INTERNATIONAL COOPERATION REPORT

ÄSPÖLABORATORIET

Difference flow measurements at the Äspö HRL, May 1995

Pekka Rouhiainen

PRG-Tec Oy

September 1995

Supported by TVO, Finland

SVENSK KÄRNBRÄNSLEHANTERING AB
SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT CO
BOX 5864 S-102 40 STOCKHOLM
TEL. +46-8-665 28 00 TELEX 13108 SKB TELEFAX +46-8-661 57 19

9603010279 960214
PDR WASTE
WM-11 PDR

ISSN 1104-3210
ISRN SKB-ICR--95/04--SE

DIFFERENCE FLOW MEASUREMENTS AT THE ÄSPÖ HRL, MAY 1995

Pekka Rouhiainen

PRG-Tec Oy

September 1995

Supported by TVO, Finland

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.

DIFFERENCE FLOW MEASUREMENTS AT THE ÄSPÖ HRL, MAY 1995

Pekka Rouhiainen

PRG-Tec Oy

September 1995

Keywords: Groundwater, Flow, Measurement, Äspö

ABSTRACT

TVO-flowmeter was used in Äspö Hard Rock Laboratory at ZEDEX project test site. Difference flow measurement was for the first time tested in underground conditions. Boreholes A4, A5 and C5 were measured with 3.5 m section length. Inflow or outflow from the sections was monitored when the holes were open and when they were closed. Calculated hydraulic heads and transmissivities are presented.

TABLE OF CONTENTS

ABSTRACT		ii
1	INTRODUCTION	1
2	PRINCIPLES OF OPERATION	2
3	INTERPRETATION	4
4	EQUIPMENT SPECIFICATIONS	6
5	MONITORING BOREHOLE PRESSURE	7
6	REPEATED MEASUREMENTS	9
7	FLOW MEASUREMENTS DURING THE PRESSURE BUILD UP	11
8	TRANSMISSIVITIES AND HYDRAULIC HEADS	14
9	DISCUSSION AND CONCLUSIONS	17
	REFERENCES	20
	APPENDICES	
	Appendix 1: List of measurements	21

1 INTRODUCTION

TVO and SKB signed in 1992 an agreement on Joint Project regarding HRL of Äspö. One of the study subjects in this project is the direct measurement of groundwater flow in boreholes. TVO has developed a novel instrument for this purpose. The work has been conducted by PRG-Tec Ltd. The instrument has been used previously in TVO's site characterisation in Finland.

Difference flow measurement is a new method that is used to obtain hydraulic conductivity and head of bedrock in boreholes. It is used as a standard method in the site investigation for disposal of radioactive waste in Finland. The objective for the flow measurements at Äspö Underground Laboratory is to

- test use the flowmeter for determination of hydraulic conductivity in underground boreholes,
- get a comparison of flowmeter results with previously performed pressure build up tests.

The equipment consists of winch and cable on a trailer, downhole probe and PC computer. SKB provided rods for pushing the tool to boreholes, a rubber cone for closing holes and a pressure sensor for monitoring the hole pressure as well as a vehicle for accessing the site, ZEDEX project boreholes A4, A5 and C5.

2 PRINCIPLES OF OPERATION

TVO-flowmeter can be used to measure groundwater flow into or out from a given borehole section. The measurements can be performed with or without pumping water from the hole. Hydraulic conductivities and hydraulic heads of fractures or fractured zones can be solved from the results if certain assumptions are made.

The new method is developed from conventional measurement of flow along the hole. However, it is not the flow along the hole itself, but its changes with depth that are useful in interpretation. Measurement of flow along a hole is problematic, because, when strong, it may hide small changes of flow thus decreasing resolution. This can be avoided if the changes of flow are measured directly. Since the differences of flow along a hole are measured directly, the method is called difference flow measurement.

With the new flow guide, flow along the hole is guided to pass beside the flow sensor. The flow that goes into or out from the borehole in the test section is guided into the flow sensor. Instead of inflatable packers, there are rubber disks at the ends of the flow guide. These isolate the borehole section to be measured, Figure 2-1.

Groundwater level in the borehole is kept constant by a special pump. In rock caverns, a corresponding situation can be achieved by keeping the holes open or closed. Hydraulic head in the hole is then constant, since hydraulic conductivity of the hole is very high compared with conductivity of bedrock. So there is minimum head difference over the rubber disks used in the flow guide. The rubber disks are designed in such a way that they always press to the borehole wall. Difference flow measurement differs from conventional double packer tests in that there is no extra pressure in the borehole section to be measured.

A single differential flow measurement in one depth interval takes normally 12 minutes. This time includes waiting time (for stabilising temperature), a flow measurement with thermal pulse method, a flow measurement with thermal dilution method and lifting the cable to the next depth interval. Thermal dilution method is used to increase the range of measurement to larger flow velocities.

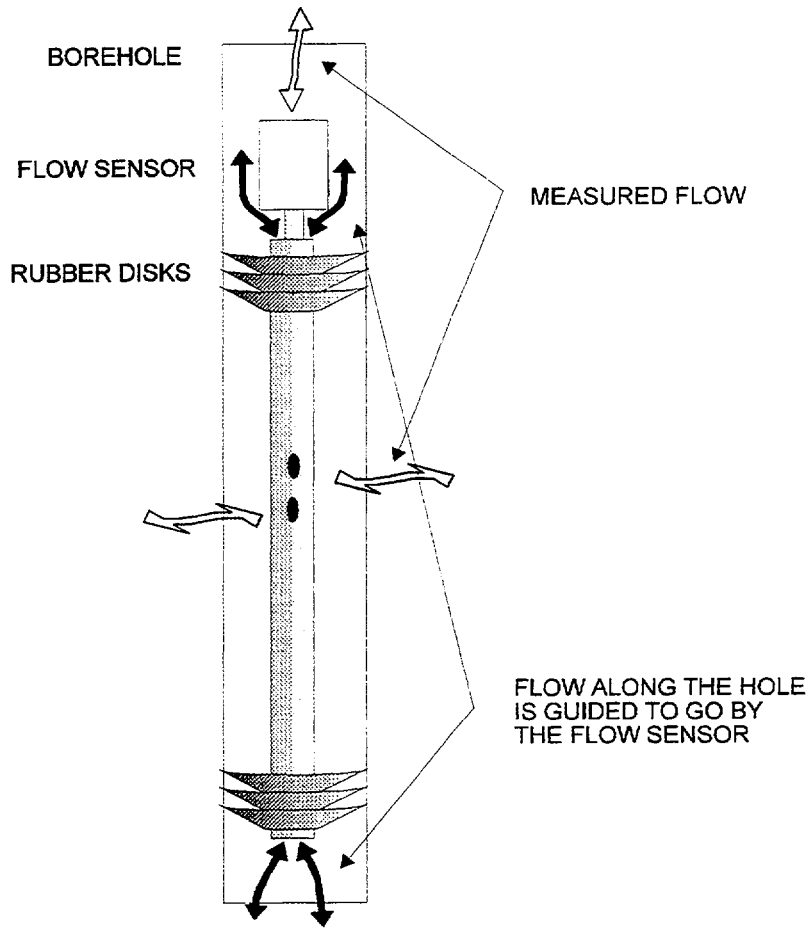

Figure 2-1. *Principle of difference flow measurement*

3 INTERPRETATION

If the measurements are carried out using two potential levels in the hole, then hydraulic heads of the zones and their conductivities can be calculated. It is assumed that static flow condition exists.

$$Q_{n1} = K_n \cdot a \cdot (h_0 - h_1) \qquad 3\text{-}1$$
$$Q_{n2} = K_n \cdot a \cdot (h_0 - h_2), \qquad 3\text{-}2$$

where
Q_{n1} and Q_{n2} are the measured flows in a section,
K_n is hydraulic conductivity,
a is a constant depending on flow geometry,
h_1 and h_2 are the hydraulic heads in the hole
h_0 is the head of the measured zone far from the hole

Since very little is generally known of flow geometry, cylindrical flow without skin zones is assumed. Cylindrical flow geometry is also justified because the borehole is in constant head and there are no strong gradients along the hole, except at the ends of the hole. For cylindrical flow constant a is:

$$a = 2 \cdot \pi \cdot L / \ln(R/r_0), \qquad 3\text{-}3$$

where
L is the length of the measured section,
R is the distance to constant potential h_0 and
r_0 is the radius of the hole

The distance to constant potential h_0 is not known and it has to be chosen. It is here taken R= 14 m.

