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Forsmark site investigation

Single-hole injection tests in borehole KFM03A

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July 2004

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Abstract

Borehole KFM03A, which is the third core-drilled borehole within the site investigations in the Forsmark area, is of SKB chemistry type. It is designed as a so called telescopic borehole, with an enlarged diameter in the upper approximately 100 m, which makes it possible to install certain borehole equipment. The borehole is sub-vertical, about 1,000 m deep and cased to a depth of about 12 m. The borehole diameter is about 77 mm in the interval 100–1,000 m.

This report presents injection tests performed using the pipe string system PSS3 in borehole KFM03A and the test results.

The main aim of the injection tests in KFM03A was to characterize the hydraulic conditions in rock adjacent to the borehole on different measurement scales (100 m, 20 m and 5 m). Hydraulic parameters such as transmissivity, hydraulic conductivity, dominating flow regime and possible outer hydraulic boundaries were determined using analysis methods for stationary as well as transient conditions. In addition, a comparison with the results of previously performed difference flow logging was made.

The injection tests gave consistent results on the different measurement scales regarding transmissivity. During most of the tests, some period with pseudo-radial flow could be identified from the injection period, making a relatively straight-forward transient evaluation possible. However, the recovery periods were often strongly affected by well-bore storage, making a transient evaluation of this period more difficult. In addition, pseudo-stationary flow often occurred during the recovery period.

The injection test results were generally consistent with the results from the previous difference flow logging in KFM03A. Some differences were found, however, particularly for sections of low transmissivity.

The injection tests provide a database for statistical analysis of the hydraulic conductivity distribution along the borehole on the different measurement scales. Basic statistical parameters are presented in this report.

Significant pressure responses were observed in the borehole intervals below the test sections during four of the tests, in the deepest part of the borehole. The estimated values of transmissivity from analysis of the pressure interference were in agreement with the estimated values of transmissivity from the injection tests.

Sammanfattning

Borrhål KFM03A, som var det tredje kärnborrhålet i platsundersökningarna i Forsmarksområdet, är av SKB kemityp. Det är utfört som ett så kallat teleskopborrhål för att göra det möjligt att installera viss borrhålsutrustning i de övre, ca 100 m med större diameter än resten av borrhålet. Borrhålet är subvertikalt, ca 1 000 m djupt och försett med foderrör till ca 12 m djup. Borrhålsdiametern är ca 77 mm i intervallet 100–1 000 m.

Föreliggande rapport beskriver genomförda injektionstester med rörgångssystemet PSS3 i borrhål KFM03A samt resultaten från desamma.

Huvudsyftet med injektionstesterna var att karaktärisera berggrundsakvifären runt borrhålet i olika mätskalor (100 m, 20 m och 5 m) med avseende på hydrogeologiska egenskaper. Hydrauliska parametrar såsom transmissivitet, konduktivitet, dominerande flödesregim och eventuella yttre hydrauliska randvillkor bestämdes med hjälp av analysmetoder för såväl stationära som transienta förhållanden.

En jämförelse med resultaten av den tidigare utförda differensflödesloggningen i KFM03A gjordes också.

Injektionstesterna gav samstämmiga resultat för de olika mätskalorna beträffande transmissivitet. Under de flesta tester kunde en viss period med pseudo-radiellt flöde identifieras från flödesperioden, vilket möjliggjorde en standardmässig transient utvärdering. Återhämtningsperioden var däremot ofta starkt påverkad av brunnsmagasinseffekter, vilket gjorde en unik transient utvärdering av denna period svårare. Dessutom uppvisade flera av testernas återhämtningsperioder pseudo-stationärt flöde.

Injektionstesterna gav även samstämmiga resultat med den tidigare differensflödesloggningen i KFM03A, även om vissa avvikelser fanns för beräknade transmissiviteter i samma 5 m sektioner, i synnerhet för lågtransmissiva sektioner.

Resultaten från injektionstesterna utgör en databas för statistisk analys av den hydrauliska konduktivitetens fördelning längs borrhålet i de olika mätskalorna. Viss statistisk analys har utförts inom ramen för denna aktivitet och grundläggande statistiska parametrar presenteras i rapporten.

Tydliga tryckresponser observerades i intervallet under testsektionen för fyra tester i den djupaste delen av borrhålet. De beräknade transmissiviterna från tryckinterferenserna överensstämde med resultaten från injektionstesterna.

Contents

1	**Introduction**	7
2	**Objectives**	9
3	**Scope**	11
3.1	Boreholes	11
3.2	Tests performed	11
3.4	Equipment checks	16
4	**Description of equipment**	17
4.1	Overview	17
	4.1.1 Measurement container	17
	4.1.2 Down-hole equipment	18
4.2	Measurement sensors	19
4.3	Data acquisition system	20
5	**Execution**	21
5.1	Preparation	21
	5.1.1 Calibration	21
	5.1.2 Functioning checks	21
	5.1.3 Cleaning of equipment	21
5.2	Test performance	21
	5.2.1 Test principle	21
	5.2.2 Test procedure	21
	5.2.3 Test strategy	22
5.3	Data handling	22
5.4	Analysis and interpretation	23
	5.4.1 Single-hole injection tests	23
	5.4.2 Pressure interference below selected test sections	25
5.5	Nonconformities	26
6	**Results**	27
6.1	Nomenclature and symbols	27
6.2	Routine evaluation of the single-hole injection tests	27
	6.2.1 General test data	27
	6.2.2 Measurement limit for flow rate and specific flow rate	27
	6.2.3 Length corrections	29
	6.2.4 General results	30
	6.2.5 Comments on the tests	40
	6.2.6 Flow regimes	62
6.3	Transmissivity values on different scales	63
6.4	Comparison with results from the difference flow logging	69
6.5	Basic statistics of hydraulic conductivity distributions	71
6.6	Comparison of results from different hydraulic tests in KFM03A	72

6.7 Pressure interferences below test sections 73
6.7.1 Pressure interference below test section 941–946 m 73
6.7.2 Pressure interference below test section 941–961 m 77
6.7.3 Pressure interference below test section 971–991 m 79
6.7.4 Pressure interference below test section 986–991 m 82
6.7.5 Summary of pressure interference below test sections 84

7 References 85

8 Appendices 87

Appendix 1 File description table (only on CD)

Appendix 2.1 General test data (only on CD)

Appendix 2.2 Pressure and flow data (only on CD)

Appendix 3 Test diagrams – Injection tests (only on CD)

Appendix 4 Diagrams from pressure interferences (only on CD)

Appendix 5 Borehole technical data (only on CD)

Appendix 6 Sicada tables (only on CD)

1 Introduction

The injection tests in borehole KFM03A at Forsmark, Sweden, were carried out during May and June 2004 by GEOSIGMA AB. The borehole KFM03A was the third deep cored borehole within the on-going site investigation in the Forsmark area. The borehole is a so called telescopic borehole. This makes it possible to install certain borehole equipment in the upper c 100 m where the diameter is larger than in the rest of the borehole. The borehole is sub-vertical, c 1,000 m deep and cased to c 12 m depth. The borehole diameter is c 77 mm in the interval 102.05–1,001.19 m. The location of the borehole is shown in Figure 1-1.

