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Äspö Hard Rock Laboratory

Tracer Retention Understanding Experiment

In-situ test of borehole equipment for tracer injection, RC-4

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February 2001

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Abstract

This report describes the testing of new down-hole equipment and a modified injection procedure for tracer tests as applied in the new borehole KXTT5 at the TRUE-1 site. The first aim was to test the new down-hole equipment in-situ under ambient flow and pressure conditions. The second aim was to demonstrate that well-defined tracer pulse injections could be performed. The third aim was to produce tracer breakthrough data from the target feature, Feature A, without disturbing effects from tailing of the tracer input function. The knowledge and experience acquired through these tests is to be used in forthcoming tracer tests within the TRUE Project.

Executive summary

The methodology used for the now finalised and reported first phase of the Tracer Retention Understanding Experiment, TRUE-1, was found to work successfully with the exception of one important detail, namely the establishment of a finite injection pulse. The extensive modelling made of the TRUE-1 tracer tests made it clear that the tailing of the injected pulse could mask effects of important transport processes such as matrix diffusion. The new down-hole equipment tested in this study is designed to decrease the volume of the borehole interval and to optimise the termination of the finite pulse injection. The new equipment has been tested successfully under laboratory conditions (Appendix 1).

The objective of this study was to demonstrate that well defined tracer pulse injections can be made and to produce tracer breakthrough data without disturbing effects from tailing of the tracer input function. Another objective was to test the new down-hole equipment in-situ under ambient flow and pressure conditions.

The study was performed by running four radially converging tracer tests in two flow paths at the TRUE-1 site. The first of the two flow paths used was the well-documented path KXTT4:R3 → KXTT3:R2 and the second flow path was the new path, KXTT5:P2 → KXTT3:R2. The tracer tests were planned in such a manner that conclusions regarding the function of the new down-hole equipment and the methodology used could be drawn.

The injection functions from the four tracer tests show distinct differences depending primarily on the injection/exchange methodology used. The tests strongly indicates that the tailing of the injection function is due to diffusion of the tracer fluid into almost stagnant parts of the injection section. The diffusion of the tracer fluid is indicated by the fact that the use of the new down-hole equipment, with a minimised section volume and no dead end volumes, does not significantly improve the efficiency of the tracer exchange. The use of a new injection/exchange methodology indicates that the duration of the exchange is the most important factor in reducing the tailing of the injection function. The duration of the exchange has to be at least the same as the duration of the tracer injection pulse in order to be successful.

Due to the fact that the four tracer tests were performed using very different injection/exchange methodologies it is not possible to draw any conclusions about the effect of the new down-hole equipment on the termination of the tracer pulses. However, it is clear that the smaller section volume of the new equipment and the possibility to use much shorter section lengths (down to 0.2 m) compared to the old equipment makes it more suitable for performing well-controlled tracer tests in the future.

Contents

1 Introduction

1.1 Background

The first phase of the Tracer Retention Understanding Experiments, TRUE-1 has now been finalised and reported (Winberg et al., 2000). TRUE-1 involved 18 tracer tests with 1-5 tracer injections in each test. The methodology used was found to work successfully with the exception of one important detail, namely the establishment of a finite injection pulse. The original design of the down-hole equipment was not optimised for finite, well-defined, pulses but rather to achieve a good initial mixing of the tracer solution with the ambient water in the injection interval.

The TRUE-1 tests were also used for extensive modelling efforts performed i.a. within the Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes. During these efforts Heer (personal communication) pointed out that the tailing of the injected pulse potentially could mask effects of important transport processes such as matrix diffusion. It was therefore decided to construct new down-hole equipment for the second phase of TRUE, specially designed to decrease the volume of the injection interval and to optimise the ending of the finite pulse injection. The equipment has been successfully tested in a laboratory set-up, cf. Appendix 1.

1.2 Objectives

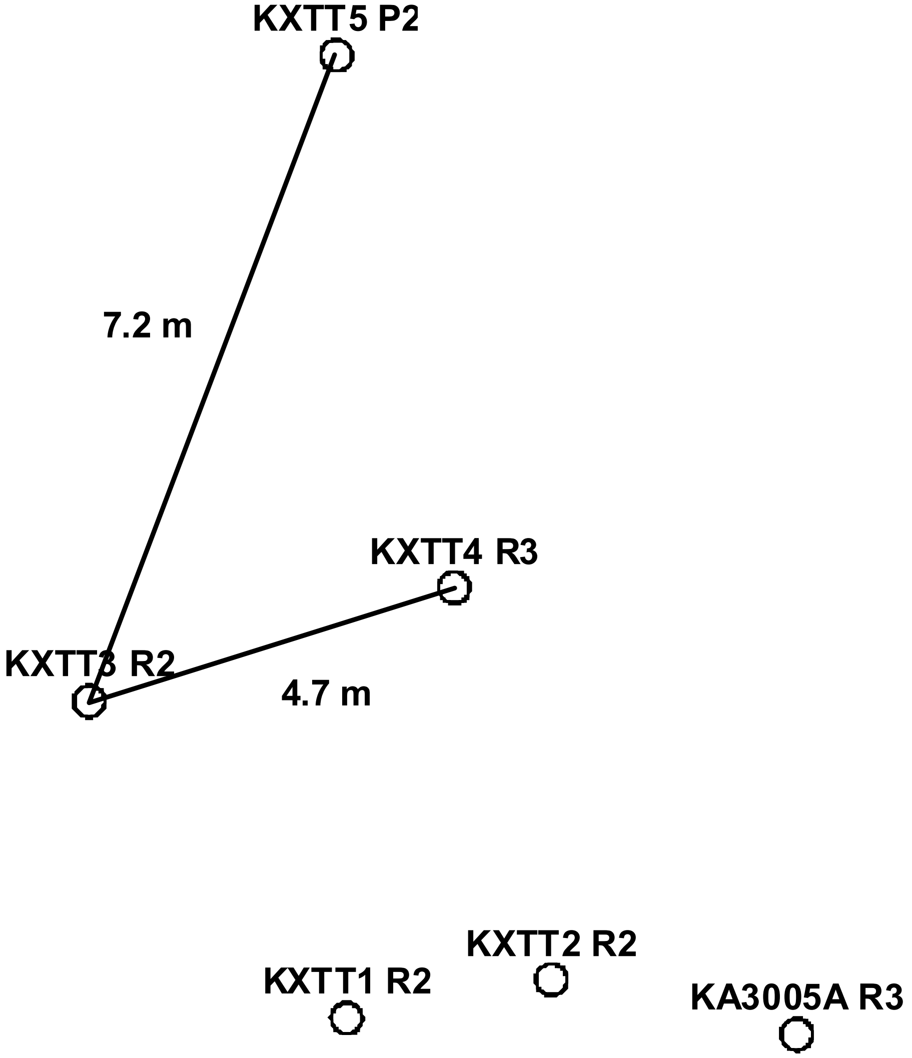
The objectives of this study are to:

- Test the new down-hole equipment in-situ under ambient flow and pressure conditions
- Demonstrate that well-defined tracer pulse injection can be performed
- Produce tracer breakthrough data from the target feature, Feature A, without disturbing effects from tailing of the tracer input function

2 Experimental setup

2.1 Site description

The TRUE-1 site is located at 2950 m tunnel length at a depth of about 400 m below sea level in the Äspö HRL. The site includes six boreholes, KXTT1 – KXTT5 and KA3005A, cf. Figure 2-1. The characterisation work at the site identified two potential candidate features for tracer tests, Features A and B, cf. Winberg (*ed*), (1996). Feature A was selected for the TRUE-1 tracer tests and 18 different tracer test configurations have been used in this feature. The fact that the TRUE-1 site is well documented and still instrumented after the concluded TRUE-1 tracer tests made it ideal for performing tests with the new down-hole equipment. Table 2-1 provides a tentative description of the planned tracer tests.



Figur 2-1. *View of the TRUE-1 site in the plane of Feature A. The travel distances are geometric (euclidean).*

Tabell 2-1. Performance of tracer tests in Feature A, TRUE-1 site. The travel distances are geometric (euclidean).