Hydraulic head and conductivity can be solved from the two measurements:

$$h_0 = (h_1 - b \cdot h_2)/(1-b), \qquad 3\text{-}4$$

$$K_n = (1/a) \cdot (Q_{n1} - Q_{n2}) / (h_2 - h_1) \qquad 3\text{-}5$$

where

$$b = Q_{n1}/Q_{n2}$$

Transmissivity is then

$$T_n = L \cdot K_n \qquad 3\text{-}6$$

Calculated transmissivity value should be taken as an order of magnitude value, because the actual flow geometry is not known. It is also assumed that flow is laminar. This may not be the case if the gradient is very high towards a borehole.

4 EQUIPMENT SPECIFICATIONS

The flowmeter monitors groundwater flow in or out from a borehole within a given section, which in this case is 3.5 m long. A flow guide is used to separate the section to be measured. The flow guide maintains the section in the same hydraulic head as the rest of the hole. Groundwater from or to the section is guided to the flow sensor. Flow is then measured by thermal pulse and thermal dilution method. The values are send digitally to the PC computer.

Type of instrument	TVO flowmeter
Borehole diameters	56 mm, 76 mm
Length of cable	1000 m
Range of measurement	6 - 30000 mL/hour
Calibrated	July 1994, December 1994
Method of calibration	Special calibration pump for known , small and steady flows

The flowmeter is described in detail by Rouhiainen (1993, 1994).

5 MONITORING BOREHOLE PRESSURE

Special rubber cones were used to close the boreholes to measure the flow in pressurised holes. The borehole casings were equipped with special tools to tighten the rubber cone. The cable and rods for the flowmeter were fed through the rubber cone. An adapter for pressure transducer was fitted on the borehole casing. Pressure data from the transducer were collected to a data logger. All the devices for pressure monitoring were provided by Swedish Nuclear Fuel and Waste Management CO (SKB).

Hydraulic heads of the boreholes are presented in Figure 5-1. The boreholes A5 and A4 were first measured as open and then as closed. The boreholes (or the rubber cone) had to be opened when the flowmeter was moved to the next position. At that time borehole pressure always dropped to air pressure. It took a long time until the holes were full of water and until they could be closed. This holds for the boreholes A4 and C5 which had a small inflow of water. Water was poured into these holes to speed up the process.

The flow was monitored during the pressure build up in the boreholes. The last flow measurement at each depth was done after at least one hour from closing the borehole. Both pressure and flow were monitored during the nights.

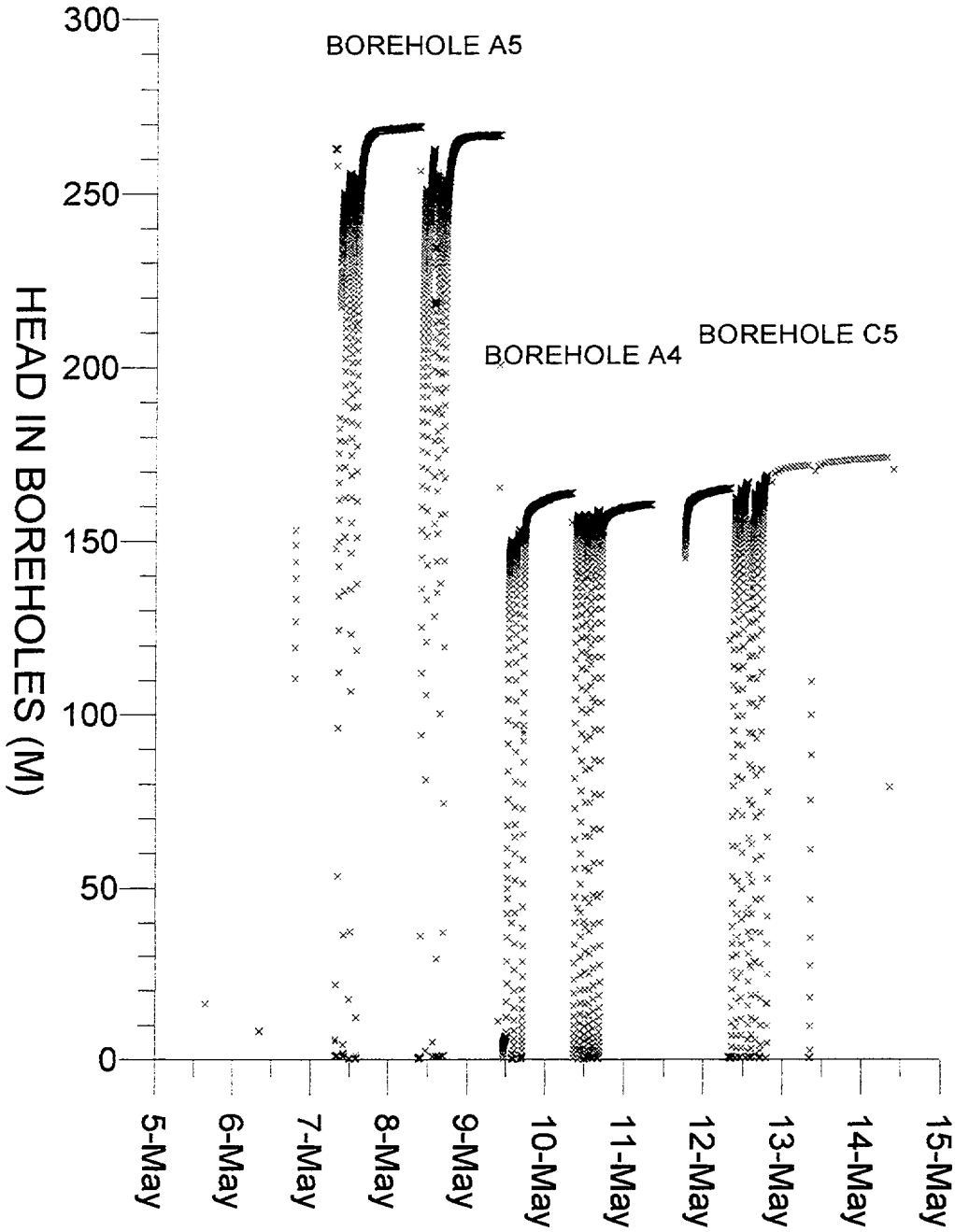

Figure 5-1. *Hydraulic heads of boreholes A4, A5 and C5 during the measurement period.*

6 REPEATED MEASUREMENTS

In borehole C5 the flow measurements were repeated two or three times when the open hole was measured. The hole was measured once more in nearly the same open hole condition. This was done just before the hole was closed at each depth. These measurements did not take much additional time since they were done during the deairating phase before the pressure build up.

The results are presented in Figure 6-1. The measurements on May 12-14 did not repeat as well as the tests on May 11. It is not clear if this is due to the high pressure history of the hole on May 12-14, because the flow values were not systematically higher in the later measurements. However, Figure 6-1 gives an idea of the repeatability of the flow measurements.

