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REPORT**

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**Data analysis and modelling of
the LPT2 Pumping and Tracer
Transport Test at Äspö**

Tracer Experiment

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VTT Energy

November 1994

Supported by TVO, Finland

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TRACER EXPERIMENT

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This document concerns a study which was conducted within an Äspö HRL joint project. The conclusions and viewpoints expressed are those of the author(s) and do not necessarily coincide with those of the client(s). The supporting organization has reviewed the document according to their documentation procedure.

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Tracer experiment

Aimo Hautojärvi

VTT Energy

**November 1994
Espoo**

ABSTRACT

The results of the LPT-2 tracer test are discussed. Two of the injected six tracers have been recovered in the pumping borehole KAS06. The break-through curves have been analyzed and interpreted to represent essentially one transport path for each of the recovered tracers. The similarity of the break-through curves into different sampling levels indicates that these curves have the same origin. The observed results can be explained by introducing some changes in the distribution of the measured water inflow rates into different levels in the withdrawal hole. The differences may arise from the different pumping flow rates used in the spinner measurement and in the test as well as other variations due to natural causes.

Both the Uranine injected from the KAS12-2 section and Re-186 injected from the KAS08-1 were transported mainly via the fracture zone NNW-2 and arrived into the section E in the KAS06. Some portion of the tracers was detected also in the section D indicating a branching from the transport path in NNW-2 via EW5 into the KAS06. The branching happens so near the KAS06 that the effect of the alternative paths at the end of the transport route cannot be seen in the break-through curves. The mean transport times were longer than could have been expected according to the given transmissivity of $4 \cdot 10^{-5} \text{ m}^2/\text{s}$ of the NNW-2 even if the difference between the hydraulic and volume apertures by a factor of 10 is taken into account.

Theoretically derived break-through curves have been compared with the experimental results by using two different types of transport equations. Also a deconvolution technique has been applied in order to extract the system response function from the given data. The conclusion is that a large hydrodynamic dispersion, which is not necessarily Fickian, can be seen. Based on the slow transport velocity it can also be concluded that relatively large cavities in the rock exist but "bottle necks" reduce the hydraulic transmissivity and flow rate.

EXECUTIVE SUMMARY

The modelling of the so called LPT-2 pumping and tracer test was performed as part of the work of the Task Force on groundwater flow and tracer transport of the Äspö HRL project.

Tracers were injected in the following borehole sections: In-114 in KAS02-4 (B4), Uranine in KAS05-3 (E3), I-131 in KAS07-4 (J4), Re-186 in KAS08-1 (M1), Re-186 in KAS08-3 (M3), and Uranine in KAS12-2 (DB). The tracers In-114 and I-131 were not recovered in the withdrawal borehole KAS06. Recoveries of Uranine from the injection E3 and Re-186 from the injection M3 are very uncertain. The only certain break-through curves observed in the LPT-2 test originate from the injections DB (Uranine from KAS12-2) and M1 (Re-186 from KAS08-1).

The break-through curves were measured at eight different levels in the withdrawal borehole and from the total discharge water. All of the curves showed a very similar behaviour for each of the two recovered tracers. This could be explained by a somewhat different water inflow distribution than measured in the spinner test. The analysis of the tracer test was thus based on the hypothesis that Uranine from KAS12-2 and Re-186 from KAS08-1 arrived in the withdrawal borehole KAS06 via essentially one transport route within the fracture zone NNW-2 each.

Theoretical model curves were convoluted with the intermittent decaying pulse injection rates and compared with the measured break-through curves. Two types of models were used. A conventional advection-dispersion model with Fickian dispersion and a "matrix diffusion" type of model where diffusion from a flow channel to stagnant areas in the flow field is possible. Both models give fair agreement with the measured results and it would be very difficult, if not impossible, to distinguish between the models or any combination of them.

A deconvolution technique was applied to extract the system behaviour as an impulse response from the given injection and break-through data. Deconvolutions are in practice often numerically difficult and the problems are as such ill-posed because of errors and limited amount of data. The oscillations in the solutions may come from the mathematics of the problem but it is, in principle, impossible to know certainly. If a problem has such properties that the deconvolution is very sensitive to certain kind of oscillations, great care should be taken in interpreting those features in the results being physical.

The results of both kinds of modelling show a relative high dispersion which is not necessarily Fickian. Péclet numbers in the order of 4 is obtained for both of the tracers or alternatively a value of 18-22 $h^{1/2}$ for the u-parameter in the "matrix diffusion" like model. The flow velocities

are relatively low compared to the hydraulic transmissivity value of $4 \cdot 10^{-5} \text{ m}^2/\text{s}$ of the fracture zone NNW-2. The fracture aperture is in the order of several centimetres when the transport is interpreted to take place in a single fracture. "Bottle necks" have to limit the transmissivity and flow in this case and the ratio of the volume aperture (from transport time) and the hydraulic aperture (as in the parallel plate model) is relatively large, in the order of 50.

A few things should be taken into account if the option for model independent analysis of break-through data is wanted to be reserved. First good quality data on the injection and break-through is needed. This point was fulfilled well in the LPT-2 test. Secondly multiple and especially regularly repeated injections makes the deconvolution analysis very unstable and sensitive to errors. This was unfortunately the case in the LPT-2 test.

If transport phenomena should be studied and transport parameters determined it is better to do this for each transport path or channel separately. Even then the task is difficult enough both for direct and inverse modelling. In the LPT-2 injection sections were very long from that point of view and several paths might have occurred. The analysis showed, however, that the results can be explained by just one single path for each of the recovered tracer. A serious study of transport phenomena and parameters requires at least a series of measurements e.g. with different flow rates or other parameters that can be varied.

INTRODUCTION

The modelling of the so called LPT-2 pumping and tracer test was performed as part of the work of the Task Force on groundwater flow and tracer transport of the Äspö HRL project . "A large scale three-dimensional tracer test was performed in fractured crystalline rock autumn 1990 in the target area at Äspö, Sweden, where the hard rock laboratory is to be constructed, The objective of this tracer test was to determine how the major fracture zones are interconnected and by comparison with the experimentally obtained results verify or refute the framework of fracture zones presented in the conceptual (= structural, remark of the author of this report) model of Äspö. The aim was also to determine transport parameters such as residence time, dispersivity, flow porosity and hydraulic conductivity of the fracture flow paths" [1].

Six different sections of boreholes at Äspö were selected in advance by means of dilution tests to find out suitable sections for injecting tracers in the LPT-2 test. Four different kind of tracers were injected in six sections and the concentrations were measured in the 600 m long withdrawal borehole. Two of the tracers were injected in two different sections but at different times. This may cause some arbitrariness in evaluating the break-through curves of these two tracers. According to our analysis, however, the later injections of these tracers were not observed in the withdrawal hole before stopping of the experiment. The other two tracers injected only in single sections each could neither be observed in the withdrawal hole within the test duration. Thus, two of the injections and their corresponding break-through curves could be modelled. In the report describing the test a somewhat different interpretation is presented regarding the tracers that were injected in two different places [1].

In this report the results of the LPT-2 tracer test will be discussed and interpretations of transport paths seen in the experiments will be given. Some properties of the transport paths are extracted from the measured break-through curves taking into account the applied injection procedure. There are two possible ways to analyze the break-through curves.

The first one is a comparison of a theoretically derived break-through curve based on an assumed model function and convolution of the model break-through curve with the injection term. This method, of course, limits a priori the possible solutions to the used model functions.

Another method is to extract the system behavior from the experimental data without any preconditions (except perhaps physically reasonable ones such as that the system response may consist of positive massflow rates only). Some assumptions have to be made in both type of analyses, however. These include usually the assumption (or approximation) of linearity i.e. that the transport phenomena are not concentration dependent

and that the processes are invariant in time. These assumptions are actually known not to be true but it is hoped that they are reasonably fair approximations.

Both types of analysis methods are dealt with in this report. The deconvolution method is often associated with numerical instabilities and difficulties. It might be possible to avoid some of these difficulties by planning the experiments and especially the injection scheme to be optimal in that respect. This will be shortly discussed in this report, too.

A SHORT DESCRIPTION OF THE EXPERIMENT

This description is based on the reported test description and evaluation [1] and only some of the most important values and test parameters are reproduced here to help the reader of this report to get an overall view of the transport part of the LPT-2 test. The structural and hydraulic modelling that has been done at our laboratory and is reported elsewhere [2] has been an essential part of analyzing and understanding the test and its results.

Dilution measurements were performed in candidate boreholes both during natural conditions and pumping of the borehole KAS06 to find suitable injection sections for the tracer test. The obtained flow rates through the investigated borehole sections during pumping are presented in Table 1 (Table 3.2 in [1]).

Table 1. Result of flow measurements in borehole sections during pumping (c.f. Appendix A in [1]).

Borehole section*	Start	Duration ¹ (h)	Flow (ml/min)	Remarks
KAS02-4	900927	55	14	First run
KAS05-1	900925	80	11	
KAS07-4	900927	55	33	
KAS08-1	900926	65	54	
KAS12-2	900926	60	111	
KAS02-2	901023	110	4	Second run
KAS05-3	901009	80	12	
	901025	80	10	
KAS08-3	901011	200	16	
	901029	55	5	
KAS14-2	901022	90	11	

* See Table 3.3 in [1] for borehole section code

¹ Duration of dilution measurements.