Run #	Flow path	Flow geometry	Pump flow (ml/min)	Injection flow (ml/min)	Travel distance (m)	Tracer
1	KXTT5:P2 → KXTT3:R2	Passive injection	630	4.17	7.2	Uranine
2	KXTT4:R3 → KXTT3:R2	Passive injection	630	4.17	4.68	Amino G
3	KXTT4:R3 → KXTT3:R2	Passive injection	2000	4.17	4.68	Amino G
4	KXTT5:P2 → KXTT3:R2	Passive injection	2000	4.17	7.2	Rhodamine Wt

2.2 Equipment and tracers used in the tests

2.2.1 Borehole equipment

The tests were performed using previously installed borehole equipment in KXTT1-KXTT4. The equipment is described in Winberg (*ed*) (1996). Each borehole is instrumented with 4-5 inflatable packers such that 4-5 borehole sections are isolated. The borehole equipment installed in borehole KXTT1-KXTT4 including packers, dummy and infiltration tubes is described in Appendix 2. The pressure lines of each section are connected to the HMS-system. Each of the sections planned to be injection or sampling sections are equipped with three nylon lines, two with an inner diameter of 4 mm and one with an inner diameter of 2 mm. The two 4 mm lines are used for injection, sampling and circulation in the borehole whereas the 2 mm lines are used for pressure monitoring.

The new borehole equipment, described in Appendix 1 and 3, was installed in the 76-mm borehole KXTT5 together with two guard packers, resulting in a total of four isolated borehole sections. The injection section is equipped with two circulation lines and one pressure monitoring line whereas the other three sections only will have one line each for pressure measurements. The pressure lines are connected to the HMS system. The design of the new borehole equipment is an improvement of the old equipment. The improvement lies in a minimising of the section volume and a more efficient mixing in the section. The circulation inlet and outlet of the new equipment (Appendix 3) are milled grooves in spiral shape evenly distributed around the packer end at the edge of the packer rubber.

2.2.2 Injection equipment

A schematic drawing of the tracer injection equipment is shown in Figure 2-2. The basic idea is to create an internal circulation of the borehole fluid in the injection borehole. The circulation makes it possible to obtain homogeneous tracer concentration inside the borehole and to sample the tracer concentration outside the borehole in order to monitor the dilution of the tracer with time.

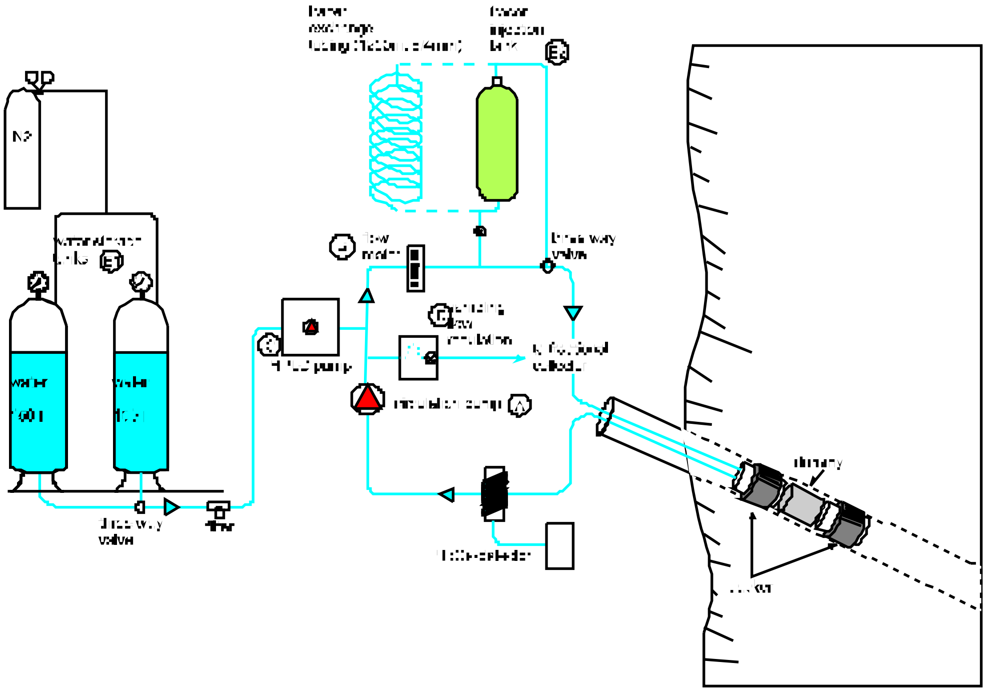


Figure 2-2. *Schematic drawing of the injection system for the TRUE-1 tracer tests.*

Circulation is controlled by a pump with variable speed (A) and measured by a flow meter (B). Tracer injections are made directly into the circulating loop with a HPLC plunger pump (C). The tracer solution in the circulating loop can be replaced with unlabelled water by switching the three-way valve such that the circulating water passes through a long (1200 m) tube filled with unlabelled water. Tracer solution then enters from one side of the tube and unlabelled water enters the circulation loop from the other side of the tube.

The tracer concentration in the injection loop is measured by sampling and subsequent laboratory analysis. The sampling is made by continuously extracting a small volume of water from the system through a flow controller (constant leak) to a fractional sampler (D). The HpGe detector was not in use during these tests.

Water from the target structure, Feature A, used for the tracer exchange is stored in a separate pressurised vessel (E1) under nitrogen atmosphere. Further details about the equipment are given in Andersson, (1996).

2.2.3 Sampling and detection equipment

The sampling system is based on the same principle as the injection system, namely a circulating system with a circulation pump and a flow meter, cf. Figure 2-3. In this case however, water is withdrawn from the borehole with a constant flow rate by means of a flow regulation unit. This unit consists of a mass flow meter coupled to a motorised valve enabling a fast and accurate flow regulation. The sampling is made with a ”constant leak” system producing 8 ml samples (same as in the injection loop) integrated over some time (5-60 minutes).

After sampling, the pumped water is led through a nylon vessel where the water is degassed. The reason for this is that measurements of dye tracer content is made by an in line field fluorometer. As fluourometry is an optical method, gas bubbles need to be removed in advance or else they may create a fictive background content of the dye tracer. Hence, the degassed water is pumped from the degassing vessel through the field fluorometer and further through an electrical conductivity probe.

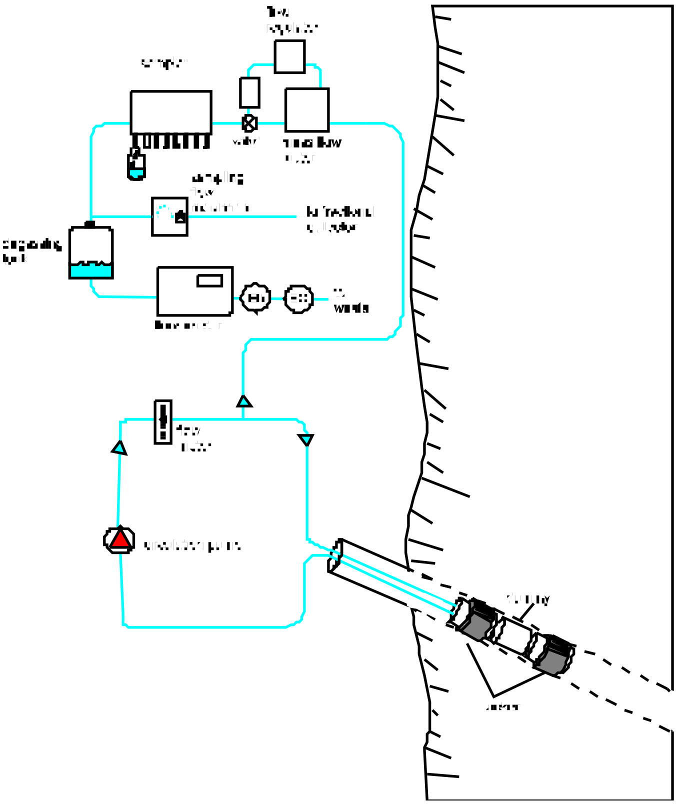


Figure 2-3. *Schematic drawing of the sampling system for the TRUE-1 tracer tests.*

2.2.4 Tracers used

The tracers chosen for these tracer tests were the fluorescent dyes, Amino G Acid, Rhodamine WT and Uranine. These three dyes have been used previously in the TRUE Project (Andersson 1996) and are known to be non-reactive.

2.3 Injection procedure

The tracer stock solution for the tracer test was prepared at the GEOSIGMA AB Laboratory in Uppsala. The tracer stock solution bottle was placed on a scale so that the actual injected volume could be calculated at the end of the injection. The injection was made directly into the circulating loop as the HPLC plunger pump was started, see Figure 2-2.

The injection of the tracer stock solution was performed as finite pulse injections with a length of two to four hours. The tracer solution was exchanged with unlabelled water after two to four hours as described in section 2.1.2. The duration of the exchange procedure lasted between 40 to 135 minutes in the different tracer tests. Before the exchange the unlabelled water in the long tube had been pressurised by adding water with the HPLC plunger pump until the pressure in the test section was reached.

