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Äspö Hard Rock Laboratory

TRUE 1st Stage Tracer test programme

Tracer tests with sorbing tracers, STT-2

Experimental description and preliminary evaluation

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July 1999

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Keywords: TRUE-1, tracer test, sorbing tracers

Abstract

This report describes the performance and evaluation of the third tracer test with radioactive sorbing tracers (STT-2) within the TRUE-1 project. The test was performed in the detailed scale at the TRUE-1 site, Äspö HRL, with the main objective to test equipment and procedures for tests with radioactive sorbing tracers to be performed in later stages of the TRUE Project. The test also aimed at increasing the understanding of transport and retention of sorbing species in crystalline rock and obtaining in situ data of sorption and study the influence of a decreased flow rate on the transport of radionuclides compared to earlier performed sorbing tracer tests in the same flow path.

STT-2 was made by injecting three conservative (non-sorbing) and nine sorbing tracers in a radially converging flow geometry over a distance of 4.7 m within Feature A. Breakthrough from ten of the twelve tracers injected was detected in the pumping section. Numerical modelling using a simple one-dimensional transport model with advection, dispersion and linear sorption, showed that the breakthrough of conservative tracers (Uranine, HTO and Br) and the weakly sorbing tracer Na could be relatively well simulated. The breakthrough curves for the moderately sorbing tracers Ba, Rb and Cs could not be well fitted, indicating that additional processes are needed to explain the breakthrough.

Executive Summary

This report describes the performance and preliminary evaluation of the third TRUE-1 tracer test with sorbing tracers, STT-2. The test was performed in the detailed scale (<10 m) within Feature A at the TRUE-1 site at the Äspö HRL.

The main objective of TRUE-1 STT-2 was to test equipment and procedures for tests with radioactive sorbing tracers to be performed in later stages of the TRUE Project. Secondly, to increase the understanding of transport and retention of sorbing species in crystalline rock and to obtain in situ sorption data and study the influence of a decreased flow rate on the transport of radionuclides compared to earlier performed sorbing tracer tests.

STT-2 was performed in Feature A in a radially converging flow geometry between borehole sections KXTT4 R3 → KXTT3 R2. In total twelve tracers, three conservative (Uranine, Tritiated water and ^{82}Br) and nine weakly to moderately radioactive sorbing tracers (^{22}Na, ^{42}K, ^{47}Ca, ^{85}Sr, ^{99m}Tc, ^{131}Ba, ^{133}Ba, ^{86}Rb and ^{134}Cs) were mixed and injected as a finite pulse with a duration of four hours. Tracer breakthrough in the pumping section was monitored for all tracers injected, except ^{99m}Tc and ^{42}K. The breakthrough curves show, for the conservative tracers, one narrow and high peak and a secondary wider and almost equally high peak. For the weakly sorbing tracers, the first peak is lower and not that distinct and for the moderately sorbing tracers it is not seen at all. This indicates that transport occurs in two different flow paths.

The experimental setup was, with some modifications, identical to the one used in STT-1b (Andersson et al., in prep.), STT-1 (Andersson et al., 1998) and PDT-3 (Andersson & Wass, 1998). To get an efficient tracer exchange (ending of tracer pulse), the exchange procedure was repeated twice during STT-2. The removal of tracer solution in STT-2 resulted in a reduction of about 90 % of the mass in the tracer injection loop. Prior to the performance of STT-1b a redox probe was installed in the sampling loop for the withdrawn water due to the use of the redox-sensitive tracer Tc. Both Tc and the redox probe were also used in STT-2. In order to continuously analyse the breakthrough of γ-emitting radionuclides (in-situ monitoring) a HPGe-detector was installed in the sampling loop measuring in line on the tubing. The conclusion from STT-1b, STT-1 and PDT-3 that the injection and sampling (pumping) system worked very well is also valid for STT-2.

The injection procedure, during which the highest doses of radioactivity could be expected, was performed with very low doses to personnel. The activity of the water discharged into the tunnel only showed a temporary increase of the background activity at the time of the breakthrough peak.

In STT-1 and PDT-3 it was found that the calculated mass recoveries were consequently >100 % (Andersson et al., 1998). The conclusion was that the excess recovery may be caused by assigning a too small volume of the borehole section. Thus, by increasing the borehole volume in KXTT4 R3 from 1898 ml to 2154 ml (13 %) a recovery of 100 %

was achieved. This larger volume has also been used for the calculations in STT-2. Calculated mass recovery based on integrated mass flux was 96 % for Uranine and 83-85 % for the other conservative tracers used (HTO and Br). The recoveries calculated based on weighing and concentration measurements of tracer mass from the exchange procedure showed some inconsistencies. The values for Uranine using the two different methods were very consistent, 96 % and 98 % respectively. For the other tracers the recoveries calculated from weighing and concentration measurements were found to be much lower than the ones calculated from integration. Based on earlier tests and uncertainties in the weighing and concentration measurements, the values determined by integration of the injection and breakthrough curves were considered to be the most appropriate to use.

The flow path KXTT4 R3 → KXTT3 R2 has earlier been investigated in seven tracer runs with pumping rates varying between 0.1 to 0.4 l/min. The general results of the tests show low recovery for low pumping rate, lower recovery for a dipole flow field and very similar transport parameters between the tests. The tests performed in exactly the same flow geometry as STT-2, RC-1 and PDT-2, show some significant differences. The most significant one is the head difference between injection and pumping that is much larger during STT-2. This is interpreted as boundary effects caused by the depletion in hydraulic head closer to the tunnel.

The main difference compared to other investigated flow paths in Feature A is that the previous converging tests show an anomalous high dispersivity for the investigated flow path. One explanation for this, put forward by Andersson &Wass (1998), may be that there are two water-conducting fractures in the injection interval with similar transport properties. The detailed flow log and the BIPS log also support this conclusion.

The transport of the radioactive sorbing tracers showed significant retardation for all tracers. The retardation coefficients determined from a simple linear surface sorption model were found to vary between R=1.5 for Na to R=140 for Cs. A comparison with retardation coefficients determined from laboratory data (Andersson et al., 1997a), from STT-1 (Andersson et al., 1998) and from STT-1b (Andersson et al., 1999) shows the same relative order between the species whereas the parameter values are significantly higher for all species in the in-situ tests and somewhat higher in STT-2 than in the other tests.

The one-dimensional model applied worked reasonably well in the simultaneous fit of the conservative tracer breakthrough (Uranine) and the weakly sorbing tracer Na or Sr. The conservative breakthrough could not be fitted with a single flow path. The fits using Uranine and one of the moderately sorbing tracers Ba, Rb or Cs were not good. Thus, the linear surface sorption process alone cannot explain the retardation of these species.

Contents

1 Introduction

1.1 Background

A programme has been defined to increase the understanding of the processes that govern retention of radionuclides transported in crystalline rock, the Tracer Retention Understanding Experiments (TRUE). The basic idea is to perform a series of tracer tests with progressively increasing complexity.

The first tracer test cycle (TRUE-1) constitutes a development stage for tracer testing technology on a detailed scale using conservative and sorbing tracers in a simple test geometry. In addition, supporting technology development is performed for understanding of tracer transport through detailed aperture distributions obtained from resin injection, and for sampling and analysis techniques for matrix diffusion.

So far, a number of tracer tests have been performed in a selected feature, Feature A, using non-sorbing (conservative) tracers namely; Preliminary Tracer Tests, PTT (Winberg (*ed*), 1996), Radially Converging Tracer Test, RC-1 (Andersson, 1996), Dipole Tracer Tests, DP-1 - DP-4 (Andersson et al., 1997b) and Complementary Tracer Tests, RC-2, DP-5 - DP-6 (Andersson & Jönsson, 1997). A number of preparatory tests for the sorbing tracers tests have been performed including a series of dilution tests (Andersson & Wass, 1997) and three tracer tests in radially converging flow geometry, PDT-1 - PDT-3 (Andersson & Wass 1998).

Two tracer tests with sorbing tracers using two different flow paths have previously been performed in Feature A, STT-1 (Andersson et al., 1998) and STT-1b (Andersson et al., in prep.). In June 1998 a third tracer test with the same test geometry as in STT-1 but with lower pumping rate was started, STT-2.

This report describes the results and preliminary evaluation of this third tracer injection with sorbing tracers, STT-2, at the TRUE-1 site at the Äspö HRL.

1.2 Objectives

The overall objective for the tests with sorbing tracers was to test equipment and procedures for tests with radioactive sorbing tracers to be performed in later stages of the TRUE Project. Secondly, to increase the understanding of transport and retention of sorbing species in crystalline rock. The purpose of STT-2 was to obtain additional in situ data of sorption from a selected flow path in Feature A and to study the influence of a decreased flow rate on the transport of radionuclides compared to STT-1 and STT-1b.

2 Experimental setup

2.1 Equipment and tracers used

2.1.1 Borehole equipment

Each borehole in the TRUE-1 array is instrumented with 4-5 inflatable packers such that 4-5 borehole sections are isolated. All isolated borehole sections are connected to the Äspö HRL Hydro Monitoring System (HMS) through data loggers (Borre6). Each of the sections planned to be injection or sampling sections are equipped with three nylon hoses, two with an inner diameter of 4 mm and one with an inner diameter of 2 mm. The two 4-mm hoses are used for injection, sampling and circulation in the borehole section whereas the 2-mm hose is used for pressure monitoring.

The borehole sections in Feature A are also equipped with volume reducers (dummies) and a perforated tube, cf. Appendix B. The perforated tube and dummies are important prerequisites to achieve a complete and fast homogenisation of the tracer solution added to the system. The volume reduction of the system, including tubing, due to the dummies is about 40 % for a 1-m section length and 60 % for a 2-m section.

2.1.2 Injection equipment

A schematic drawing of the tracer injection equipment is shown in Figure 2-1. 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.

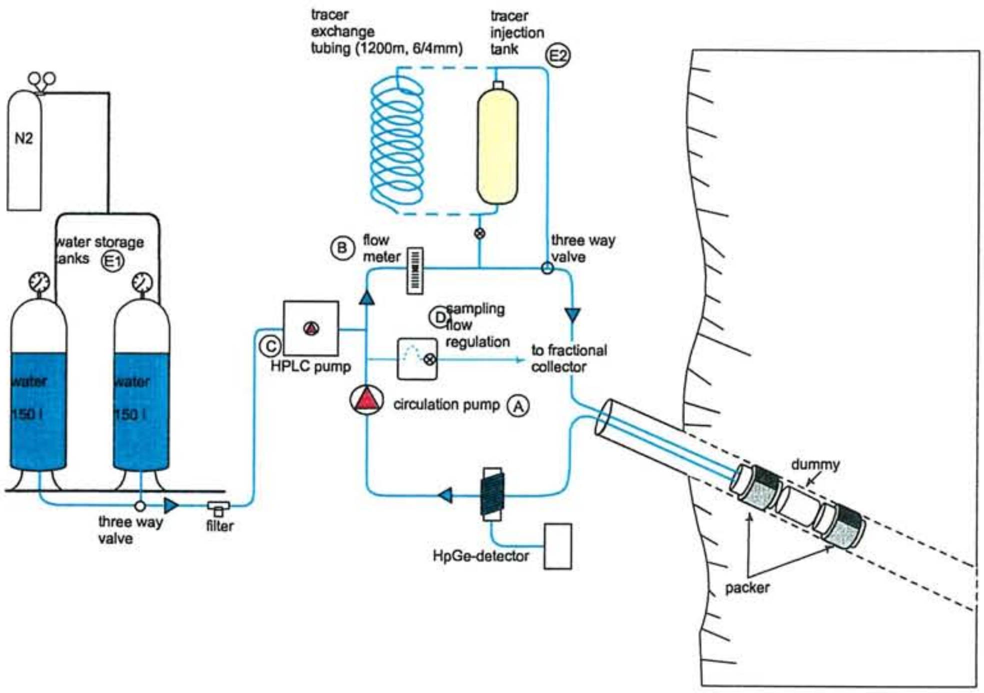

Figure 2-1 Schematic drawing of the injection system for the TRUE-1 tracer tests with sorbing tracers.

Circulation is controlled by a pump with variable speed (A) and measured by a flow meter (B). Tracer injections are made either directly into the circulating loop with a HPLC plunger pump (C) or by switching a three-way valve so that the circulating water passes through a stainless steel vessel (E2) filled with tracer solution. Thus, unlabelled water from the circulation loop enters the bottom of the vessel and tracer labelled water enters the circulation loop from the top of the vessel. The three-way valve is then switched back again after replacing the volume of the vessel. The tracer solution in the circulation loop can also be replaced with unlabelled water by switching the three-way valve so that the circulating water passes through a long (1200 m) tube filled with unlabelled formation 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. Water from Feature A used for the tracer exchange is stored in a separate pressurised vessel (E1) under nitrogen atmosphere.

The tracer concentration in the injection loop is measured both in situ and by sampling and subsequent 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 in situ monitoring of tracer content in the injection system (source term) is made by using a HPGe-detector measuring in-line on the tubing (γ-emitting radionuclides). Further details about the equipment are given in Andersson, (1996).

2.1.3 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 2-2. 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 tracer concentration in the detection loop is measured both in situ and by sampling and subsequent analysis. The sampling is made with two independent systems, a ”constant leak” system producing 8 ml samples (same as the injection loop) integrated over some time (5-100 minutes) and a 24-valve sampling unit producing discrete 1 litre samples. In order to continuously analyse the breakthrough of γ-emitting radionuclides (in-situ monitoring) a HPGe-detector was installed in the sampling loop measuring in line on the tubing.

After sampling, the pumped water is led through a redox potential probe and further through a nylon vessel where the water is degassed. The reason for degassing is that measurement of dye tracer content is made by an in line field fluorometer. As fluorometry is an optical method, gas bubbles need to be removed in advance otherwise they will 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.

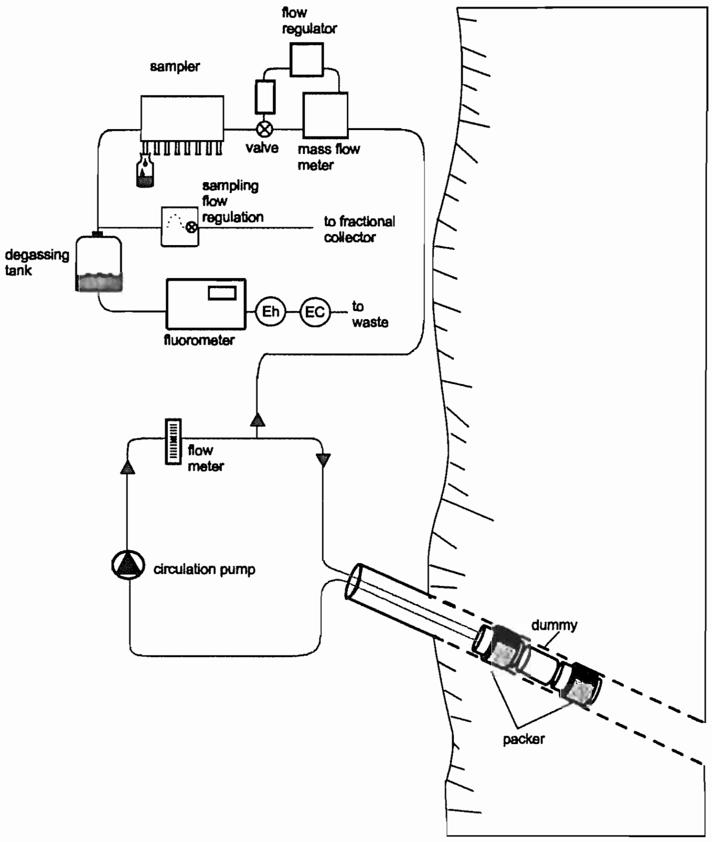

Figure 2-2 Schematic drawing of the sampling system for the TRUE-1 tracer tests with sorbing tracers.

2.1.4 Tracers used

During STT-2, a mix of totally twelve different tracers, both conservative and sorbing, was injected. The sorbing tracers used were nine radioactive, γ-emitting, isotopes of mono- and divalent cations, cf. Table 3-2. These tracers needed to be injected in such low concentrations that the chemical conditions in Feature A were kept unchanged. Another restriction was the maximum permitted dose rates. The conservative tracers used were Uranine (Sodium Fluorescein), tritiated water (HTO) and the radioactive γ-emitting tracer ^{82}Br. The equipment was also tested for sorption of the tracers used in STT-2 and no significant sorption could be detected, cf. Ittner & Byegård (1997).

2.2 Injection Procedure

A tracer solution (3.5 litres) containing all twelve tracers was prepared at SKB BASLAB. The radionuclides were dissolved in de-ionised water and mixed into a tracer stock solution with H^3HO (HTO) and Uranine. The stock solution was pH-adjusted to ~7.5 by addition of diluted NaOH. A sample was taken before transport of the stock solution to the experimental site. After transport to the TRUE-1 site the tracer solution was pumped from the transport vessel into the stainless steel injection tank using a peristaltic pump. Non-traced water (about 1 litre) was added from the water storage vessel to fill the injection tank completely. The injection tank was then pressurised by adding water with the HPLC injection pump until the pressure in the injection section was reached. The three-way valve in the injection loop was then switched and the injection started, cf. Figure 2-1.