Tracers were injected in the following borehole sections: In-114 in KAS02-4 (B4), Uranine in KAS05-3 (E3), I-131 in KAS07-4 (J4), Re-186 in KAS08-1 (M1), Re-186 in KAS08-3 (M3), and Uranine in KAS12-2 (DB). The tracers In-114 and I-131 were not recovered in the withdrawal borehole KAS06. Recoveries of Uranine from the injection E3 and Re-186 from the injection M3 are very uncertain and this will be discussed in more detail in the following sections. The only certain

break-through curves observed in the LPT-2 test originate from the injections DB (Uranine from KAS12-2) and M1 (Re-186 from KAS08-1).

Looking at the experimental arrangement with the aid of the 3-D structural model used in the groundwater flow modelling [2] it can be seen that both of the recovered tracer injections were injected in or very near the fracture zone NNW-2 as shown in Figures 1-3. The potential transport routes via the zone NNW-2 are also sketched in Figure 2.

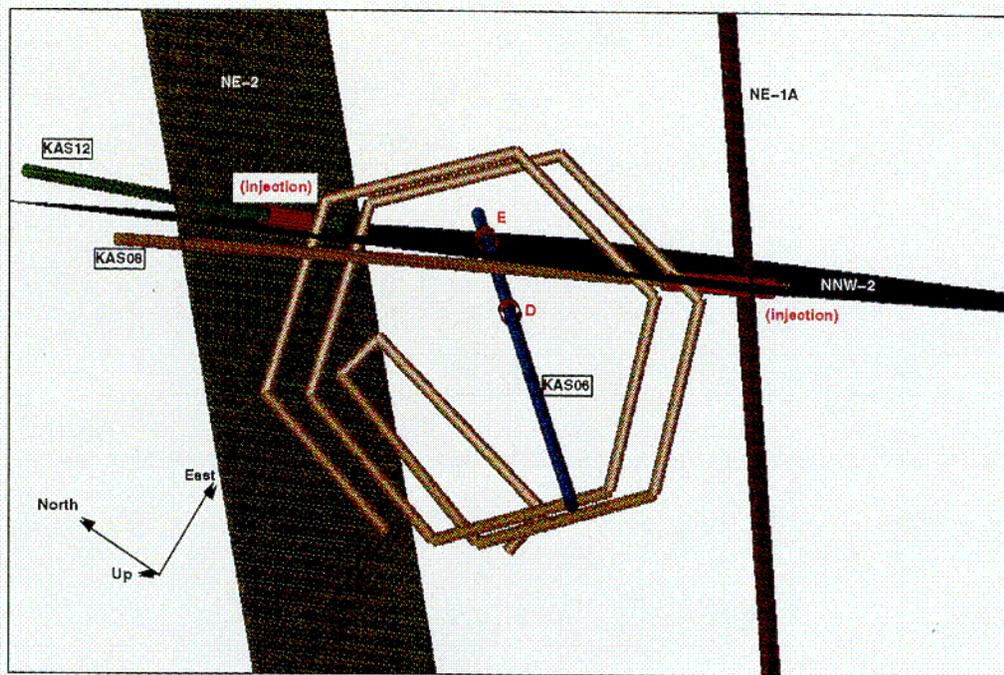


Figure 1. Structures and boreholes seen from above (EW-5 excluded).

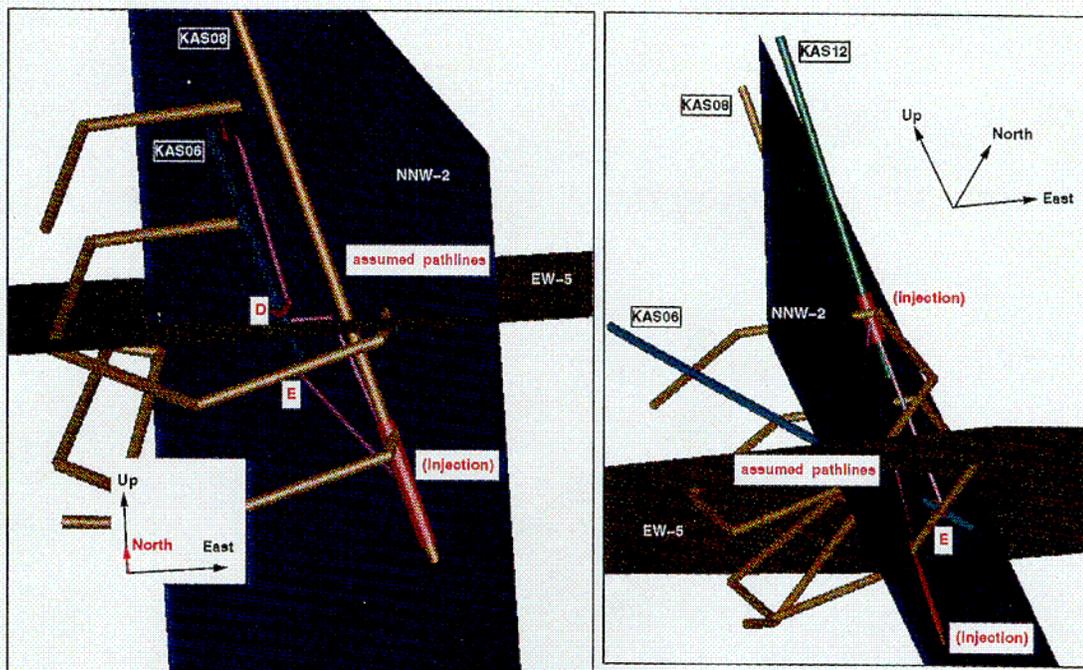


Figure 2. Structures and boreholes seen from south and southeast. Possible transport paths from the injection sections to the inflow levels E and D in KAS06 are shown.

C-01

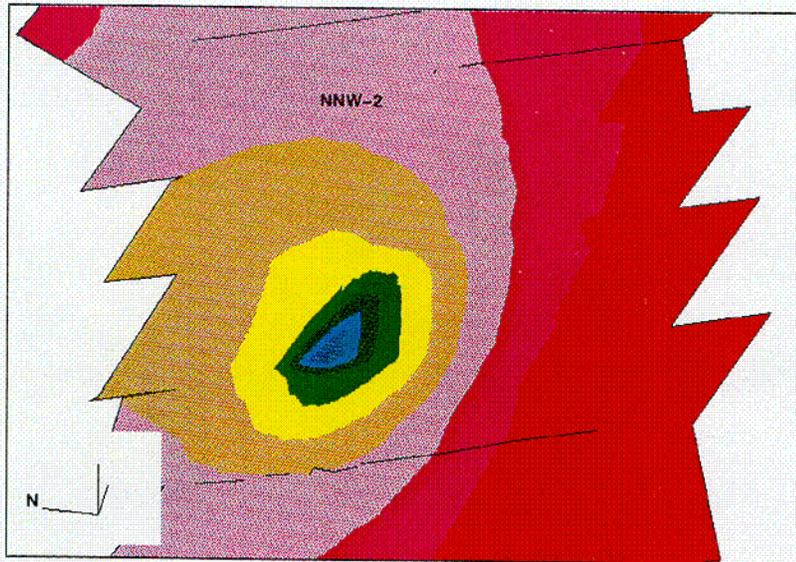
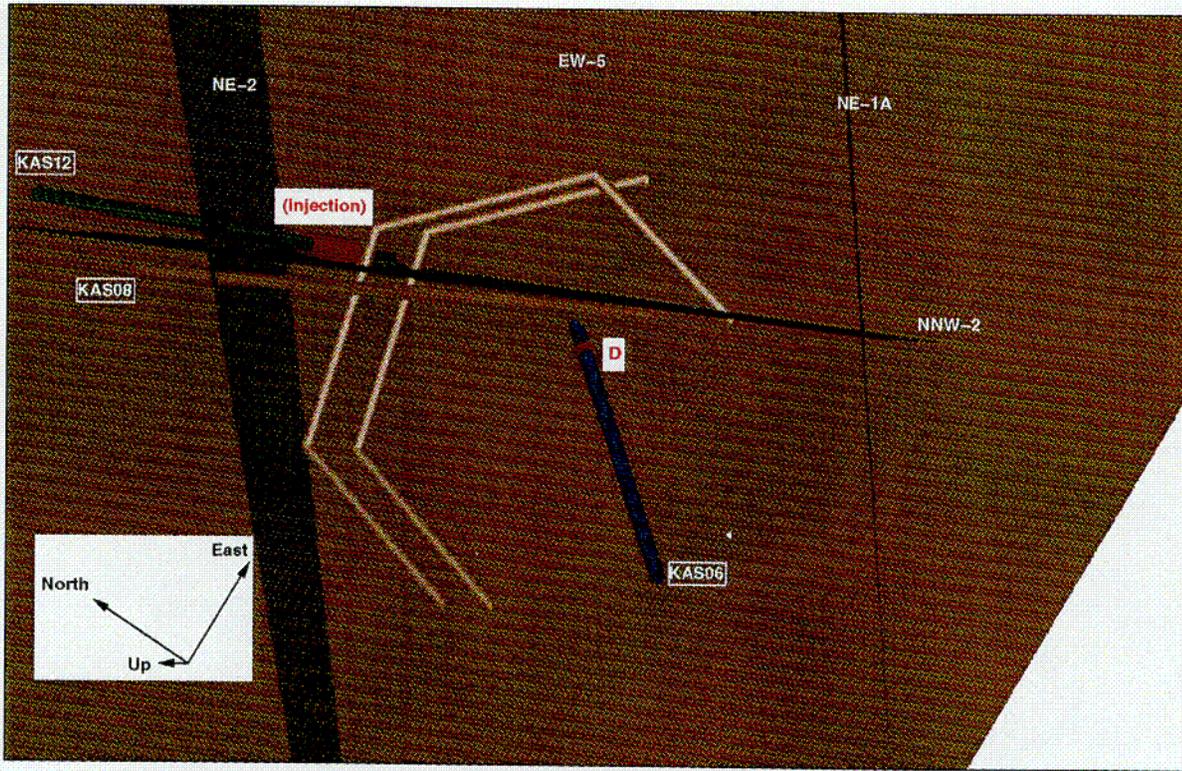


Figure 3. Structures and boreholes seen from above (EW-5 included) and the head field in NNW-2 due to pumping of KAS06.