2.4 Sampling and detection procedures

The injection concentration in the injection sections and the concentration in the pumping section were monitored using the equipment described in sections 2.2.2 and 2.2.3. The decrease in injection concentration was measured by sampling for tracer concentration with samples taken every second minute during the injection phase, and then every 30 minutes until the start of the exchange when the sampling frequency was again set to one sample every two minutes. After the exchange was completed the sampling frequency was decreased gradually to one sample every 100 minutes.

The sampling in the pumping borehole was performed using the sampling system described in section 2.2.3. The ”constant leak” system was set to sample the pumped water in the pumping section every five minutes until the start of the exchange. The sampling frequency was then gradually decreased to one sample every 60 minutes.

The analyses of the tracer concentration in the water samples were made using spectrofluorometry using a Jasco FP-777 at GEOSIGMA AB Laboratory in Uppsala. All water samples were buffered to a pH of 8 to 9 before the analysis was made.

3 Results and interpretation

3.1 Log of events

The tracer test period on site at Äspö HRL described in this report started on December 16th, 1999 with dilution tests in KXTT5:P2 and ended on January 17th, 2000 when the last radially converging tracer test was terminated. The tracer injections and the pumping were performed without major disturbances. The log of events is presented in Table 3-1.

Table 3-1. Log of events

Day	Time	Event
991216	18:40	Start tracer dilution test KXTT5:P2
991217	14:00	Start pumping KXTT3:R2
991220	14:00	Stop tracer dilution test KXTT5:P2
991220	14:05	Stop pumping KXTT5:P2
000110	18:00	Start tracer dilution test KXTT5:P2
000111	9:40	Start pumping KXTT3:R2
000111	16:10	Stop tracer dilution test KXTT5:P2
000111	16:20	Start radially converging tracer test, KXTT5:P2
000111	17:00	Start radially converging tracer test, KXTT4:P3
000113	15:27	Stop pumping KXTT3:R2
000113	15:36	Start pumping KXTT3:R2
000113	16:45	Stop radially converging tracer test, KXTT4:R3 and KXTT5:P2
000113	17:45	Start radially converging tracer test, KXTT4:R3
000113	18:25	Start radially converging tracer test, KXTT5:P2
000117	17:04	Stop radially converging tracer test, KXTT4:R3 and KXTT5:P2
000117	17:00	Stop pumping KXTT3:R2

3.2 Tracer dilution tests

The decrease in tracer concentration versus time was used to calculate the flow rates through the injection interval by plotting the natural logarithm of concentration versus elapsed time. Theoretically, a straight-line relationship exists between the natural logarithm of the relative tracer concentration (C/C_o) and time (t)

$$Q_{bh} = -V \cdot \Delta(\ln \cdot (C/C_0) \cdot t^{-1}) \qquad (3\text{-}1)$$

Q_{bh} (m^3/s) is the groundwater flow rate through the borehole section and V is the volume of the borehole section (m^3).

Two tracer dilution tests were performed in KXTT5:P2. The dilution tests were performed to measure flow under natural as well as pumped conditions. The tracer injections were performed as decaying pulses The injection function of the first tracer test is presented in Figure 3-1 as the logarithm of concentration (Ln C) versus elapsed time. The flow was determined to be 1.5 ml/h under natural conditions. With a pumping rate of 630 ml/min in the pumping section (KXTT3:R2) the flow increased to 4.3 ml/h. The injection function of the second test is presented in Figure 3-2. The test was performed under natural conditions and gave a flow of 1.7 ml/h. The flow measured under natural conditions differ somewhat between the two tests. The discrepancy is most likely a result of the fewer number of samples taken in the second test (Figure 3-1 and 3-2).

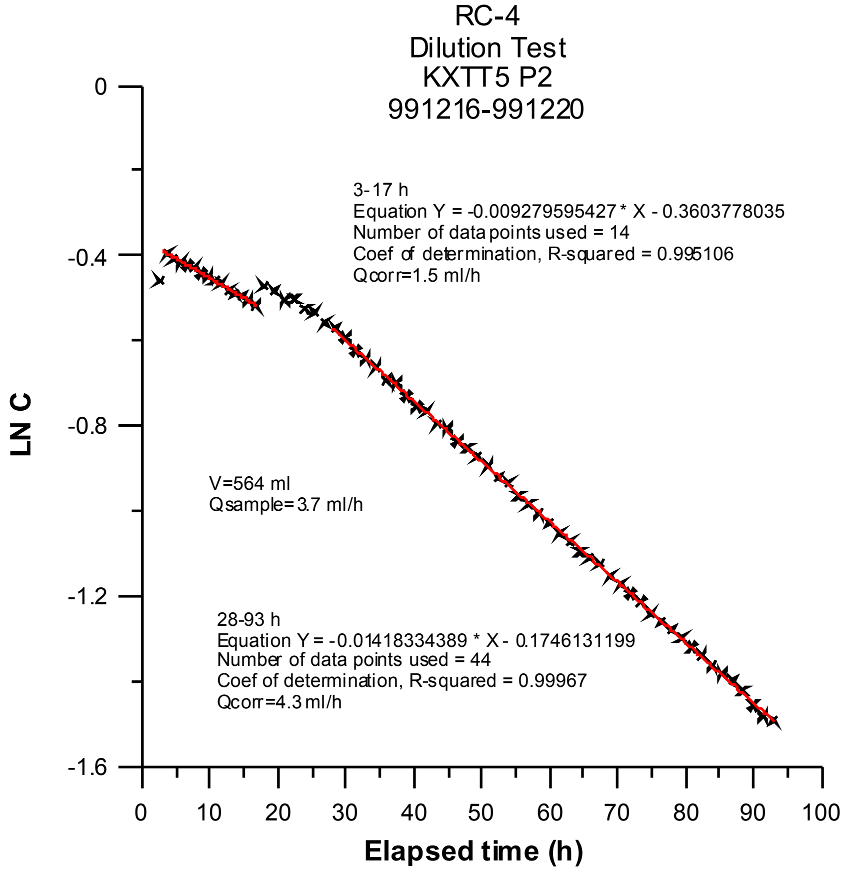


Figure 3-1. *Tracer concentration function (Ln C) versus elapsed time and the best straight line fits for natural and pumped conditions. Pumping rate 630 ml/min.*

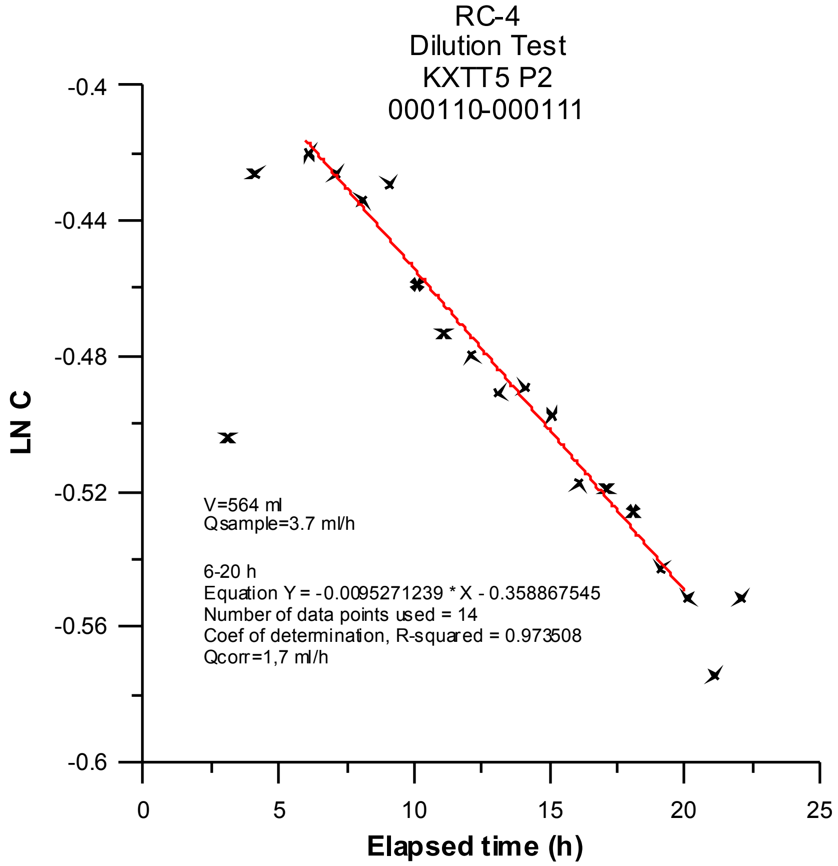


Figure 3-2. *Tracer concentration function (Ln C) versus elapsed time and the best straight line fit under natural conditions.*

3.3 Tracer injections

The tracer tests were performed using both the traditional and the new down-hole equipment. The two different set-ups of down-hole equipment were employed in different boreholes. The tracer tests in the two sections were performed in such a manner that the injection procedure as well as the exchange could be evaluated. Tracer injection data is presented in Table 3-2. The injection concentrations versus the elapsed time for the tracers Amino G Acid, Rhodamine Wt and Uranine are plotted in Figure 3-2 to 3-6.

