeability for these shallow reservoirs where DHEs are in use is not readily available, with the possible exception of the Klamath Falls, Oregon, reservoir. The Moana data shows variations in hydraulic conductivity of $10^{-4}$ to $10^{-7}$ m/s, a factor of 1000. This would indicate that if all other factors of the well and DHE system were the same, the outputs should vary by a factor of 1000. This is not found to be the case.

The link between the reservoir and the fluid circulating in the well (mixing ratio) has not been established, and it is the purpose of the current work to attempt to define this link. This paper presents further information following on from that reported in Pan et al. (1982). Full details of this work to date is reported in Pan (1983).

## 2. EXPERIMENTAL WORK: RESULTS AND DISCUSSION

### Laboratory

The laboratory experimental rig is fully described in Pan (1983). It consists of (a) the well - a 5.4 m length of steel pipe 73 am inside diameter; (b) the heat source - a 1100 watt electric heater fitted around the pipe, which could be fixed in any position along the pipe axis, and (c) the DHEs: (1) 12 am I.D. copper tube formed into a full length U tube; (2) an outer copper tube of 24 mm I.D., and an inner copper tube of 12 mm I.D. forming an annular or tube-in-tube DEE.

The well was insulated along its length with 35 mm thick polystyrene foam, and copper constantan thermocouples were used for temperature measurement. The heat exchangers were fed from the laboratory domestic water system; mass flows were measured with a measuring cylinder and atop watch. To simulate well fluid circulation, an external pump circuit was used. Later, a PVC promoter tube 33.5 mm O.D., perforated at the bottom and below water level at the top, was installed.

The early results reported in Pan et al. (1982) demonstrated that the U and Annular type DHEs gave similar extraction rates with, in the case of the annular DHE, flow down the annulus and up the iner pipe giving the greater output. In addition, with external circulation, flow from the bottom to the top achieved a higher output (about 8%) than with flow from top to bottom, with the temperature profiles being typical of those found in wells with perforated casings with good cross flow in the permeable zone providing a natural circulation of well fluid. The circulation flows were chosen to give velocities, in the well, of the order of 7-10 cm/s, values measured by Culver and Reistad (1978). It is realised that this simulation is not modelling the natural circulation that occurs at full scale, but it does generate a similar temperature profile to that found in a typical naturally-circulating well.

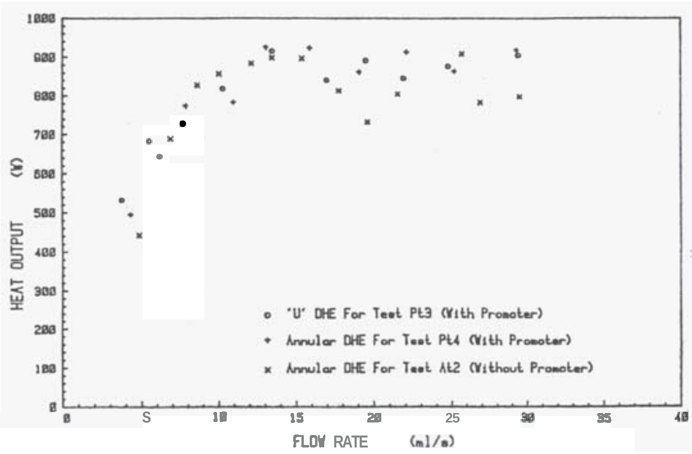


Fig. 1

Fig. 1 shows the effect of the promoter on the DHE output. As for the earlier results, the U and Annular DHEs gave similar outputs. For the annular DHE, up to a flow of about 15 ml/s, the promoter has little effect on DHE output, but for greater flows the output is increased. Also, the heat output characteristic with promoter fitted does not show the oscillation experienced with the earlier rerults. Bo detailed satisfactory explanation for this phenomenon is offered; however, it is thought to be associated with a transition-type fluid mechanics and heat transfer mechanism which requires further investigation.