C-02

In addition to the sampling of the total discharge water samples were taken at predetermined levels in the withdrawal borehole by means of a multilevel sampler. Spinner measurements had been performed to determine distinct inflow levels in KAS06 and samples were taken above each of the main inflow points. The inflow rates at different levels are presented in Figure 4 (reproduced according to Fig. 4.2 in [1]).

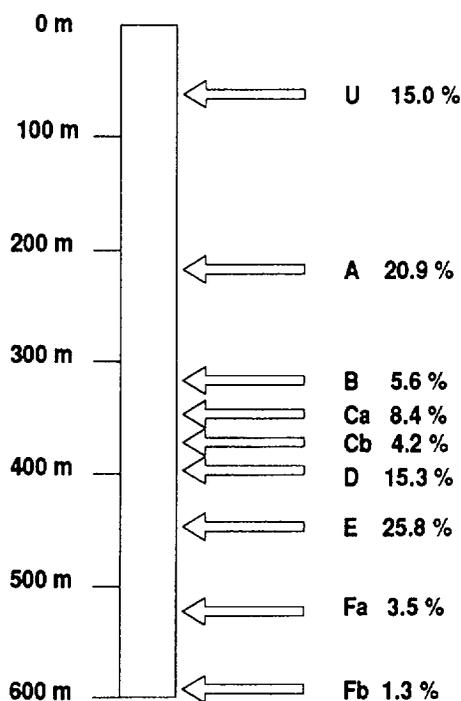


Figure 4. Inflow distribution in KAS06 determined from spinner data. Letters A-F refers to name of conductor and U to the interval 0-100 m (c.f. Table 4.1 in [1]).

3 EVALUATION OF THE BREAK-THROUGH AND INJECTION DATA

3.1 Uranine

The dye tracer uranine was injected in the section KAS12-2 as intermittent decaying pulse injection [1]. The injection pulse is shown in Figure 5 as given in the data delivery to the Task Force. The break-

through curves at different levels in the pumping borehole were measured and are represented as concentrations in Figure 6, likewise.

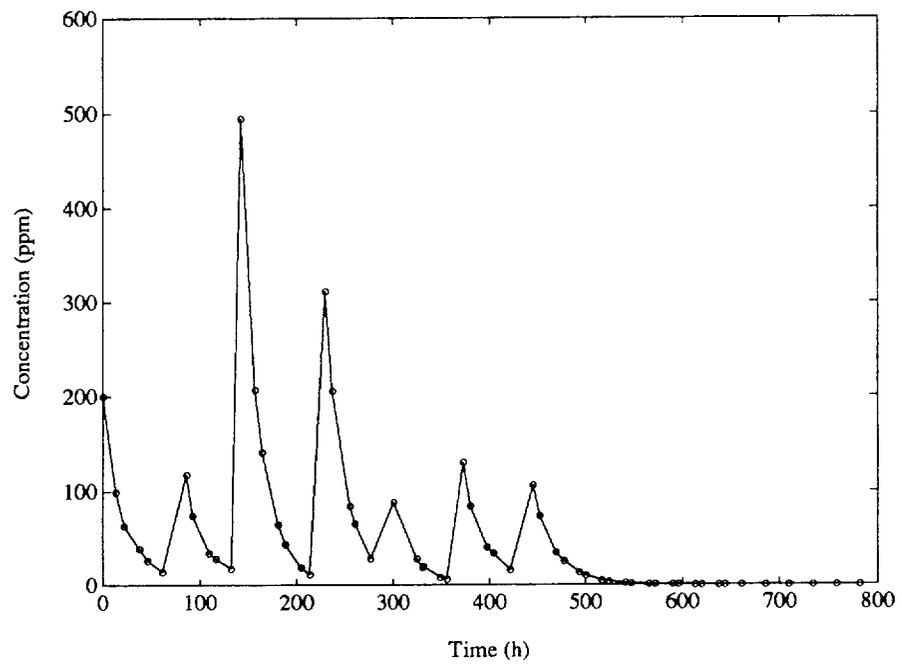


Figure 5. Concentration of Uranine in the injection section KAS12-2

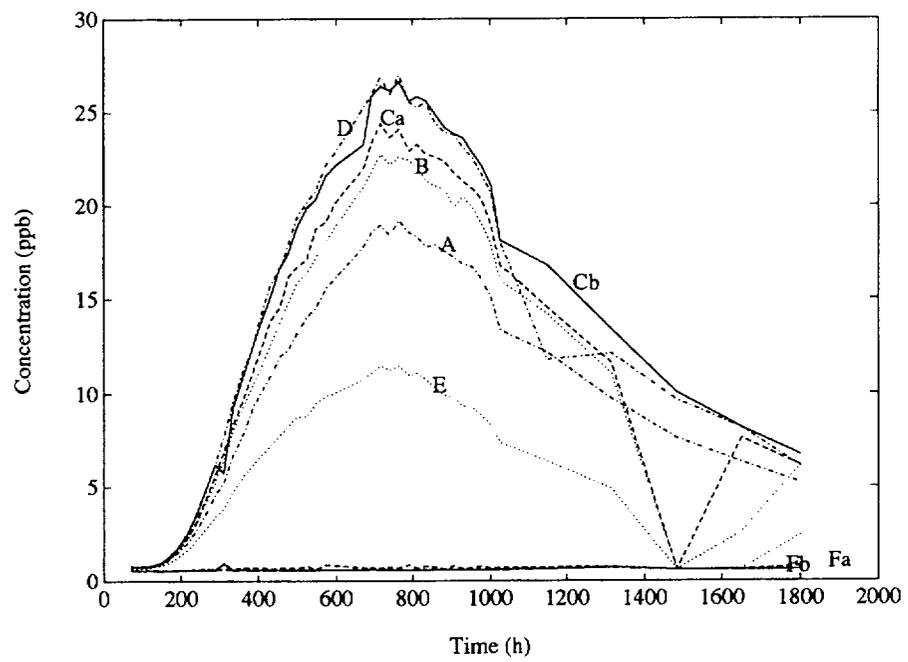


Figure 6. Concentrations of Uranine at different levels in KAS06.

A striking feature of the B-T curves is the similarity of these curves. The curves were measured as concentrations in the cumulatively increasing flow upwards in the borehole. The similarity of the concentration curves can be checked by normalizing the concentrations arbitrarily to equal values. The normalized concentration curves are shown in Figure 7. The curves differ essentially from each other only at very few points. To get the individual massflow break-through curves the inflowing amounts of water at different levels should be known. A flow rate scan with a spinner along the borehole was performed [1] and interpretation of the results gives the flow rate distribution at different levels as shown in Figure 4. The massflow rates into individual levels can be obtained by subtracting the cumulative massflow at a lower level from the cumulative massflow at the next higher level for all of the found inflow levels. The resulting massflow rates of uranine are shown in Figure 8. The tracer massflow rates are given as water inflow rate weighted concentrations (given in ppb) which means just multiplying the measured concentrations by the relative inflow rates. Real massflow rates are obtained by

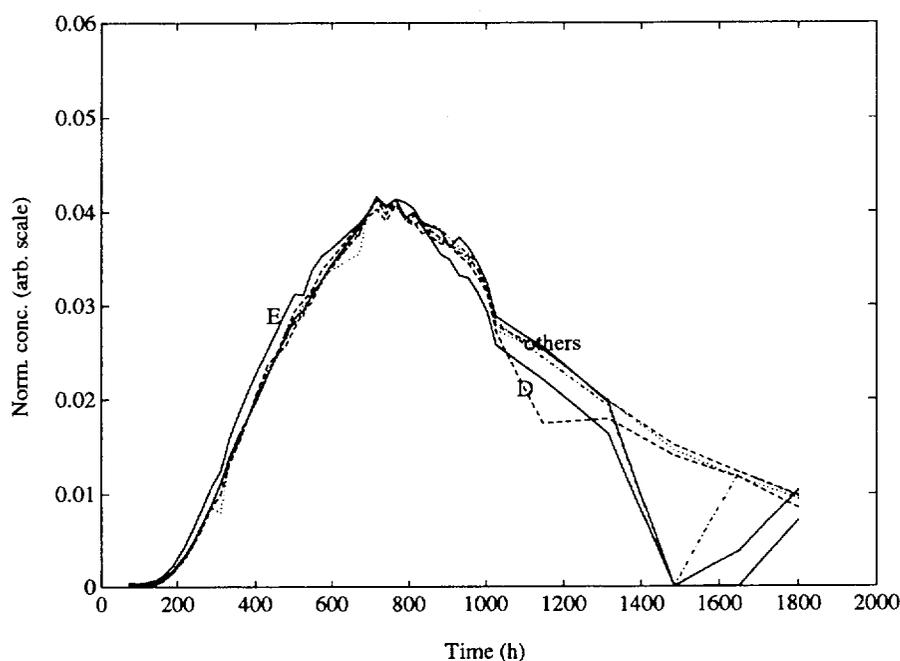


Figure 7. Normalized concentration curves of Uranine at different levels in KAS06.

multiplying by the discharge rate of 135 l/min. The individual massflow rates are, of course, very sensitive to the inflow rate distribution.