In KFM03A, difference flow logging was previously performed, during August 2003 and May 2004. According to the results of this investigation, 41 conductive fractures were detected and the most conductive ones were found at 358.5, 364.8, 371.6, 388.6, 451.3 and 643.9 m depth. The fracture at 388.6 m had an estimated transmissivity of 2×10^{-4} m^2/s, the other five were ranging from c 1×10^{-6} m^2/s to c 7×10^{-6} m^2/s Rouhainen and Pöllänen, 2004 /1/.

This document reports the results obtained from the injection tests in borehole KFM03A. The activity is performed within the Forsmark site investigation. The work was carried out in compliance with the SKB internal controlling documents presented in Table 1-1. Data and results were delivered to the SKB site characterization database SICADA under field note no Forsmark 337.

Table 1-1. SKB internal controlling documents for performance of the activity.

Activity Plan	Number	Version
Hydraulic injection tests in borehole KFM03A with PSS3.	AP PF 400-04-26	1.0
Method descriptions and instructions	**Number**	**Version**
Mätsystembeskrivning (MSB) – Allmän del. Pipe String System (PSS3).	SKB MD 345.100	1.0
Mätsystembeskrivning för: Kalibrering, PSS3.	SKB MD 345.122	1.0
Mätsystembeskrivning för: Skötsel, service, serviceprotokoll, PSS3.	SKB MD 345.124	1.0
Metodbeskrivning för hydrauliska injektionstester.	SKB MD 323.001	1.0
Instruktion för analys av injektions- och enhålspumptester.	SKB MD 320.004	1.0
Instruktion för rengöring av borrhålsutrustning och viss markbaserad utrustning.	SKB MD 600.004	1.0

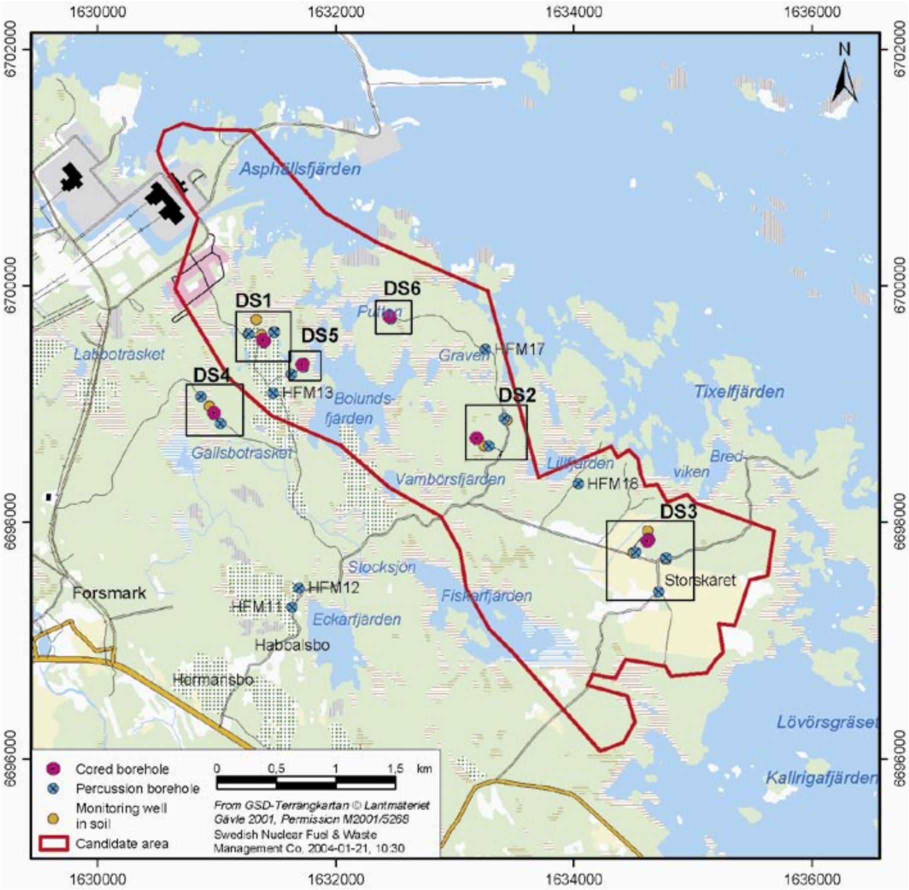

Figure 1-1. *The investigation area at Forsmark including the candidate area selected for more detailed investigations. Borehole KFM03A is situated at drilling site DS3.*

2 Objectives

The main aim of the injection tests in borehole KFM03A was to characterize the hydraulic properties of the rock adjacent to the borehole on different measurement scales (100 m, 20 m and 5 m). The primary parameter to be determined was hydraulic transmissivity from which hydraulic conductivity can be derived. The results of the injection tests provide a database which can be used for statistical analyses of the hydraulic conductivity distribution along the borehole on different measurement scales. Basic statistical analyses are presented in this report.

Other hydraulic parameters of interest were flow regimes and outer hydraulic boundaries. These parameters were analysed using transient evaluation on the test responses during the flow- and recovery periods.

A comparison with the results of the previously performed difference flow logging in KFM03A was also included in the activity, as a check of the plausibility of the test results. Further, the combined analysis of the injection tests and the difference flow logging provides a more comprehensive understanding of the hydraulic conditions of borehole KFM03A.