Table 3-2. Tracer injection data

Borehole section	KXTT5:P2	KXTT4:R3	KXTT4:R3	KXTT5:P2	KXTT3:P2
Tracer	Uranine	Amino G	Amino G	Rhodamine Wt	
Down-hole equipment	New	Traditional	Traditional	New	
Injection time (min)	13.5	26	26	5	
Injection flow (ml/h)	4.17	4.17	4.17	4.17	
Duration of tracer pulse (min)	240	305	*	120	
Duration of exchange(min)	40	48	*	135	
Number of section volumes exchanged	8.4	3	*	20	
Exchange/ tracer pulse **	0.167	0.157	*	1.125	
Reduction of tracer mass due to the exchange (%)	97.9	97	*	99.9	
Section location in borehole (m)	9.61-9.81	11.92-13.92	11.92-13.92	9.61-9.81	8.42-10.92
Volume of injection system (ml)	564	2154	2154	564	
Volume of withdrawal system (ml)					5252

* The injection was performed as a decaying pulse (no exchange).

** Ratio of duration of the exchange and the tracer pulse

The reduction of tracer mass due to the exchange of the tracer solution in the injection loop has in previously performed tracer tests been approximately 90-95 %, cf. Winberg et al. (2000). The exchanged volume has been equal to about three section volumes. The tracer exchange procedure performed in this study gave a higher reduction of the tracer mass in the injection loop (Table 3-2). This is a significant improvement considering that the last few percent of the tracer mass in the injection loop has been very difficult to reduce in previously performed tests. The reduction of the tracer mass in the injection loop is calculated as the ratio of the tracer concentration at the end of the tracer injection period and the highest tracer concentration after the exchange has been made.

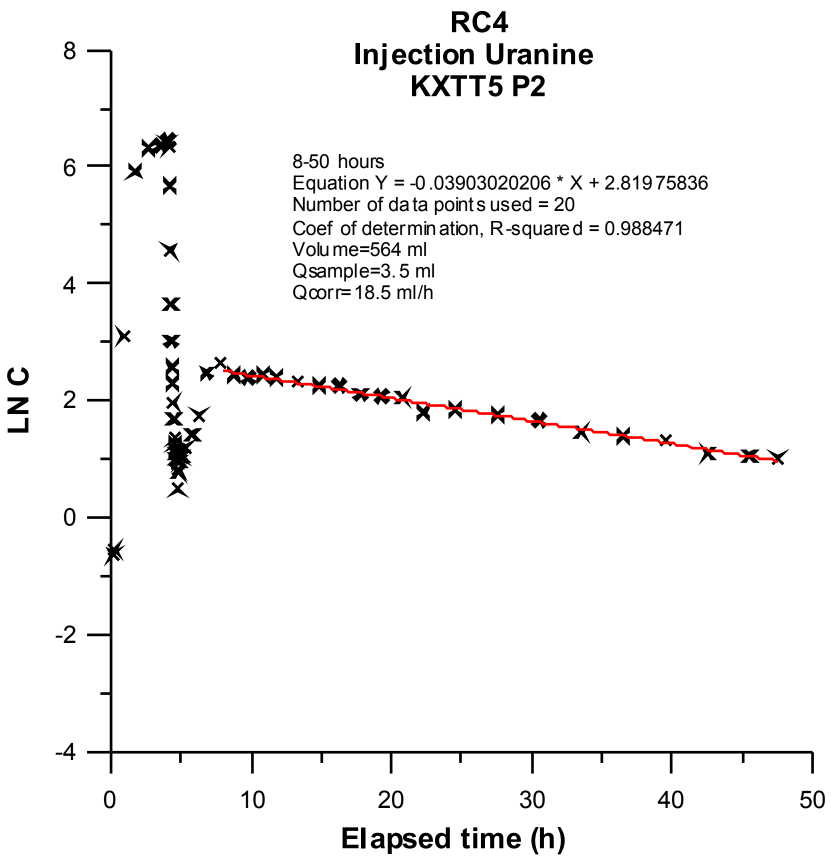


Figure 3-3. *Tracer injection concentration (lnC) versus elapsed time, t(h), for Uranine in the injection section KXTT5:P2.*

In the first tracer injection in KXTT5:P2, run 1 (Figure 3-3), the duration of the tracer exchange was based on the desire to exchange approximately 8 section volumes (Table 3-2). The ratio between the duration of the exchange and the injection pulse duration was 0.167 and the tracer mass in the injection loop was reduced by 97.9%. This is an improvement compared to previously made exchanges, but still not as good as desired.

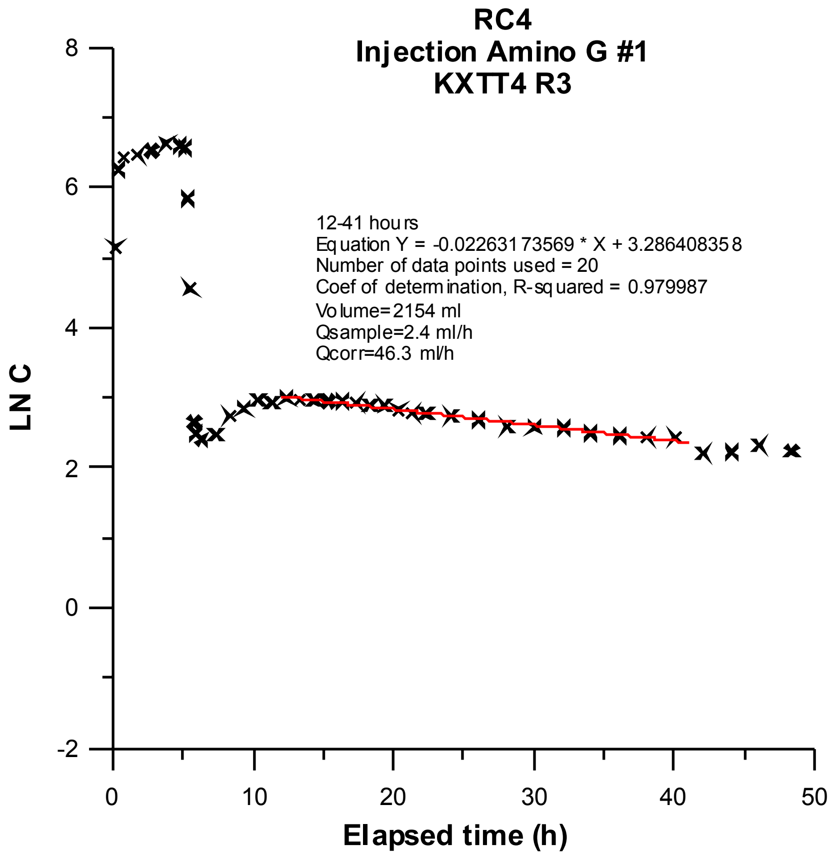


Figure 3-4. *Tracer injection concentration (lnC) versus elapsed time, t(h), for Amino G in the injection section KXTT4:R3.*

The first tracer injection in KXTT4:R3, run 2 (Figure 3-4), was performed using the same methodology that has been used previously, i.e. basing the duration of the exchange on the desire to exchange three section volumes. The ratio of the duration of the exchange and the injection pulse duration was 0,157, which is lower than in run 1. The achieved reduction of tracer mass in the injection loop was 97 %, which is also lower than in run 1.