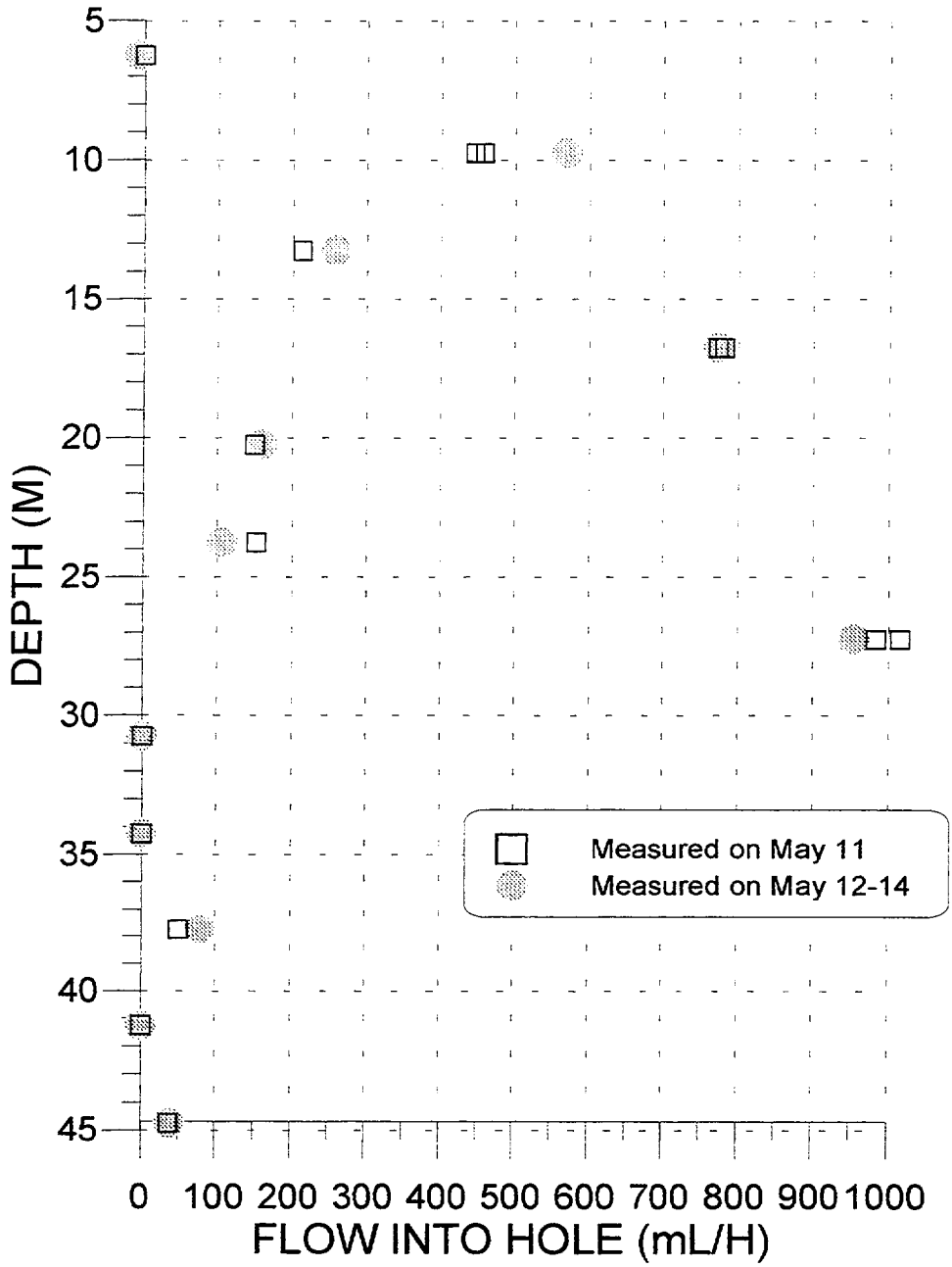

Figure 6-1. *Repeatability test in borehole C5*

7 FLOW MEASUREMENTS DURING THE PRESSURE BUILD UP

Flow transient in Figure 7-1 (borehole C5, 18.5-22.0 m) is positive all the times during the pressure build up. Positive sign is chosen for the flow into the hole. Flow decreases from 156 ml/h to 5.3 ml/h within two hours.

In the other example, Figure 7-2 (borehole A4, 7.75-11.25 m), water flows first into the hole by the rate 140 ml/h. There is no flow when hydraulic head in the hole is 20-30 m. Then water flows out from the hole and reaches its maximum 700 ml/h in that direction.

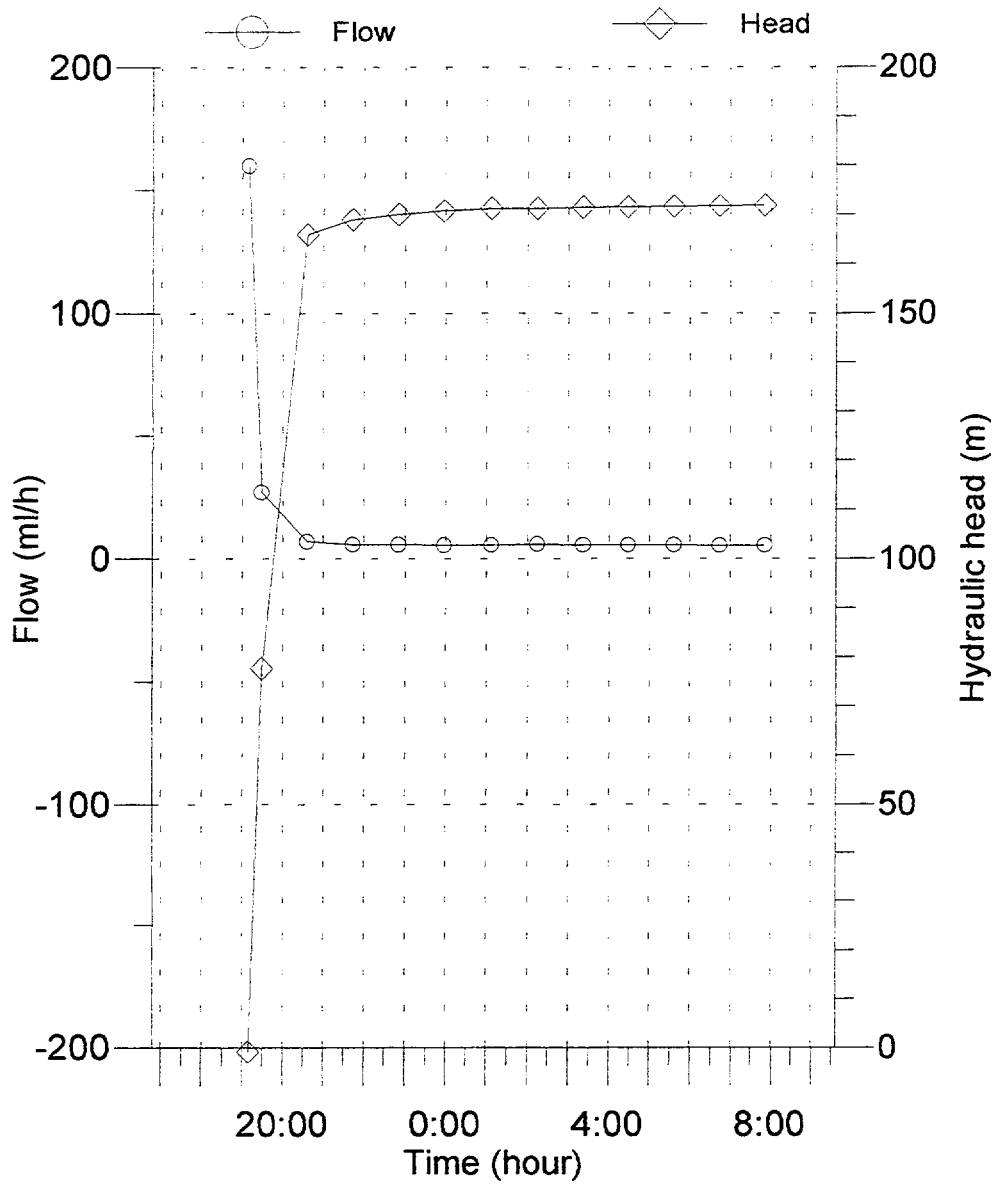

Figure 7-1. *Flow and pressure transients in borehole C5 at 18.5-22.0 m on May 12-13.*