3 Scope

3.1 Boreholes

Technical data of the tested borehole are shown in Table 3-1 and in Appendix 5. The reference point of the boreholes is defined as the centre of top of casing (ToC), given as "Elevation" in the table below. The Swedish National coordinate system (RT90) is used for the horizontal coordinates together with RHB70 for the elevation. "Northing" and "Easting" refer to the top of the boreholes.

Table 3-1. Technical data of the borehole KFM03A (printout from SKB database, SICADA).

Borehole length (m)	1,001.190				
Drilling Period (s)	**From date**	**To date**	**Secup (m)**	**Seclow (m)**	**Drilling Type**
	2003-03-18	2003-03-28	0.000	100.340	Percussion drilling
	2003-04-16	2003-06-23	100.340	1,001.190	Core drilling
Starting point coordinate	**Length (m)**	**Northing (m)**	**Easting (m)**	**Elevation**	**Coord System**
	0.000	6697852.096	1634630.737	8.285	RT90-RHB70
Angles	**Length (m)**	**Bearing**	**Inclination (– = down)**		
	0.000	271.523	–85.747		
Borehole diameter	**Secup (m)**	**Seclow (m)**	**Hole diam (m)**		
	0.000	11.960	0.200		
	11.960	100.290	0.196		
	100.290	100.340	0.163		
	100.340	102.050	0.086		
	102.050	1,001.190	0.077		
Core diameter	**Secup (m)**	**Seclow (m)**	**Core diam (m)**		
	100.340	102.050	0.072		
	102.050	1,001.190	0.051		
Casing diameter	**Secup (m)**	**Seclow (m)**	**Case in (m)**	**Case out (m)**	
	0.000	11.960	0.200	0.208	
	0.000	1.650	0.392	0.406	
	0.000	11.830	0.265	0.273	

3.2 Tests performed

The injection tests in borehole KFM03A, performed according to Activity Plan AP PF 400-04-26 (SKB internal controlling document), are listed in Table 3-2. The injection tests were carried out with the Pipe String System (PSS3). The test procedure, together with the equipment, is described in the measurement system description for PSS (SKB MD 345.100, SKB internal controlling document) and in the corresponding method descriptions for hydraulic injection tests (SKB MD 323.001, Metodbeskrivning för

Hydrauliska injektionstester, SKB internal controlling document). In some of the test sections, the test was not performed as intended, because that the time required for achieving constant head in the test section was too long, or due to that equipment malfunctions caused pressure and/or flow rate disturbances. Whenever such disturbances were expected to affect the data evaluation, the test was repeated. Test number (Test no in Table 3-2) refers to the number of tests performed in the actual section. For evaluation, data from the last test in each test section were used.

The upper and lower limits for the test sections were in most cases close to (within a few decimetres of) the upper and lower section limits used during the previous sequential difference flow logging in KFM03A /1/. However, a few exceptions to this were made in order to test as much of the borehole as possible.

Table 3-2. Single-hole injection tests performed in borehole KFM03A.

Bore hole	Test section		Section length	Test type[1)]	Test no	Test start date, time	Test stop date, time
Bh ID	secup	seclow		(1–6)		YYYYMMDD hh:mm	YYYYMMDD hh:mm
KFM03A	106	206	100	3	1	20040517 17:11	20040517 19:07
KFM03A	201	301	100	3	1	20040517 20:08	20040517 22:05
KFM03A	301	401	100	3	1	20040517 23:16	20040518 10:42
KFM03A	401	501	100	3	1	20040518 14:12	20040518 15:37
KFM03A	401	501	100	3	2	20040518 15:45	20040518 17:32
KFM03A	501	601	100	3	1	20040518 18:58	20040518 20:59
KFM03A	601	701	100	3	1	20040518 22:07	20040519 00:00
KFM03A	701	801	100	3	1	20040519 08:38	20040519 10:48
KFM03A	801	901	100	3	1	20040524 07:47	20040524 09:37
KFM03A	106	126	20	3	1	20040525 10:46	20040525 12:56
KFM03A	121	141	20	3	1	20040525 13:11	20040525 14:25
KFM03A	141	161	20	3	1	20040525 14:44	20040525 16:01
KFM03A	161	181	20	3	1	20040601 12:52	20040601 14:09
KFM03A	181	201	20	3	1	20040525 16:46	20040525 17:57
KFM03A	201	221	20	3	1	20040525 18:19	20040525 19:33
KFM03A	221	241	20	3	1	20040525 19:53	20040525 20:50
KFM03A	241	261	20	3	1	20040525 21:11	20040525 22:24
KFM03A	261	281	20	3	1	20040525 22:44	20040525 23:58
KFM03A	281	301	20	3	1	20040526 06:30	20040526 07:47
KFM03A	301	321	20	3	1	20040526 08:05	20040526 09:21
KFM03A	321	341	20	3	1	20040526 09:50	20040526 11:12
KFM03A	341	361	20	3	1	20040526 11:30	20040526 13:31
KFM03A	361	381	20	3	1	20040526 13:50	20040526 15:05
KFM03A	381	401	20	3	1	20040526 16:00	20040526 18:09
KFM03A	401	421	20	3	1	20040526 18:43	20040526 20:25
KFM03A	421	441	20	3	1	20040526 20:59	20040526 22:38
KFM03A	441	461	20	3	1	20040526 23:12	20040527 00:37
KFM03A	461	481	20	3	1	20040527 07:43	20040527 08:58
KFM03A	481	501	20	3	1	20040527 09:18	20040527 10:32
KFM03A	501	521	20	3	1	20040527 10:53	20040527 13:00
KFM03A	518	538	20	3	1	20040527 13:14	20040527 14:27