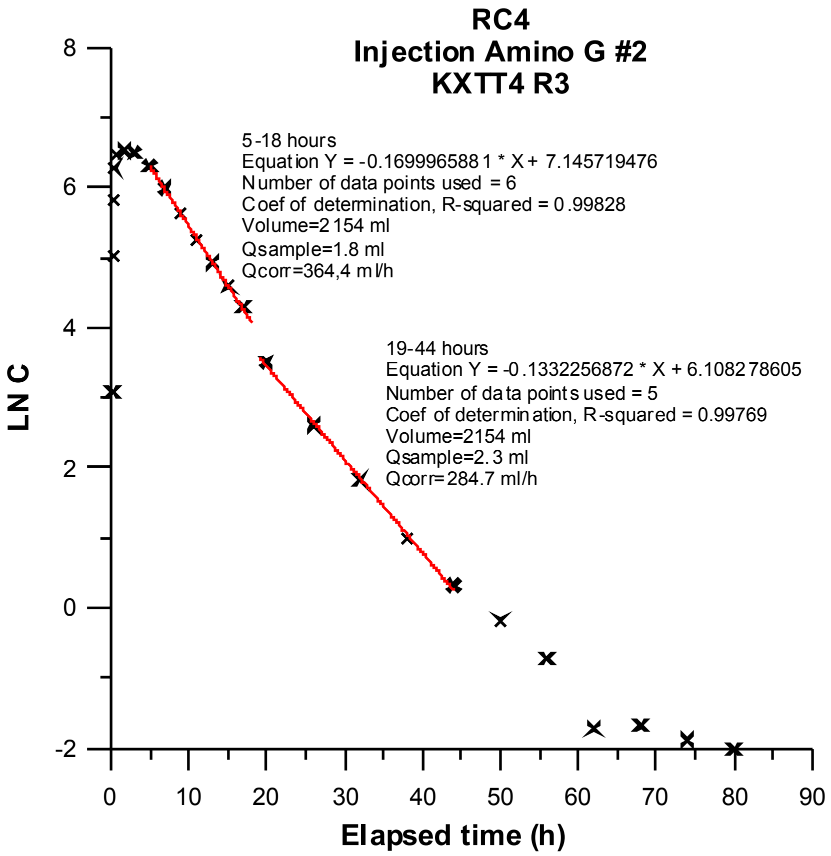


Figure 3-5. *Tracer injection concentration (lnC) versus elapsed time, t(h), for Amino G in the injection section KXTT4:R3.*

The second tracer injection in KXTT4:R3, run 3 (Figure 3-5), was (for practical reasons) performed as a decaying pulse and is therefore not easily comparable to the other tracer injections.

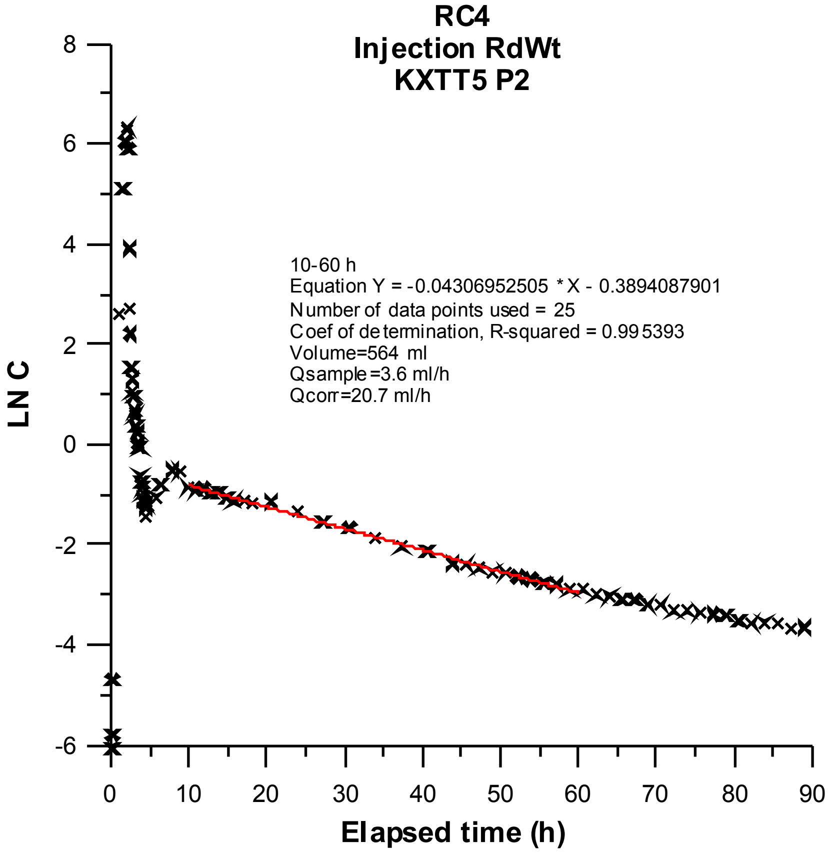


Figure 3-6. *Tracer injection concentration (lnC) versus elapsed time, t(h), for Rhodamine Wt in the injection section KXTT5:P2.*

In run 4, the second tracer injection in KXTT5:P2 (Figure 3-6), the duration of the tracer injection pulse was shorter and the duration of the exchange was considerably longer than in any of the previous tests (Table 3-2). The number of exchanged section volumes was as high as 20 and the ratio of the duration of the exchange and the injection pulse duration was 1.125. The tracer exchange procedure reduced the tracer mass in the injection loop by 99.9 %.

3.4 Tracer breakthrough

The tracer breakthrough was monitored in the pumping section KXTT3:R2. The breakthrough curves (Figures 3-7 to 3-10) show more or less distinct peaks. The flow path KXTT4:R3 → KXTT3:R2 is known to be fast and to produce a high mass recovery. First arrival of the tracer in the pumping section decreases from run 2 to run 3 (Table 3-3). The faster first arrival in run 3 is the result of an increase in the pumping rate in the pumping section. The tracer mass recovery in run 2 and 3 are 81 and 90 % ,respectively , after 50 hours of elapsed time.

The two tracer tests performed in the flow path KXTT5:P2 → KXTT3:R3 (run 1 and 4) show significantly longer first arrival time in the pumping section. The time for first arrival in run 1 is approximately 50 hours and 30 hours in run 4. The shorter arrival time in run 4 is due to the increase in pumping rate. The recovery for run 1 is low and is most likely a result of the low pumping rate and the fact that the sampling was terminated too soon and/or that a large portion of the mass is carried away by the "background flow". If the sampling had continued the recovery would have increased somewhat.

Table 3-3. Tracer mass recovery

Flow path	Run	Pumping rate (ml/min)	First arrival (h)	Mass Recovery (%)
KXTT5:P2	1	630	50	3
KXTT4:R3	2	630	1.1	81
KXTT4:R3	3	2000	0.5	90
KXTT5:P2	4	2000	30	88

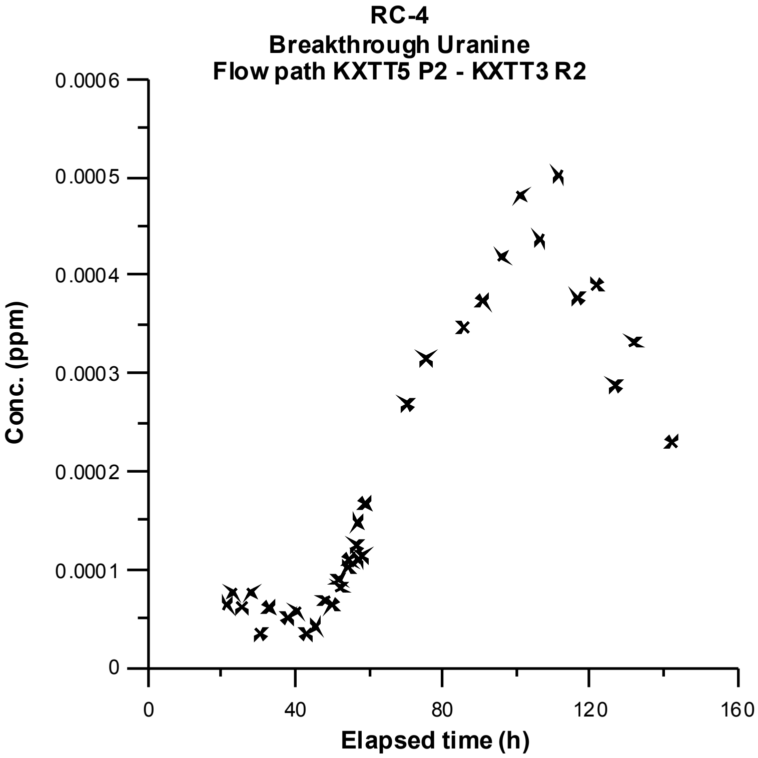


Figure 3-7. KXTT5:P2, run 1. Tracer breakthrough in KXTT3:R2 versus elapsed time (h). Pumping rate 630 ml/min.