The measured concentrations at different sampling levels are well mixed and represent quite well the massflows of the tracers when concentrations are multiplied by the mean water flow rate at the corresponding level as described in detail in [3]. This can be also checked by comparing the sum of massflow rates measured independently with the multilevel

sampler and from the total discharge. The curves for Uranine are presented in Figure 9. It can be noticed that main differences appear after 1000 hours. A possible explanation to that might be that the measuring procedure had to be changed at that time because the spectrofluorometer was returned back to the original laboratory from the site and a longer time of about week elapsed between sampling and analyses [3]. This delay may cause decreased measured concentrations and thus measured values represent lower limits of the real concentrations. The values representing the total discharge samples seem to be lower which might be associated with a higher concentration of dye absorbing precipitates (Fe oxi-hydroxides) in more iron rich waters from the upper most layer.

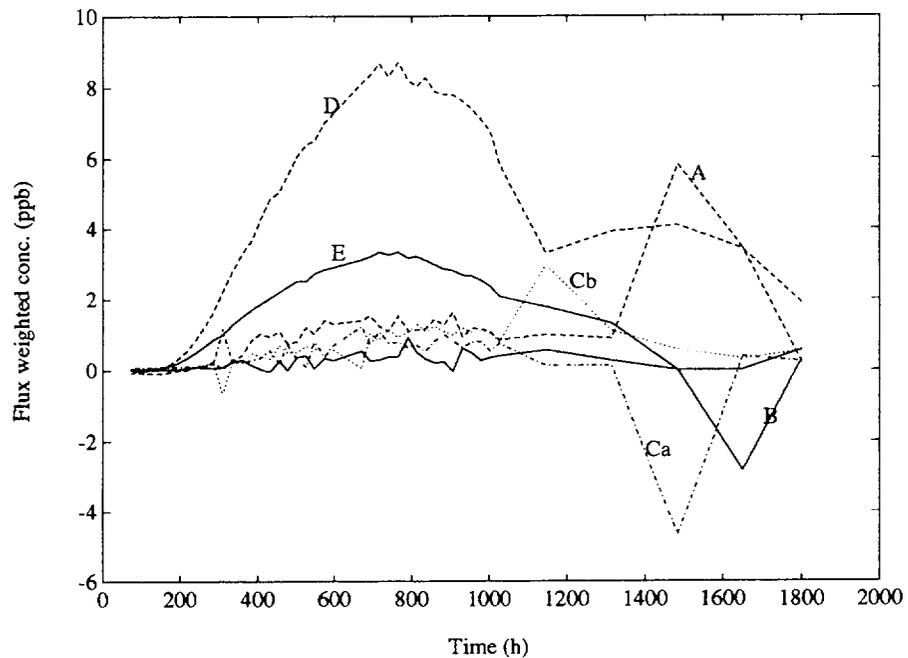


Figure 8. Individual massflow rates into different levels in KAS06 as flux weighted concentrations (conc. multiplied by relative water inflow rates).

The fact that all of the break-through curves measured as concentrations to the different inflow levels in KAS06 are very similar makes it very improbable that they would represent different independent transport paths. This affects the data analysis strategy that should be used.

If the relative inflow rates are exactly those given in [1] (see also Figure 4 in this report) the massflow rates of Uranine into different levels are as given in Figure 8. There appears to be some minor massflow rates also to other levels than E and D. After 1000 hours the variations are large and often opposite in behavior. The explanation might be the concentration analysis error or not stable but varying relative water inflow rates.

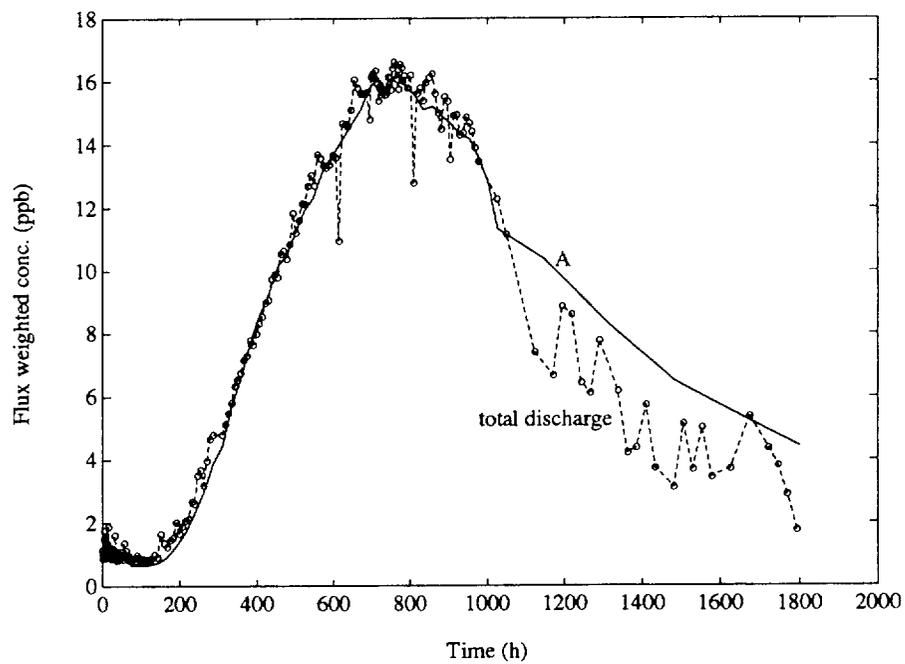


Figure 9. Flux weighted concentrations of the total discharge water and the cumulative tracer inflow into the level A in KAS06.

When the apparent massflow rates are considered to follow from errors in the relative water inflow rates (or time dependent changes in those) it is reasonable to sum the apparent massflow rates from levels that may not actually contribute to the massflow. This then stabilizes the variations in individual rates without loss of information on the physical behavior of the system.

Massflow rates into the section E, into the sections D+others, and out from the bore hole with the discharge water are presented in Figure 10. The massflow rate into the section E is normalized by a factor of 3.6 for the sake of comparison. All these three curves show very similar behaviour up to the time 1000 hours and are reasonably similar also after that taking the potential analysis errors into account. The massflow rate into the section D is in absolute units very near the massflow rate measured from the total discharge water also alone without the contribution from other levels and does not leave very much space for additional massflows into the remaining levels.

If the explanation of the LPT-2 tracer test results is as hypothesized above there is a question of the "right" relative water inflow rates. Does there exist a set of inflow rates that would be consistent with the given hypothesis and which would then be the rates during the LPT-2 test.

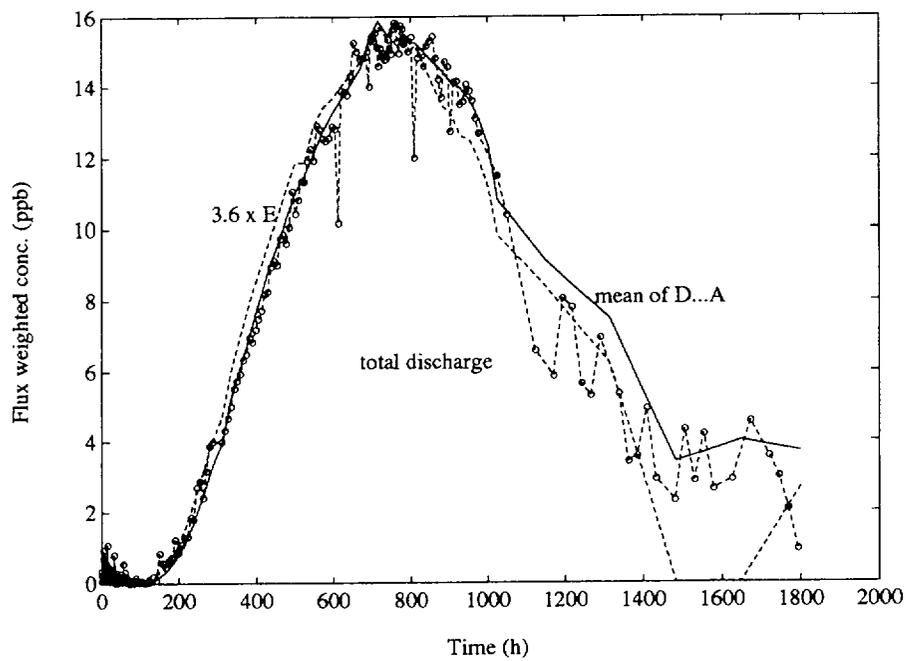


Figure 10. Flux weighted concentrations of Uranine into levels E, D+others, and in the discharge water with the new water inflow distribution as given in Table 2.

Using the water inflow rates presented in Table 2 gives the massflow rate results presented in Figures 11 and 12 for the individual sections.

Table 2. Water inflow rate distributions in an alternative explanation of LPT-2 tracer test results compared with the given spinner test results [1].