The temperature profiles in the well and promoter with an annular DHE operating are shown in Fig. 2.' They indicate a convection loop with an isothermal temperature in the promoter. An unsuccessful attempt was made to measure the circulating well fluid velocity; however, the measured temperature profiles are similar to those observed during the circulation pump teste in which a mean velocity of about 13 cm/s was set up.

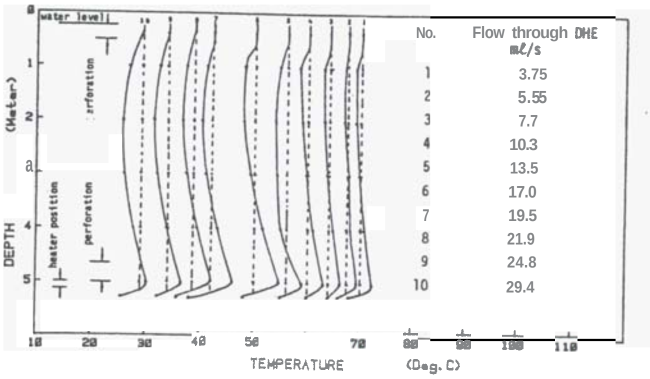


Fig. 2: Temperature profiles in the well and promoter with an annular DHE operating,

Some fluid temperature measurements were taken through the DHE and are shown in Fig. 3, in which the effects of flow rate are illustrated. For the U type (Fig. 3), the fluid temperature increased to a peak at 7 m, that is, 2 m up the return leg for flow rates below 20 ml/s, when it decreased in the DHE up to the outlet. At flow rates above 20 ml/s the temperature tends to rise continuously through the total length of DHE. The annular results indicated a peak temperature occurring at the bottom of the well, with a drop in temperature as the fluid rises through the inner tube.

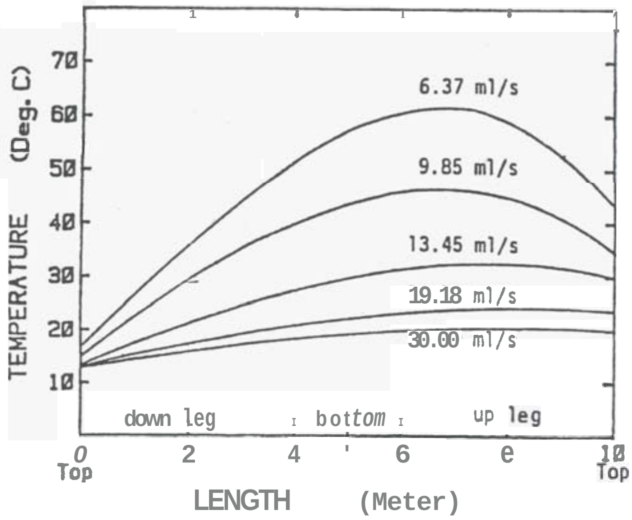


Fig. 3: Temperature variation through the 'U'-type DEE.

These temperature profiles are significant in that they indicate a change in the direction of heat transfer between the DHE and the well fluid. As an example, figure 4 shows, for a U type DHE, the variation of temperature difference ($\Delta T$) between well and DHE fluid. When T > 0, heat transfer is from the well to the DHE and $\Delta T < 0$ the reverse direction.

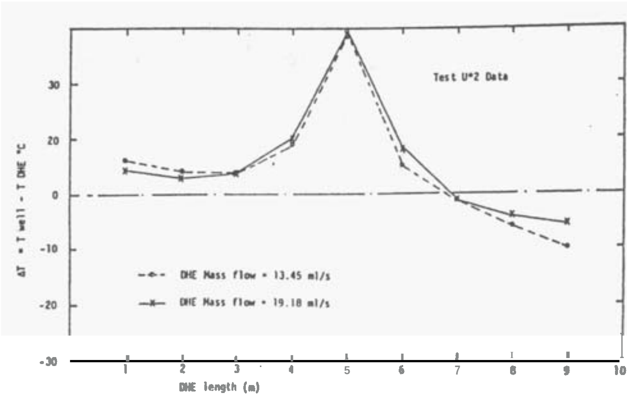


Fig. 4: Temperature difference between well and inside DHE vs DHE length.