The injection of tracer was performed as a finite pulse injection with a length of four hours. After four hours of injection the tracer solution was exchanged with unlabelled water as described in Chapter 2.1.2. The exchange procedure lasted 50 minutes. A second exchange was made one hour after the end of the first one to achieve an even more efficient exchange (>90 %). The latter exchange lasted for 40 minutes.

The recovered tracer solution was stored in the exchange tubing and in plastic vessels for subsequent measurement and assessment of recovered mass.

2.3 Sampling and detection procedures

Both the injection concentrations (activities) and the concentrations in the pumped water were monitored using the equipment described in Chapter 2.1.2 and 2.1.3. The decrease in injection concentration was measured by sampling for Uranine and HTO with samples taken every 2nd minute during the initial 40 minutes of injection and then every 30 minutes up to 4 hours. The sampling frequency was then increased again to every 4th minute during the exchange procedure from 4 to 6.5 hours. Afterwards, samples were taken once every hour, gradually decreasing to one sample/10 hours.

During the tracer injection and breakthrough periods, the radioactivity was measured by on-line γ-spectroscopy using a HPGe-detector (25 % relative efficiency, EG&G ORTEC, USA). The volume of the tube passing the detector at a distance of ~1 cm was ~1 ml and the detector was calibrated using a tube filled with a mixed radionuclide standard (Amersham QCY44). The radionuclides were measured with the in line detector in the injection loop with a somewhat higher frequency than the discrete sampling during the first seven hours. After this period activity measurements were made over a period of one hour, gradually decreasing to 24 hour periods at later stages of sampling (~500 hours). In the breakthrough loop, the in-line measurements were made with the same frequency as the discrete sampling.

The sampling in the pumping borehole was performed using the two independent sampling systems described in Chapter 2.1.3. Both systems were set to take samples once every 10th minute during the first 13 hours. The sampling frequency was then gradually decreased to one sample/96 hours at the end of the test period.

The samples were stored in special transport cases and transported to SKB BASLAB for analysis. The samples were subsequently divided and treated in different ways depending on the analysis method to be employed. A flow chart describing the different treatment and analysis steps at BASLAB is shown in Figure 2-3.

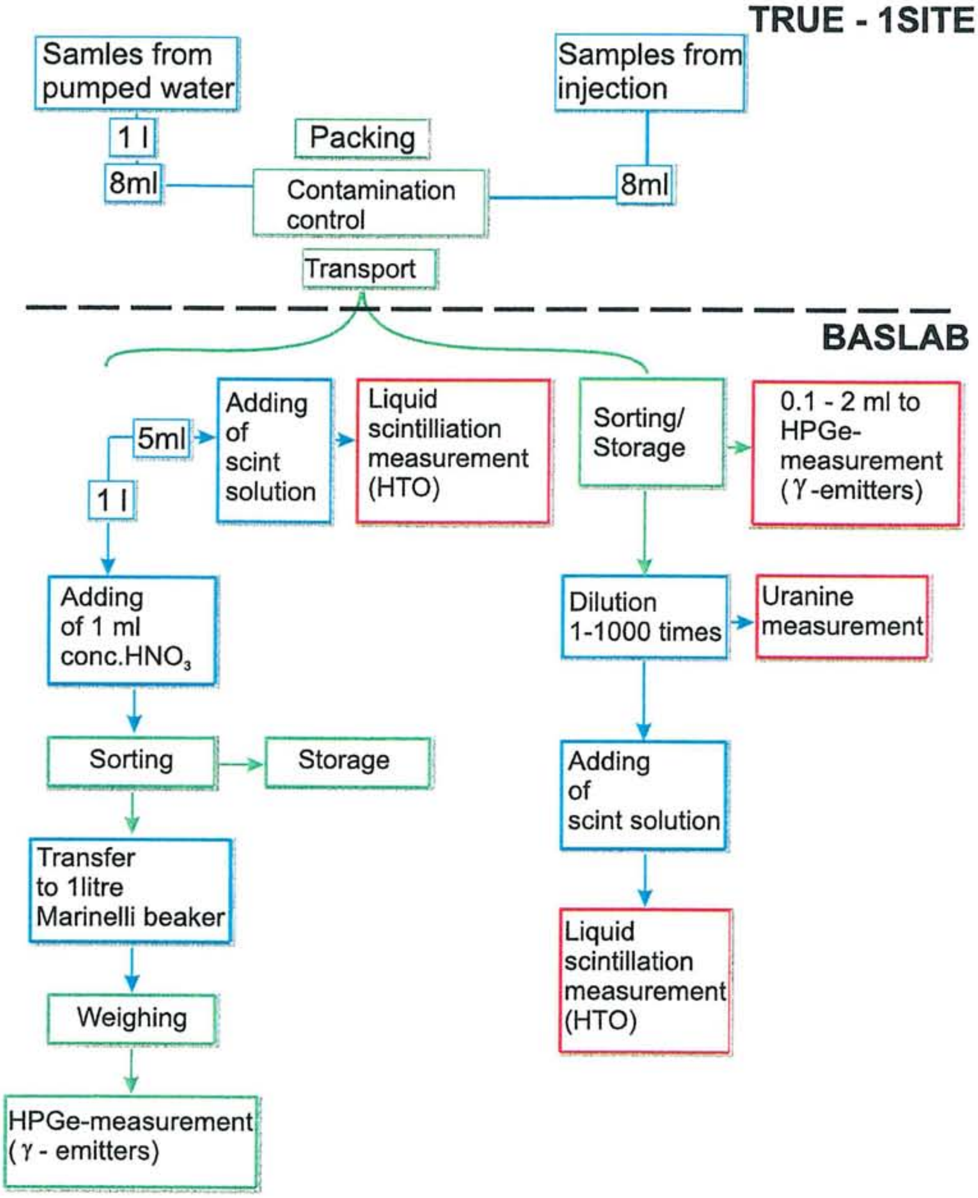

Figure 2-3 Schematic drawing of the handling and analysis of samples from STT-2 at BASLAB.

2.4 Environmental sampling and control

Besides measuring samples from the TRUE-1 experimental site, environmental samples have been taken in the tunnel to monitor potential leakage/spills. A gamma detector was installed in the tunnel weir, located at tunnel length 3/020 m, to which the drainage from the experimental site is connected. The detector was connected to the Äspö computer network allowing continuous monitoring. The radiation levels are shown in Figure 2-4, where levels are given in counts per second (cps). During the breakthrough from STT-2 a slight increase can be seen the day after injection. A sample taken in the weir on June 6th and analysed at BASLAB shows activities of HTO of about 140 Bq/l, ^{22}Na 1.7 Bq/l and ^{85}Sr 1.2 Bq/l. This agrees well with the expected concentration due to the estimated dilution of the site drainage in the weir. The activities of the other nuclides were below detection limits. No non-natural radioactivity has been detected in the other environmental samples.

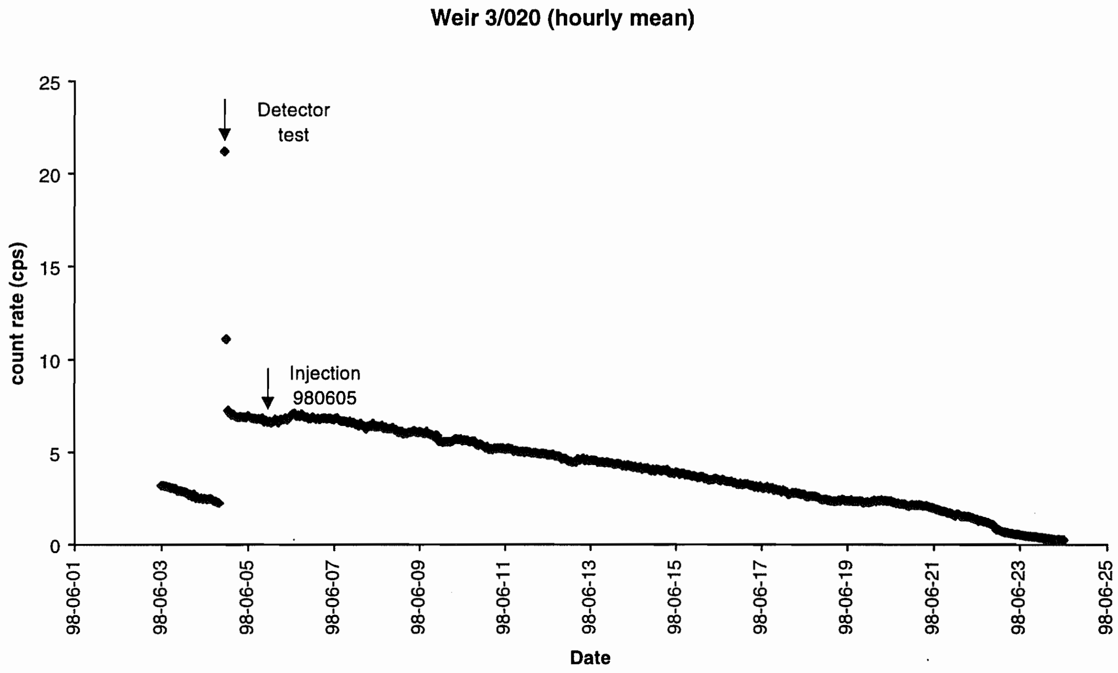

Figure 2-4 Hourly mean values of radiation level (counts per second) in the tunnel weir at 3/020 m during STT-2.

3 Results

3.1 Log of events

The test period described in this report lasted between June 5th, 1998 and December 10th, 1998. The tracer injection and pumping were performed without major disturbances until September 30th, when a pump failure occurred as a combination of a power failure and a clogged filter. The pump (flow regulator) was replaced and pumping continued. This "new" flow regulator was not connected to the HMS-system and a change back to the earlier one used (connected to HMS) was made after necessary repair. The pumping was stopped on December 10th, 1998.

Table 3-1 Log of events during STT-2.

Date	Time	Event
970612	13.30	Start pumping in KXTT3 R2, Q=0.400 l/min
980526	14.15	Decreased pumping in KXTT3 R2, Q=0.200 l/min
980605	11.10	Start tracer injection KXTT4 R3
980605	15.10	Start water injection (removal of tracer solution) in KXTT4 R3
980605	16.00	Stop water injection in KXTT4 R3
980605	17.00	Start water injection (removal of tracer solution) in KXTT4 R3
980605	17.40	Stop water injection in KXTT4 R3
980923	16.40-17.00	Changing tube in injection loop KXTT4 R3
980929	8.30-	Increasing flow in KXTT3 R2 during the day from 0.200 l/min to 0.220 l/min. Clogged filter?
980930	9.30	Pump failure in KXTT3 R2 due to power failure and clogged filter. Flow decreased to ~0.130 l/min.
981002	~11.00	Flow regulator changed in KXTT3 R2, not connected to HMS. Q=0.200 l/min
981020	14.40	Change back to the earlier used, repaired flow regulator in KXTT3 R2, connected to HMS. Q=0.200 l/min
981210	13.50	Stop pumping in KXTT3 R2

3.2 Tracer injections

The twelve tracers injected during STT-2 are listed in Table 3-2 together with the maximum concentrations measured in the injection loop. The decrease in concentration versus time was used to calculate the flow rates through the borehole section by plotting the natural logarithm of concentration versus time. Theoretically, a straight line relationship exists between the natural logarithm of the relative tracer concentration (C/C_0) and time (t):

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

where 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).

Table 3-2 Tracers used in STT-2, half-life and maximum concentration (activity) measured in the injection loop.

Tracer	Half-life	Injection conc. C_0 *
Uranine	-	66.9 mg/l
HTO (Tritiated water)	12.3 y	$2.30 \cdot 10^8$ Bq/kg
^{82}Br (Bromine)	35.3 h	$8.31 \cdot 10^6$ Bq/kg
^{22}Na (Sodium)	2.6 y	$2.48 \cdot 10^6$ Bq/kg
^{47}Ca (Calcium)	4.5 d	$6.01 \cdot 10^5$ Bq/kg
^{85}Sr (Strontium)	64.9 d	$7.13 \cdot 10^6$ Bq/kg
^{42}K (Potassium)	12.4 h	$1.04 \cdot 10^6$ Bq/kg
^{99m}Tc (Technetium)	6.0 h	$1.65 \cdot 10^7$ Bq/kg
^{131}Ba (Barium)	11.5 d	$2.30 \cdot 10^6$ Bq/kg
^{133}Ba (Barium)	10.5 y	$4.58 \cdot 10^5$ Bq/kg
^{86}Rb (Rubidium)	18.7 d	$9.58 \cdot 10^6$ Bq/kg
^{134}Cs (Caesium)	2.1 y	$5.81 \cdot 10^6$ Bq/kg

* maximum concentration measured in injection section

In Figure 3-1 the injection concentrations versus time, normalised to the maximum injection concentration (activity) for the different tracers, are plotted in the same diagram, cf. Table 3-2. It clearly shows the effect of retention on the borehole walls in the injection interval resulting in a much faster decrease in concentration for the more strongly sorbing species like Ba, Rb, Tc and Cs. Thus, only the conservative tracers were used to determine injection flow rates. Due to the large uncertainties in the data caused by short half-life in combination with large analysis errors the data set for K-42 and Ca-47 are quite scattered. The dilution curve for the conservative tracer Uranine is shown in Figure 3-2. The calculated injection flow rates (compensated for sample volumes) are given in Table 3-3. The tracer injection curve for Uranine is also presented in log-log scale in Appendix A.

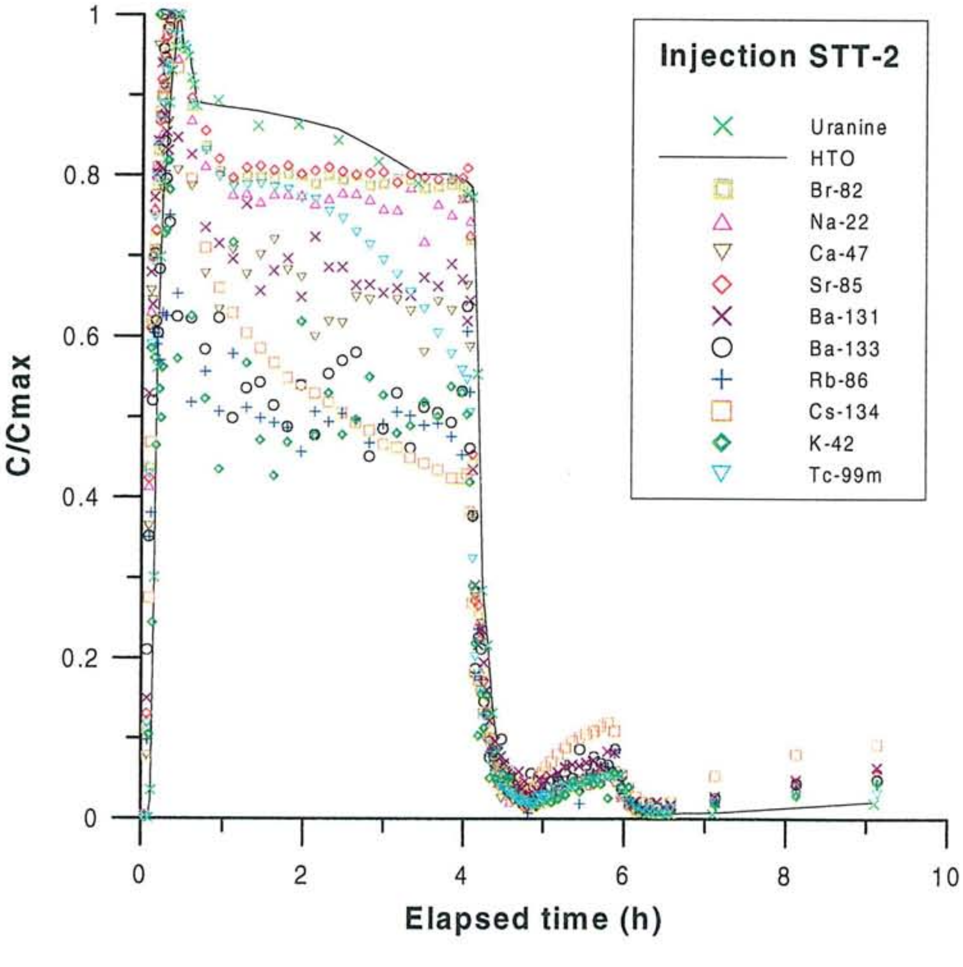

Figure 3-1 Tracer injection concentrations (activities) normalised to maximum measured concentration (activity) in the injection section KXTT4 R3 during the first 10 hours of injection.