Bore hole	Test section		Section length	Test type[1)]	Test no	Test start date, time	Test stop date, time
Bh ID	secup	seclow		(1–6)		YYYYMMDD hh:mm	YYYYMMDD hh:mm
KFM03A	521	541	20	3	1	20040527 15:30	20040527 16:55
KFM03A	541	561	20	3	1	20040601 19:57	20040601 21:19
KFM03A	561	581	20	3	1	20040601 21:53	20040601 23:10
KFM03A	581	601	20	3	1	20040602 06:07	20040602 07:23
KFM03A	601	621	20	3	1	20040602 07:40	20040602 08:39
KFM03A	621	641	20	3	1	20040602 08:56	20040602 09:38
KFM03A	641	661	20	3	1	20040602 10:02	20040602 11:15
KFM03A	661	681	20	3	1	20040602 11:28	20040602 13:09
KFM03A	681	701	20	3	1	20040602 13:38	20040602 14:57
KFM03A	701	721	20	3	1	20040602 15:29	20040602 16:46
KFM03A	721	741	20	3	1	20040602 17:07	20040602 18:25
KFM03A	741	761	20	3	1	20040602 18:58	20040602 20:41
KFM03A	761	781	20	3	1	20040602 21:44	20040602 23:16
KFM03A	781	801	20	3	1	20040603 06:02	20040603 07:17
KFM03A	801	821	20	3	1	20040603 07:35	20040603 08:52
KFM03A	821	841	20	3	1	20040603 09:07	20040603 10:23
KFM03A	841	861	20	3	1	20040603 10:40	20040603 11:54
KFM03A	861	881	20	3	1	20040603 12:52	20040603 14:14
KFM03A	881	901	20	3	1	20040603 14:28	20040603 15:43
KFM03A	901	921	20	3	1	20040603 16:03	20040603 17:00
KFM03A	921	941	20	3	1	20040603 17:31	20040603 18:27
KFM03A	941	961	20	3	1	20040603 18:56	20040603 20:20
KFM03A	961	981	20	3	1	20040603 20:48	20040603 22:30
KFM03A	971	991	20	3	1	20040603 22:52	20040604 00:10
KFM03A	104	109	5	3	1	20040622 13:37	20040622 14:56
KFM03A	106	111	5	3	1	20040607 05:54	20040607 07:21
KFM03A	111	116	5	3	1	20040607 07:35	20040607 08:49
KFM03A	116	121	5	3	1	20040607 08:59	20040607 10:18
KFM03A	121	126	5	3	1	20040607 10:26	20040607 11:43
KFM03A	126	131	5	3	1	20040607 12:28	20040607 13:48
KFM03A	131	136	5	3	1	20040607 14:02	20040607 15:24
KFM03A	136	141	5	3	1	20040607 15:49	20040607 17:37
KFM03A	161	166	5	3	1	20040607 18:21	20040607 20:06
KFM03A	166	171	5	3	1	20040607 20:32	20040607 21:53
KFM03A	171	176	5	3	1	20040607 22:09	20040607 23:40
KFM03A	176	181	5	3	1	20040608 06:09	20040608 07:02
KFM03A	241	246	5	3	1	20040608 07:44	20040608 08:38
KFM03A	246	251	5	3	1	20040608 08:54	20040608 09:45
KFM03A	251	256	5	3	1	20040608 09:53	20040608 11:12
KFM03A	256	261	5	3	1	20040608 11:21	20040608 13:10
KFM03A	261	266	5	3	1	20040608 13:21	20040608 14:41
KFM03A	266	271	5	3	1	20040608 14:49	20040608 16:15
KFM03A	271	276	5	3	1	20040608 16:28	20040608 17:26
KFM03A	276	281	5	3	1	20040608 17:42	20040608 18:33
KFM03A	281	286	5	3	1	20040608 18:50	20040608 19:51

Bore hole	Test section		Section length	Test type[1)]	Test no	Test start date, time	Test stop date, time
Bh ID	secup	seclow		(1–6)		YYYYMMDD hh:mm	YYYYMMDD hh:mm
KFM03A	286	291	5	3	1	20040608 20:05	20040608 21:03
KFM03A	291	296	5	3	1	20040608 21:21	20040608 22:49
KFM03A	296	301	5	3	1	20040608 23:11	20040609 07:04
KFM03A	301	306	5	3	1	20040609 07:15	20040609 08:03
KFM03A	306	311	5	3	1	20040609 08:13	20040609 09:31
KFM03A	311	316	5	3	1	20040609 09:39	20040609 10:54
KFM03A	316	321	5	3	1	20040609 11:02	20040609 13:10
KFM03A	321	326	5	3	1	20040609 13:21	20040609 14:39
KFM03A	326	331	5	3	1	20040609 14:51	20040609 16:11
KFM03A	331	336	5	3	1	20040609 16:27	20040609 17:56
KFM03A	336	341	5	3	1	20040609 18:20	20040609 19:47
KFM03A	341	346	5	3	1	20040609 20:02	20040609 21:04
KFM03A	346	351	5	3	1	20040609 21:25	20040609 22:26
KFM03A	348	353	5	3	1	20040609 22:46	20040609 23:35
KFM03A	351	356	5	3	1	20040609 23:53	20040610 06:42
KFM03A	356	361	5	3	1	20040610 06:52	20040610 08:10
KFM03A	361	366	5	3	1	20040610 08:18	20040610 09:36
KFM03A	366	371	5	3	1	20040610 09:48	20040610 11:06
KFM03A	371	376	5	3	1	20040610 11:14	20040610 13:21
KFM03A	376	381	5	3	1	20040610 13:28	20040610 14:49
KFM03A	381	386	5	3	1	20040610 15:04	20040610 16:22
KFM03A	386	391	5	3	1	20040610 16:43	20040610 18:12
KFM03A	391	396	5	3	1	20040610 18:33	20040610 20:05
KFM03A	396	401	5	3	1	20040610 20:31	20040610 21:54
KFM03A	401	406	5	3	1	20040610 22:10	20040610 23:35
KFM03A	406	411	5	3	1	20040611 06:09	20040611 07:31
KFM03A	411	416	5	3	1	20040611 07:40	20040611 09:00
KFM03A	416	421	5	3	1	20040611 09:07	20040611 10:25
KFM03A	441	446	5	3	1	20040611 10:49	20040611 12:56
KFM03A	446	451	5	3	1	20040611 13:06	20040611 14:27
KFM03A	451	456	5	3	1	20040611 14:36	20040611 16:09
KFM03A	456	461	5	3	1	20040611 16:24	20040611 17:24
KFM03A	461	466	5	3	1	20040611 17:42	20040611 19:07
KFM03A	466	471	5	3	1	20040611 19:17	20040611 20:18
KFM03A	471	476	5	3	1	20040611 20:32	20040611 21:33
KFM03A	476	481	5	3	1	20040611 21:53	20040611 22:41
KFM03A	481	486	5	3	1	20040611 22:50	20040611 23:41
KFM03A	486	491	5	3	1	20040614 06:01	20040614 06:57
KFM03A	491	496	5	3	1	20040614 07:10	20040614 07:57
KFM03A	496	501	5	3	1	20040614 08:13	20040614 09:31
KFM03A	501	506	5	3	1	20040614 09:45	20040614 10:30
KFM03A	506	511	5	3	1	20040614 10:40	20040614 12:43
KFM03A	511	516	5	3	1	20040614 12:56	20040614 14:14
KFM03A	516	521	5	3	1	20040614 14:26	20040614 15:47
KFM03A	521	526	5	3	1	20040614 15:55	20040614 16:53