For these model tests no attempt was made to optimise dimensions or to experiment with different materials. These parameters were investigated using the computer programme discussed in Section 3.

## Full Scale

Some further tests have been conducted on the Tauhara College wells since those reported in Pan et al. (1982). The details of the wells and the DHE installations are given in Table 1.

| | WELL 1 Pilot hole) | WELL 2 (THM5) | WELL 3 (THM8) |
|---|---|---|---|
| **A. WELL DATA** | | | |
| Well depth (m) | 206 | 200 | 206 |
| Hole dia (mm) | 76.2 (3in) | 194 (7 5/8in) | 216 (8½in) |
| Anchor Casing dia (a) | 100 | 219 (8 5/8in) | 244 (9 5/8in) |
| Anchor Casing depth m) | 0-45 | 0-40 | 0-31 |
| Plain Casing dia | 80 | 140 (5½in) | 194 (7 5/8in) |
| Plain using depth (m) | 45-80 | 52.3-170; 179.6-199.7 | 31.5 - 81.2 |
| Slotted Liner dia (mm) | | 140 (5½in) | 194 (7 5/8in) |
| Slotted Liner depth (m) | | 40-52.3; 170-179.6 | 81.2-206 |
| **B. DHE DATA** | | | |
| WE diameter ID (mm) | 25.4 (lin) | 43.31 (1½in) | 43.31 (1½in) |
| Depth of DHE | 200 | 200 | 206 |
| **C. PROMOTER PIPE** | | | |
| Diameter (mm) | N/A | Note slotted casing above. | 88 O.D.-80 1.0. |
| Depth (m) | | | 200 |
| Perforated depth (m) | | | 40-50; 180-200 |
| **0. MEASUREMENT TUBE** | | | |
| Muter (mm) | N/A | N/A | 25.4 |
| Depth (m) | | | 20[illegible] |

TABLE 1: WELL AND DHE DATA - TAUHARA COLLEGE

All these wells have been completed differently, with well 2 having a full-length casing perforated at two levels similar to the installations at Klamath Falls, Oregon, USA (Culver and Reistad, 1978a), while well 3 has a slotted casing and a promoter tube. A perforated measurement tube is also fitted which allows downhole instrument traverses without fear of fouling and losing the instrument.

Downhole temperature measurements were conducted with a calibrated thermistor probe, with DHE flows measured by Annubar and DHE temperatures with mercury in glass thermometers placed in oil filled thermometer pockets.

Figure 5 shows temperature profiles for Well 2. The initial profile was taken in August 1979 soon after completion and before the DHE was installed. Between the perforations (39-48 m and 165-175 m) the temperature is near isothermal (120°C) indicating a strong circulation, up the annulus and down the casing; approximately an 80°C temperature difference exists between the bottom and top of the water column. With the DHE operating normally, the temperature in the casing falls to about 50°C. The prafile is isothermal throughout, the large temperature difference measured during the initial run is not seen, that is, there is no driving force. It is concluded that the fluid in the well is not circulating and the temperature on both sides of the casing is the same. The other two profiles on this figure demonstrate the recovery rate for the well when the flow through the DHE is stopped. A probe left downhole for 48 hours showed a temperature recovery rate of 0.65 deg. C/hr.

The function and operation of the promoter pipe is discussed in Allis and James (1979). Well 2 has a large diameter promoter pipe with the DHE inside, i.e. undersized casing; Well 3 has a relatively small promoter pipe in which the DHE fits alongside. Allis (1981) suggests that the maximum velocity in the convection cell should occur with either the DHE inside a casing which is approximately 0.7 times the well diameter or with the DHE alongside a promoter pipe of 0.5 times the well diameter. For the Well 3 installation the promoter pipe is 0.45 times the well diameter.