The concentration of the conservative tracers Uranine and Tritiated water (HTO) are higher and also somewhat delayed compared to the sorbing ones during the rising and falling parts of the curve. This is an effect of the different sampling/detection systems where the sorbing species are measured in line and Uranine and HTO concentrations are derived from discrete samples resulting in samples averaged over a longer time period than in the in line measurements. However, the delay is only about 5 minutes and is therefore not considered to be important for the evaluation of the test. The relative concentration is also higher due to the averaging of the maximum concentration. A similar effect can be seen between 5 and 10 hours of injection where the low sampling flow rate gives a significant delay for Uranine and HTO.

The time period between 4 and 10 hours requires some comments. After 4 hours of injection the tracer solution was exchanged with unlabelled water as described in Chapter 2.1.2. The exchange procedure lasted for 50 minutes. Since the exchange procedure in STT-1 had not been so effective (Andersson et al., 1998) and the tracer concentration (activity) was increasing significantly in the injection section after the first exchange, a second exchange was made one hour after the end of the first one. This procedure was also used in STT-1b. The second exchange lasted for 40 minutes. The tracer exchange procedure gave a total reduction of about 90 % of the mass in the injection loop. The tracer solution is introduced into the borehole volume through a stainless steel tube perforated with several narrow holes to achieve optimal mixing at a certain pre-selected circulation rate, in this case q=10 l/h, cf. Appendix B. Some of these holes are very narrow and it is likely that precipitations have been formed around the holes limiting the flow. This may result in less mixing in parts of the borehole volume, i.e. more or less stagnant volumes. Hence, when the exchange procedure is finished, concentrated tracer solution from these more stagnant parts of the borehole volume slowly mixes with the unlabelled water volume and the concentration of tracer rises again, cf. Figure 3-1 and 3-2.

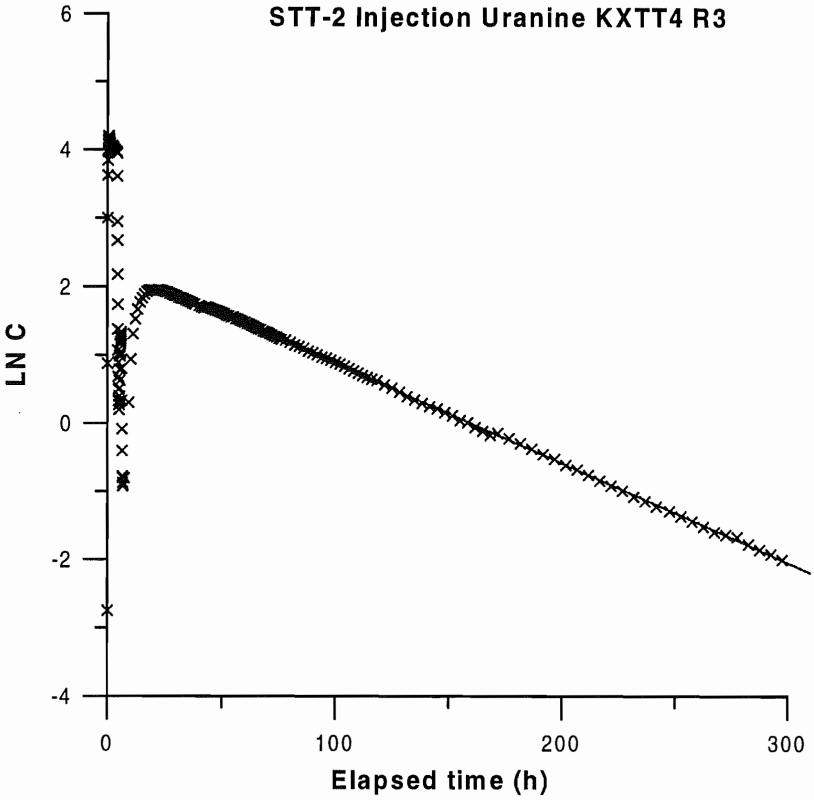

Figure 3-2 Tracer injection concentration (lnC) versus elapsed time, t (h), for Uranine in the injection section KXTT4 R3 during the first 300 hours of injection in STT-2.

Two time periods with somewhat different injection flow rates were identified, cf. Table 3-3 and Figure 3-2. During the first period (0-4 h) the calculated flow rates for Uranine and Tritiated water (HTO) are quite consistent and high while they are much lower for ^{82}Br. This is attributed to a higher uncertainty in the calculated values as indicated by the correlation coefficients for the straight-line fit to the data. The time period after the exchange procedure shows more consistent flow rates for all three tracers. For all calculations of mass flux and recovery presented in this report, the value determined for Uranine has been used. The flow rate determined for 25-310 hours has been used for the entire injection period due to the high certainty in data indicated by a high correlation coefficient.

In STT-1 it was found that the calculated mass recoveries were consistently >100 % (Andersson et al., 1998). This was also observed during PDT-3 (Andersson & Wass, 1998). The conclusion is that assigning a too small volume of the borehole section used in Equation 3-1 may cause a significant error and results in the excess recovery. Such an error may occur even if the borehole and dummy diameters are only a few tenths of a millimetre different from what have been assumed as nominal. Thus, by increasing the borehole volume in KXTT4 R3 from 1898 ml to 2154 ml (13 %) a recovery of 100 % was achieved. This larger volume has also been used for the calculations in STT-2.

Table 3-3 Injection flow rates at different time periods during STT-2 calculated from the dilution of the used conservative tracers. R is the correlation coefficient for the straight line fit.

Tracer	Elapsed time (h)	Flow (ml/h)	R
Uranine	0-4	86.2	0.9649
	25-310	28.8	0.9997
HTO	0-4	82.5	0.9618
	25-330	29.4	0.9997
Br-82	0-4	10.6	0.5798
	21-178	28.2	0.9989

3.3 Tracer breakthrough

3.3.1 Tracer breakthrough data interpretation

Tracer breakthrough in the pumping section was observed for ten of the twelve tracers injected. The tracers not detected in the pumping section were ^{99m}Tc and ^{42}K. Breakthrough of ^{99m}Tc was not expected as it is strongly sorbing under reducing conditions. ^{42}K could not be detected due to the short half-life (12 h). The breakthrough curves (Figures 3-3 and 3-4) show, for the conservative tracers, one narrow and high peak and a secondary wider and almost equally high peak. For the weakly sorbing tracers, the first peak is lower and not that distinct and for the moderately sorbing tracers it is not seen at all. This indicates that transport occurs in two different flow paths. Breakthrough data for ^{47}Ca are quite scattered due to the large uncertainties in the data caused by the short half-life of ^{47}Ca in combination with large analysis errors. Both figures show plots where the concentrations (activities) are normalised to the injection concentration at *t*=2 hours in order to get a good comparison between the different species. The reason for not choosing the maximum concentration is that the latter value is more uncertain due to the concentration peak during the initial part of the injection. All ten breakthrough curves are presented separately in log-log scale in Appendix A.

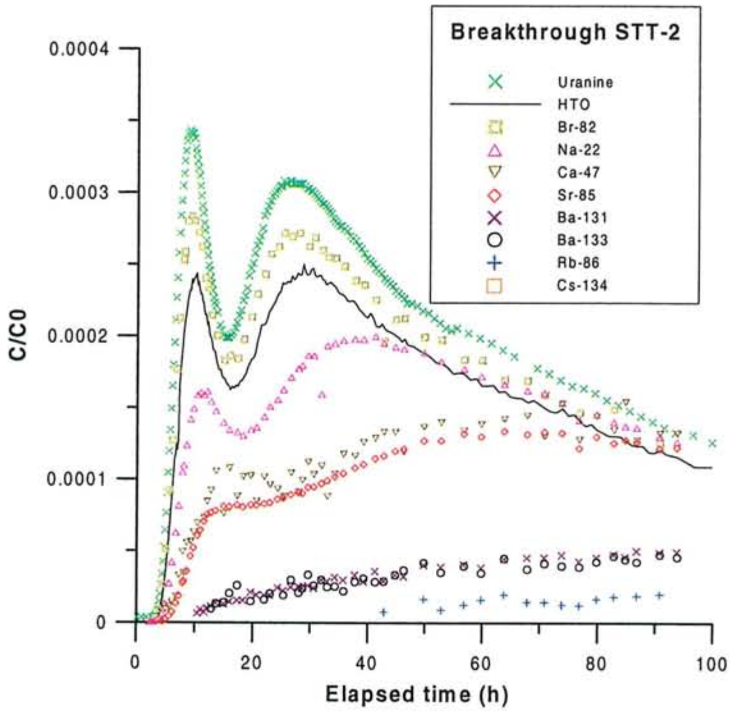

Figure 3-3 Tracer breakthrough after 100 hours in the pumping section KXTT3 R2 during STT-2. Tracer concentrations are normalised to injection concentrations at t=2 hours.

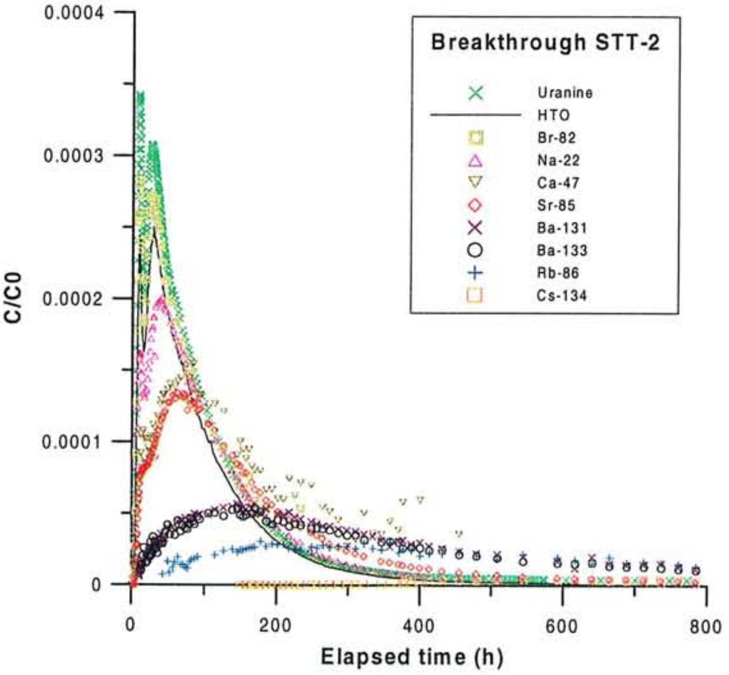

Figure 3-4 Tracer breakthrough after 800 hours in the pumping section KXTT3 R2 during STT-2. Tracer concentrations are normalised to injection concentrations at t=2 hours.

Tracer travel times, t_5, t_{50} and t_{95}, defined as times when 5, 50 and 95 % of the recovered mass has arrived in the pumping section at the stop time of sampling, t_t, were calculated (Table 3-4). The time t_{inj} corresponds to the time at which the monitoring of the injection concentration is terminated.

Table 3-4 Tracer travel times, t_5, t_{50} and t_{95} based on injected mass at t_{inj} for tracers injected during STT-2.

Tracer	t_5 (h)	t_{50} (h)	t_{95} (h)	t_{inj} (h)	t_t (h)
Uranine	11.2	79	805	828	886
HTO	13.5	91	-	578	641
Br-82	12.3	86	-	212	234
Na-22	18.8	120	-	664	3078
Ca-47	25.8	145	433	242	458
Sr-85	30.6	190	-	904	3078
Ba-131	84.3	916	-	592	1130
Ba-133	82.3	949	-	856	3078
Rb-86	157.6	-	-	458	1322
Cs-134	1528	-	-	1848	3078

Based on the mean travel times, t_m, determined from the parameter estimation of the conservative tracers (cf. Section 3.3.2), values of the fracture conductivity, K_{fr} (m/s), were calculated for STT-2 assuming radial flow and validity of Darcy's law (Gustafsson & Klockars, 1981);

$$K_{fr}= \ln(r/r_w)\cdot(r^2-r_w^2) \,/\, 2\cdot t_m\cdot \Delta h \qquad 3\text{-}2$$

where: r = travel distance (m)

r_w= borehole radius (m)

t_m= mean travel time of tracer (s)

Δh= head difference (m)

The equivalent fracture aperture, b (m), was calculated from:

$$b = Q \cdot t_m / \pi \cdot (r^2 - r_w^2) \qquad \text{3-3}$$

where Q (m^3/s), is the mean pumping rate.

Flow porosity, θ_k, was calculated using:

$$\theta_k = K/K_{fr} \qquad \text{3-4}$$

where K is the hydraulic conductivity of the packed-off section of the borehole determined from steady state evaluation of the interference test (Moye's formulae):

$$K = (Q/\Delta h \cdot L) \cdot (1 + (\ln\,(L/2r_w)/2\pi)) \qquad \text{3-5}$$

where L (m) is the length of the packed-off section. It should be noted that the term flow porosity may be misleading to use in a fractured heterogeneous rock as it is defined for a porous media. However, it is often used in fractured media as a scaling factor for transport, but then defined over a finite thickness which, in his case, is defined as the length of the packed-off borehole section ($L = 2.0$ m).

The values calculated using Equations 3-2 through 3-4 are presented together with parameters determined from the numerical modelling of the conservative tracer breakthrough in Table 3-5.

3.3.2 Numerical modelling

The breakthrough curves from STT-2 were evaluated using the one-dimensional advection-dispersion equation with linear sorption (for example Van Genuchten and Alves, 1982):

$$R \frac{\partial C}{\partial t} = -v \frac{\partial C}{\partial l} + D_l \frac{\partial^2 C}{\partial^2} \qquad \text{3-6}$$

where

t is time (s), l is distance along flow path (m), v is the average water velocity along the flow path (m/s), C is the solute concentration, D is the dispersion coefficient (m^2/s), and R is the retardation coefficient.

The following initial and boundary conditions were used:

$$C(l,t) = 0 \quad t = 0 \qquad \text{3-7}$$

$$\frac{\partial C\,(l,t)}{\partial l} = 0 \qquad 1 = \infty \qquad \text{3-8}$$

$$-D \frac{\partial C}{\partial l} + vC = vf(t) \quad 1 = 0 \qquad \text{3-9}$$

where the input function $f(t)$ is:

$$f(t) = C_0 \quad 0 < t \leq t_0 \qquad 3\text{-}10$$

$$f(t) = 0 \quad t > t_0$$

where C_0 is the input concentration and t_0 is the duration of the input period.

Variable tracer input concentration was simulated by superimposing solutions of the above equations. The measured input tracer concentrations were discretised into time intervals, where each time interval was assigned a constant input concentration.

The model applied was used to estimate parameters using an automated parameter estimation program, PAREST (Nordqvist, 1994). The program uses non-linear least square regression. This method finds the best-fit parameters by an iterative procedure, which is thoroughly described in Andersson et al. (1998). This procedure has been used for all tracer tests performed in the TRUE-1 programme.

One of the most interesting parameters to estimate in this case is the retardation factor for the various sorbing tracers. This was accomplished by applying two breakthrough curves simultaneously in the regression procedure. One of the tracers was then considered conservative, while the retardation factor for the other tracer relative to the first one could be determined.

The parameters that were estimated were the average velocity (v), dispersion coefficient (D), the retardation factor (R), and two proportionality factors (f and f_c). The factor f represents the dilution caused by the flow field, while the factor f_c simply is the injection concentration of the retarded solute relative to the conservative one. Whether these factors are estimated or considered known (from measurements) is a subjective choice of the interpreter. In this case it was decided to estimate the proportionality factors, and check whether the values appeared to be reasonable when compared to independent measurements of pumping rates and input concentrations.

The perhaps more common approach to determine R is to estimate v from each breakthrough curve simultaneously, and then take the ratio of the velocities. However, the approach used here should give better results, because both curves are forced to have the same dispersion coefficient and dilution factor (f), which should help revealing model errors. In addition, estimation errors for the parameters should be lower because more points (observations with non-zero sensitivities) are used in the regression.

Another concern when using multiple data sets for regression is that magnitudes of the dependent variable may differ considerably. This is in this case handled by using the reliability weight matrix, **W**. Each observation was assigned a weight reflecting the analytical uncertainty of the tracer sample. Standard deviations of the results of the laboratory samples of the nuclides were obtained based on the measurement time in the laboratory, while the Uranine measurements were assigned an error of one percent of the value down to the detection limit. All nuclide observations were assigned weights equal to the inverse of the variance (standard deviation squared), while the weights for the Uranine samples were assumed to be proportional to the inverse of the assumed error.

The model simulations for STT-2 included two different runs. First a separate run for the conservative tracers assuming conservative transport (no retardation) where all transport processes are described as some apparent dispersivity. This run serves as a check of the input data files and also produces a mean travel time for the tracer. Secondly, each sorbing tracer breakthrough curve was fitted simultaneously with the conservative tracer Uranine. In the presentation of results of earlier tests also separate runs for each sorbing tracer have been presented. This has shown to be easily misinterpreted why it is not made for STT-2.