Bore hole	Test section		Section length	Test type[1)]	Test no	Test start date, time	Test stop date, time
Bh ID	**secup**	**seclow**		**(1–6)**		**YYYYMMDD hh:mm**	**YYYYMMDD hh:mm**
KFM03A	526	531	5	3	1	20040614 17:01	20040614 17:44
KFM03A	531	536	5	3	1	20040614 17:52	20040614 19:07
KFM03A	536	541	5	3	1	20040614 19:17	20040614 19:59
KFM03A	541	546	5	3	1	20040614 20:08	20040614 20:51
KFM03A	581	586	5	3	1	20040614 21:16	20040614 22:00
KFM03A	586	591	5	3	1	20040614 22:09	20040614 22:52
KFM03A	591	596	5	3	1	20040614 23:03	20040615 00:17
KFM03A	596	601	5	3	1	20040615 06:27	20040615 07:42
KFM03A	641	646	5	3	1	20040615 08:07	20040615 09:29
KFM03A	646	651	5	3	1	20040615 09:43	20040615 10:32
KFM03A	651	656	5	3	1	20040615 10:46	20040615 12:55
KFM03A	656	661	5	3	1	20040615 13:08	20040615 14:01
KFM03A	681	686	5	3	1	20040615 16:28	20040615 17:06
KFM03A	686	691	5	3	1	20040615 17:18	20040615 18:30
KFM03A	691	696	5	3	1	20040615 18:38	20040615 19:55
KFM03A	691	696	5	3	2	20040615 22:37	20040615 23:52
KFM03A	696	701	5	3	1	20040616 06:34	20040616 07:22
KFM03A	721	726	5	3	1	20040616 07:50	20040616 09:48
KFM03A	726	731	5	3	1	20040616 10:00	20040616 10:42
KFM03A	731	736	5	3	1	20040616 10:55	20040616 12:41
KFM03A	736	741	5	3	1	20040616 12:50	20040616 13:35
KFM03A	761	766	5	3	1	20040616 15:09	20040616 15:54
KFM03A	766	771	5	3	1	20040616 16:09	20040616 16:55
KFM03A	771	776	5	3	1	20040616 17:06	20040616 18:20
KFM03A	776	781	5	3	1	20040616 18:29	20040616 19:43
KFM03A	801	806	5	3	1	20040616 20:02	20040616 21:22
KFM03A	806	811	5	3	1	20040616 21:31	20040616 22:14
KFM03A	811	816	5	3	1	20040616 22:23	20040616 23:37
KFM03A	816	821	5	3	1	20040616 23:47	20040617 06:19
KFM03A	941	946	5	3	1	20040617 07:31	20040617 08:52
KFM03A	946	951	5	3	1	20040617 09:03	20040617 10:27
KFM03A	951	956	5	3	1	20040617 10:46	20040617 11:35
KFM03A	956	961	5	3	1	20040618 06:28	20040618 07:16
KFM03A	971	976	5	3	1	20040618 07:34	20040618 08:17
KFM03A	976	981	5	3	1	20040618 08:29	20040618 09:21
KFM03A	981	986	5	3	1	20040618 09:36	20040618 10:33
KFM03A	986	991	5	3	1	20040618 10:47	20040618 13:20
KFM03A	987	992	5	3	1	20040618 15:18	20040618 16:35

[1)] 3: Injection test

3.4 Equipment checks

The PSS3 equipment was fully serviced, according to SKB internal controlling documents (SKB MD 345.124, service, and SKB MD 345.122, calibration), in February 2004. Some service and calibration was also made in April 2004.

Functioning checks were performed during the installation of the PSS equipment at the test site. In order to check the function of the pressure sensors, the air pressure was recorded and found to be as expected. While lowering, the sensors showed good agreement with the total head of water ($p/\rho g$). The temperature sensor displayed expected values in both air and water.

Simple functioning checks of down-hole sensors were done at every change of test section interval. Checks were also done continuously while lowering the pipe string along the borehole.

4 Description of equipment

4.1 Overview

4.1.1 Measurement container

All of the equipment needed to perform the injection tests is located in a steel container (Figure 4-1). The container is divided into two compartments; a data-room and workshop. The container is placed on pallets in order to obtain a suitable working level in relation to the borehole casing.

The hoisting rig is of a hydraulic chain-feed type. The jaws, holding the pipe string, are opened hydraulically and closed mechanically by springs. The rig is equipped with a load transmitter and the load limit may be adjusted. The maximum load is 22 kN.

The packers and the test valve are operated hydraulically by water filled pressure vessels. Expansion and release of packers, as well as opening and closing of the test valve, is done using magnetic valves controlled by the software in the data acquisition system.

The injection system consists of a tank, a pump and a flow meter. The injection flow rate may be manually or automatically controlled. At small flow rates, a water filled pressure vessel connected to a nitrogen gas regulator is used instead of the pump.