Figure 6 shows the temperature in the well during normal operation. The measured temperature profiles in the well and promoter tube were almost the same. This is an indication that there is little or no circulation within the well. Another profile obtained after the DHE flow had been cut off for 24 hours is shown, and again the same profile in both promoter and well was obtained.

The effectiveness of the promoter is primarily dependent on the natural cross flow of hot water through the perforated or open hole at the bottom of the well. A significant temperature gradient across the wall of the promoter in both wells at Tauhara does not exist when the DHE is running, and it is therefore concluded that there is a lack of cross flow, which would suggest that these wells have poor permeability. In addition, conductive heat losses through the walls of the steel promoter pipes greatly reduce the driving force of any induced convection cell. The ratio of convective to conductive heat flow for a steel promoter is analysed by Allis (1981) in which he shows that, using appropriate physical properties for the fluid, this ratio reduces to approximtely $D^2/L$ where D is the diameter of the promoter pipe in

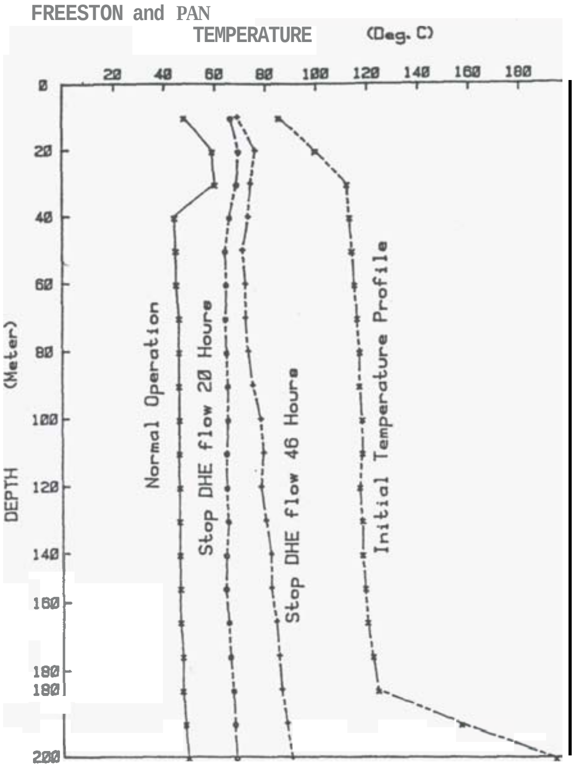


Fig. 5: Well 2 temperature profiles.

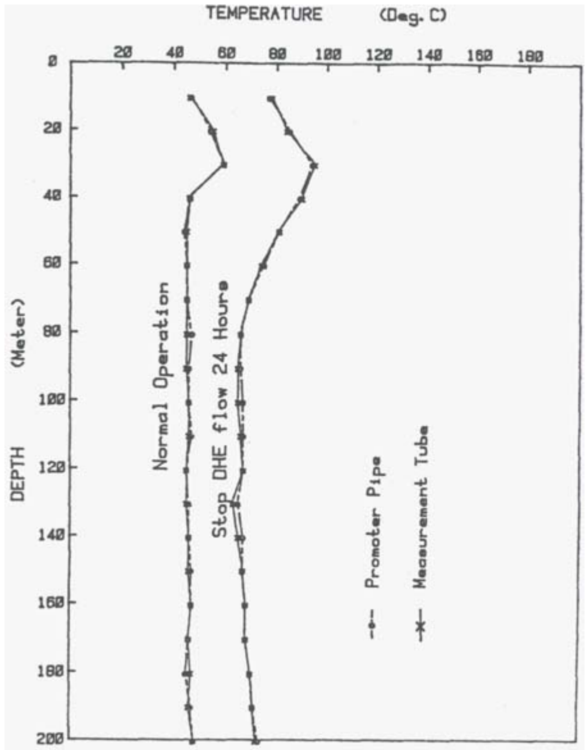


Fig. 6: Well 3 temperature profiles.