The injection was simulated for each tracer by discretisation of the measured input function in 40-50 time steps. Figure 3-5 shows the discretisation of the first 25 hours of the input function for Uranine.

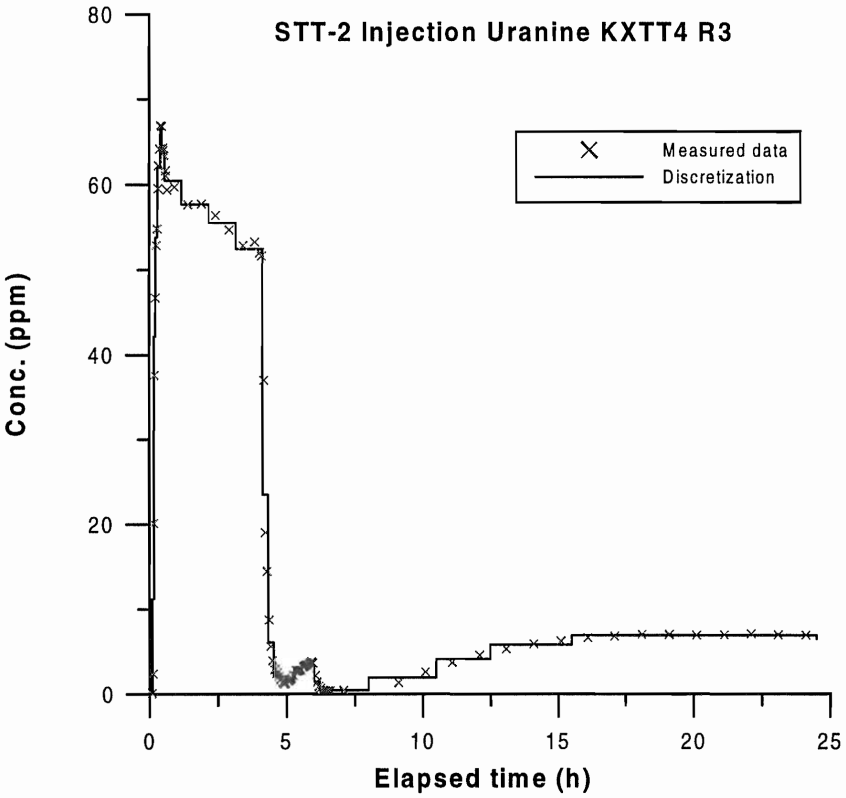

Figure 3-5 Discretisation of tracer injection function for Uranine in section KXTT4 R3 during STT-2 used for modelling with PAREST.

Figure 3-6 shows the best-fit runs for Uranine using one and two flow paths respectively. The model fitted both peaks very well using two flow paths, while the single path fit was much worse. Therefore, two flow paths were used in all model runs, even though the tailing was somewhat better fitted using one flow path only. Flow and transport parameters for the flow path KXTT4 R3 → KXTT3 R2 obtained from tests STT-1 and STT-2 are given in Table 3-5. STT-2 is the first tracer test in this geometry where two flow paths were assumed and used in model runs, hence the parameters may be difficult to compare directly. However, the values of dispersivity for the two-path model are much more realistic than for STT-1, cf Chapter 4.2.

Table 3-5. Summary of flow and transport parameters determined for the flow path KXTT4 R3 → KXTT3 R2 (distance 4.68 m)

Test	Q (l/min)	Δh (m)	R_i (%)	D/v (m)	K_{fr} (m/s)	b (m)	θ_k
STT-1	0.4	7.2-10.5	100	2.0	$4.2 \cdot 10^{-4}$	$1.4 \cdot 10^{-3}$	$0.8 \cdot 10^{-3}$
STT-2	0.2	5.6-8	96	0.35^{*}	$3.4 \cdot 10^{-4*}$	$1.3 \cdot 10^{-3*}$	$1.1 \cdot 10^{-3*}$
				0.46^{**}	$1.0 \cdot 10^{-4**}$	$4.5 \cdot 10^{-3**}$	$4.0 \cdot 10^{-3**}$

* Flow path #1

** Flow path #2

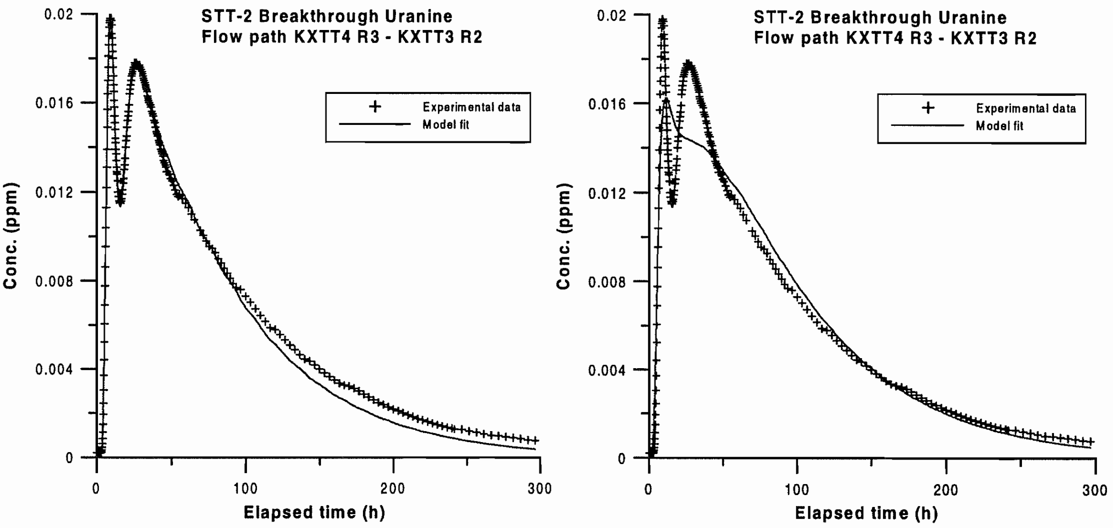

Figure 3-6 Comparison between measured and simulated breakthrough of Uranine in the pumping section KXTT3 R2 during STT-2, a) two flow paths, b) one flow path.

The modelling of each conservative tracer separately using two flow paths resulted in relatively good fits (Figure 3-6 and 3-7) with quite low standard errors, 1-7 %. For Uranine and Br-82 both peaks of the breakthrough curve are well fitted while the tail part is worse, especially for Br. For Tritiated water (HTO) the second peak is underestimated in the model fit but instead the tailing of the breakthrough curve is relatively well fitted. The parameters determined from the model runs of conservative tracers separately are presented in Table 3-6.

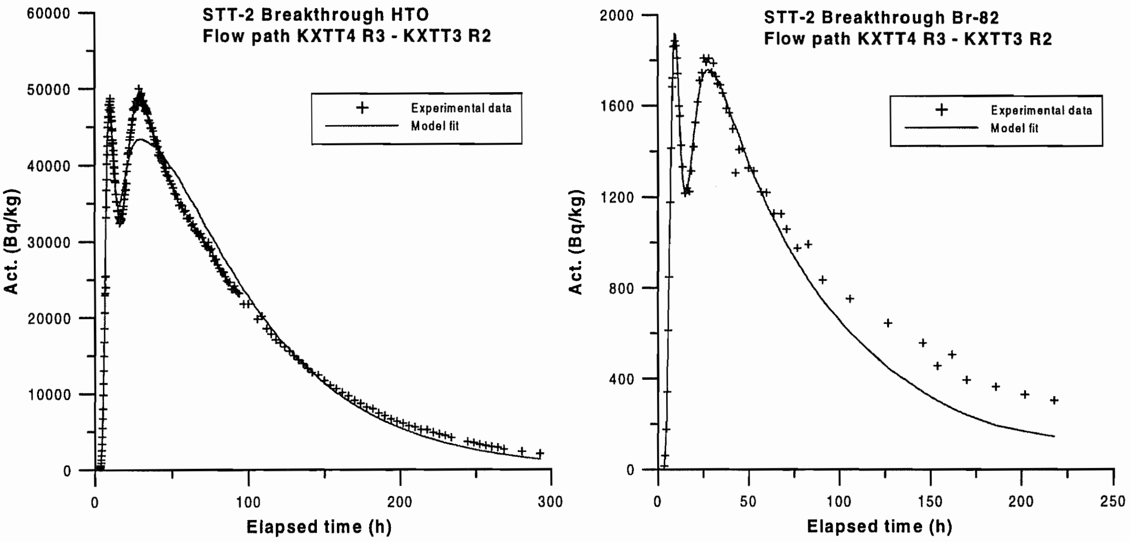

Figure 3-7 Comparison between measured and simulated breakthrough of the radioactive conservative tracers in the pumping section KXTT3 R2 during STT-2. Separate runs for each tracer, a) Tritiated water (HTO), b) Br-82.

Table 3-6 Evaluated parameters for the conservative tracers in STT-2 using PAREST (advection-dispersion model). Separate runs for each tracer. Values within brackets are standard errors in percent.

Tracer	Mean velocity, v (m/s)	Mean travel time, t_0 (h)	Dispersivity, D/v (m)	Proportionality factor, f
Uranine	$1.74 \cdot 10^{-4}$ (1) *	7.5 (1) *	0.35 (3) *	$6.2 \cdot 10^{-4}$ (1) *
	$5.05 \cdot 10^{-5}$ (1) **	25.8 (1) **	0.46 (3) **	$1.4 \cdot 10^{-3}$ (1) **
HTO	$1.78 \cdot 10^{-4}$ (2) *	7.3 (2) *	0.25 (4) *	$3.1 \cdot 10^{-4}$ (6) *
	$4.39 \cdot 10^{-5}$ (2) **	29.6 (2) **	1.2 (7) **	$1.6 \cdot 10^{-3}$ (1) **
Br-82	$1.68 \cdot 10^{-4}$ (1) *	7.7 (1) *	0.32 (3) *	$4.9 \cdot 10^{-4}$ (2) *
	$4.746 \cdot 10^{-5}$ (1) **	27.4 (1) **	0.54 (5) **	$1.3 \cdot 10^{-3}$ (2) **

* Flow path #1
** Flow path #2

The model runs using simultaneous fit of the conservative tracer Uranine and a sorbing tracer are presented in Figure 3-8 (weakly sorbing tracers) and Figure 3-9 (moderately sorbing tracers) and the corresponding parameter values are given in Table 3-7. The values of mean travel time, dispersivity and proportionally factor are in general quite consistent with low standard errors, except for Sr. Some parameters (especially dispersivity) for Na and Cs are associated with somewhat higher standard errors. Retardation coefficients vary between 1.5 for ^{22}Na up to 140 for ^{134}Cs.

The model can relatively well fit the breakthrough curve for a weakly sorbing tracer like Na while the fits for the moderately sorbing tracers Ba, Rb and Cs are much worse especially in the tail part, cf. Figure 3-8 and 3-9. This indicates that the retardation of Ba, Rb and Cs cannot be explained by a simple surface sorption model. This finding is consistent with observations from STT-1 and STT-1b.

Table 3-7 Evaluated parameters for STT-2 using PAREST (advection-dispersion-linear sorption model). Simultaneous runs Uranine and sorbing tracer. Values within brackets are standard errors in percent.

Tracer	v (m/s)	t_0 (h)	D/v (m)	f	R	f_c
Uranine	$1.74 \cdot 10^{-4}$ (1)*	7.5 (1)*	0.35 (3)*	$6.2 \cdot 10^{-4}$ (1)*	1	1
	$5.05 \cdot 10^{-5}$ (1)**	25.8 (1)**	0.46 (3)**	$1.4 \cdot 10^{-3}$ (1)**		
Na-22	$2.06 \cdot 10^{-4}$ (2)*	6.3 (2)*	0.38 (9)*	$3.6 \cdot 10^{-4}$ (9)*	1.54 (2)	0.82 (1)
	$5.08 \cdot 10^{-5}$ (2)**	25.6 (2)**	1.5 (10)**	$1.8 \cdot 10^{-3}$ (2)**		
Ca-47	$1.74 \cdot 10^{-4}$ (1)*	7.5 (1)*	0.35 (3)*	$6.2 \cdot 10^{-4}$ (1)*	2.34 (3)	0.70 (4)
	$5.04 \cdot 10^{-5}$ (1)**	25.8 (1)**	0.46 (3)**	$1.4 \cdot 10^{-3}$ (1)**		
Sr-85	$7.42 \cdot 10^{-5}$ (6)*	17.5 (6)*	3.0 (5)*	$1.9 \cdot 10^{-3}$ (14)*	2.62 (2)	0.74 (2)
	$1.19 \cdot 10^{-5}$(88)**	110 (88)**	6.1(193)**	$6.5 \cdot 10^{-4}$ (41)**		
Ba-131	$1.74 \cdot 10^{-4}$ (1)*	7.4 (1)*	0.34 (3)*	$6.1 \cdot 10^{-4}$ (2)*	6.96 (2)	0.44 (2)
	$5.02 \cdot 10^{-5}$ (1)**	25.9 (1)**	0.48 (4)**	$1.4 \cdot 10^{-3}$ (1)**		
Ba-133	$1.76 \cdot 10^{-4}$ (1)*	7.4 (1)*	0.33 (4)*	$6.0 \cdot 10^{-4}$ (2)*	14.7 (3)	0.55 (3)
	$5.04 \cdot 10^{-5}$ (1)**	25.8 (1)**	0.51 (4)**	$1.4 \cdot 10^{-3}$ (1)**		
Rb-86	$1.74 \cdot 10^{-4}$ (1)*	7.5 (1)*	0.34 (2)*	$6.2 \cdot 10^{-4}$ (1)*	18.4 (5)	0.44 (5)
	$5.04 \cdot 10^{-5}$ (1)**	25.8 (1)**	0.46 (3)**	$1.4 \cdot 10^{-3}$ (1)**		
Cs-134	$1.46 \cdot 10^{-4}$ (3)*	8.9 (3)*	0.72 (5)*	$8.1 \cdot 10^{-4}$ (4)*	140 (2)	0.37 (2)
	$4.70 \cdot 10^{-5}$ (1)**	27.7 (1)**	0.36 (8)**	$1.2 \cdot 10^{-3}$ (4)**		

* Flow path #1
** Flow path #2

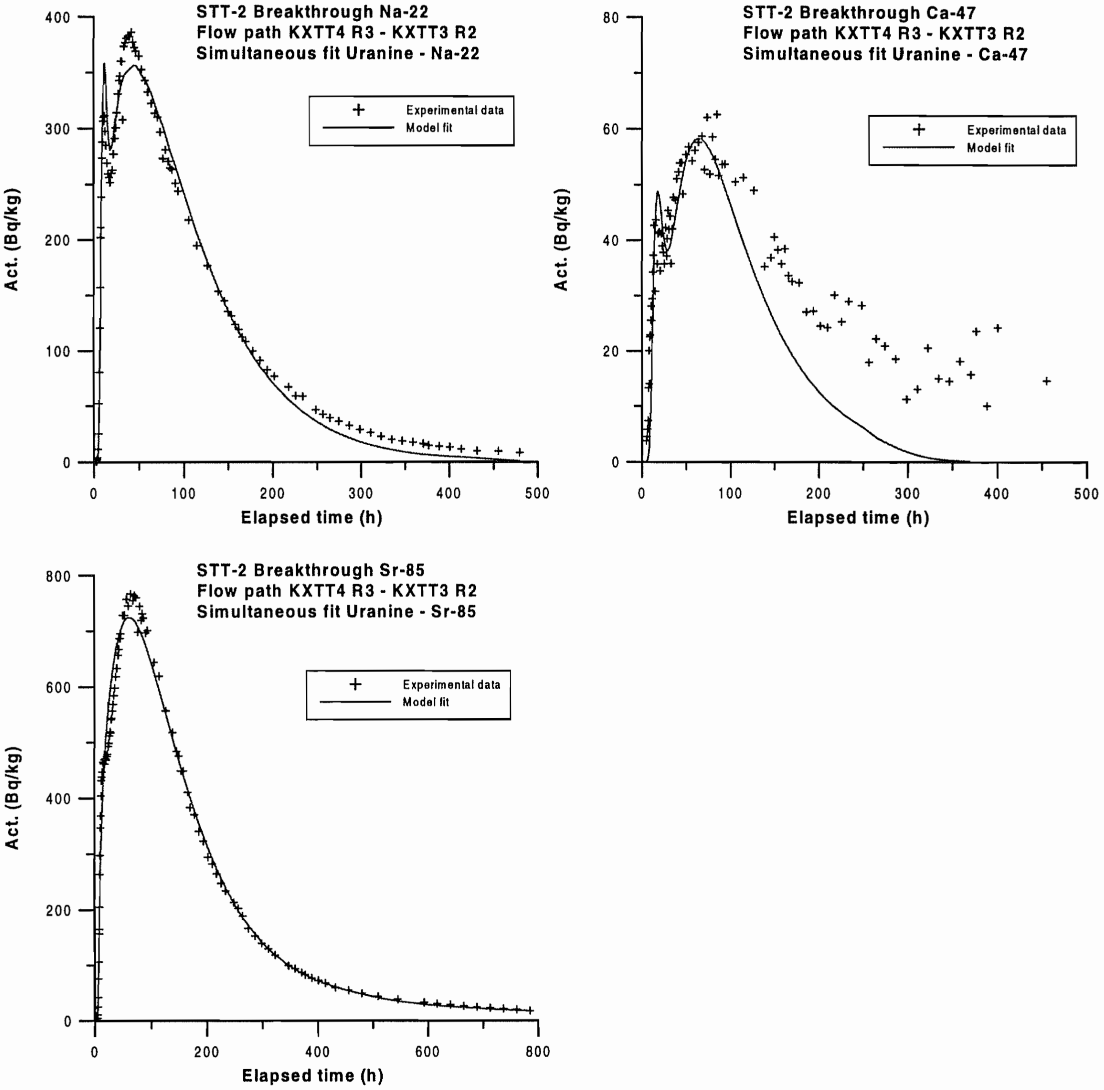

Figure 3-8 Comparison between measured and simulated breakthrough of the radioactive weakly sorbing tracers in the pumping section KXTT3 R2 during STT-2. Simultaneous run of Uranine and, a) Na-22, b) Ca-47, c) Sr-85.