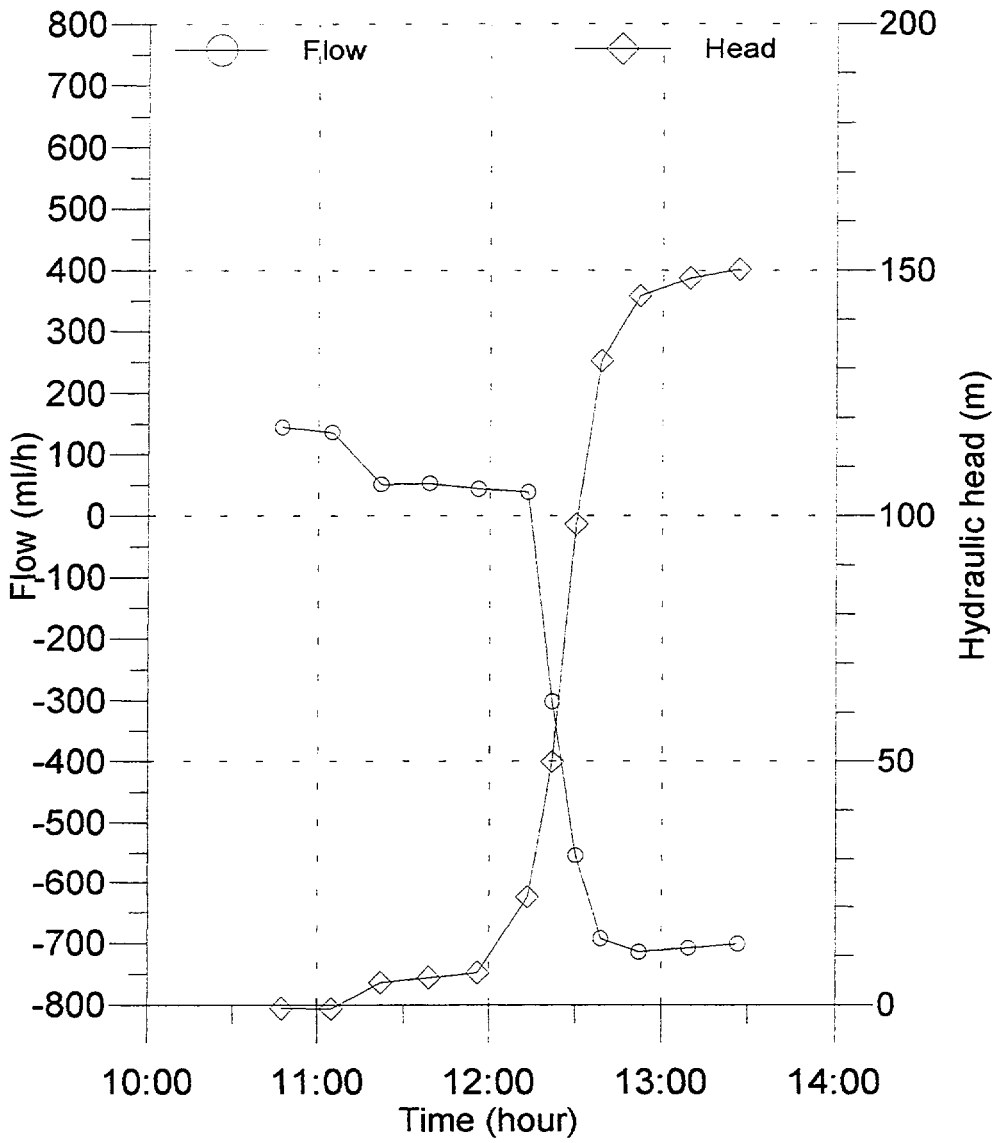

Figure 7-2. *Flow and pressure transients in borehole A4 at 7.75.5-11.25 m on May 9.*

8 TRANSMISSIVITIES AND HYDRAULIC HEADS

Hydraulic heads and transmissivities can be calculated from two flow measurements at the same depth with different borehole head. These pairs are collected in Table 8-1. The length of the measured section is always 3.5 m. In the left side of Table 8-1 there are the measured flows in the open holes. If there are several repeated measurements the last one is chosen. In the right side of Table 8-1 there are the last measured flows in the closed boreholes and the measured heads in the boreholes.

Calculated heads of the sections are presented if there is a measured flow (other than zero) in both measurements of a pair. Transmissivities are presented if there is a measured flow (other than zero) in one measurement of a pair. In the other cases transmissivity is estimated to be less than 1E-11 m^2/s. This value can be calculated if the detection limit is taken as 6 ml/h and the minimum head difference at all depths is taken as 150 m.

In borehole A5 at depth 14.75 - 18.25 m the flow into the borehole was very high even when the hole was closed. The calibrated range of the flowmeter was exceeded. Flow values that are given for tests 6725 and 6743 in Table 8-1 are obtained simply by extrapolating the calibration function. Evidently flow 250000 ml/h for test nr 6725 is too high. Total outflow from borehole A5 was 3.6 l/min instead of 4.4 l/min that is the sum of all flowmeter results in the open hole.

The sum of all flows in closed holes should be zero if all depth sections are measured. This does not fit well in borehole A5 where much more inflow than outflow was found. It is likely that flow 130000 ml/h for test 6743 is too high. It is also possible that some flowing fractures were missed at depth deeper than 39.25 m or at depth upwards from 4.25 m.

Calculated hydraulic head 559 m in borehole A5 at depth 14.75 - 18.25 m is very high. It is actually impossible because depth level of ZEDEX site is about 420 m and that is also theoretical maximum of hydraulic head. The results of the tests 6725 and 6743 are unreliable or wrong. They are over the calibrated range of the flowmeter. Hydraulic head in A5 at depth 14.75 - 18.75 m is very high anyway, since there is strong inflow even in the closed borehole. Hydraulic head in A5 at depth 14.75 - 18.75 m must be more than 263 m which was the head of the closed borehole during test nr 6743.

In borehole A4 very little flow was measured when the hole was open. The sum of the measured flows is 106 ml/h. On the other hand the measured outflow from open A4 was 1900 ml/h, that is 20 times more. It is highly

likely that some flowing fractures were missed. This is supported by the fact that there was only inflow in closed A4, the place of outflow was not found.

Inflow into open borehole A4 was so small that water level went down when the tool was lifted. This was not noticed during the measurements. Lifting the cable and rods acts equally as pumping water from the hole. This pumping rate is 1700 ml for each 3.5 m lifting. The pumping rate is much faster when the electronics tube comes out from water. In addition to this some water flew out from the hole when the tool was near the bottom and it acted as a piston in the hole when the flowmeter was lifted to the next position. From the information in appendix 1 it can be estimated that lifting the cable and rods caused pumping of about 15 l. In the same time 5.7 l water flew into the hole. So the water level went down about four meters. The piston effect and lifting of the electronics tube from water is not taken into account in this estimation.

At depth 4.25 - 7.75 in A4 the flow sensor was in air (test nr. 6741) This was noticed afterwards from thermal dilution measurements that showed extremely slow cooling. The same happened again at the same depth when the hole was closed (tests 6868, 6869 and 6870, appendix 1). There is certain doubt that the test nr 6740 was also affected by partially air filled test section. Flow value 70.4 ml/h is smaller than in the repeated test just before closing the hole (tests 6856 and 6857 appendix 1, Figure 7-2).

The results in C5 are consistent both in the open and closed borehole.