cm and L its length in metres. For Well 3, this gives $D^2/L$ = 0.32, i.e. much less than 1.0, so that conductive heat flow through the promoter wall dominates the heat transfer process. Clearly, one reason for the poor performance of the promoter in this well is its small diameter and relatively long length. Since the promoter length is generally fixed by the depth of the well to reach the hot aquifer, for small diameter wells the promoter pipe, to be effective, should be composed of a material of low thermal conductivity.

As stated earlier, for fluid to be convected a temperature difference needs to exist between the fluid in the well and promoter tube. The magnitude of this temperature difference is dependent upon the velocity of circulation, a balance being obtained between the pressure drop and the buoyancy force created by the density differences. Using the hydraulic diameter concept, an estimate of pressure drop as a function of velocity, and the buoyancy force as a function of temperature difference, were made for the laboratory and Well 3 configurations. Assuming that for the model a mean circulation velocity of 9 cm/s existed when a promoter was installed, a $\Delta T$ of 7.3°C would be estimated, which is close to the value measured. For a circulation velocity of 5 cm/s in Well 3, because of the high pressure loss caused by excessive wetted area (promoter, measurement on DHE pipes) only a 0.5°C temperature difference is required. This is unlikely to be measured with the field instrumentation used. It is therefore conceivable that there could be a convective circulation velocity of the order of 5 cm/s in this well. It is also clear that other methods of detecting this circulation need to be used before the details of the heat transfer mechanism can be obtained.

The maximum heat output of these DHEs is in the range 40 to 50 kW each for mass flow rates above about 1 kg/s. This is lower than would be expected, and is obviously linked to the well temperature which in itself is a function of the initial reservoir temperature and permeability. Increasing the mass flow rate through the heat exchangers beyond 1 kg/s does not greatly increase the energy extraction rate. However, it does decrease the difference between the DHE inlet and outlet temperatures and reduces the temperature of the fluid available to the load. When the DHE is part of a closed water flow system, as generally used for space heating, the DHE adjusts itself to its steady state heat output.

## 3. COMPUTER STUDY

Culver and Reistad (1978a) present a computer study of the characteristics of a DHE installation for Klamath-type wells. A network analysis is used in which the various resistances, heat and fluid flow paths are modelled. This analysis has been further developed by the authors and used to estimate the effects of geometry, temperature, physical properties of fluid and materials on the heat output from a DHE.

Circulation of well fluid has been shown to enhance the heat extraction rate. The process taking place at the bottom Of a well which penetrates a hot aquifer and which gives a cross flow normal to the well resulting in well fluid circulation is called mixing. It is modelled in the computer by allowing a fraction of the hot fluid to mix with the circulating fluid which is moving up the annulus and down inside the casing (or in the reverse direction). This ratio (Rm) is known as the mixing ratio and was introduced in the original work of Culver and Reistad (1978a) in an attempt to account for the drawdown of the reservoir temperature due to extraction of heat by the DHE. It is associated with permeability of the reservoir and heat extraction rate of the DHE. A high mixing ratio implies a low permeability. Typical values of Rm for the, Klamath wells - a field with good cross flows - are in the range 0.5 to 0.8.