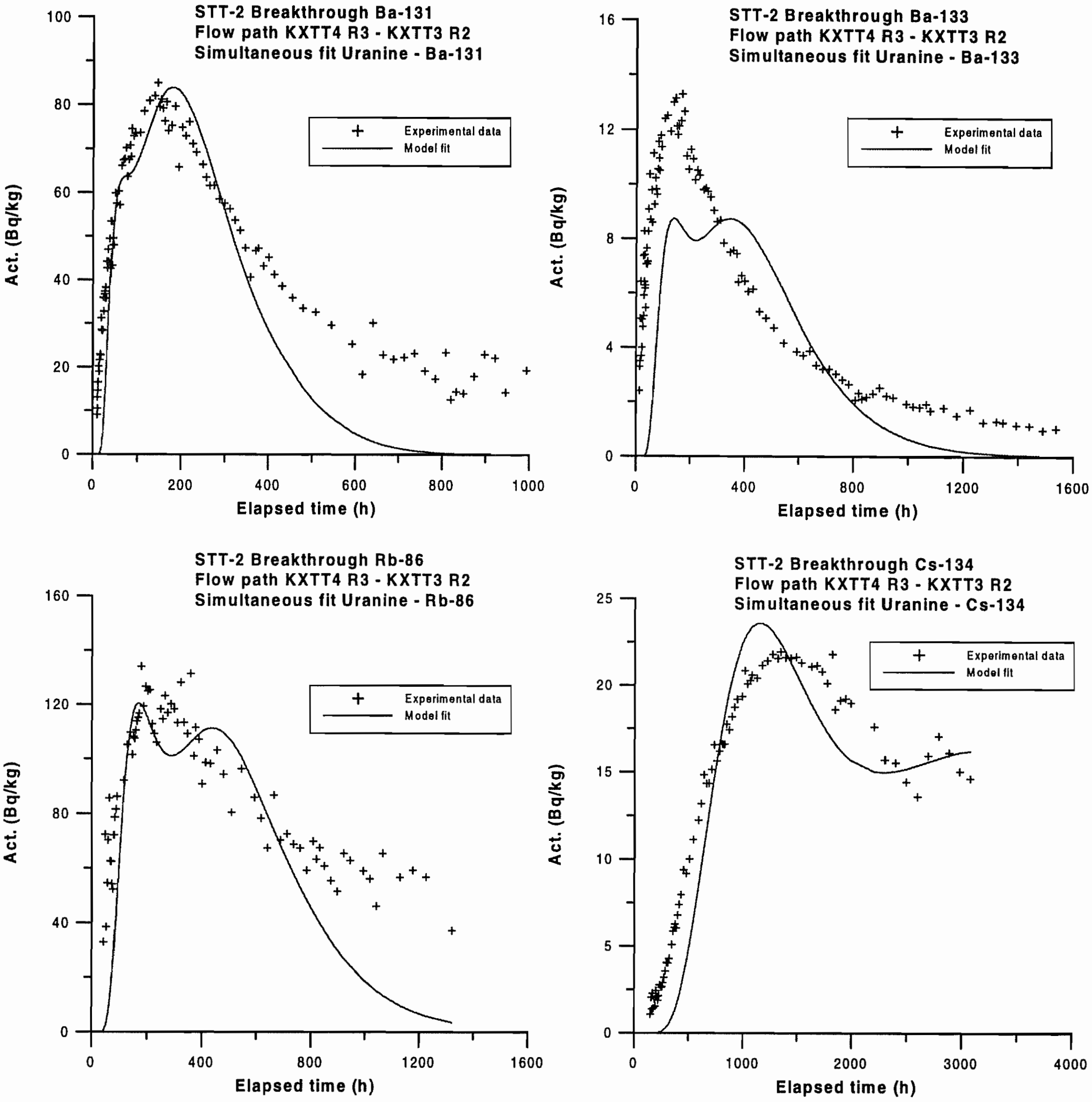

Figure 3-9 Comparison between measured and simulated breakthrough of the radioactive moderately sorbing tracers in the pumping section KXTT3 R2 during STT-2. Simultaneous run of Uranine and, a) Ba-131, b) Ba-133, c) Rb-86, d) Cs-134.

3.3.3 Tracer mass recovery

Tracer mass recovery was calculated in two different ways for the nine tracers detected in the pumping section. Common for both methods was that the tracer mass recovered in the pumping borehole was determined by integration of the breakthrough curves for mass flux (mg/h or Bq/h) versus time (h). The injected mass was determined in the same way but also by weighing and measuring the concentration of the tracer solution removed from the injection section during the exchange procedure and calculating the difference to the known mass added to the stock solution (mass balance), cf. Table 3-8.

The mass recoveries calculated from integration are in general higher (except for Uranine) than the measured ones and the differences are rather large. The reason for this may be that the injected mass was only a small portion of the total mass in the stock solution. There was also a problem with large errors in the measurements of the γ-emitting radioactive tracers. These data were therefore calculated assuming that 9 % of the total stock activity was injected (based on the obtained HTO value). For the moderately sorbing tracers (Br, Rb and Cs) the sorbed amount during the four hours of injection was added to the 9 % of the stock activity. Hence, a relatively large uncertainty can be expected in the determination of injected mass from weighing. Based on these considerations the mass recovery values determined from integration of the injection and breakthrough curves are considered to be the most appropriate to use.

Table 3-8 Tracer mass recovery during STT-2 determined by integration, R_i, and by weighing, R_w (t_t is the time for the last sample taken).

Tracer	R_i (%)	R_w (%)	t_t (h)
Uranine	96	98	885
HTO	83	58	640
Br-82	85	65	234
Na-22	83	61	3078
Ca-47	97	59	456
Sr-85	79	65	3078
Ba-131	56	33	1130
Ba-133	66	30	3078
Rb-86	49	22	1322
Cs-134	11	6	3078

3.4 Supporting data

The head distribution during the test period was governed by the imposed pumping in KXTT3 R2. The pumping rate in the withdrawal borehole section was stable and constant during the entire test, 0.201 l/min (Figure 3-10), except for a pump failure that occurred on September 30th, 1998. The pump (flow regulator) was replaced and pumping continued. This "new" flow regulator was not connected to the HMS-system and a change back to the earlier system (connected to HMS) was made after repair. The electrical conductivity (Figure 3-10) is stable at about 1160 mS/m during the test until the end of September when registration is ended due to precipitation and clogging of the probe. The redox potential (Figure 3-10) stabilises around -270 mV but is strongly affected by the changes of flow regulators when air gets into the system.

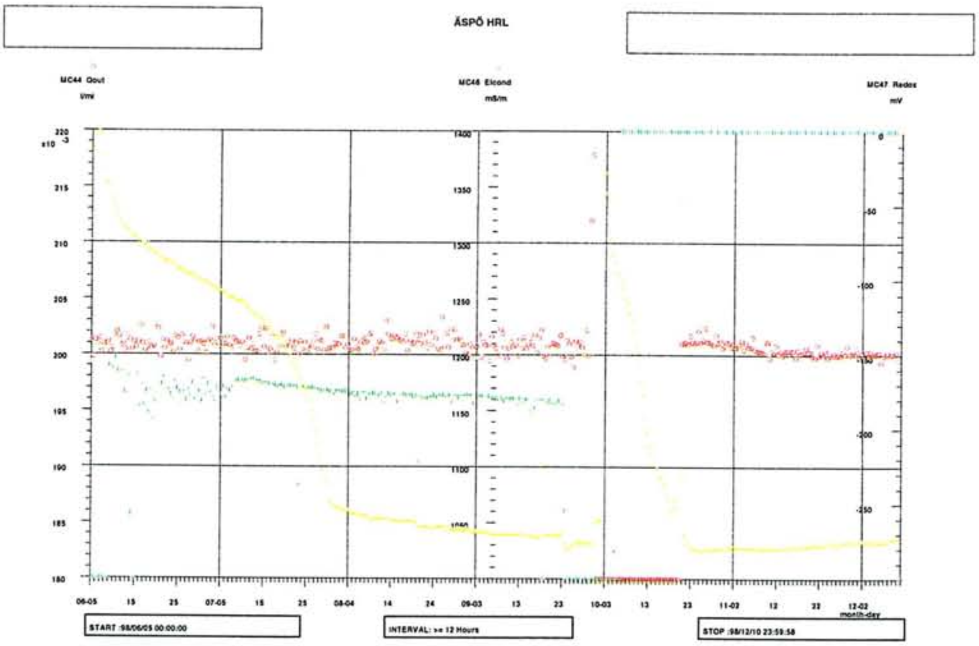

Figure 3-10 Pumping rate (o), electrical conductivity (+) and redox potential (x) of the pumped water in KXTT3 R2 during STT-2, June 5th, 1998 to December 10th, 1998.

The overall head variations during the period, illustrated by borehole HA1960A (Figure 3-11), which is a borehole penetrating the major bounding fracture zone NNW-4, are relatively large (± 2.5 m). The most prominent events are a decrease in hydraulic head starting on October 21st and the following increase starting on October 28th. The reason for this is an excavation of a niche in the TBM hall in connection to the major fracture zone NNW-4.

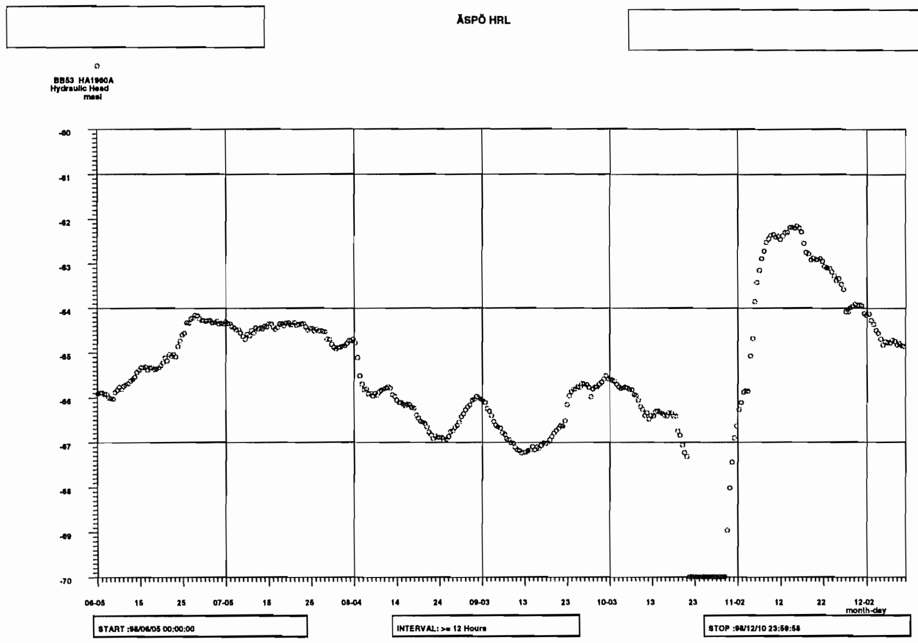

Figure 3-11 Hydraulic head in borehole HA1960A during STT-2, June 5th, 1998 to December 10th, 1998.

The values of hydraulic head in Feature A presented in Figure 3-12 show similar variations as observed in HA1960A, with the drop in head between October 21st and 28th as the most striking event. As a result of the pump failure on September 30th and the following pump exchange on October 2nd, the hydraulic head increased in all sections shown in Figure 3-12. There is also an increase in head on September 23rd when a tube was changed in the injection loop.

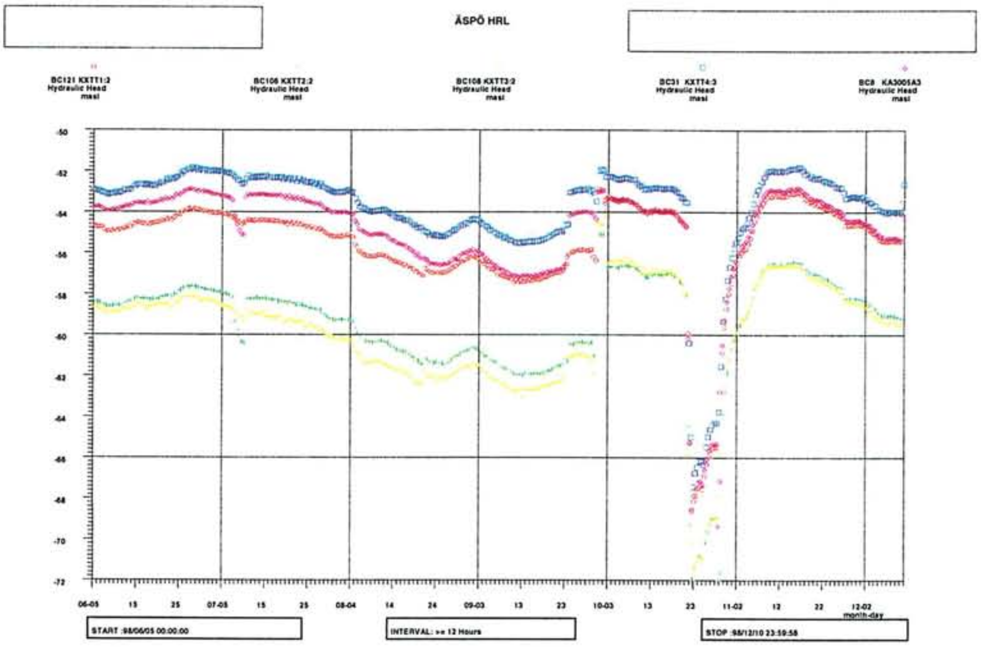

Figure 3-12 Hydraulic head in Feature A during STT-2, June 5th, 1998 to December 10th, 1998.

Figure 3-13 shows the head distribution for injection and observation sections at the TRUE-1 site during STT-2 as the head difference compared to the head in the pumping section KXTT3 R2. The head difference has been slightly increasing from 5.6 to 8 m up to about 120 days of pumping. At that time a pump failure occurred resulting in a significant decrease of the head difference caused by a decrease in the pump flow rate, cf. Table 3-1.

A comparison of the drawdown in the injection and sampling sections during RC-1, PDT-2 and STT-2 (Table 3-9) shows a significant difference for STT-2. The values for STT-2 are taken at pump stop in December 1998.

Table 3-9. Drawdown (*S*) in injection (KXTT4 R3) and pumping (KXTT3 R2) intervals during RC-1 (January 1996), PDT-2 (May 1997) and STT-2 (December 1998).