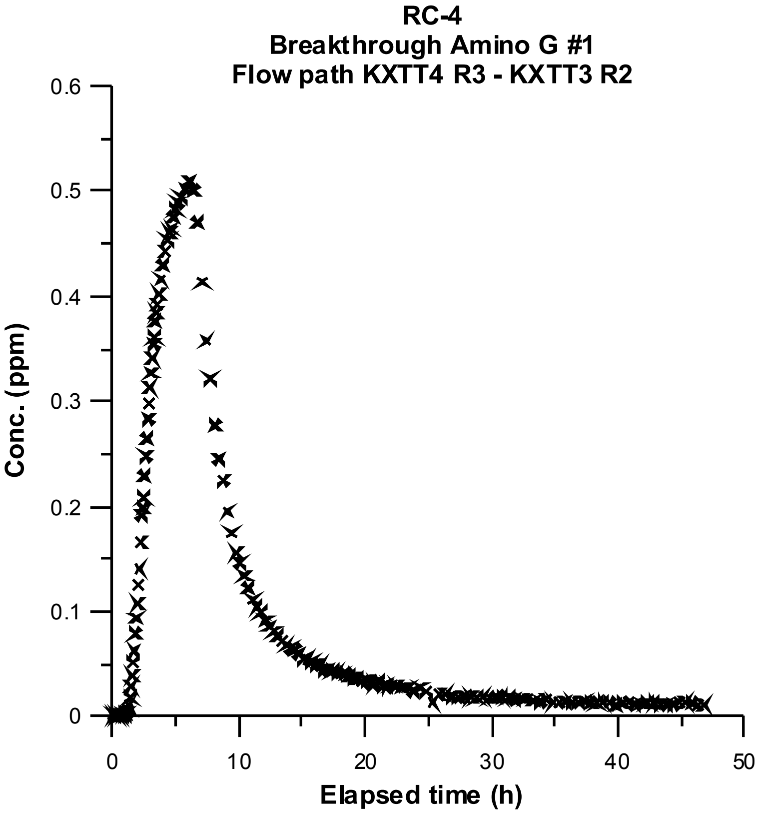


Figure 3-8. *KXTT4:R3, run 2. Tracer breakthrough in KXTT3:R2 versus elapsed time (h). Pumping rate 630 ml/min.*

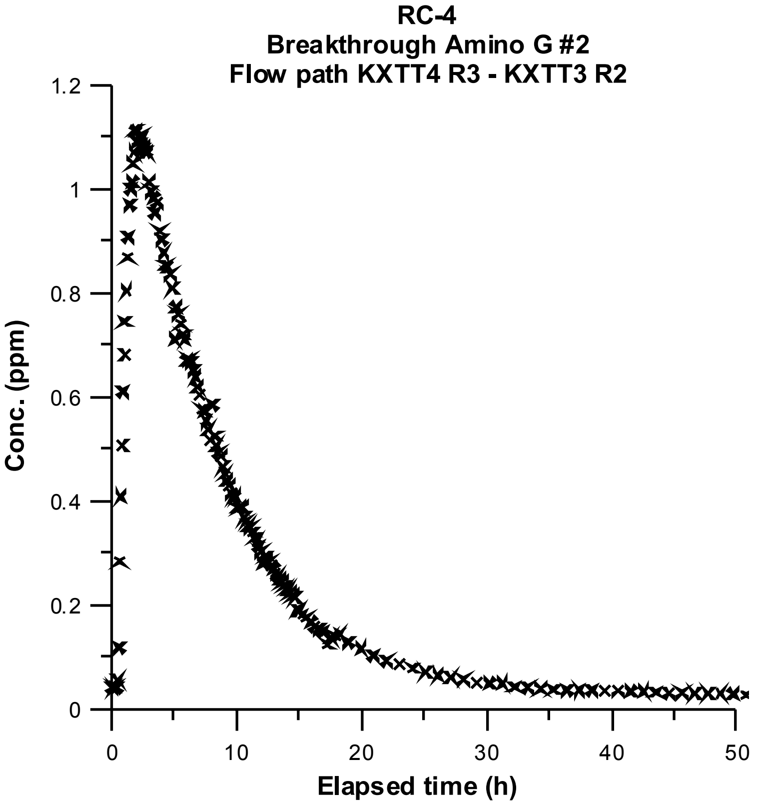


Figure 3-9. *KXTT4:R3, run 3. Tracer breakthrough in KXTT3:R2 versus elapsed time (h). Pumping rate 2000 ml/min.*

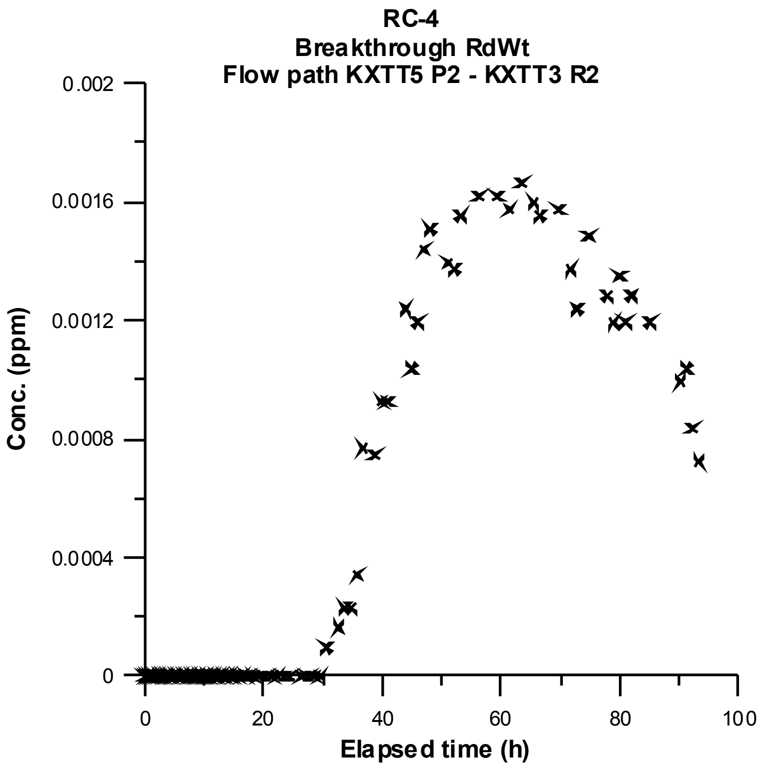


Figure 3-10. *KXTT5:P2, run 4. Tracer breakthrough in KXTT3:R2 versus elapsed time (h). Pumping rate 2000 ml/min.*

4 Discussion and conclusions

The results from the tracer tests show that the duration of the tracer injection pulse is an important decisive factor in the planing and design of the tracer exchange. It seems as if the diffusion of the tracer fluid into fractures that are to be considered as almost stagnant parts of the injection section gives a significant effect on the tracer input function. This is shown by the fact that even if the new equipment with a minimised section volume and no dead-end volumes is used, the efficiency of the tracer exchange procedure is not significantly improved. As time is the key factor in the diffusion process, it is essential that the duration of the exchange procedure is at least as long as the length of the tracer pulse duration in order for the exchange of the tracer labelled water to be successful. Further, it seems as if the ratio of the duration of the exchange and the duration of the tracer pulse can be used as a measure of how effective the exchange will be. It is desirable that the ratio is 1.0 or higher. This demonstrates that well-defined tracer pulse injections can be performed if the tracer injection procedure is planned and executed with a desire to give the ratio of the duration of the exchange and the duration of the tracer pulse a value of at least 1.0.

The significance of the new down-hole equipment on the tracer pulse in not as clear as could be wished. A comparison of the old and the new down-hole equipment is not easily made since the two borehole sections are significantly different with respect to section diameter, volume and length (Table 2-1). However, it is clear that the smaller section volume of the new equipment and the possibility to use much shorter section lengths (down to 0.2 m) than the old equipment makes the new equipment more suitable for performing well-controlled tracer tests in the future.

5 References

Andersson P, 1996. TRUE 1^{st} stage tracer test programme. Experimental data and preliminary evaluation of the TRUE-1 radially converging tracer test (RC-1). Äspö Hard Rock Laboratory Progress Report HRL-96-24.

Winberg A (ed), 1996. First TRUE Stage – tracer Retention Understanding Experiments. Descriptive structural – hydraulic models on block and detailed scales of the TRUE-1 site. Swedish Nuclear Fuel and Waste Management Company. Äspö Hard Rock Laboratory International Cooperation Report ICR-96-04.

Winberg A, Andersson P, Hermansson J, Byegård J, Cvetkovic V, Birgersson L, 2000. Final report of the first stage of the tracer retention understanding experiments. Swedish Nuclear Fuel and Waste Management Company. Äspö Hard Rock Laboratory Technical Report TR-00-07.

Appendix 1

Development of new double-packer system for TRUE-2.

Test report

Name

PU 72 Double packer system for tracer tests

Function/Application

The double packer system is designed for tracer tests where it is of the greatest importance that the water volume in the section is small. The packer system is also designed to give efficient mixing in the entire section during the tracer injection.