Section	New rate [%]	New cumulative rate [%]	Spinner rate [%]	Spinner cumul. [%]
F _b	1.3	1.3	1.3	1.3
F _a	3.5	4.8	3.5	4.8
E	33.8	38.6	25.8	30.6
D	20.3	58.9	15.3	45.9
C _b	1.0	59.9	4.2	50.1
C _a	5.0	64.9	8.4	58.5
B	4.0	68.9	5.6	64.1
A	13.0	81.9	20.9	85.0
U	18.1	100.0	15.0	100.0

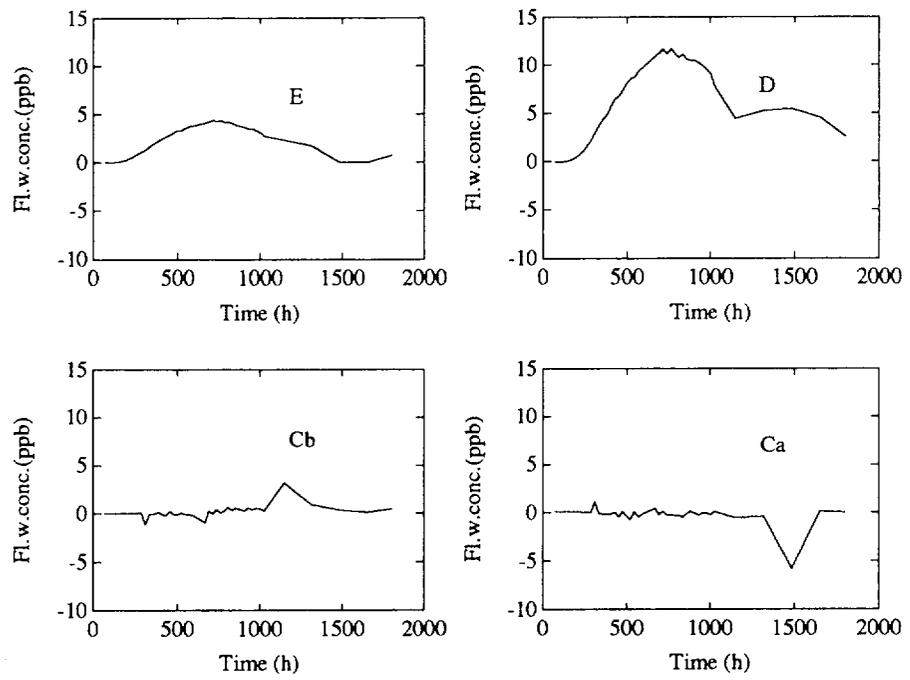


Figure 11. Individual massflow rates into levels E, D, C_b , and C_a with the new water inflow distribution in Table 2.

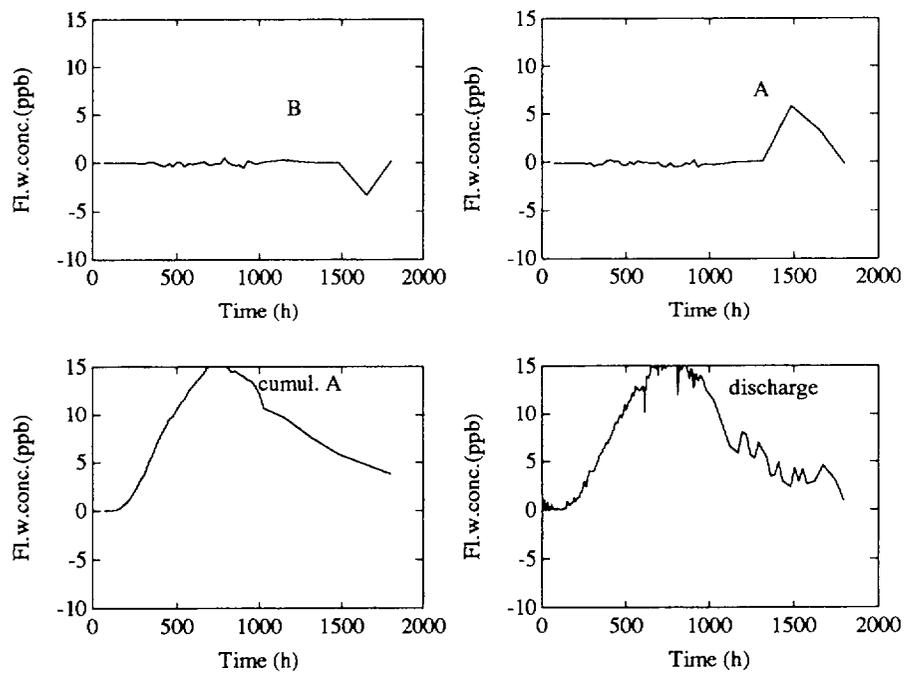


Figure 12. Individual massflow rates into levels B, A, $E+D+C_b+C_a+B+A$, and totally with the discharge water with the new water inflow distribution in Table 2.

The dip in the "D-curve" is at the same time as an increase in the C_b . Also C_a , B, and A cancel partly each other. It should be noted that here the behavior would be determined just by one single point (two in the case of A) and should be assessed very carefully.

As conclusion it can be said that an explanation with tracer mass flow only into sections E and D is a realistic one and in addition these break-through curves are too similar to be caused by independent flow paths. It is, however, possible that the paths into these sections deviate from each other so near the KAS06 that no drastic differences can be obtained. The transport behaviour is determined in the more distant parts of the route where the tracer resides most of the time. This would mean that Uranine is transported from KAS12-2 first only via NNW-2 and branches then to the section D via EW5.

3.2 Radioactive tracer Re-186

The second tracer that could be recovered was a radioactive one, Re-186. Its injection and concentration as well as massflow rate break-through curves based on the distributed data and corresponding those of uranine are presented in Figures 13, 14, and 15, respectively.

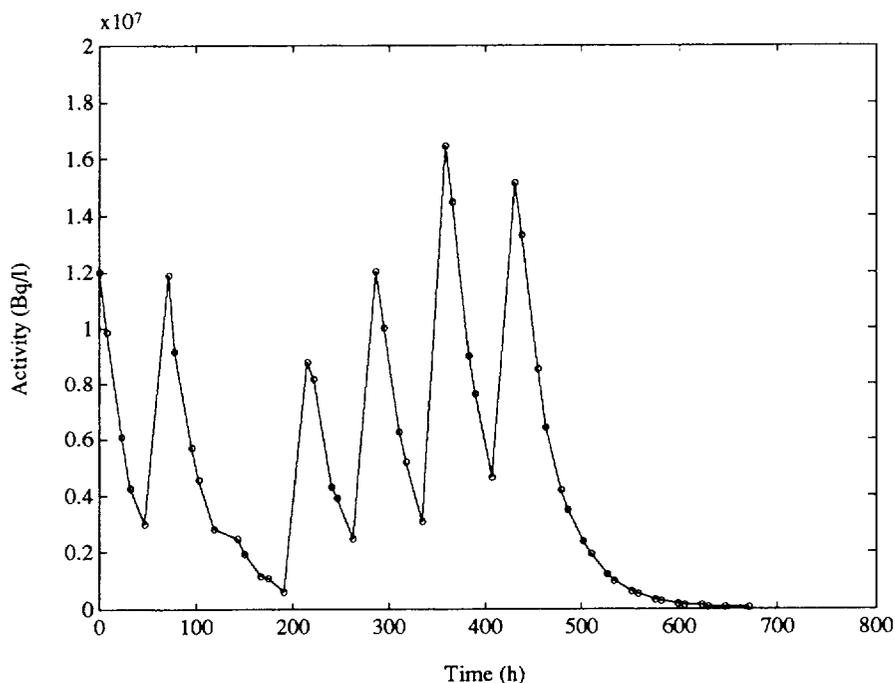


Figure 13. Concentration of Re-186 in the injection section KAS08-1.

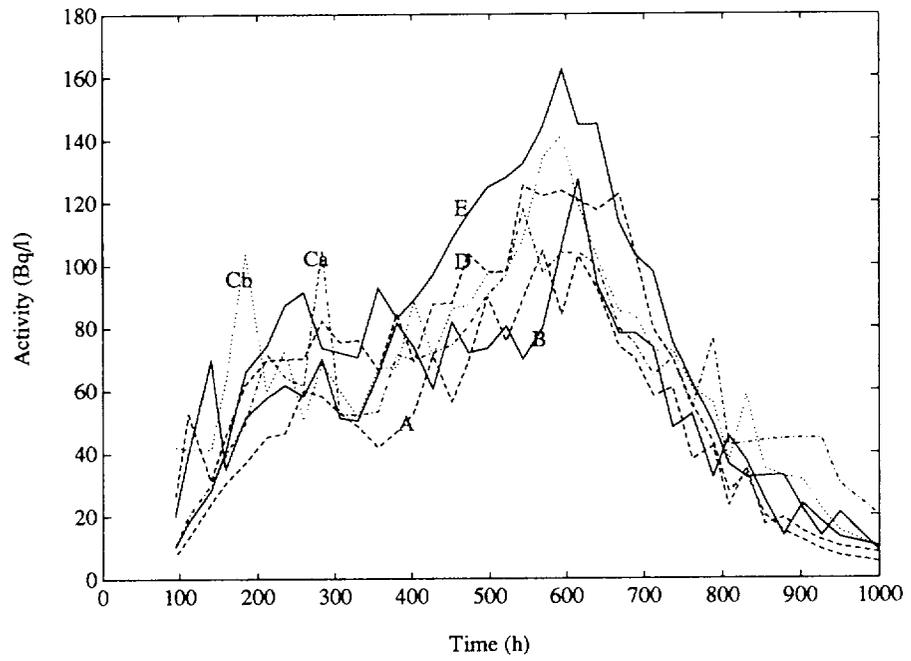


Figure 14. Concentrations of Re-186 at different levels in KAS06.