Test #	S_{inj} (m)	S_{pump} (m)
RC-1	0.3	3.1
PDT-2	0.5	3.1
STT-2	1.3	6.7

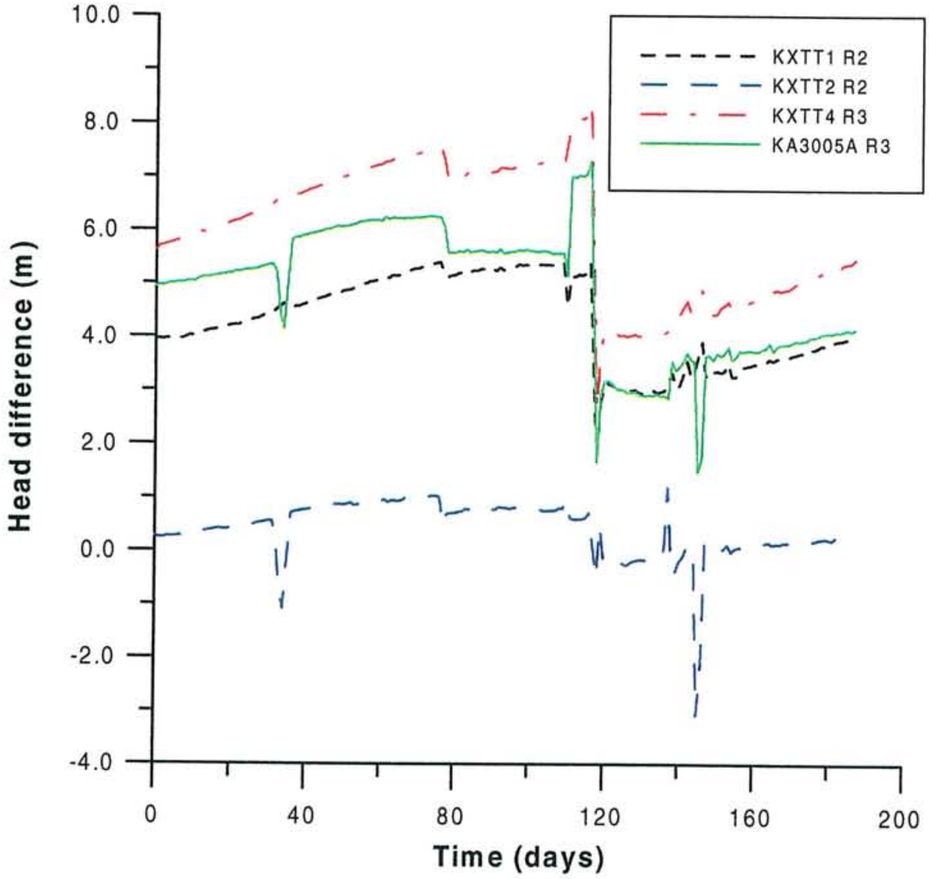

Figure 3-13 Head difference (m) versus time (days) for injection and observation sections compared to the pumping section KXTT3 R2 during STT-2.

4 Discussion and conclusions

4.1 Experimental setup and performance

The experimental setup for STT-2 was, with some modifications, identical to the one used in STT-1b (Andersson et al., in prep.), STT-1 (Andersson et al., 1998) and PDT-3 (Andersson & Wass, 1998). To get a more efficient tracer exchange (ending of tracer pulse), the exchange procedure was repeated twice during STT-2. This was also done in STT-1b with good result. The removal of tracer solution in STT-2 gave reduction of about 90 % of the mass in the injection section compared to about 95 % in STT-1b.

Plotting the injection and breakthrough curves (as mass flux versus time) in the same plot shows that the slow release of the 10 % remaining tracer solution in the injection interval dominates the later part of the breakthrough curve. This tailing may potentially mask important transport processes such as matrix diffusion or diffusion into stagnant parts of the flow path (Heer, pers. comm., 1999). Therefore, it is essential to reduce the initial tracer concentration at least down to 0.5 % in future experiments. This will require a totally new instrumentation concept for the down-hole equipment as the current concept was not designed for finite pulse injections.

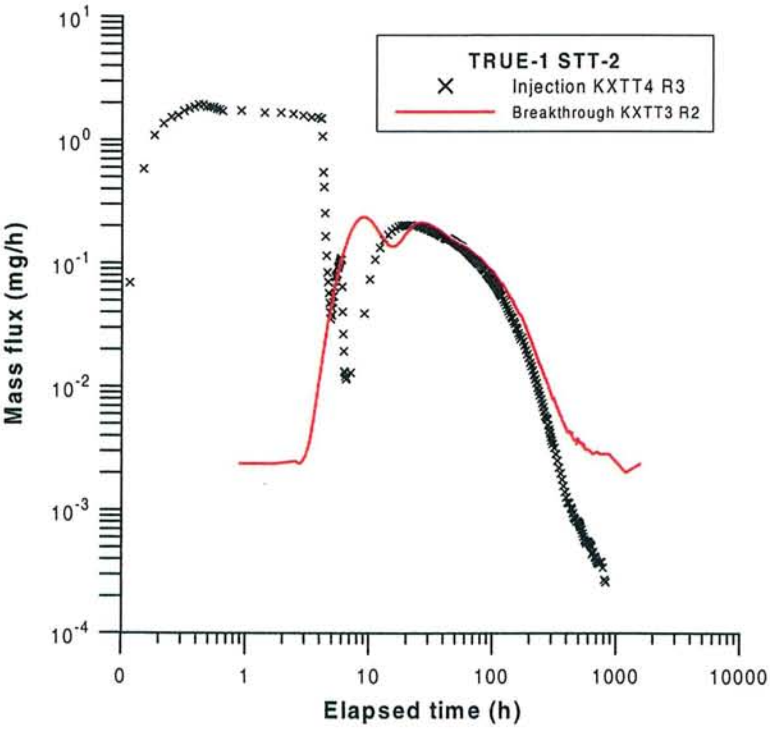

Figure 4-1. Tracer injection and breakthrough data (log-log scale) for Uranine from STT-2, flow path KXTT4 R3 → KXTT3 R2.

The injection procedure, during which the highest dose rates are to be expected, was performed with very low doses to the personnel. The activity of the water discharged into the tunnel waste water system only showed a temporary increase of the background activity during the breakthrough.

In STT-1 and PDT-3 it was found that the calculated mass recoveries were consistently >100 % (Andersson et al., 1998). The conclusion is that assigning a too small volume of the borehole section may cause the excess recovery, cf. Section 3.2. Thus, by increasing the borehole volume in KXTT4 R3 from 1898 ml to 2154 ml (13 %) a recovery of 100 % was achieved. This larger volume has also been used for the calculations in STT-2. Calculated mass recovery based on integrated mass flux was 96 % for Uranine and 83-85 % for the other conservative tracers used (HTO and Br). The recoveries calculated based on weighing and concentration measurements of tracer mass from the exchange procedure showed some inconsistencies. The values for Uranine using the two different methods were very consistent, 96 % and 98 % respectively. For the other tracers the recoveries calculated from weighing and concentration measurements were found to be much lower than the ones calculated from integration. Based on experience from earlier tests and uncertainties in the weighing and concentration measurements, the values determined by integration of the injection and breakthrough curves were considered to be the most appropriate to use.

4.2 Flow and transport in Feature A

The flow path KXTT4 R3 → KXTT3 R2 has earlier been investigated in seven tracer runs with pumping rates varying between 0.1 to 0.4 l/min. The general results of the tests show low recovery for low pumping rates, lower recovery for a dipole flow field and very similar transport parameters evaluated from the tests, cf. Table 4-1. The tests performed in exactly the same flow geometry as STT-2, RC-1 and PDT-2, show some significant differences. The most significant one is the head difference between injection and pumping that is much higher during STT-2. This increased pumping gradient also results in a significantly increased injection flow rate, from 7-8 ml/h during RC-1 and PDT-2 to 29 ml/h during STT-2. This is interpreted as boundary effects caused by the depletion in hydraulic head closer to the tunnel.

The main difference compared to other investigated flow paths in Feature A is that the previous converging tests show an anomalous high dispersivity for the tested flow path. One explanation for this, put forward by Andersson &Wass (1998), may be that there are two water-conducting fractures in the injection interval with similar transport properties. The detailed flow log and the BIPS log also support this conclusion, cf. Figure 4-2. According to the orientation of the two structures they should intersect approximately 5 m from KXTT4 R3, i.e. very close to borehole KXTT3. These two flow paths have not been possible to identify in earlier experiments where the shape of the breakthrough curves shows a singular and broad peak. Thus, the dominating flow path may have overlapped the secondary one in earlier tests. The reason why they now appear separated in time may be the changing boundary conditions at the site suggested by the changes in head distribution.

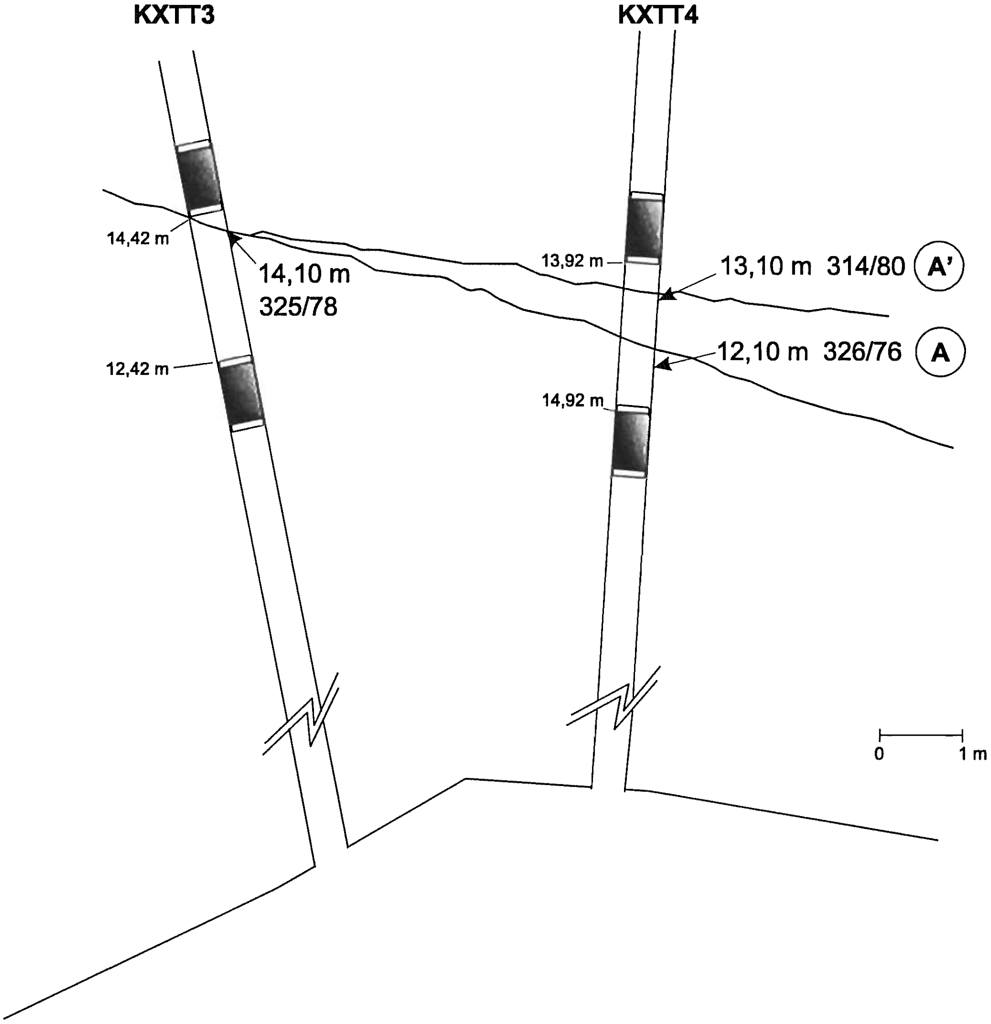

Figure 4-2. Schematic view of Feature A along flow path KXTT4 R3 → KXTT3 R2.

Table 4-1. Summary of flow and transport parameters determined for the flow path KXTT4 R3 → KXTT3 R2 (distance 4.68 m)

Test	Q (l/min)	Δh (m)	R_i (%)	D/v (m)	K_{fr} (m/s)	b (m)	θ_k
RC-1	0.2 (0.4)	2.8 (6.9)	100	1.6	$7.1 \cdot 10^{-4}$	$1.4 \cdot 10^{-3}$	$0.5 \cdot 10^{-3}$
DP-5	0.1	3.0	28	0.34	$2.0 \cdot 10^{-4}$	$1.6 \cdot 10^{-3}$	$0.5 \cdot 10^{-3}$
DP-6	0.2	3.6	70	0.48	$4.1 \cdot 10^{-4}$	$2.4 \cdot 10^{-3}$	$0.4 \cdot 10^{-3}$
PDT-1	0.1	1.0	74	0.6	$6.4 \cdot 10^{-4}$	$2.1 \cdot 10^{-3}$	$0.5 \cdot 10^{-3}$
PDT-2	0.2	2.3	99	1.1	$5.9 \cdot 10^{-4}$	$2.0 \cdot 10^{-3}$	$0.6 \cdot 10^{-3}$
PDT-3	0.4	6.8	95	1.7	$4.8 \cdot 10^{-4}$	$1.7 \cdot 10^{-3}$	$0.7 \cdot 10^{-3}$
STT-1	0.4	7.2-10.5	100	2.0	$4.2 \cdot 10^{-4}$	$1.4 \cdot 10^{-3}$	$0.8 \cdot 10^{-3}$
STT-2	0.2	5.6-8	96	0.35^{*}	$3.4 \cdot 10^{-4*}$	$1.3 \cdot 10^{-3*}$	$1.1 \cdot 10^{-3*}$
				0.46^{**}	$1.0 \cdot 10^{-4**}$	$4.5 \cdot 10^{-3**}$	$4.0 \cdot 10^{-3**}$

* Flow path #1
** Flow path #2

The transport of the radioactive sorbing tracers showed significant retardation for all tracers. The retardation coefficients determined from a simple linear surface sorption model were found to vary between R=1.5 for Na to R=140 for Cs. A comparison with retardation coefficients determined from laboratory data (Andersson et al., 1997a), from STT-1 (Andersson et al., 1998) and from STT-1b (Andersson et al., 1999) shows the same relative order between the species whereas the parameter values are significantly higher for all species in the in-situ tests and somewhat higher in STT-2 than in the other tests (Table 4-2).

Table 4-2. Comparison between retardation coefficients, *R*, determined from laboratory data and from evaluation of three in-situ tracer tests.

Tracer	*R* (lab)*	*R* (STT-1)**	*R* (STT-2)**	*R* (STT-1b)**
Na	1.001-1.01	1.5	1.5	1.4
Ca	1.006-1.06	1.6	2.3	-
Sr	1.008-1.04	2.1	2.6	1.9
K	-	-	-	2.8
Ba	1.08-2.2	8.6	7-14	-
Rb	1.12-3.0	15	18	17
Co	-	-	-	57
Cs	2-21	69	140	118

* Determined from the equation $R=1+(2/b)\cdot K_a$,(b=0.001 m), where K_a (m) is the surface sorption coefficient determined in laboratory tests (Andersson et al., 1997a).

** *R* (field) includes all retardation processes in the applied model.

The applied model worked reasonably well in the simultaneous fit of the conservative tracer breakthrough (Uranine) and the weakly sorbing tracer Na or Sr. The conservative breakthrough could not be fitted with a single flow path. The fits using Uranine and one of the moderately sorbing tracers Ba, Rb or Cs were not good. Thus, the linear surface sorption process alone cannot explain the retardation of these species. It should be noted that the values of the surface retardation factors are model dependent. This model may lead to an overestimation of the surface retardation factors, especially for the moderately sorbing tracers, since all retardation (including possible matrix diffusion and sorption) is included in one surface retardation factor.