Specifications

The following demands has been put on the packer system:

- the system must be possible to manufacture for sections of lengths between 0.2-1 m
- the surrounding packers must be possible to manufacture in lenghts between 0.5-1m
- the circulation in the section shall be possible to carry out in such a fashion that homogeneous mixing of a tracer is obtained. Pressures shall be possible to measure in the section
- it must be possible to fit five 6 mm and seven 4 mm additional lead-throughs in the packer
- the system must resist difference pressures over the packer of 5 Mpa
- all material used in the section shall if possible be stainless steel

Test programme

The testing of the tracer homogenisation, here called the ¨filter function¨, was carried out in a transparent 76 mm plastic tube. The tests were divided into in two sets. In the first set, concentration data were collected with an online fluorometer. The second set of tests was executed so that the ¨filter function¨ could be recorded with a video camera. The conditions in the system were identical in the two sets of tests. The volume of the borehole section was 137 ml. The total volume of the system, including the lines and the flowthrough cell of the fluorometer, was 540 ml of which 137 ml was the borehole section volume. In the first set of tests the injection rate and injection time were calculated from the circulation rate and volume of the system.

Injection equipment

The test of the filter function was performed using the equipment set-ups for tracer tests previously used in the TRUE-1 tracer tests. A schematic drawing of the tracer injection equipment is shown in Figure 1. The intention is to create an internal circulation of the borehole fluid in the injection borehole. The circulation makes it possible to obtain homogeneous tracer concentration inside the borehole section and to sample the tracer concentration outside the borehole in order to monitor the dilution of the tracer with time.

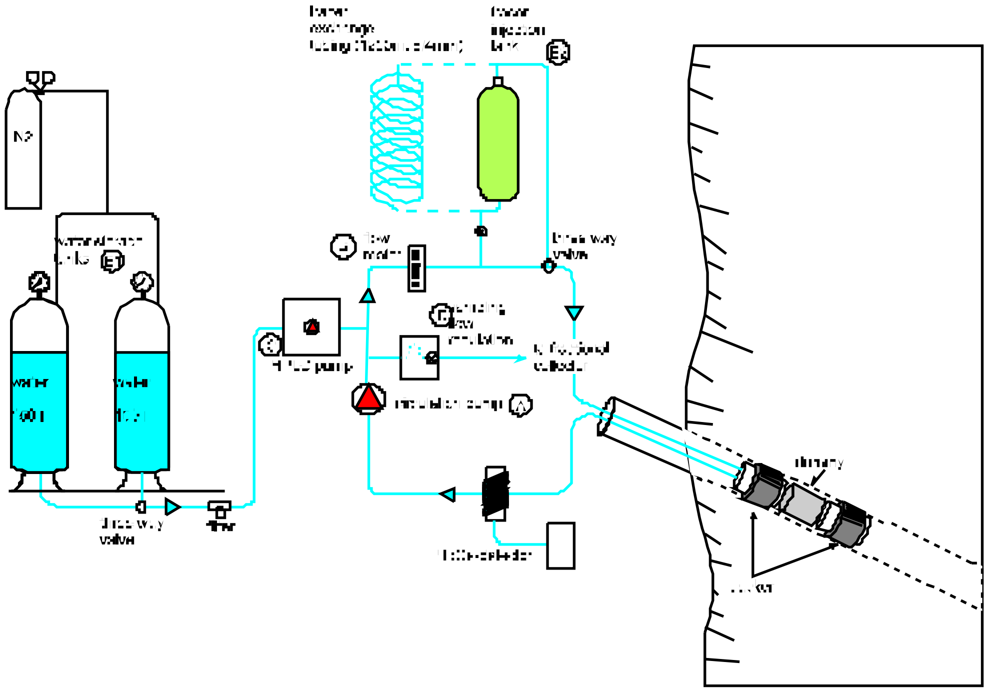


Figure 1. *Schematic drawing of the injection system at the TRUE-1 site.*

The circulation is controlled by a pump with variable speed (A) and measured by a flow meter (B). Tracer injections are made directly into the circulating loop with a HPLC plunger pump (C). The tracer solution in the circulation loop can be replaced with unlabelled water by switching the three-way valve such that the circulating water passes through a long (200 m) tube filled with unlabelled water. The tracer solution then enters from one side of the tube and unlabelled water enters the circulation loop from the other side of the tube.

Results and interpretation

Table 1. Circulation and injection rate before and after the tracer injection.

Circulation rate [l/h]	Injection rate [ml/min]	Pressure before tracer inj. [bar]	Pressure after tracer inj. [bar]
5	0,83	0,5	1
10	1,67	0,5	1
15	2,50	0,5	1,2

The tracer concentration in the injection loop was measured continuously using an online fluorometer replacing the HpGe-detector in Figure 1. Table 1 shows the circulation and injection rate and the pressures in the section before and after the injection.

Figure 2 shows the concentration in the system for the three tests described above. The number of oscillations before the concentration converges asymptotically is approximately the same for all three tests. The elapsed time before the concentration converges is decreasing with increasing circulation rate and the amplitude of the oscillation increases as the circulation rate of the system increases. These oscillations are mainly an effect of the poor mixing in the tubing.

The tests also included an exchange were the labelled water was exchanged with unlabelled water. The test was performed under the same conditions as the tests described above. The rate of circulation was set to 10 l/h and the injection rate was 1.67 ml/min. The exchange was made one hour after the injection was completed. At time of the exchange the concentration in the system was stabilised (Figure 3). The exchanged volume was three times the volume of the system. Figure 3 shows the course of the injection as well as the exchange. It can be clearly seen that the exchange is very successful. The slight increase in concentration after the exchange is probably due to diffusion of tracer marked water trapped in connections and switches.

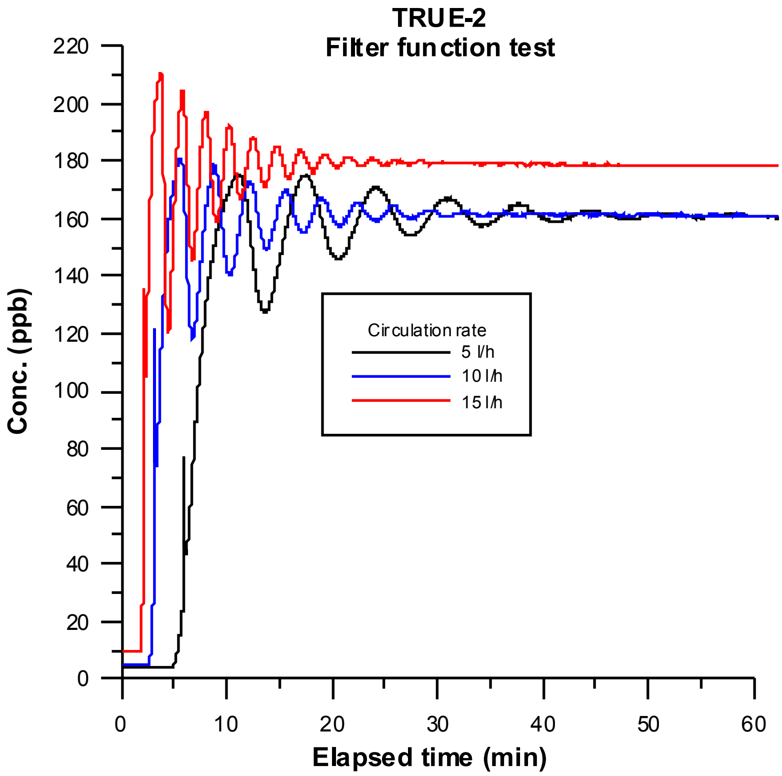


***Figure 2**. Laboratory test of tracer homogenisation. The plots show the concentrations of the three tests starting at the time of the injection.*