The mixing ratio for the Tauhara field has been estimated using the programme and the data reported above. Using the mixing ratio option for the Tauhara Well 3 geometry, a reservoir temperature of 180°C and the measured output, values of Rm = 0.936, 0.938 and 0.97 are obtained for DHE flow rates of 1.84, 1.28 and 0.64 kg/s respectively (Figure 7). Rm is alo a function of heat extraction, a lightly loaded well giving higher values of Rm. As state earlier, above 1 kg/s the output is approximately constant and the mixing ratio could also be expected to be constant, but as the flow is reduced below 1 kg/s for this well, Rm increases, these values of Rm indicating small cross flws - a low permeability well. It is also noted from this figure that mixing ratio influences greatly the available output from a DHE system. A mixing ratio of about 0.9 would double the available energy extraction rate. A similar value for Rm is obtained using experimental data from Well 2. Having obtained a mixing ratio it is now possible, using the programme, to demonstrate the effect of a wide range of variables on the DHE performance. For example, the DHE output temperature can be predicted with confidence, and the effect of scaling on the output can be studied. Scaling introduces an additional resistance, particularly across the walls of the promoter. However, for the Tauhara system, because of the high mixing ratio the programme shows that normal scaling of the DHE and promoter has little effect on the output. Similarly, changing to a PVC promoter rather than steel does not increase the output significantly. It is more worthwhile to use a good insulator for the promoter, where there is a permeable reservoir.

It would be expected that for zero cross flow, the mixing ratio would be 1.0. As a result, the heat output by hot fluid from an aquifer by convection is zero. A well circulation can then only be established if a temperature gradient controlled by conduction exists in the well. The model test well with the promoter installed as discussed generated a circulating well fluid. The basic theory is still applicable although the meaning of the mixing ratio has changed. The energy input to the system is now by conduction from the electrical heater rather than by convection by the movement of hot fluid across the bottom of the well, and is linked to the mechanism by which the well temperatures without a DHE are modified when the DHE is switched on. With this loose definition, an attempt was made to match the computed performance with the measured data. A similar procedure to that discussed above was used to obtain a hypothetical mixing ratio (Rm = 0.954). This was then used to demonstrate the effects of changes in output caused by variations in some of the system parameters. A satisfactory match with measured performance was obtained.

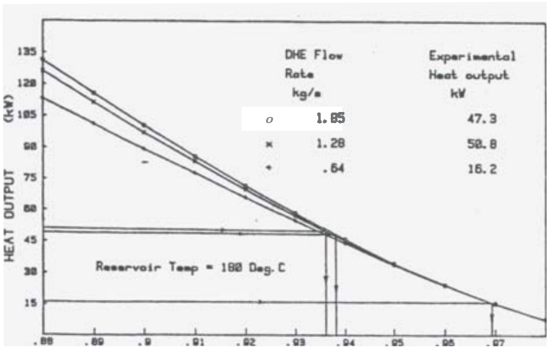


Fig. 7: Determination of Tauhara Well 3 mixing ratio.

## 4. COUCLUSIONS

The laboratory experiments demonstrated that:

(a) The performance characteristics of an annular type DHE (flow down annulus and up the inner tube) are comparable to a 'U' type.

(b) A perforated PVC promoter produced a strong circulation which enhanced the output. The well temperature profiles were similar to those measured when the well fluid was pumped through an external circuit.

(c) Temperature differences measured across the walls of the DHE indicated changes occurred in the direction of heat transfer as the DHE fluid circulated through its length. The position of changeover was a function of DHE mass flow rate.

The Tauhara experiments showed that:

(a) The wells were of low permeability resulting in a low well temperature with the DHE running, and hence low output.

(b) The promoter installed in Well 3 is not a success. The low permeability of the reservoir and the long steel and small diameter promoter do not generate a significant circulation of well fluid.

(c) The heat output of the system adjusts itself to a maximum value which is not influenced by DHE mass flow rate, the heat extraction matching the input to the well.

The computer programme enables a DHE system to be optimised once a realistic value for the mixing ratio is obtained. The analysis demonstrates that:

(a) A promoter tube should use a low conductivity material and have as large a diameter as possible. It is more profitable to use a promoter where there is a good permeable reservoir.

(b) A mixing ratio of 0.94 was estimated for Tauhara College wells, and for the model tests a hypothetical value of 0.954 was calculated. Values of this order of magnitude indicate low permeability.

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