Table 8-1. Calculated head and transmissivity values

Bore hole	Depth (m), upper end	Test nr.	Head in the hole (m)	Flow (ml/h), positive into hole	Test nr.	Head in the hole (m)	Flow (ml/h), positive into hole	Head in the section (m)	Transmis-sivity of the section (m^2/s)
A5	35.75	6718	0	0.0	6788	251.2	0.0	-	< 1E-11
A5	32.25	6719	0	0.0	6795	261.2	0.0	-	< 1E-11
A5	28.75	6720	0	0.0	6798	255.3	0.0	-	< 1E-11
A5	25.25	6721	0	0.0	6801	252.0	0.0	-	< 1E-11
A5	21.75	6722	0	0.0	6804	251.1	0.0	-	< 1E-11
A5	18.25	6724	0	5.1	6855	266.4	0.0	-	5.3E-12
A5	14.75	6725	0	250000	6743	262.8	130000	559	1.2E-07
A5	11.25	6726	0	14400	6752	249.7	-37100	70	5.7E-08
A5	7.75	6727	0	55.2	6784	269.4	-5.1	247	6.1E-11
A5	4.25	6728	0	79.8	6766	254.3	-315	51	4.3E-10
A4	32.25	6730	0	7.2	6894	163.8	0.0	-	1.2E-11
A4	28.75	6732	0	5.2	6900	157.3	0.0	-	9.1E-12
A4	25.25	6733	0	5.5	6906	157.7	0.0	-	9.6E-12
A4	21.75	6734	0	8.6	6910	156.0	0.0	-	1.5E-11
A4	18.25	6735	0	0.0	6914	104.8	0.0	-	< 1E-11
A4	14.75	6736	0	0.0	6920	158.8	-7.3	-	1.3E-11
A4	11.25	6738	0	9.4	6938	159.4	-35.4	33	7.7E-11
A4	7.75	6740	0	70.4	6867	150.2	-702	13.7	1.4E-09
A4	4.25	6741	0	-	6876	152.0	0.0	-	-
C5	43.00	6940	0	37.7	6996	162.4	9.1	214	4.8E-11
C5	39.50	6943	0	0.0	7000	164.9	0.0	-	< 1E-11
C5	36.00	6945	0	49.8	7006	167.0	14.1	233	5.9E-11
C5	32.50	6946	0	0.0	7009	155.4	0.0	-	< 1E-11
C5	29.00	6947	0	0.0	7013	162.9	0.0	-	< 1E-11
C5	25.50	6949	0	1020	7019	166.3	-410	119	2.4E-09
C5	22.00	6951	0	152	7025	168.7	-52.3	125	3.3E-10
C5	18.50	6953	0	149	7038	171.8	5.3	178	2.3E-10
C5	15.00	6955	0	772	7061	173.9	308	289	7.3E-10
C5	11.50	6957	0	213	7067	170.6	5.1	175	3.3E-10
C5	8.00	6959	0	446	7072	168.3	91.4	212	5.8E-10
C5	4.50	6961	0	0.0	6992	164.9	-10.6	-	1.8E-11

9 DISCUSSION AND CONCLUSIONS

The field work went relatively well. The measurement is fast in the open holes. The work in the closed holes was slower than expected because pressure had to be released during lifting of the flowmeter. Closing of the borehole worked very well.

The required time of a measurement above ground is about 12 minutes for each section and for each head level in the borehole. It is about the same below ground in open boreholes.

Measurements in closed boreholes take much more time because of pressure stabilisation. The present method of interpretation assumes stabile pressure which actually never exists. One has to choose waiting time that is good enough. Above ground this is not a problem because head of the borehole can be changed a night before measurements. Below ground this is more problematic because the hole must be opened during each lifting of the flowmeter. The pressure build up curves are presented in Figure 5-1. Pressure in the boreholes rises rapidly during the first hour after closing the hole. Pressure changes slowly after two hours from closing the hole. It can be roughly evaluated that after one hour pressure in the hole is about 90% of its "final" value and after two hours it is more than 95% of estimated final value. Earlier transient measurements indicate that this transient behaviour may be site, borehole or depth dependent.

The results of the measurements are transmissivity and hydraulic head of fractures. The question is how "good" these values are. Usually the aim is to get values that represent not only the borehole but larger volume of bedrock. There are many things that make achieving representative values difficult:

- It is not known if drilling had opened or closed fractures.

- Calculated transmissivities depend on assumed flow geometry. Flow geometry, dimensions, variability of fracture properties in a single fracture, nearby zones are usually not known.

- Turbulent flow may exist if the gradient is very high towards a borehole.

- There are always errors in flow, head and depth measurements.

In spite of the mentioned problems calculated transmissivities are still considered useful. This is because transmissivity varies many orders of

magnitude. Main features are usually representative to larger volume of bedrock than the nearest surrounding of the hole.

It is interesting that the calculated hydraulic heads do not depend on geometrical properties but only on the ratio of the flows measured with different heads in the borehole. Hydraulic head values should be then less sensitive to unknown fracture geometry. However, in some cases small errors in flow measurement can lead to large errors in hydraulic head. This can happen if the difference of used hydraulic heads in the borehole is much smaller than the difference of hydraulic heads between fractures. This was not the case at the ZEDEX site.

Difference flow measurement deviates in some points from conventional double packer tests. In double packer test the section between packers is often in higher head than the rest of the borehole. In difference flow measurement the borehole is in constant head if water in the hole has constant density. The calculated transmissivity represents transmissivity component across the borehole. This can be considered both limitation and benefit. It is limitation because only one component of transmissity is measured. It is benefit because it makes it possible to separate transmissivity components if three perpendicular boreholes are available.

The deviation between the two methods may not be very extreme in practice. Preliminary comparisons with the two methods indicate that the measured transmissivities are normally within same decade.

Flow geometry in difference flow measurement is utilised in surface work as follows. Boreholes are first measured with 10 meter's section length. Then the boreholes are measured with 2 meter's section length, but only where flow existed in 10 meter's measurement. This makes 2 meter's measurements faster and a reliability test possible. The sum of five 2 meter's transmissivities should be equal with the corresponding 10 meter's transmissivity.

Rubber disks are used instead of packers in difference flow measurements. They cannot hold as much head difference as packers. There are no problems when hydraulic head in the borehole is constant. If there is very high flow through the flow sensor or through the whole flow guide there may be head difference over the rubber disks because of flow friction. The flow sensor is made as open as possible to minimise flow friction. Friction losses can be calculated from the dimensions of the flowsensor. For example at a relatively high flow of 100 l/h, the head difference is about 1 cm. Above this flow speed, flow becomes turbulent and head difference increases rapidly. Leakage of the rubber disks due to flow friction is normally unlikely because both ends of the section can hold head difference more than 1.5 m to both directions.

Flow resistance of the electronics tube is higher than that of the flow sensor. Friction losses due to the electronics tube do not cause head difference over

the rubber disks. Friction losses can cause errors to calculated transmissivity and head values if there are large flows and small heads.

Leakage of rubber disks can still cause problems in practice. They have been working very well in relatively fractured bedrock. They have probably failed where the borehole is clearly widened. This has been noticed in the reliability tests mentioned above. In some cases caliper (borehole diameter) measurement showed anomalies exactly at the locations of rubber disks where 2 meter's and 10 meter's measurements did not fit.

There are a few things to do to improve the data quality for the next time. Uncertain results should be avoided by all possible means. This means that repeated tests should be favoured. Measurements of flow along the holes could be used to check the difference flow values. This is easy to carry out technically.

REFERENCES

Rouhiainen P. 1993. TVO-Flowmeter, Report YJT-93-1.

Rouhiainen P. 1994. Eromittaus virtausmittarilla, menetelmä- ja laitekuvaus, workreport PATU-94-24 (in Finnish).