5 References

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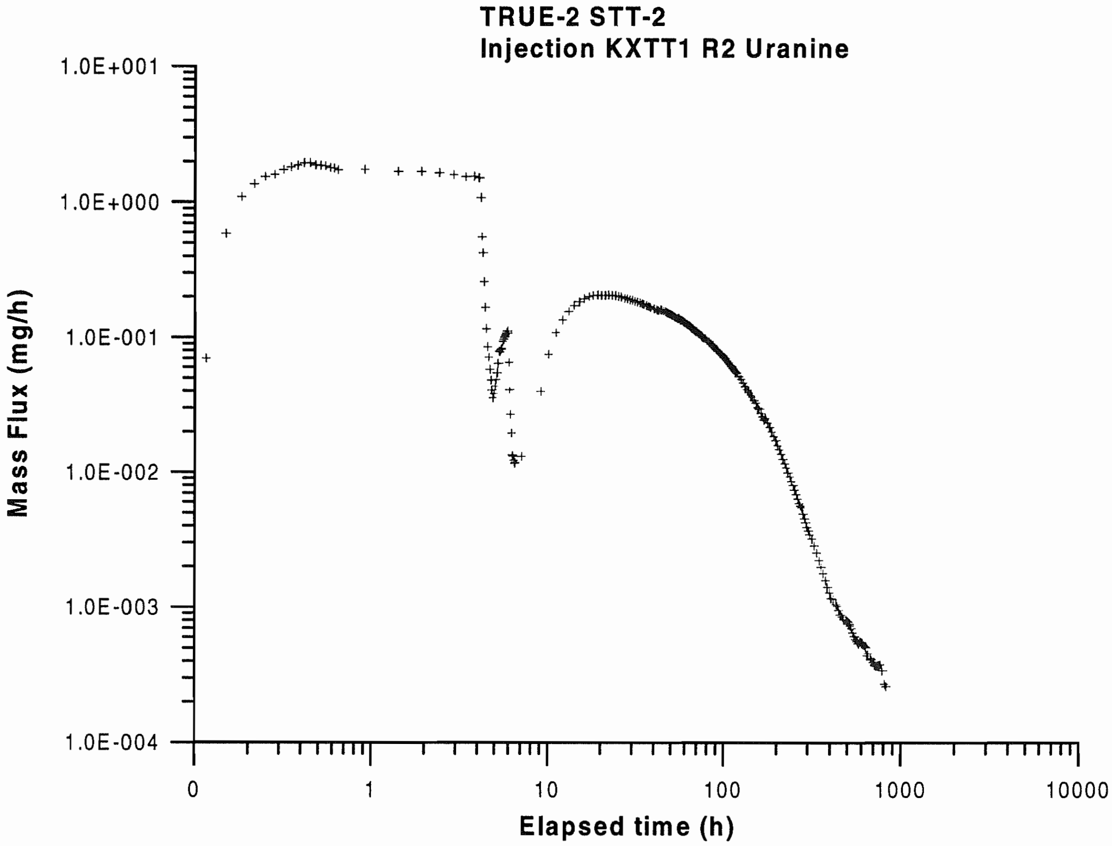
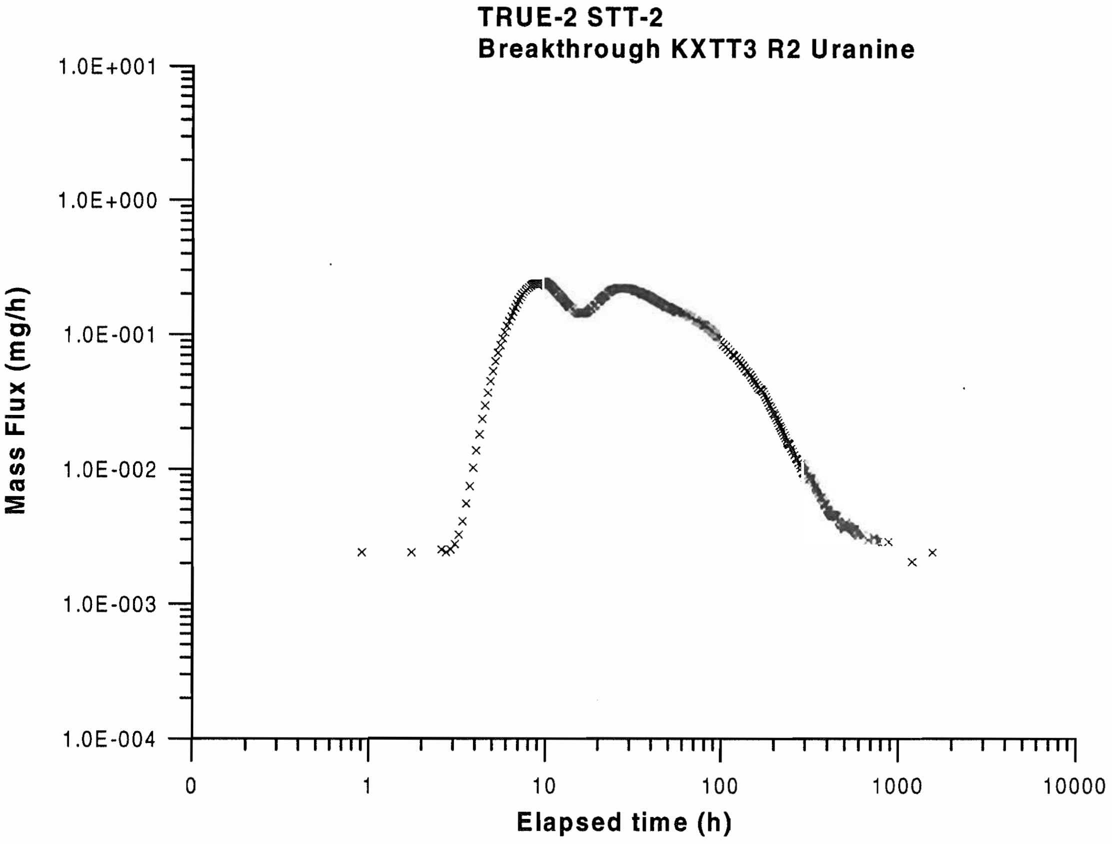
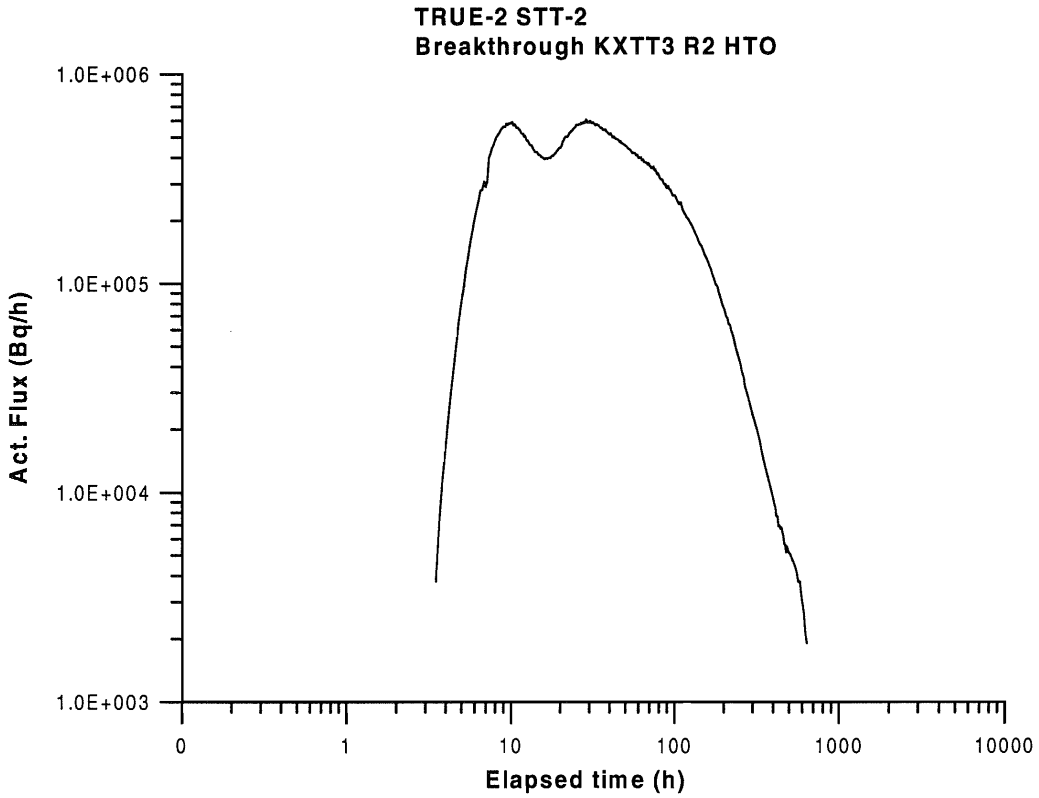
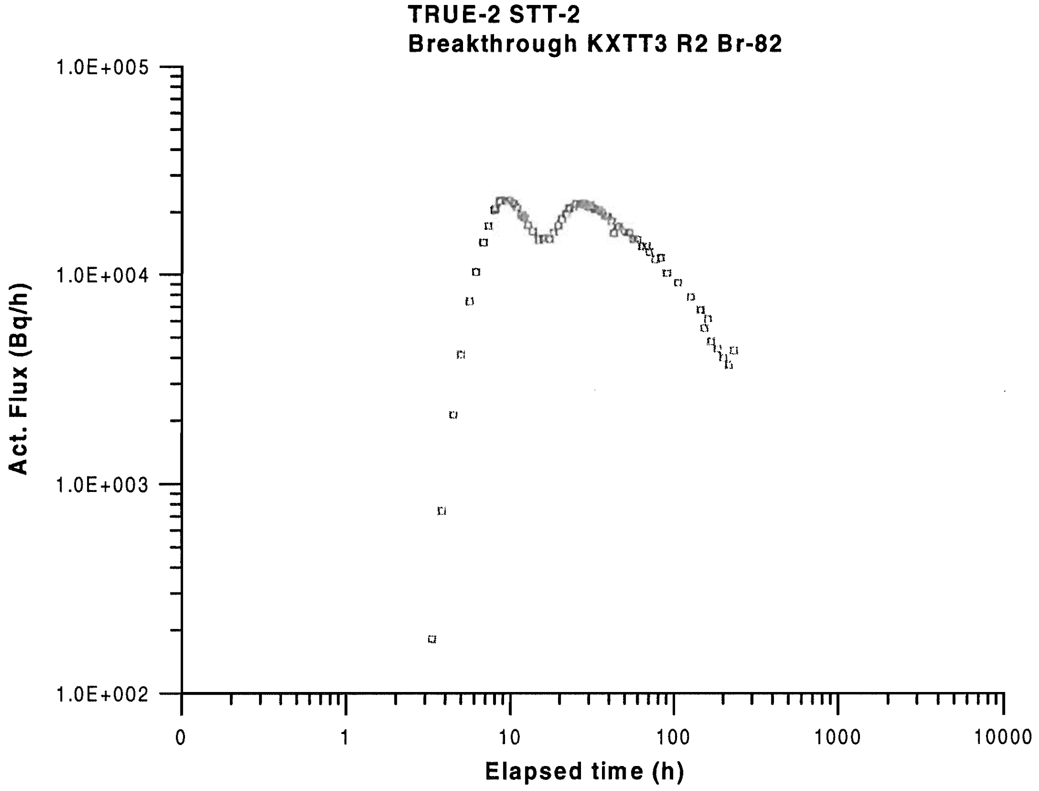
Appendix A

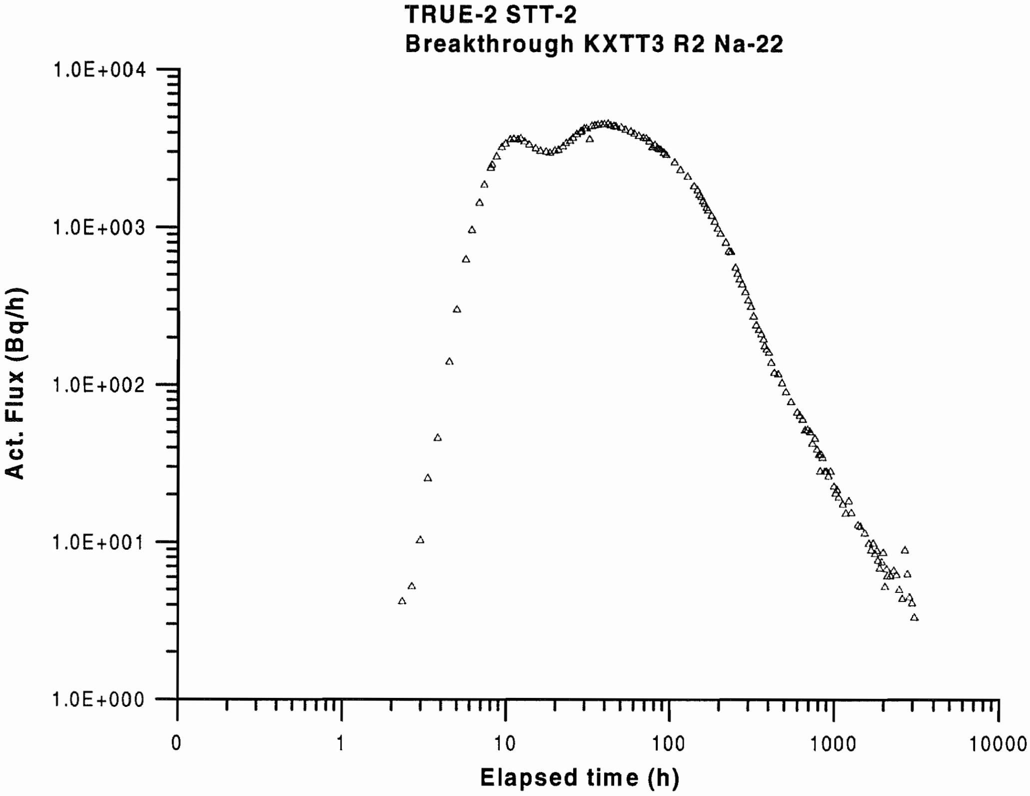
Tracer breakthrough data (log-log scale) from STT-2.

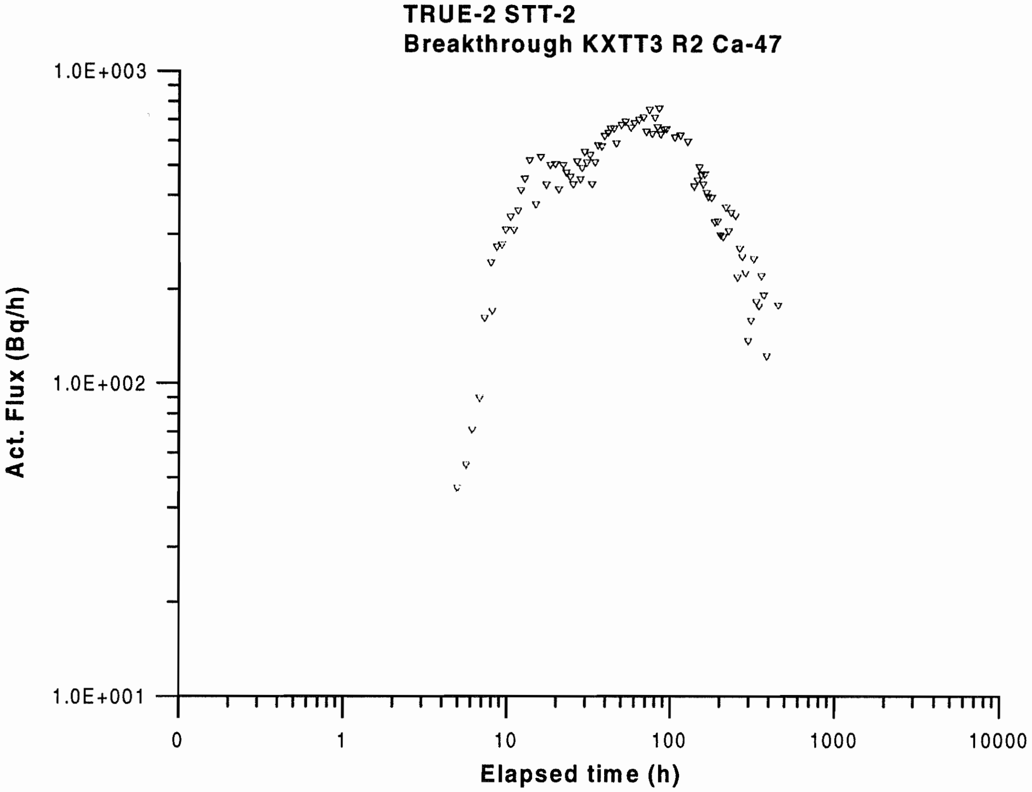

TRUE-2 STT-2
Injection KXTT1 R2 Uranine
Mass Flux (mg/h)
1.0E+001
1.0E+000
1.0E-001
1.0E-002
1.0E-003
1.0E-004
Elapsed time (h)
0
1
10
100
1000
10000

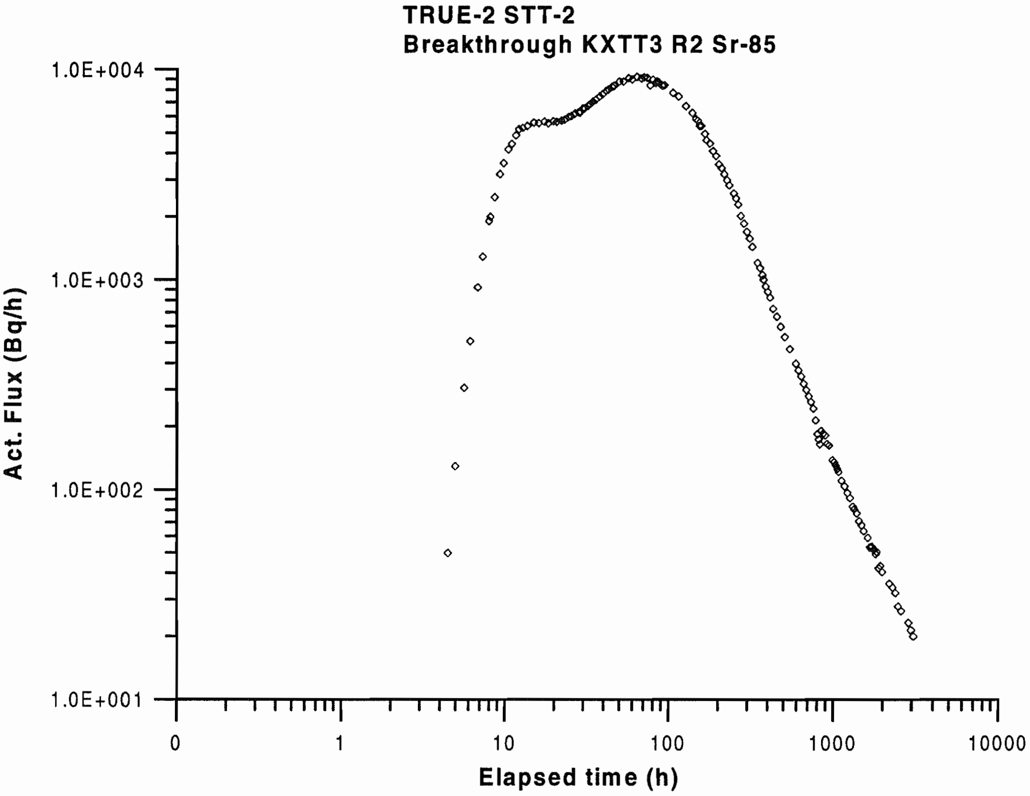

TRUE-2 STT-2
Breakthrough KXTT3 R2 Uranine
Mass Flux (mg/h)
1.0E+001
1.0E+000
1.0E-001
1.0E-002
1.0E-003
1.0E-004
Elapsed time (h)
0
1
10
100
1000
10000