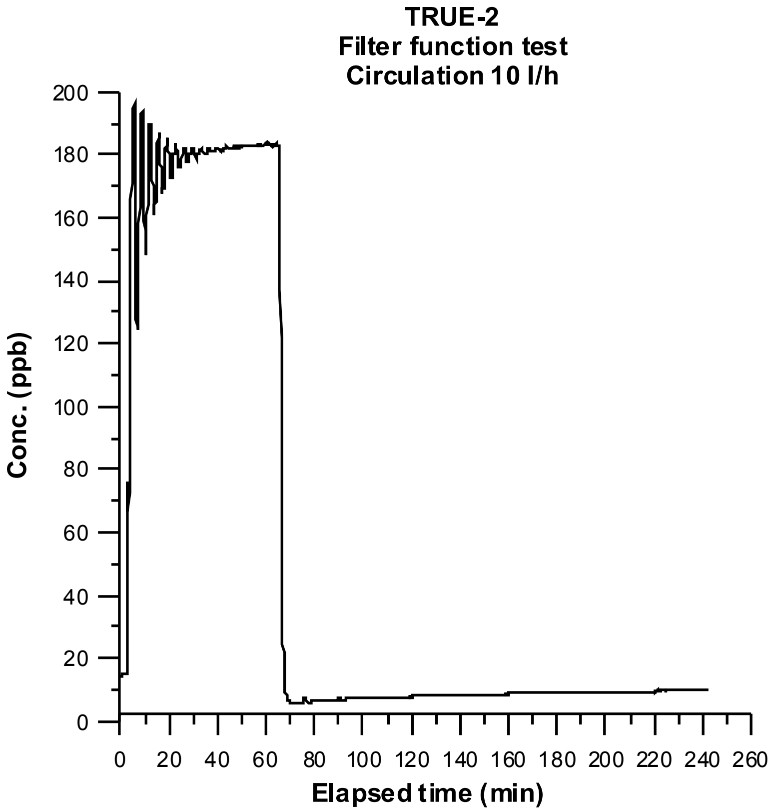


***Figure 3**. Laboratory test of tracer homogenisation. The plot shows the tracer concentration during the course of injection and the exchange.*

Conclusions

The results from the two sets of tests, Figure 2 and the video film, both show that the mixing of the tracer in the section is satisfactory. The successful exchange of the labelled water for unlabelled water (Figure 3) accentuates the apprehension that the mixing of the tracer in the section is satisfactory.

All the demands put on the packer system in the part Specifications are hereby fulfilled.

Client/ Projectleader

(SKB / Anders Winberg)

Test date

1999-07-07 – 1999-07-08 and 1999-07-28

Test locality

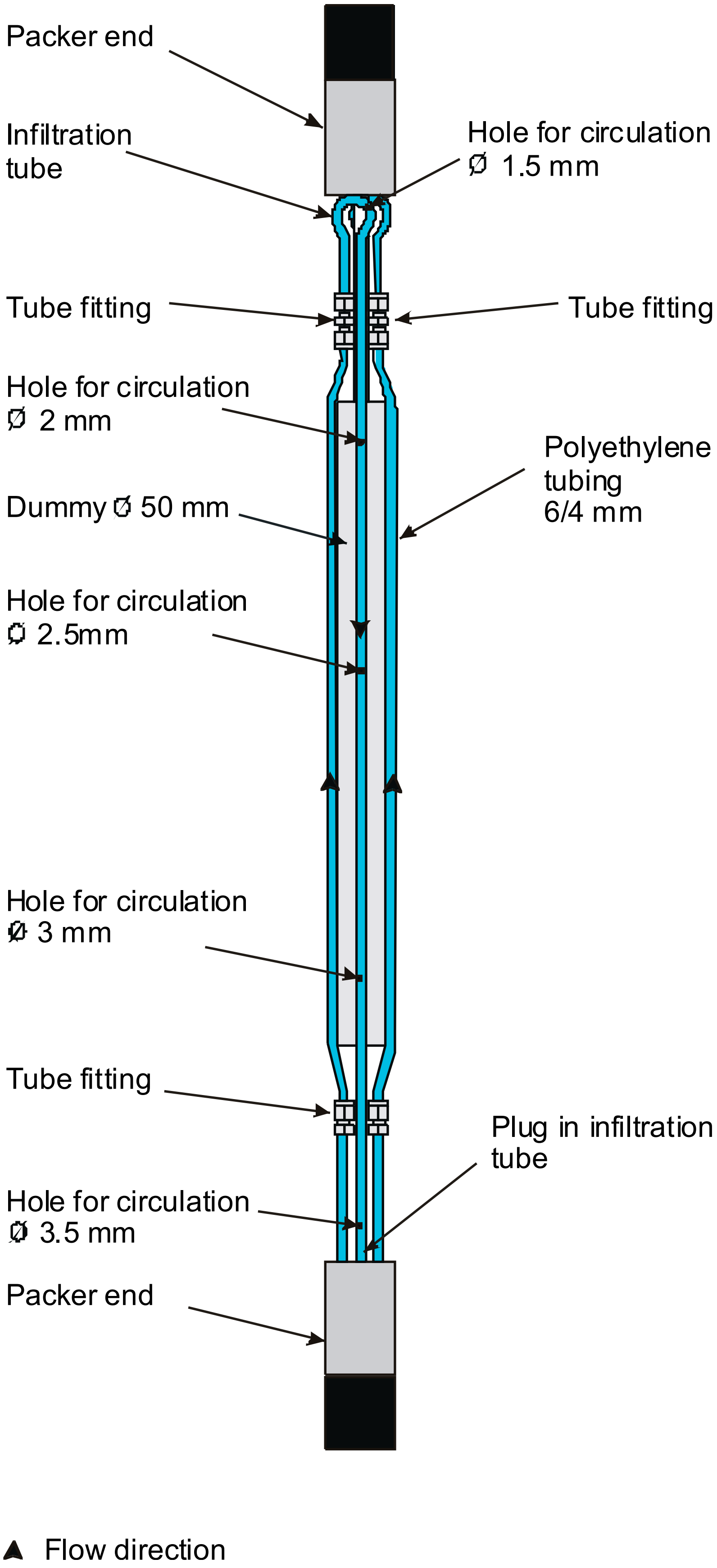
The tests were performed at GEOSIGMA workshop at Librobäck Uppsala

Test manager/operator

Peter Andersson/Magnus Holmqvist

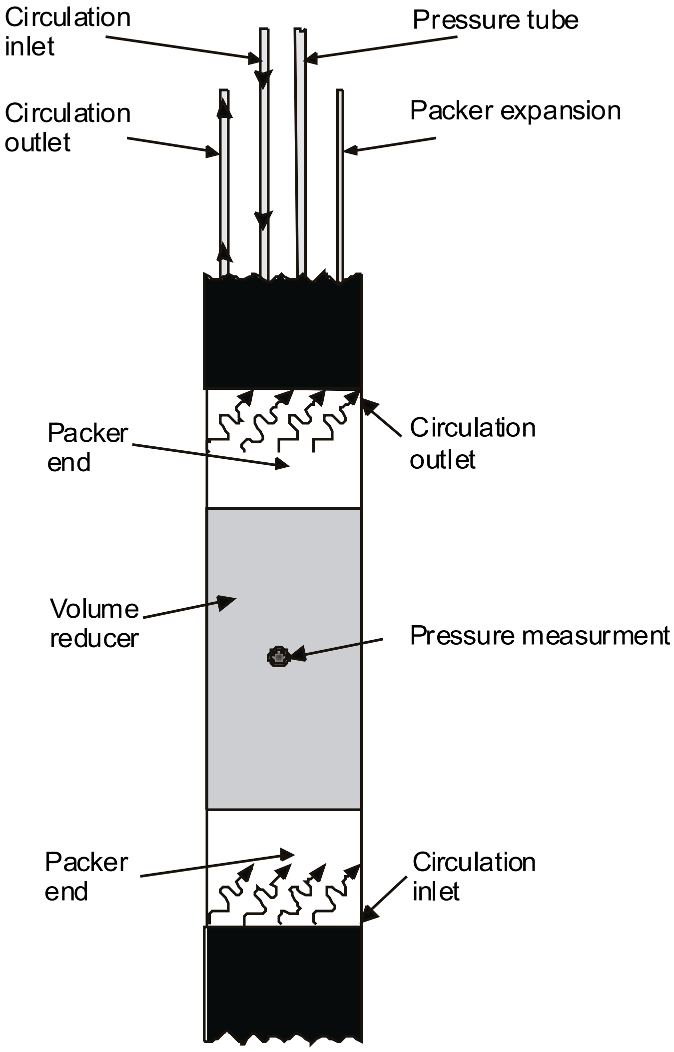
Appendix 2

Old borehole equipment including packers, dummy and infiltration tubes.


Packer end
Infiltration tube
Hole for circulation Ø 1.5 mm
Tube fitting
Tube fitting
Hole for circulation Ø 2 mm
Polyethylene tubing 6/4 mm
Dummy Ø 50 mm
Hole for circulation Ø 2.5mm
Hole for circulation Ø 3 mm
Tube fitting
Plug in infiltration tube
Hole for circulation Ø 3.5 mm
Packer end
▲ Flow direction

Appendix 3

New borehole equipment including packers, volume reducer and tubes.


Circulation inlet
Pressure tube
Circulation outlet
Packer expansion
Packer end
Circulation outlet
Volume reducer
Pressure measurment
Packer end
Circulation inlet