Test nr	Time (days in May)	Bore-hole	Depth (m), upper end	Hydraulic head (m)	Flow (ml/h), positive into hole
6718	5.371632	A5	35.75	0	0
6719	5.382211	A5	32.25	0	0
6720	5.391887	A5	28.75	0	0
6721	5.400023	A5	25.25	0	0
6722	5.408183	A5	21.75	0	0
6723	5.416782	A5	18.25	0	7.016966
6724	5.424132	A5	18.25	0	5.120636
6725	5.433102	A5	14.75	0	248239.8
6726	5.446042	A5	11.25	0	14431.39
6727	5.453785	A5	7.75	0	55.19185
6728	5.461586	A5	4.25	0	79.7941
6729	5.602986	A4	32.25	0	0
6730	5.613379	A4	32.25	0	7.245743
6731	5.62257	A4	28.75	0	6.083475
6732	5.649641	A4	28.75	0	5.187248
6733	5.659537	A4	25.25	0	5.525521
6734	5.668241	A4	21.75	0	8.642068
6735	5.677083	A4	18.25	0	0
6736	5.690359	A4	14.75	0	0
6738	5.707153	A4	11.25	0	9.362982
6740	5.721366	A4	7.75	0	70.3629
6741	5.728889	A4	4.25	0	0
6742	7.312697	A5	14.75	262.89	157535.7
6743	7.316771	A5	14.75	262.84	131613.1
6744	7.364942	A5	11.25	217.2	-41731.99
6745	7.36875	A5	11.25	217.2	-39617.39
6746	7.37331	A5	11.25	220.44	-38395.27
6747	7.376771	A5	11.25	225.65	-38701.65
6748	7.380394	A5	11.25	231.94	-37160.94
6749	7.386366	A5	11.25	235	-39328.05
6750	7.393785	A5	11.25	239.98	-37752.02
6751	7.404734	A5	11.25	245.05	-34139.91
6752	7.417188	A5	11.25	249.68	-37057.37
6753	7.434144	A5	8.25	215.92	-28.85862
6754	7.444988	A5	8.25	236.05	-13.91344
6755	7.455151	A5	8.25	244.25	-10.84988
6756	7.465833	A5	8.25	2249.14	-9.305573
6757	7.476516	A5	8.25	2252.44	-7.915736
6758	7.487199	A5	8.25	254.94	-7.133826
6759	7.515474	A5	4.25	191.97	-241.9939
6760	7.522847	A5	4.25	214.48	-279.2491
6761	7.529248	A5	4.25	229.96	-296.3578
6762	7.537511	A5	4.25	238.81	-308.7625
6763	7.545753	A5	4.25	2444.7	-305.119

Test nr	Time (days in May)	Bore-hole	Depth (m), upper end	Hydraulic head (m)	Flow (ml/h), positive into hole
6764	7.55397	A5	4.25	248.7	-315.3409
6765	7.562188	A5	4.25	251.97	-315.3409
6766	7.570405	A5	4.25	254.29	-315.3409
6767	7.589317	A5	7.75	201.45	-45.9845
6768	7.596331	A5	7.75	224.63	-21.05807
6769	7.620891	A5	7.75	250.47	-10.03821
6770	7.646701	A5	7.75	258.6	-7.729178
6771	7.672512	A5	7.75	262.44	-7.529368
6772	7.698276	A5	7.75	264.44	-6.925118
6773	7.724062	A5	7.75	265.82	-5.76671
6774	7.749849	A5	7.75	266.57	-5.571062
6775	7.775637	A5	7.75	267.11	-5.980722
6776	7.801424	A5	7.75	267.44	-5.603271
6777	7.827222	A5	7.75	267.8	-5.132364
6778	7.853033	A5	7.75	267.97	-5.43794
6779	7.878843	A5	7.75	268.01	-5.40159
6780	7.904653	A5	7.75	268.17	-5.165624
6781	7.930451	A5	7.75	268.32	-5.453667
6782	7.956262	A5	7.75	268.36	-5.40841
6783	7.982072	A5	7.75	268.32	-4.919495
6784	8.34199	A5	7.75	269.37	-5.054963
6785	8.41691	A5	35.75	191.58	-8.875641
6786	8.431087	A5	35.75	229.07	0
6787	8.443068	A5	35.75	241.98	0
6788	8.457535	A5	35.75	251.2	0
6789	8.4825	A5	32.25	188.03	-10.64019
6790	8.496922	A5	32.25	227.05	0
6791	8.508912	A5	32.25	241.53	0
6792	8.520868	A5	32.25	249.14	0
6793	8.532778	A5	32.25	254.48	0
6794	8.544653	A5	32.25	258.34	0
6795	8.556528	A5	32.25	261.2	0
6796	8.582118	A5	28.75	224.01	-8.87851
6797	8.595984	A5	28.75	247.83	0
6798	8.607975	A5	28.75	255.3	0
6799	8.624074	A5	25.25	213.28	-10.14743
6800	8.638449	A5	25.25	243.35	0
6801	8.65044	A5	25.25	252.03	0
6802	8.664583	A5	21.75	218.72	-9.129866
6803	8.677037	A5	21.75	242.52	0
6804	8.68897	A5	21.75	251.1	0
6805	8.711215	A5	18.25	211.76	-10.13513
6806	8.725659	A5	18.25	239.93	0
6807	8.737651	A5	18.25	248.48	0
6808	8.749572	A5	18.25	253.4	0
6854	9.298773	A5	18.25	266.44	0

Test nr	Time (days in May)	Bore-hole	Depth (m), upper end	Hydraulic head (m)	Flow (ml/h), positive into hole
6855	9.310729	A5	18.25	266.44	0
6856	9.449664	A4	7.75	-.7	144.0146
6857	9.461597	A4	7.75	-.8	135.9936
6858	9.473518	A4	7.75	4.56	50.70722
6859	9.485428	A4	7.75	5.54	52.79613
6860	9.497327	A4	7.75	6.51	43.2213
6861	9.509236	A4	7.75	21.96	38.18483
6862	9.515185	A4	7.75	49.9	-302.2181
6863	9.520822	A4	7.75	98.31	-554.3643
6864	9.526956	A4	7.75	131.53	-692.8102
6865	9.536215	A4	7.75	144.78	-714.3381
6866	9.548171	A4	7.75	148.38	-707.7775
6867	9.560127	A4	7.75	150.15	-701.5945
6868	9.578055	A4	4.25	1.57	-
6869	9.587686	A4	4.25	-.1	-
6870	9.597963	A4	4.25	-.1	-
6871	9.605533	A4	4.25	15.03	-79.63734
6872	9.610614	A4	4.25	80.61	-24.54726
6873	9.619351	A4	4.25	136.12	0
6874	9.63125	A4	4.25	147.93	0
6875	9.643137	A4	4.25	150.82	0
6876	9.655035	A4	4.25	151.99	0
6878	9.709294	A4	32.25	33.1	-23.70001
6879	9.721354	A4	32.25	121.24	0
6880	9.740243	A4	32.25	153.44	0
6881	9.759109	A4	32.25	156.79	0
6882	9.778009	A4	32.25	158.21	0
6883	9.796922	A4	32.25	158.79	0
6884	9.815833	A4	32.25	159.24	0
6885	9.834734	A4	32.25	159.7	0
6886	9.853646	A4	32.25	159.99	0
6887	9.872546	A4	32.25	160.25	0
6888	9.891459	A4	32.25	160.52	0
6889	9.910371	A4	32.25	160.68	0
6890	9.929271	A4	32.25	160.9	0
6891	9.948183	A4	32.25	161.17	0
6892	9.967095	A4	32.25	161.5	0
6893	9.985995	A4	32.25	161.66	0
6894	10.33064	A4	32.25	163.75	0
6895	10.34953	A4	28.75	-.8	9.438673
6896	10.3651	A4	28.75	-.31	6.865205
6897	10.37404	A4	28.75	23.1	-39.51421
6898	10.38845	A4	28.75	140.93	0
6899	10.40065	A4	28.75	154.56	0
6900	10.41205	A4	28.75	157.27	0
6901	10.43279	A4	25.25	-.52	7.676392