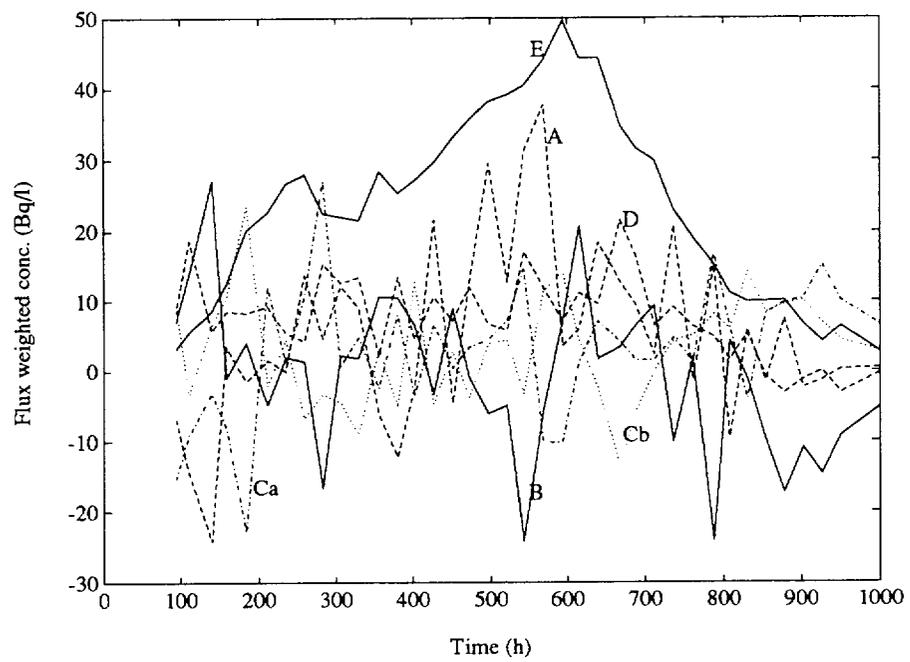


Figure 15. Individual massflow rates of Re-186 into different levels in KAS06.

The same reasoning as for Uranine applies also for the Re-186 tracer with a minor difference. The measured concentration curves are very

similar within the statistics of the measurements. The branching into the sections E and D is slightly different favoring more E in this case.

The massflow rate measured by the multilevel sampler is in this case larger than the massflow rate measured from the discharge water as can be seen from Figure 16.

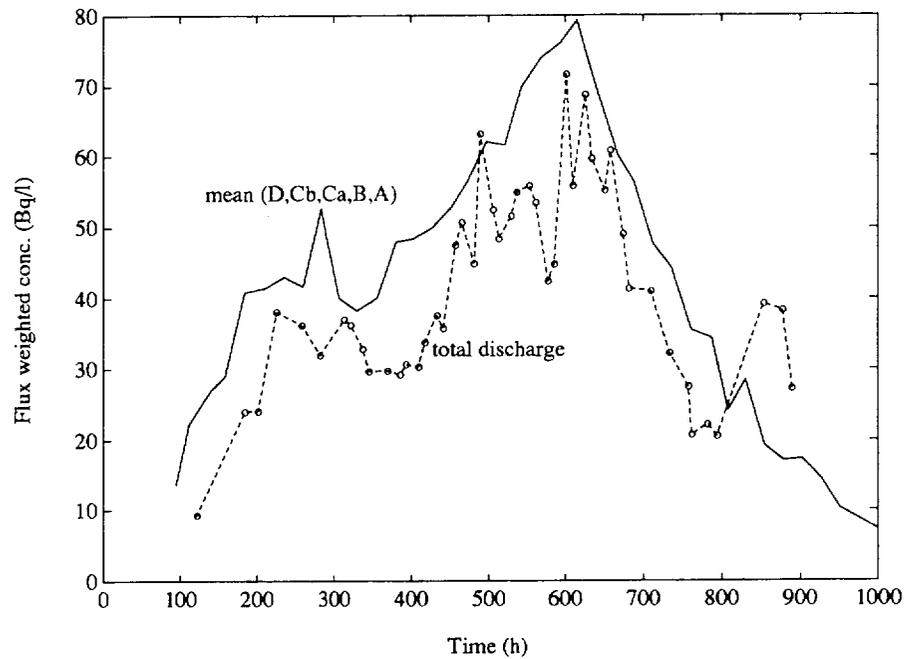


Figure 16. Massflow rates of Re-186 measured from the discharge water and by the multilevel sampler in KAS06.

Massflow rates of Re-186 into the section E, into the sections D+others, and out from the borehole with the discharge water are presented in Figure 17. All these three curves show very similar behavior taking the measuring statistics into account. The cumulative massflow rate into the level D is in absolute units very near the total massflow rate out of the KAS06 which indicates that there does not exist much additional massflows into the remaining levels.

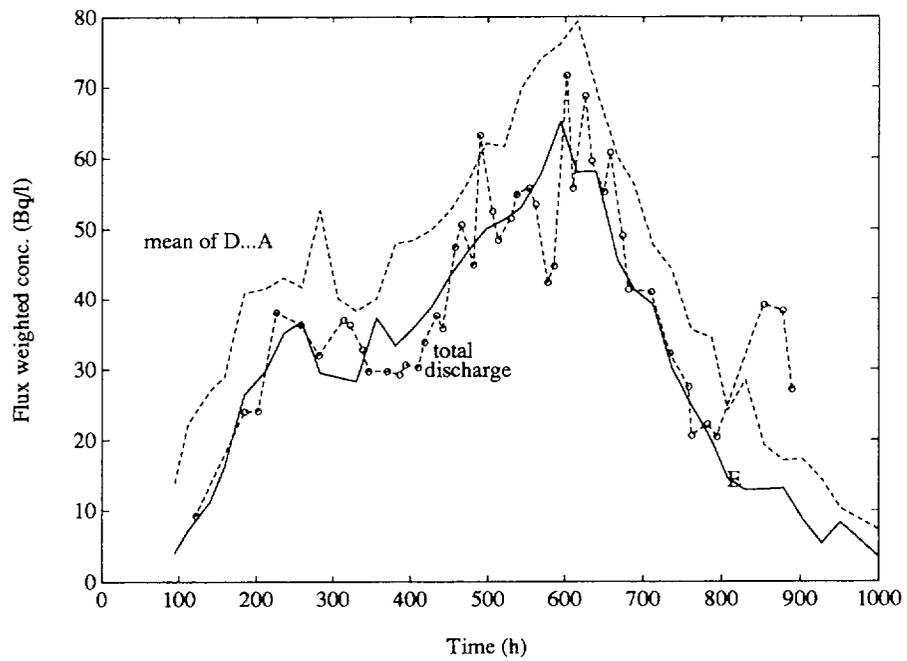


Figure 17. Massflow rates of Re-186 into levels E, D+others, and with the discharge water in KAS06.

4

TRANSPORT MODELLING AND ANALYSIS

A simple model of pumping of a two-dimensional fracture (NNW-2) gives estimates of the mean transport times as a function of the fracture transmissivity as shown in Figure 18. With the given value of $4 \cdot 10^{-5} \text{ m}^2/\text{s}$ the mean transport times should be about 100 and 120 hours for Re-186 and Uranine, respectively. The observed mean transport times are about 500 h and 600 h for Uranine and Re-186, respectively. In the modelling the fact, that fracture apertures calculated from the hydraulic transmissivity and the tracer transport time differ usually by a factor 5-20 or even more, has been taken into account by introducing a factor $C_V = 10$ to represent this difference. It seems that a much larger factor (~ 50) would be needed to explain the LPT-2 test results by using this kind of concept.

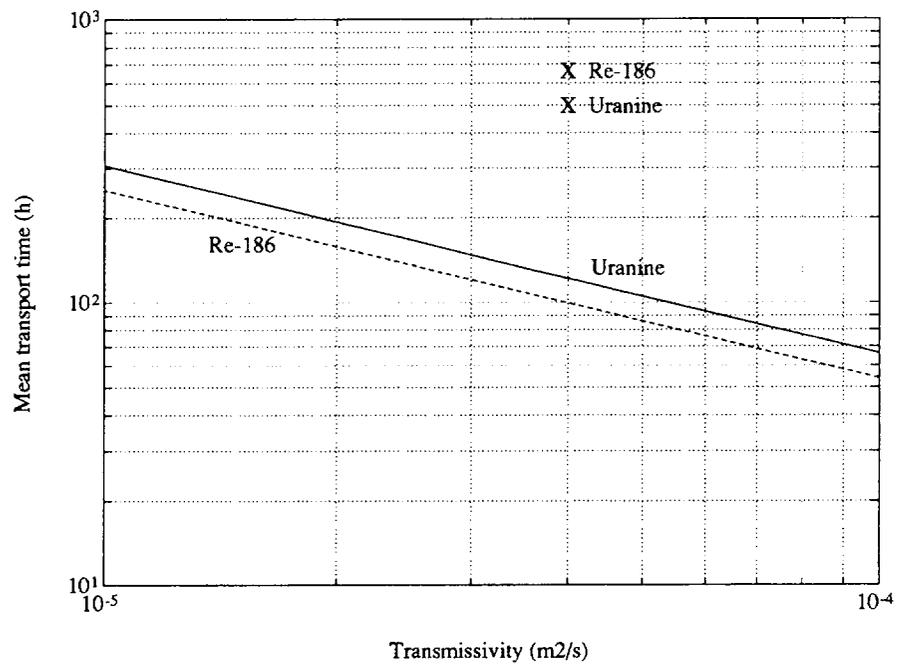


Figure 18. Calculated transport times in a radially converging flow field for Uranine and Re-186 as a function of the hydraulic transmissivity. Measured values are denoted in the figure, too. The factor C_v was assumed to have a value of 10.