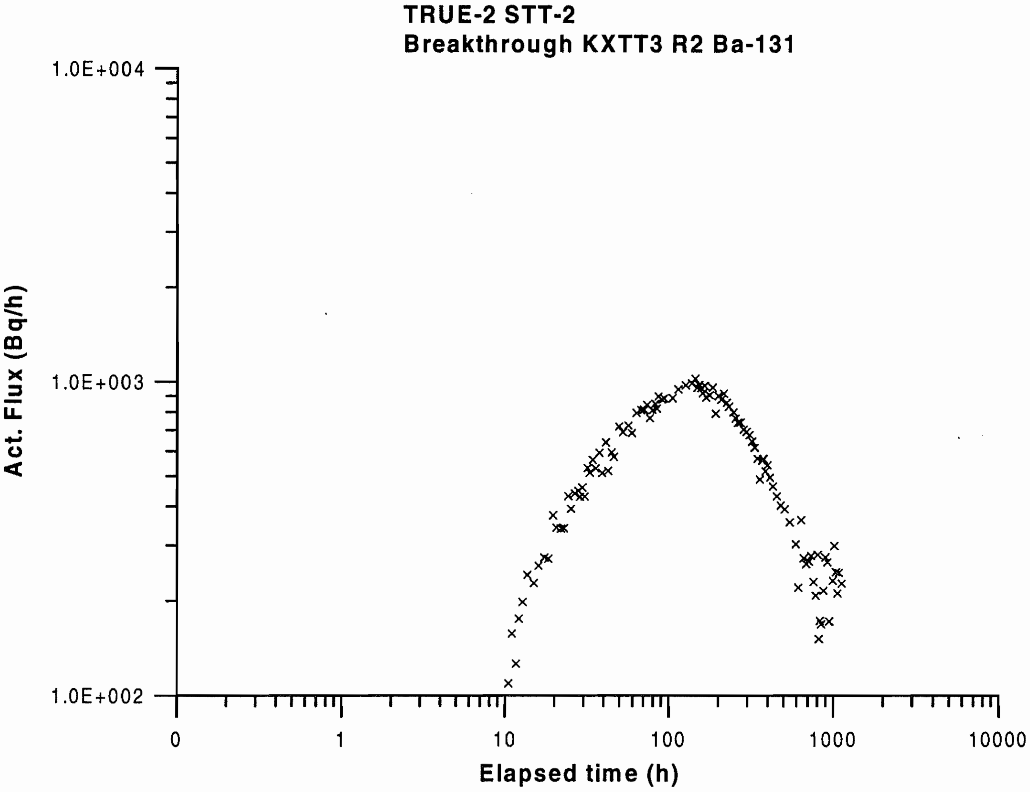

TRUE-2 STT-2
Breakthrough KXTT3 R2 HTO
Act. Flux (Bq/h)
1.0E+006
1.0E+005
1.0E+004
1.0E+003
0
1
10
100
1000
10000
Elapsed time (h)

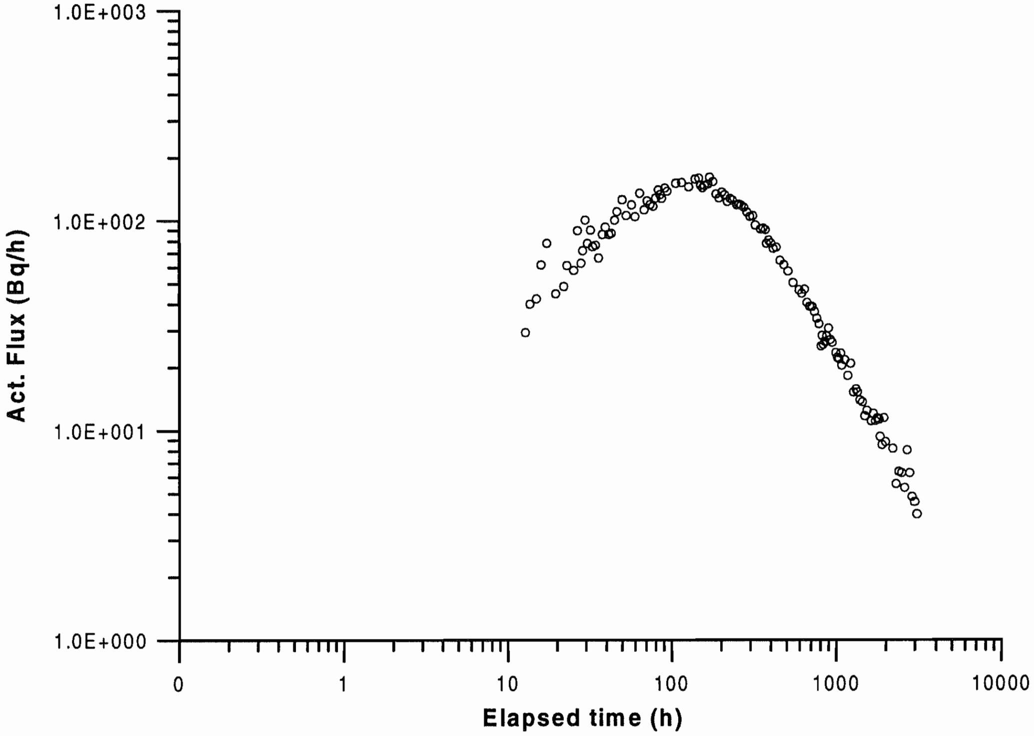

TRUE-2 STT-2
Breakthrough KXTT3 R2 Br-82
Act. Flux (Bq/h)
1.0E+005
1.0E+004
1.0E+003
1.0E+002
0
1
10
100
1000
10000
Elapsed time (h)


TRUE-2 STT-2
Breakthrough KXTT3 R2 Na-22
Act. Flux (Bq/h)
1.0E+004
1.0E+003
1.0E+002
1.0E+001
1.0E+000
0
1
10
100
1000
10000
Elapsed time (h)

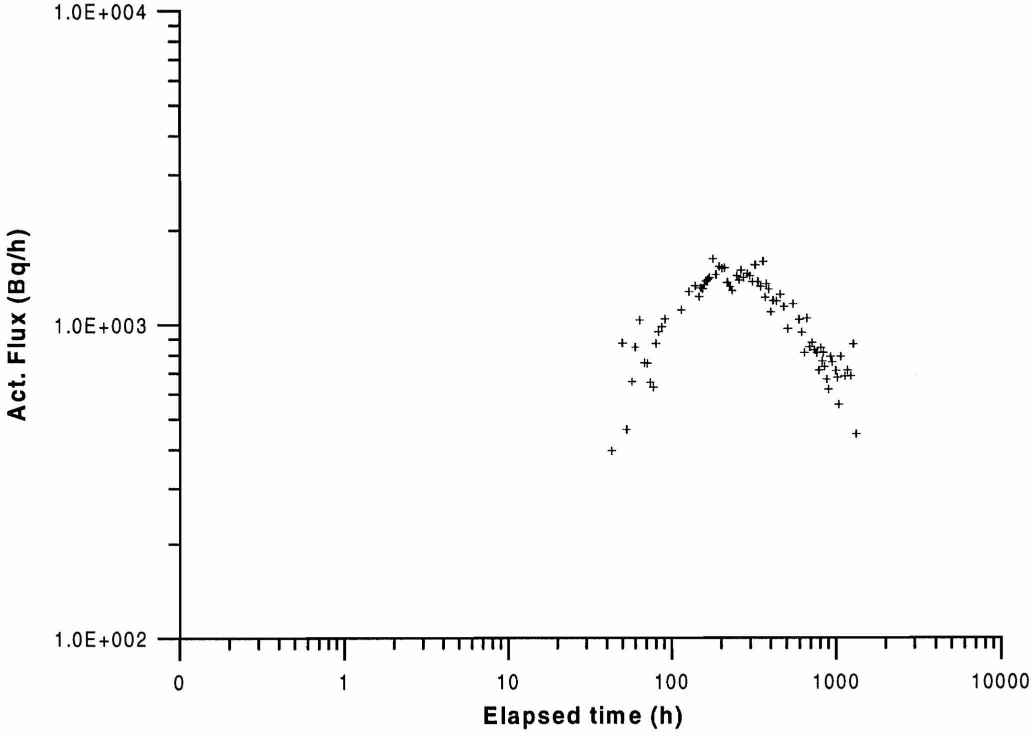

TRUE-2 STT-2
Breakthrough KXTT3 R2 Ca-47
Act. Flux (Bq/h)
1.0E+003
1.0E+002
1.0E+001
0
1
10
100
1000
10000
Elapsed time (h)


TRUE-2 STT-2
Breakthrough KXTT3 R2 Sr-85
Act. Flux (Bq/h)
1.0E+004
1.0E+003
1.0E+002
1.0E+001
0
1
10
100
1000
10000
Elapsed time (h)

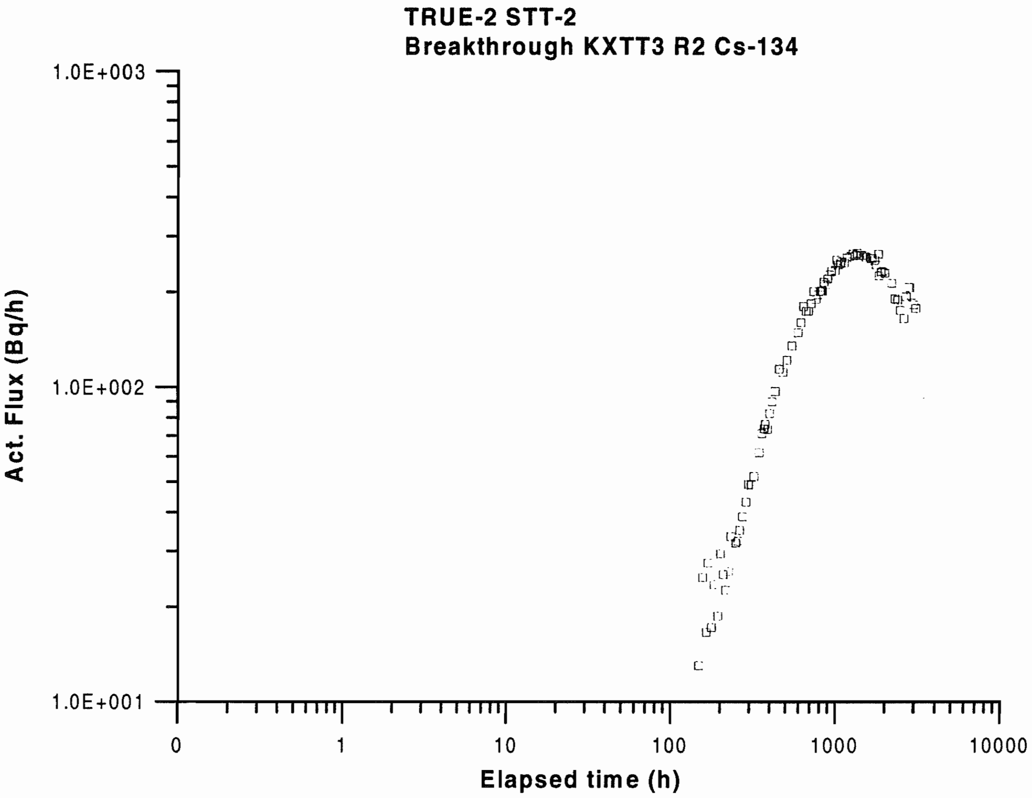

TRUE-2 STT-2
Breakthrough KXTT3 R2 Ba-131
Act. Flux (Bq/h)
1.0E+004
1.0E+003
1.0E+002
0
1
10
100
1000
10000
Elapsed time (h)



TRUE-2 STT-2
Breakthrough KXTT3 R2 Ba-133

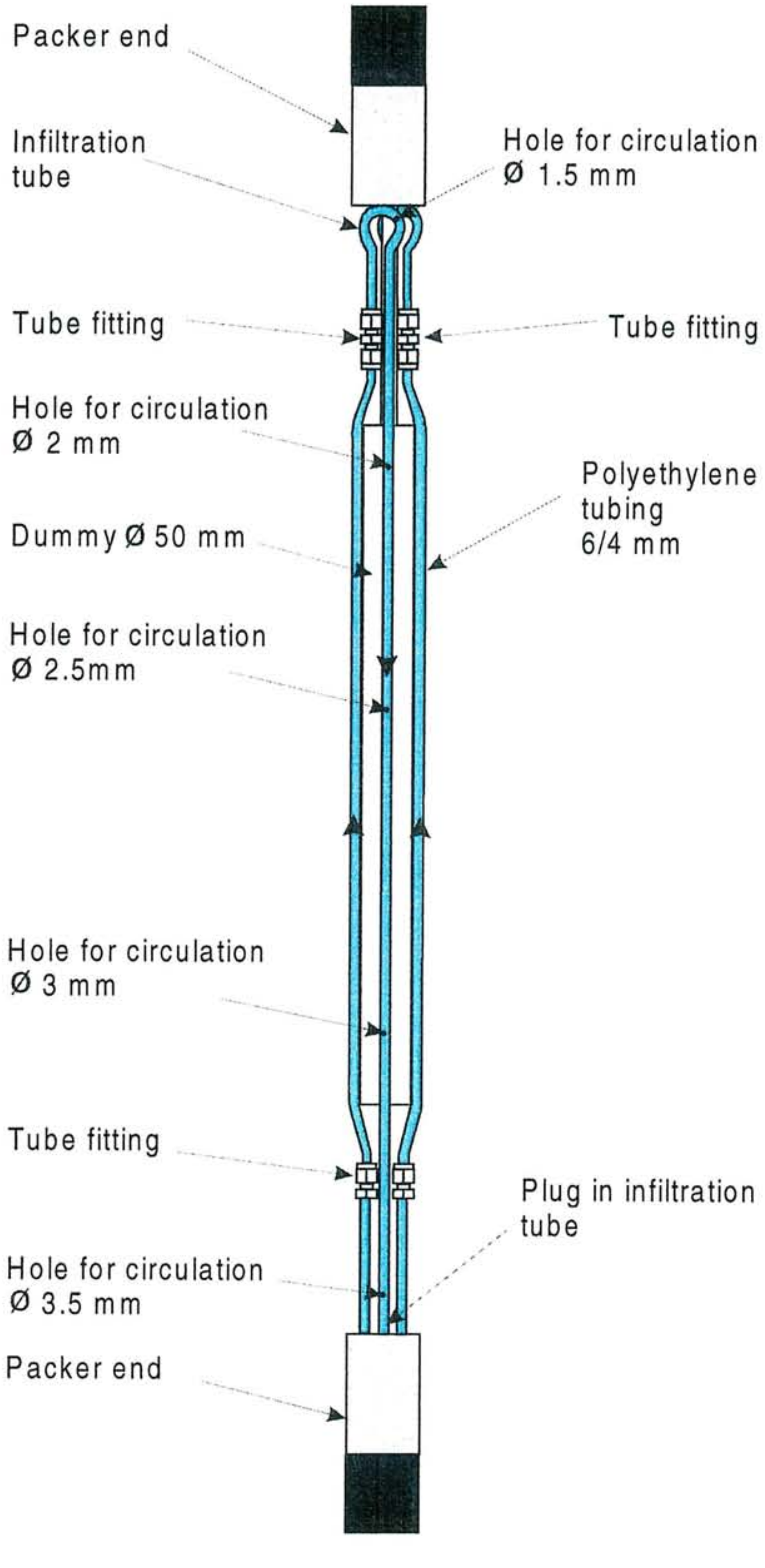


TRUE-2 STT-2
Breakthrough KXTT3 R2 Rb-86


TRUE-2 STT-2
Breakthrough KXTT3 R2 Cs-134
Act. Flux (Bq/h)
1.0E+003
1.0E+002
1.0E+001
0
1
10
100
1000
10000
Elapsed time (h)

Appendix B

Borehole equipment including packers, dummy and infiltration tubes.



▲ Flow direction