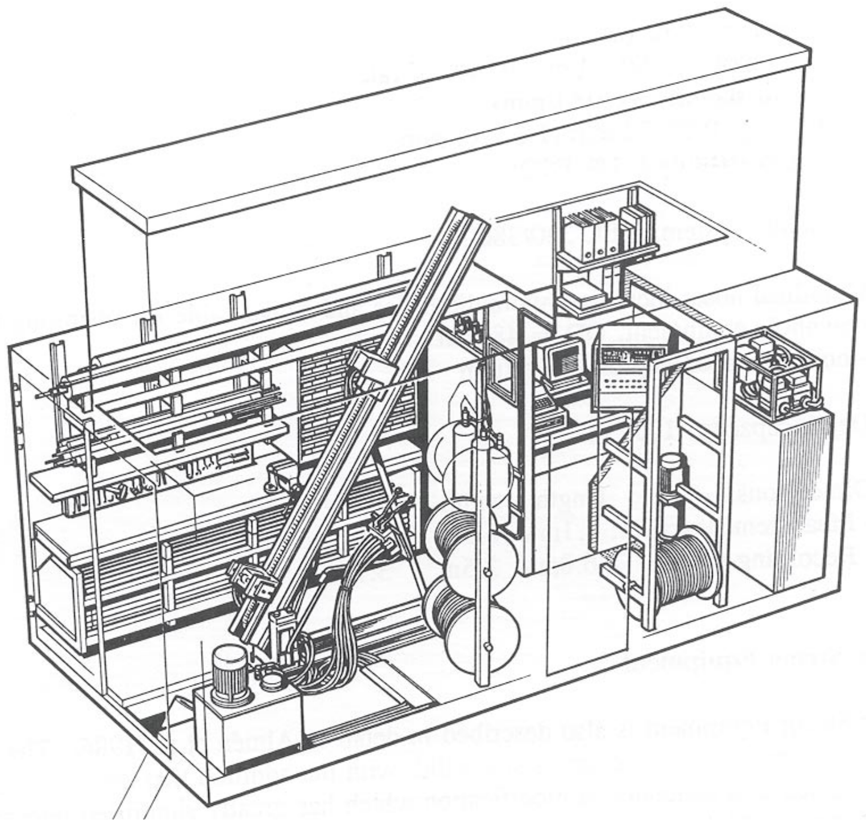

Figure 4-1. *Outline of the PSS3 container with equipment.*

4.1.2 Down-hole equipment

A schematic drawing of the down-hole equipment is shown in Figure 4-2. The pipe string consists of aluminium pipes of 3 m length, connected by stainless steel taps sealed with double o-rings. Pressure is measured above (P_a), within (P) and below (P_b) the test section, which is isolated by two packers. The groundwater temperature in the test section is also measured. The hydraulic connection between the pipe string and the test section can be closed or opened by a test valve operated by the measurement system.

At the lower end of the borehole equipment, a level indicator (caliper type) gives a signal as the reference depth marks along the borehole are passed.

The length of the test section may be varied (5, 20 or 100 metres).

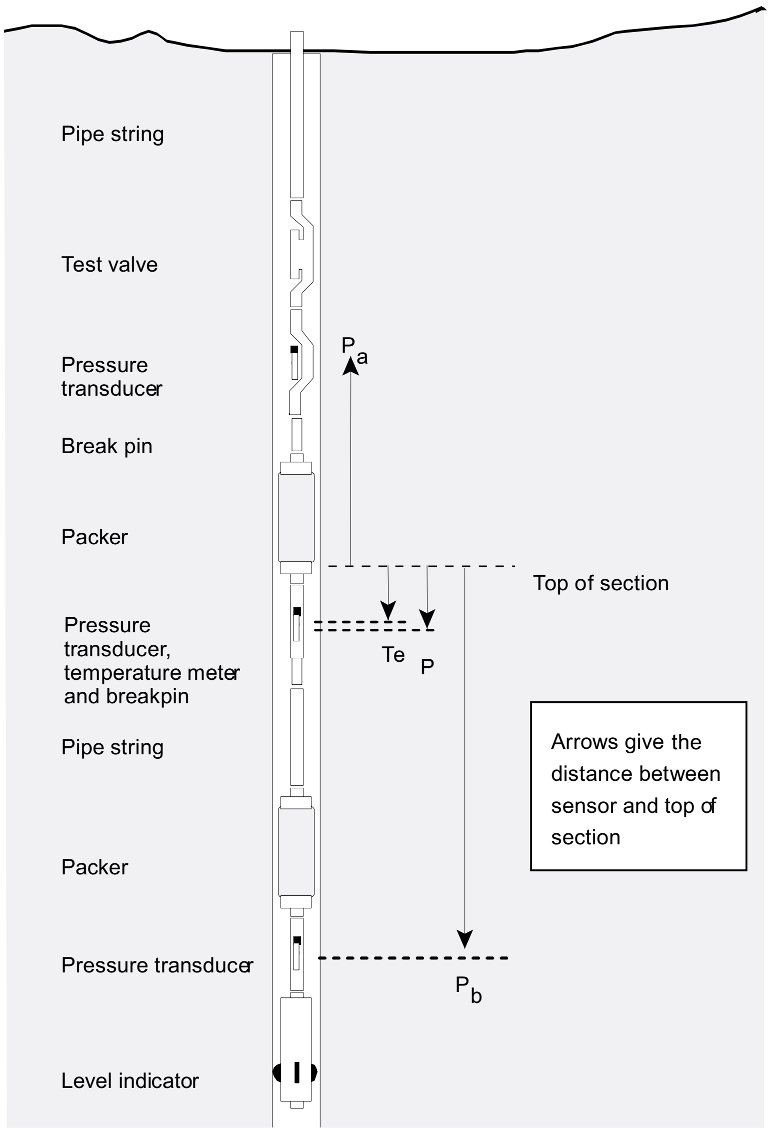

Figure 4-2. *Schematic drawing of the down-hole equipment in the PSS3 system.*

4.2 Measurement sensors

Technical data for the measurement sensors in the PSS system together with corresponding data of the system are shown in Table 4-1.

Table 4-1. Technical data for sensors together with estimated data for the PSS system (based on current experience).

Technical specification					
Parameter		**Unit**	**Sensor**	**PSS**	**Comments**
Absolute pressure	Output signal	mA	4–20		
	Meas range	MPa	0–13.5		
	Resolution	kPa	< 1.0		
	Accuracy[1)]	% F S	0.1		
Differential pressure, 200 kPa	Accuracy	kPa		< ± 5	Estimated value
Temperature	Output signal	mA	4–20		
	Meas range	°C	0–32		
	Resolution	°C	< 0.01		
	Accuracy	°C	± 0.1		
Flow Qbig	Output signal	mA	4–20		
	Meas. range	m^3/s	1.67×10^{-5}–1.67×10^{-3}		
	Resolution	m^3/s	6.7×10^{-8}		
	Accuracy[2)]	% O R	0.15–3	0.2–1	The specific accuracy is depending on actual flow
Flow Qsmall	Output signal	mA	4–20		
	Meas range	m^3/s	1.67×10^{-8}–1.67×10^{-5}		
	Resolution	m^3/s	6.7×10^{-10}		
	Accuracy[2)]	% O R	0.4–10	0.4–20	The specific accuracy is depending on actual flow

[1)] 0.1% of Full Scale. Includes hysteresis, linearity and repeatability.