4.1

Convolution with a model function

A trial function may be used to find out some characteristic transport behavior and parameters. A commonly used approach is the advection-dispersion model where a mean velocity and a Fickian dispersion are combined to explain the transport behavior. Fitting the parameters (velocity and dispersion coefficient) of this model so that the model curve convoluted with the measured source term curve gives a good agreement with the measured break-through curve characterizes the transport behaviour. The equation for a travelling Gaussian pulse is

$$C / C_o = \frac{1}{2\sqrt{\pi Dt}} e^{-\frac{(x-vt)^2}{4Dt}} \quad (1)$$

which is called the model A in Figures 19 and 20.

Another model which is often used in tracer test evaluations is the so called matrix diffusion model. The matrix diffusion model can be generalized to include any diffusive interaction of a flow channel and stagnant areas around the channel as long as the concentration in the

channel itself can be regarded as well mixed during the transport. The diffusion does not necessarily have to be directed into the rock matrix only but also into any areas where the flow velocity is negligible, e.g. in the fracture plane itself. The equation describing this situation is

$$C / C_o = \frac{u}{\sqrt{\pi} (t-t_o)^{3/2}} e^{-\frac{u^2}{t-t_o}} \quad (2)$$

where the parameter u depends on the flow and diffusion properties of the system and t_o is the transport time without interaction with stagnant areas. For a case of diffusion into the rock matrix only the parameter u can be expressed in the following way

$$u = \frac{WL \sqrt{\epsilon_p R_p D_e}}{Q} \quad (3)$$

where W is the width of the flow channel, L is the length of the transport path, ϵ_p is the porosity of the rock matrix, R_p is the retardation factor in the rock matrix, D_e is the effective diffusion coefficient, and Q is the flow rate in the transport channel. This model is called the model B in Figures 19 and 20.

A comparison of the modelled and measured break-through curves for Uranine are presented in Figure 19. The injection pulse has been convoluted with the impulse response model functions A and B and some fitting by eye of the parameters in the models gives the presented break-through curves. The corresponding results are presented for Re-186 in Figure 20. The applied values of transport parameters are: $v=0.4$ m/h, $D=20$ m²/h, $u=18$ h^{1/2} for Uranine and $v=0.3$ m/h, $D=15$ m²/h, $u=22$ h^{1/2} for Re-186. The transport paths seem to have similar properties the only difference being that Re-186 is transported in a 25 % slower flow. This might be due to hydraulic properties of the transport paths or just hydraulic boundary conditions for the flow situation.

To get a comparable view with the dye tracer and a consistent data set for deconvolution the radioactive decay should be recorrected in the results to correspond a common single moment of time both for the B-T curves and the injections. Several consecutive pulses were injected which were corrected in the distributed data back to each injection start. The break-through curve is a result of seven different injections and the data points in the distributed data were corrected back to each sampling time. The time of 500 hours from the start of the first injection was chosen as the time to which the injection and break-through data were recorrected for radioactive decay. These curves look then somewhat different compared to those given in [1].

compared to those given in [1].

The agreement is almost equal fair for both of the models and tracers and it would be practically impossible to distinguish between the processes that affect the break-through curve just on the basis of these curves. A combination of these processes would give even a better fit but there are surely other processes and phenomena that have not been taken into account and a further fitting would be irrelevant.

If taken as mathematical trial functions the models A and B are just two out of a large number of possible ones. A good fit as such does not in that sense prove anything about the "validity" of the model. Other studies are needed to prove if this or that physical process and model is applicable in the measuring situation at hand. A worse (mathematical) fit may very well be nearer the physical truth than a better one if the data includes errors and processes that are not taken into account.

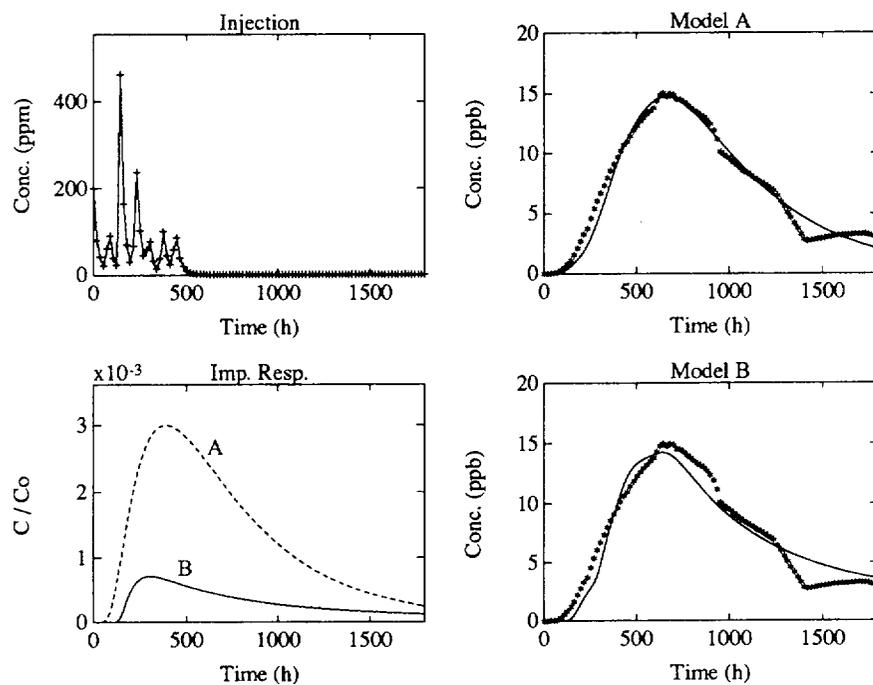


Figure 19. Comparison of the modelled and measured break-through curves of Uranine. The impulse response functions of models A and B have been convoluted with the injection pulse.

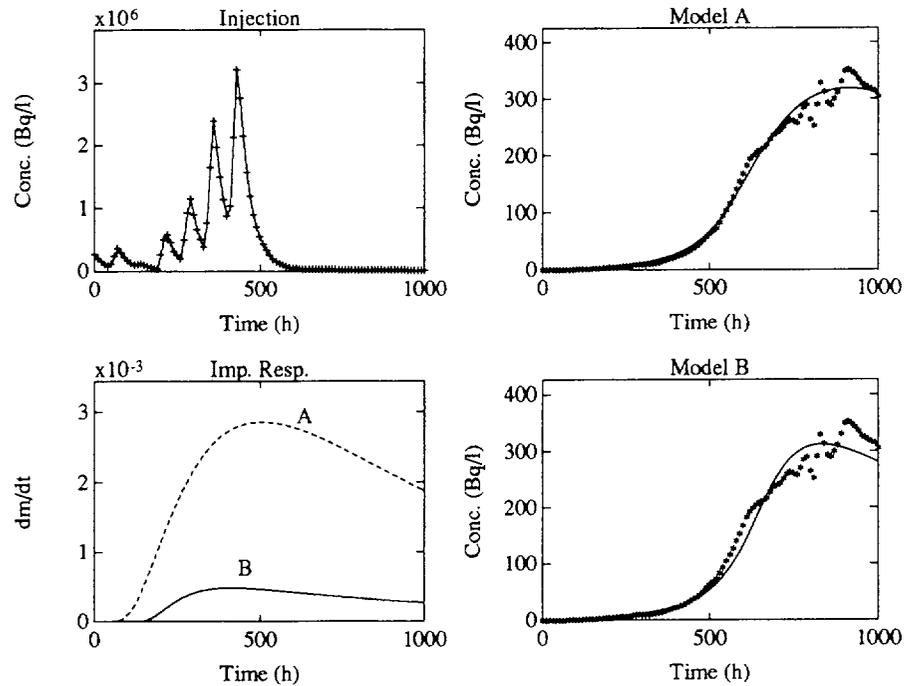


Figure 20. Comparison of the modelled and measured break-through curves of Re-186. The impulse response functions of models A and B have been convoluted with the injection pulse.

4.2

Impulse response extracted by deconvolution

The deconvolution problem with data having some errors is inherently ill-posed. Most deconvolution codes give just the so called optimum solution which is very often "a wiggly curve" where most of the wiggles have no physical meaning. A recently developed approach takes into account also possible errors and does not even pretend to give "the solution" but "a set of acceptable solutions" or an estimate of the lower and upper bounds of the unknowns. The method is called Extreme Value Estimation (EVE) [4,5]. The analysis was done only for the total break-through curves because, as discussed above, there seems to be only vague indications of any other massflows than into the levels E and D. These two massflows are also very similar for each of the tracers representing thus a common transport behavior.