Test nr	Time (days in May)	Bore-hole	Depth (m), upper end	Hydraulic head (m)	Flow (ml/h), positive into hole
6902	10.44414	A4	25.25	-.5	0
6903	10.4561	A4	25.25	59.87	-54.50141
6904	10.4686	A4	25.25	142.64	0
6905	10.48053	A4	25.25	154.79	0
6906	10.49241	A4	25.25	157.69	0
6907	10.50932	A4	21.75	9.7	-96.05471
6908	10.51581	A4	21.75	92.7	-50.33489
6909	10.52778	A4	21.75	149.37	0
6910	10.53971	A4	21.75	155.96	0
6911	10.55668	A4	18.25	6.29	-96.96945
6912	10.56863	A4	18.25	120.14	-44.90027
6913	10.58059	A4	18.25	153.04	0
6914	10.5925	A4	18.25	104.76	0
6915	10.6056	A4	14.75	1.04	2211.171
6916	10.61755	A4	14.75	57.11	-76.78356
6917	10.62838	A4	14.75	146.66	-12.4257
6918	10.64028	A4	14.75	154.3	-9.132882
6920	10.66413	A4	14.75	158.8	-7.260798
6921	10.68574	A4	11.25	3.73	-101.3302
6922	10.69013	A4	11.25	33.19	-97.94825
6923	10.70906	A4	11.25	151.79	-37.97765
6924	10.72797	A4	11.25	155.31	-36.07154
6925	10.74689	A4	11.25	156.43	-35.98285
6926	10.7658	A4	11.25	156.95	-35.94628
6927	10.7847	A4	11.25	157.73	-35.69226
6928	10.80361	A4	11.25	157.67	-37.32391
6929	10.82252	A4	11.25	157.93	-35.56062
6930	10.84142	A4	11.25	158.28	-35.48327
6931	10.86034	A4	11.25	158.51	-35.47733
6932	10.87925	A4	11.25	158.65	-35.60838
6933	10.89816	A4	11.25	158.76	-35.60838
6934	10.91706	A4	11.25	158.75	-34.98558
6935	10.93597	A4	11.25	158.95	-35.35313
6936	10.95488	A4	11.25	159.39	-35.43584
6937	10.9738	A4	11.25	159.5	-35.44176
6938	10.99271	A4	11.25	159.41	-35.35313
6939	11.44824	C5	43	0	36.9255
6940	11.45752	C5	43	0	37.71241
6941	11.46847	C5	39.5	0	0
6942	11.48734	C5	39.5	0	0
6943	11.50625	C5	39.5	0	0
6944	11.51951	C5	36	0	50.37401
6945	11.52898	C5	36	0	49.78973
6946	11.56472	C5	32.5	0	0
6947	11.57588	C5	29	0	0
6948	11.58391	C5	25.5	0	983.6505

Test nr	Time (days in May)	Bore-hole	Depth (m), upper end	Hydraulic head (m)	Flow (ml/h), positive into hole
6949	11.58848	C5	25.5	0	1015.391
6950	11.59655	C5	22	0	151.4372
6951	11.60186	C5	22	0	151.4931
6952	11.61059	C5	18.5	0	149.075
6953	11.61495	C5	18.5	0	149.1291
6954	11.6229	C5	15	0	780.6136
6955	11.62654	C5	15	0	772.2917
6956	11.6366	C5	11.5	0	212.5161
6957	11.64208	C5	11.5	0	212.5161
6958	11.6508	C5	8	0	459.0841
6959	11.66969	C5	8	0	445.7252
6960	11.68885	C5	4.5	0	0
6961	11.70131	C5	4.5	0	0
6962	11.73833	C5	4.5	0	-6.597744
6963	11.75126	C5	4.5	144.9	-40.79209
6964	11.77017	C5	4.5	155.2	-28.94413
6965	11.78909	C5	4.5	158.9	-26.05782
6966	11.80802	C5	4.5	160.6	-24.18257
6967	11.82696	C5	4.5	161.5	-22.8324
6968	11.8459	C5	4.5	161.8	-21.55594
6969	11.86483	C5	4.5	162	-20.57957
6970	11.88376	C5	4.5	162.4	-19.76808
6971	11.9027	C5	4.5	162.6	-18.88937
6972	11.92163	C5	4.5	162.8	-18.19422
6973	11.94058	C5	4.5	163	-17.61344
6974	11.95951	C5	4.5	163.3	-16.99557
6975	11.97846	C5	4.5	163.5	-16.06072
6976	11.9974	C5	4.5	163.5	-15.74093
6977	12.01894	C5	4.5	163.7	-15.01587
6978	12.03788	C5	4.5	163.7	-14.95166
6979	12.05682	C5	4.5	163.8	-14.27061
6980	12.07575	C5	4.5	164	-13.96977
6981	12.09469	C5	4.5	164.1	-13.54476
6982	12.11362	C5	4.5	164.2	-13.21321
6983	12.13256	C5	4.5	164.3	-13.08141
6984	12.1515	C5	4.5	164.4	-12.96302
6985	12.17044	C5	4.5	164.4	-12.25717
6986	12.18939	C5	4.5	164.6	-12.05655
6987	12.20832	C5	4.5	164.7	-11.97581
6988	12.22726	C5	4.5	164.8	-11.3875
6989	12.24619	C5	4.5	164.8	-11.28683
6990	12.26513	C5	4.5	164.8	-10.93429
6991	12.28406	C5	4.5	164.9	-10.97461
6992	12.30301	C5	4.5	164.9	-10.56327
6993	12.35789	C5	43	.41	39.01522
6994	12.36642	C5	43	53.48	23.18575

Test nr	Time (days in May)	Bore-hole	Depth (m), upper end	Hydraulic head (m)	Flow (ml/h), positive into hole
6995	12.38535	C5	43	154.65	9.599935
6996	12.39848	C5	43	162.42	9.055159
6997	12.41353	C5	39.5	-.89	0
6998	12.42308	C5	39.5	91.23	-15.17889
6999	12.43426	C5	39.5	149.43	0
7000	12.45941	C5	39.5	164.87	0
7001	12.47317	C5	36	-.6	80.41193
7002	12.48647	C5	36	135.53	0
7003	12.49893	C5	36	158.64	9.744264
7004	12.5109	C5	36	164.01	11.90055
7005	12.52259	C5	36	165.94	13.31912
7006	12.5345	C5	36	166.96	14.06486
7007	12.55941	C5	32.5	-1.37	0
7008	12.57137	C5	32.5	121.92	-17.12786
7009	12.58334	C5	32.5	155.4	0
7010	12.59775	C5	29	-.94	0
7011	12.60971	C5	29	126.69	-13.66599
7012	12.62196	C5	29	155.99	0
7013	12.63391	C5	29	162.86	0
7014	12.65201	C5	25.5	-1	954.9243
7015	12.66061	C5	25.5	110.31	202.2412
7016	12.67277	C5	25.5	154.56	-311.7841
7017	12.68207	C5	25.5	162.67	-374.4854
7018	12.69257	C5	25.5	164.61	-410.4189
7019	12.70854	C5	25.5	166.32	-409.6388
7020	12.71861	C5	22	-1	106.5924
7021	12.73047	C5	22	144.08	-38.76002
7022	12.74247	C5	22	161.28	-50.4241
7023	12.75442	C5	22	165.93	-52.52192
7024	12.76638	C5	22	167.7	-52.23899
7025	12.77833	C5	22	168.68	-52.25178
7026	12.79797	C5	18.5	-.92	159.8161
7027	12.81157	C5	18.5	77.68	27.10823
7028	12.85824	C5	18.5	166	6.974081
7029	12.90492	C5	18.5	169	5.770308
7030	12.95161	C5	18.5	170	5.643539
7031	12.99829	C5	18.5	170.7	5.445081
7032	13.04668	C5	18.5	171.2	5.584141
7033	13.09337	C5	18.5	171.2	5.813427
7034	13.14005	C5	18.5	171.4	5.589517
7035	13.18672	C5	18.5	171.5	5.542208
7036	13.23341	C5	18.5	171.6	5.53915
7037	13.28009	C5	18.5	171.7	5.27693
7038	13.32677	C5	18.5	171.8	5.315364
7039	13.34601	C5	15	.45	772.4136
7040	13.35297	C5	15	99.92	513.3373