[2)] Maximum error in % of actual reading (% o r). The higher numbers correspond to the lower flow.

The sensor positions are fixed relative to the top of the test section. In Table 4-2, the position of the sensors is given with top of test section as reference (Figure 4-2).

Table 4-2. Position of sensors in the borehole and displacement volume of equipment in the test section.

Parameter	**Length of test section (m)**		
	5	**20**	**100**
Equipment displacement volume in test section [1)]	4	18	92
Total volume of test section [2)]	23	93	466
Position for sensor P_a, pressure above test section, (m above secup) [3)]	1.88	1.88	1.88
Position for sensor P, pressure in test section, (m above secup) [3)]	–3.54	–18.54	–98.54
Position for sensor T_{sec}, Temperature in test section, (m above secup) [3)]	–4.10	–19.10	–99.10
Position for sensor P_b, pressure below test section, (m above secup) [3)]	–7.00	–22.00	–102.00

[1)] Displacement volume in test section due to pipe string, signal cable and packer ends (in litre).

[2)] Total volume of test section (V = section length*π*d²/4).

[3)] Position of sensor relative top of test section. A negative value indicates a position below top of test section, (secup).

4.3 Data acquisition system

The data acquisition system in the PSS equipment contains a standard office PC connected to an I/O-unit (Datascan 7320). Using the Orchestrator software, pumping and injection tests are monitored and borehole sensor data are collected. In addition to the borehole parameters, packer and atmospheric pressure, container air temperature and water temperature are logged. Test evaluation may be performed on-site after a conducted test. An external display enables monitoring of test parameters.

The data acquisition system may be used to start and stop the automatic control system (computer and servo motors). These are connected as shown in Figure 4-3. The control system monitors the flow regulator and uses differential pressure across the regulating valve together with pressure in test section as input signals.

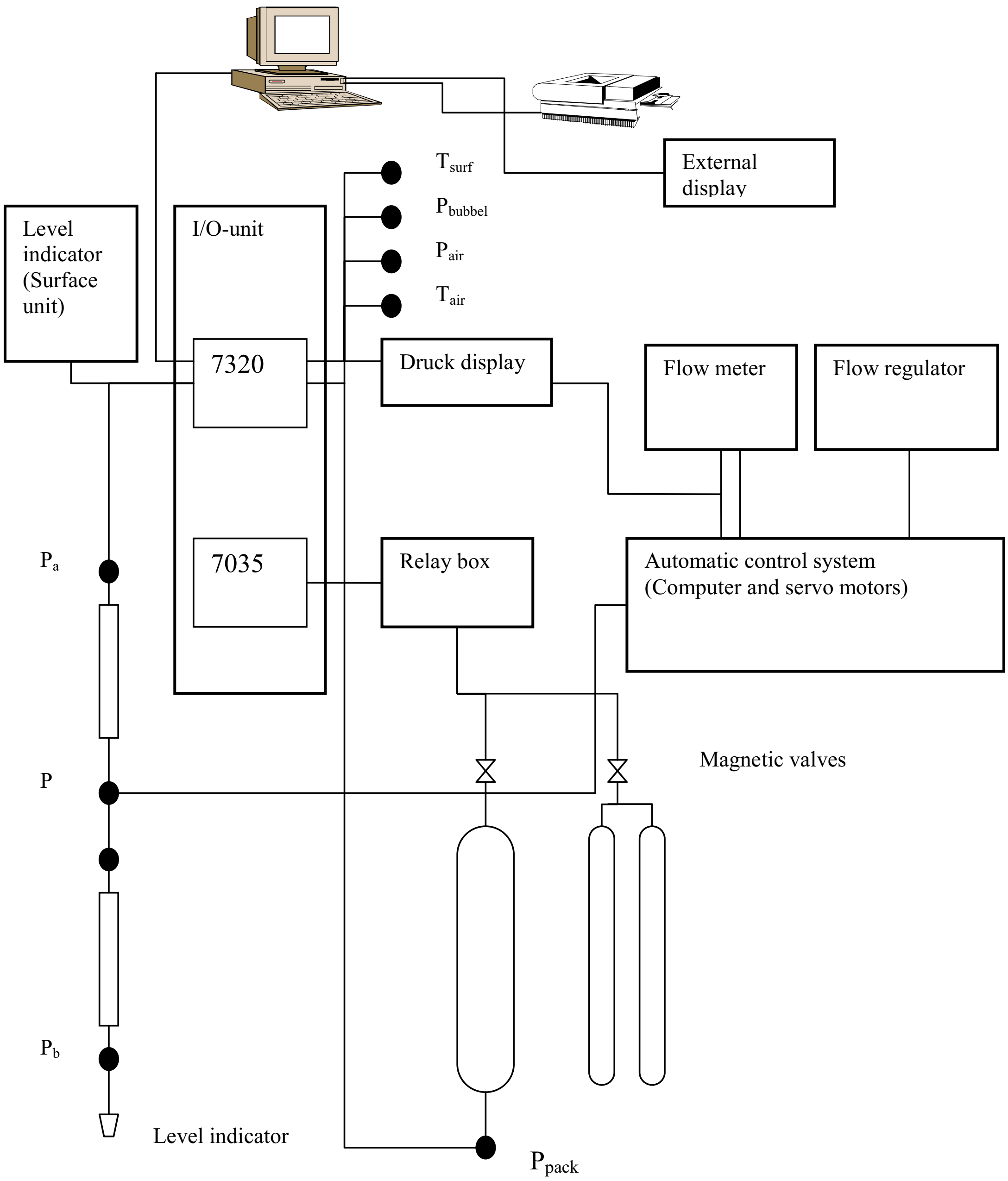

Figure 4-3. *Schematic drawing of the data acquisition system and the automatic control system in PSS.*

5 Execution

5.1 Preparation

5.1.1 Calibration

All sensors included in PSS are calibrated at the GEOSIGMA engineering service station in Uppsala. Calibration is generally performed prior to each measurement campaign. Results from calibration, e.g. calibration constants, of sensors are kept in a document folder in PSS. If a sensor is replaced at the test site, calibration constants are altered as well. If a new, un-calibrated, sensor is to be used, calibration may be performed afterwards and data re-calculated.