For the analysis the injection data and the break-through data had to be discretized into even intervals. Hundred intervals were used for both of the tracers. Linear interpolations between the data points were used in the discretization. The inputs and results of the EVE analyses are shown for Uranine in Figure 21. The corresponding curves for Re-186 are shown in Figure 22.

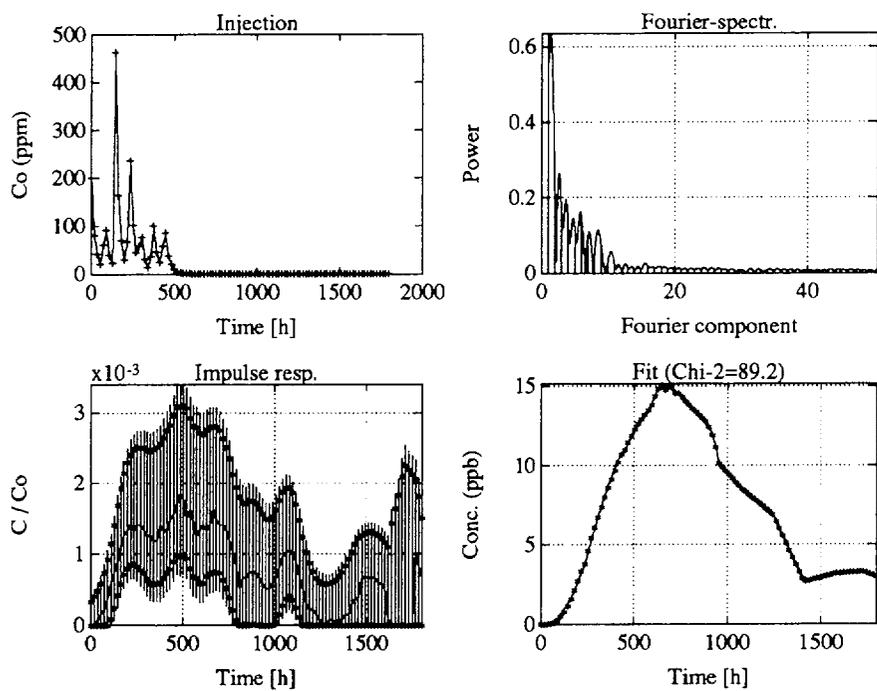


Figure 21. Deconvolution results and the Fourier transform of the Töplitz matrix for Uranine. The optimum solution is convoluted with injection to show the fit with the break-through curve.

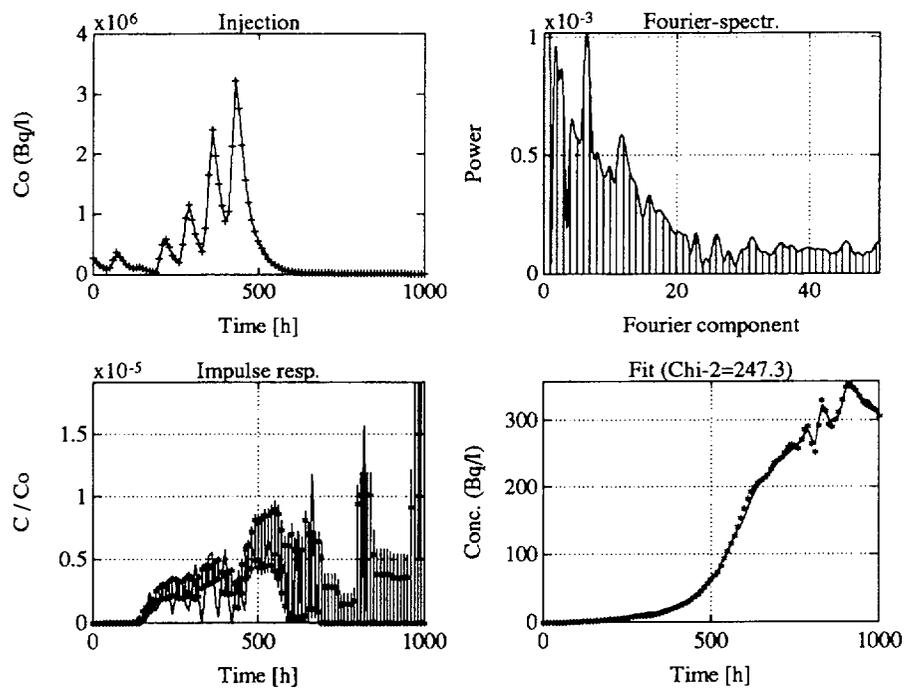


Figure 22. Deconvolution results and the Fourier transform of the Töplitz matrix for Re-186. The optimum solution is convoluted with injection to show the fit with the break-through curve.

The deconvolution is known to lead easily to oscillations of solutions. Such oscillations are seen also in this case. Some hint for the origin of the oscillations may be found from the Fourier analysis of the data and especially in the transformed injection pulse. Weak Fourier components in the source term may cause oscillatory behavior of the solution. The Fourier transforms of the injection pulses for both of the recovered tracers are given in Figures 21 and 22, too.

In addition the so called Singular Value Decomposition (SVD) technique has been applied to study the same problem. This approach is presented only very shortly in the following. The convolution of the injection and impulse response can be presented in the form $y = K c$, where y is the measured break-through pulse, K is the Töplitz type of lower triangular matrix created from the injection pulse, and c is the impulse response to be solved. The matrix K can be decomposed in the form $K = U S V^H$ by the SVD method. The wanted solution of the problem (without the positivity constrain) is then $c = V S^{-1} U^H y$ where V^H and U^H denote transposes of the unitary matrices V and U , respectively ($U^{-1} = U^H$ and $V^{-1} = V^H$).

The diagonal of the S contain the singular values. The columns of the V are the singular vectors and they contribute potentially the more to the solution c the smaller are the corresponding singular values. Some of the singular vectors associated with small singular values may be assessed to be caused by errors and disturbance in the data and thus not representing any physically relevant contribution. Such components may then be rejected from the solution.

It might be difficult to decide which singular vectors to include in the solution and which to leave out. The SVD reveals in the time domain in any case the critical vectors of the source term that are very sensitive in the analysis and should be assessed carefully when interpreting the physical behaviour.

It is known that regularly repeated pulses make the deconvolution more difficult. A single pulse which in this case is exponentially decaying would be much better from the deconvolution analysis point of view. Even a second pulse would worsen the situation in this respect radically.

If the problem would be solved without the positivity constrain the solution would be simply $c = K^{-1} y$. Thus, the more the matrix K resembles a singular matrix the more difficult and unstable the problem is. One measure of the stability of the analysis is the condition number of the Töplitz matrix K . One exponentially decaying injection pulse would give a value of 7.8 and a second pulse increases the value to 75. The condition numbers of the (101 x 101) matrices for the Uranine and Re-186 injections are $3.5 \cdot 10^5$ and $1.6 \cdot 10^5$, respectively. These matrices

lead to such heavy oscillations that the problem cannot be solved directly at all by inverting the matrix K .

It can be concluded that the oscillatory behavior seen in the LPT-2 deconvolution analysis is obviously not physically relevant but artificial following from the mathematics. A more favorable injection scheme can make the deconvolution analysis much more stable and robust.

5

CONCLUSIONS

To assess the relevance of the eventual differences between the massflow rate curves into different sampling levels and to deduce if a tracer arrived via different pathways it is very important to take an error estimate of the groundwater inflow rates and also measured tracer concentrations into account. The similarity of the massflow rates of tracers indicate just one transport pathway for both of the recovered tracers. The differences may be rather easily explained by uncertainties especially in the groundwater flow rate measurements at different levels. It should be remembered that the spinner measurements were done with a lower flow rate and much sooner than in the LPT-2 test after the start of the pumping.

If the tracers arrived essentially along one transport path, the transport modelling is rather straightforward: a fit of transport parameters (in this work either according to the conventional advection-dispersion theory or matrix diffusion like exchange of tracer between the flow channel and stagnant areas in the flow field) to have a good overall fit with the data. A better fit with a combined model would not necessarily prove more about the transport processes. A fit with an advection-dispersion model with a small contribution of "matrix diffusion" may give a better fit but the real physical reasons of the somewhat worse fit without "matrix diffusion" may be some other process, e.g. a non-Fickian dispersion in that particular flow situation. The improvement by adding the process of "matrix diffusion" would then be only an artifact.

A minimum requirement of serious studies of transport processes is a whole systematic series of measurements where experimental parameters such as the flow rate are varied. Preferably only one well defined transport path at a time should be involved.

It is concluded that break-through curves of two out of six tracers were measured in the LPT-2 test. Taking into account uncertainties in the used groundwater inflow rates at different levels in the pumped borehole and similarities of the break-through curves it seems probable that tracers injected from the sections KAS12-2 and KAS08-1 did arrive into the withdrawal borehole KAS06 essentially via one pathway each. The break-through curves can be explained either by hydrodynamic dispersion with

Péclet numbers around 4 or by matrix diffusion like behaviour with a parameter $u = 18 - 22 \text{ h}^{1/2}$. The half-life of the radioactive tracer Re-186 is too short for a reliable determination of the main part of the break-through curve. Due to the short half-life compared to the mean transport time the early parts of the break-through curve are strongly emphasized. The transport paths are similar for Uranine and Re-186 but Re-186 is transported 25 % slower.

6

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