Test nr	Time (days in May)	Bore-hole	Depth (m), upper end	Hydraulic head (m)	Flow (ml/h), positive into hole
7041	13.39698	C5	15	170	339.5854
7042	13.44366	C5	15	171.4	327.9668
7043	13.49035	C5	15	171.9	328.4902
7044	13.53703	C5	15	172.2	328.4902
7045	13.5837	C5	15	172.6	317.3311
7046	13.63038	C5	15	172.7	317.3311
7047	13.67706	C5	15	172.8	317.3311
7048	13.72375	C5	15	173.99	317.3311
7049	13.77043	C5	15	173	317.3311
7050	13.81712	C5	15	173.14	317.3311
7051	13.86381	C5	15	173.22	317.3311
7052	13.91049	C5	15	173.35	317.3311
7053	13.95716	C5	15	173.4	317.3311
7054	14.00385	C5	15	173.6	317.4308
7055	14.05053	C5	15	173.6	307.6568
7056	14.09722	C5	15	173.7	307.6857
7057	14.14391	C5	15	173.7	307.6857
7058	14.19059	C5	15	173.8	307.1088
7059	14.23727	C5	15	173.9	307.6857
7060	14.28396	C5	15	173.9	307.6857
7061	14.33064	C5	15	173.9	307.6857
7062	14.3483	C5	11.5	0	258.2547
7063	14.36186	C5	11.5	100.5	26.50702
7064	14.3738	C5	11.5	159	10.94707
7065	14.38571	C5	11.5	160	7.004666
7066	14.39794	C5	11.5	170.5	5.774848
7067	14.41017	C5	11.5	170.6	5.135241
7068	14.42257	C5	8	0	569.2817
7069	14.43183	C5	8	103	215.6804
7070	14.4434	C5	8	159	117.1574
7071	14.45311	C5	8	166	98.54999
7072	14.46302	C5	8	168.3	91.40572

List of International Cooperation Reports

ICR 93-01
Flowmeter measurement in borehole KAS 16
P Rouhiainen
June 1993
Supported by TVO, Finland

ICR 93-02
Development of ROCK-CAD model for Äspö Hard Rock Laboratory site
Pauli Saksa, Juha Lindh,
Eero Heikkinen
Fintact KY, Helsinki, Finland
December 1993
Supported by TVO, Finland

ICR 93-03
Scoping calculations for the Matrix Diffusion Experiment
Lars Birgersson[1], Hans Widén[1],
Thomas Ågren[1], Ivars Neretnieks[2],
Luis Moreno[2]
1 Kemakta Konsult AB, Stockholm, Sweden
2 Royal Institute of Technology, Stockholm, Sweden
November 1993
Supported by SKB, Sweden

ICR 93-04
Scoping calculations for the Multiple Well Tracer Experiment - efficient design for identifying transport processes
Rune Nordqvist, Erik Gustafsson,
Peter Andersson
Geosigma AB, Uppsala, Sweden
December 1993
Supported by SKB, Sweden

ICR 94-01
Scoping calculations for the Multiple Well Tracer Experiment using a variable aperture model
Luis Moreno, Ivars Neretnieks
Dept. of Chemical Engineering and Technology,
Royal Institute of Technology, Stockholm, Sweden
January 1994
Supported by SKB, Sweden

ICR 94-02
Äspö Hard Rock Laboratory. Test plan for ZEDEX - Zone of Excavation Disturbance EXperiment. Release 1.0
February 1994
Supported by ANDRA, NIREX, SKB

ICR 94-03
The Multiple Well Tracer Experiment - Scoping calculations
Urban Svensson
Computer-Aided Fluid Engineering
March 1994
Supported by SKB, Sweden

ICR 94-04
Design constraints and process discrimination for the Detailed Scale Tracer Experiments at Äspö - Multiple Well Tracer Experiment and Matrix Diffusion Experiment
Jan-Olof Selroos[1], Anders Winberg[2], Vladimir Cvetkovic[2]
1 Water Resources Eng., KTH
2 Conterra AB
April 1994
Supported by SKB, Sweden

ICR 94-05
Analysis of LPT2 using the Channel Network model
Björn Gylling[1], Luis Moreno[1], Ivars Neretnieks[1], Lars Birgersson[2]
1 Department of Chemical Engineering and Technology, Royal Institute of Technology, Stockholm, Sweden
2 Kemakta Konsult AB, Stockholm, Sweden
April 1994
Supported by SKB, Sweden

ICR 94-06
SKB/DOE Hard Rock Laboratory Studies Task 3. Geochemical investigations using stable and radiogenic isotopic methods
Bill Wallin[1], Zell Peterman[2]
1 Geokema AB, Lidingö, Sweden
2 U.S. Geological Survey, Denver, Colorado, USA
January 1994
Supported by SKB and U.S.DOE

ICR 94-07
Analyses of LPT2 in the Äspö HRL with continuous anisotropic heterogeneous model
Akira Kobayashi[1], Ryo Yamashita[2], Masakazu Chijimatsu[2], Hiroyuki Nishiyama[3], Yuzo Ohnishi[3]
1 Iwate University, Iwate, Japan
2 Hazama Corporation, Ibaraki, Japan
3 Kyoto University, Kyoto, Japan
September 1994
Supported by PNC, Japan

ICR 94-08
Application of three-dimensional smeared fracture model to the groundwater flow and the solute migration of LPT-2 experiment
T Igarashi, Y Tanaka, M Kawanishi
Abiko Research Laboratory, Central Research Institute of Electric Power Industry, Abiko, Japan
October 1994
Supported by CRIEPI, Japan

ICR 94-09
Discrete-fracture modelling of the Äspö LPT-2, large-scale pumping and tracer test
Masahiro Uchida[1], Thomas Doe[2], William Dershowitz[2], Andrew Thomas[2], Peter Wallmann[2], Atsushi Sawada[1]
1 Power Reactor and Nuclear Fuel Development Co., Tokai, Japan
2 Golder Associates Inc., Seattle, WA, USA
March 1994
Supported by PNC, Japan

ICR 94-10
Äspö Hard Rock Laboratory
International workshop on the use of tunnel boring machines for deep repositories
Äspö, June 13-14 1994
Göran Bäckblom (ed.)
Swedish Nuclear Fuel and Waste Management Co.
October 1994
Supported by SKB, Sweden

ICR 94-11
Data analysis and modelling of the LPT2 Pumping and Tracer Transport Test at Äspö.
Tracer experiment
Aimo Hautojärvi
VTT Energy
November 1994
Supported by TVO, Finland

ICR 94-12
Modelling the LPT2 Pumping and Tracer Test at Äspö. Pumping test
Veikko Taivassalo, Lasse Koskinen,
Mikko Laitinen, Jari Löfman, Ferenc Mészáros
VTT Energy
November 1994
Supported by TVO, Finland

ICR 94-13
Proceedings of The Äspö International Geochemistry Workshop, June 2-3, 1994, Äspö Hard Rock Laboratory
Peter Wikberg (chairman), Steven Banwart (proc. ed.)
December 1994
Supported by SKB, TVO, Nirex, ANDRA, CRIEPI

ICR 94-14
Hydrodynamic modelling of the Äspö HRL. Discrete fracture model
D Billaux[1], F Guérin[2], J Wendling[2]
1 ITASCA
2 ANTEA
November 1994
Supported by ANDRA, France

ICR 94-15
Hydrodynamic modelling of the Äspö Hard Rock Laboratory. ROCKFLOW code
M L Noyer, E Fillion
ANTEA
December 1994
Supported by ANDRA, France

ICR 94-16
Hydrodynamic modelling of the original steady state and LPT2 experiments. MARTHE and SESAME codes
Y Barthelemy, J Schwartz, K Sebti
ANTEA
December 1994
Supported by ANDRA, France

ICR 95-01
Simulations of pressure and salinity fields at Äspö
Jari Löfman, Veikko Taivassalo
VTT Energy, Espoo, Finland
June 1995
Supported by TVO, Finland

ICR 95-02
Definition and characterisation of the N-S fracture system - tunnel sections 1/600m to 2/400m.
Relationships to grouted sections - some remarks -
W Kickmaier
June 1993
Supported by NAGRA, Switzerland

ICR 95-03
Groundwater degassing and two-phase flow:
Pilot hole test report
Jil T Geller[1], Jerker Jarsjö[2]
1 Earth Sciences Division, Lawrence Berkeley National Laboratory, USA
2 Water Resources Engineering, Royal Institute of Technology, Sweden
August 1995
Supported by U.S .DOE, USA and SKB, Sweden