5.1.2 Functioning checks

Equipment functioning checks were performed during the establishment of PSS at the test site. Simple function checks of down-hole sensors were done at every change of test section length, as well as while lowering the pipe string along the borehole.

5.1.3 Cleaning of equipment

Cleaning of the borehole equipmentis performed according to the cleaning instruction (SKB MD 600.004, Instruktion för rengöring av borrhålsutrustning och viss markbaserad utrustning), level 1.

5.2 Test performance

5.2.1 Test principle

The injection tests in KFM03A were generally carried out while maintaining a constant head of 200 kPa (20 m) in the test section. Before start of the injection period, approximately steady-state pressure conditions prevailed in the test section. After the injection period, the pressure recovery was measured.

For injection tests with 20 m and 5 m section length, the injection phase was interrupted if the injection flow was apparently below the measurement limit. Thereafter, the recovery was measured for at least 5 minutes to verify the low conductivity of the section.

5.2.2 Test procedure

Generally, the tests were performed according to the Activity Plan AP PF 400-04-26. Exceptions to this are presented in Section 5.5.

A test cycle includes the following phases: 1) Transfer of down-hole equipment to the next section, 2) Packer inflation, 3) Pressure stabilisation, 4) Injection, 5) Pressure recovery and 6) Packer deflation.

The estimated times for the various phases are presented in Table 5-1. Regarding the packer inflation times and actual injection and recovery times, slightly different procedures were used for the tests in 100 m sections compared to the tests in 20 m and 5 m sections according to the Activity Plan. Furthermore, slightly longer test times were used for the tests in 100 m sections, cf Table 5-1.

Table 5-1. Packer inflation times, pressure stabilisation times and test times used for the injection tests in KFM03A.

Test section length (m)	Packer inflation time (min)	Time for pressure stabilisation (min)	Injection period (min)	Recovery period (min)	Total time/test (min)[1)]
100	30	15	30	30	105
20	25	5	20	20	70
5	25	5	20	20	70

[1)] Exclusive of trip times in the borehole

5.2.3 Test strategy

Firstly, injection tests in 100 m sections were performed in the interval 106–901 m. The test at 892–992 m was not performed due to a damaged signal cable (for further information see Section 5.5). The limits of the test sections were, as far as possible, the same as was used by the difference flow logging to facilitate comparison of the results.

Secondly, injection tests in 20 m sections were carried out in tested 100 m sections with a definable flow rate. All 100 m sections were measured in five successive injection tests using a 20 m section length. In addition, injection tests with 20 m section length were performed in the interval below 901 m which had not been tested with a 100 m section length.

Finally, injection tests with 5 m section length were conducted in all 20 m sections with a definable flow rate. Four tests using a 5 m section length were performed within the 20 m intervals. The total number of injection tests was, thus, dependent on the results of the previous tests.

Since the results of the tests in 100 m sections would have a strong effect on the continued test program, it was particularly important to ensure reliable results of these tests, including sections close to the lower measurement limit.

5.3 Data handling

With the PSS system, primary data are handled using the Orchestrator software (Version 2.3.8). During a test, data are continuously logged in *.odl-files. After the test is finished, a report file (*.ht2) with space separated data is generated. The *.ht2-file (mio-format) contains logged parameters as well as test-specific information, such as calibration constants and background data. The parameters are presented as percentage of sensor measurement range and not in engineering units. The report file in ASCII-format is the raw data file delivered to the data base SICADA.

The *.ht2-files are automatically named with borehole id, top of test section and date and time of test start (as for example __KFM03A_0106.00_200405171711.ht2). The name differs slightly from the convention stated in Instructions for analysis of injection and single-borehole pump test, SKB MD 320.004.

Using the IPPLOT software (Version 2.0), the *.ht2-files are converted to parameter files suitable for plotting using the code SKB-plot and analysis with the AQTESOLV software.

A backup of data files was created on a regular basis by CD-storage and by sending the files to the Geosigma office in Uppsala by a file transfer protocol. A file description table is presented in Appendix 1.

5.4 Analysis and interpretation

5.4.1 Single-hole injection tests

As discussed in Section 5.2.1, the injection tests in KFM03A were performed as transient constant head tests followed by a pressure recovery period. The routine data processing of the measured data was done according to the Instruction for analysis of injection and single-hole pumping tests (SKB MD 320.004). From the injection period, the (reciprocal) flow rate versus time was plotted in log-log and lin-log diagrams together with the corresponding derivative. From the recovery period, the pressure and pressure change were plotted versus Agarwal equivalent time in lin-log and log-log diagrams, respectively, together with the corresponding derivatives.

Initially, a qualitative evaluation of actual flow regimes, e.g. wellbore storage (WBS), pseudo-radial flow (PRF), pseudo-spherical flow (PSF) and pseudo-stationary flow (PSS), respectively, was performed. In addition, indications of outer boundary conditions during the tests were identified. The qualitative evaluation was mainly made from the log-log diagrams of the responses during the flow and recovery periods. In particular, time intervals with pseudo-radial flow, reflected by a constant (horizontal) derivative in the test diagrams, were identified. Apparent no-flow (NFB) and constant head boundaries (CHB) or equivalent boundary conditions of fractures are reflected by an increase/decrease of the derivative. In addition, a preliminary steady-state analysis of transmissivity according to Moye's formula (denoted T_M) was made for the injection period for all tests.

From the results of the qualitative evaluation, appropriate interpretation methods for the quantitative evaluation of the tests were selected. If possible, transient analysis was made on both the flow and recovery periods of the tests. Several of the responses during the recovery period were strongly influenced by wellbore storage effects. In addition, for many tests, the recovery period only indicated pseudo-stationary flow. Thus, for most tests pseudo-radial flow was not reached during this period. On the other hand, during the injection period, a certain time interval with pseudo-radial flow could, in most tests, be identified. Consequently, standard methods for single-hole tests with wellbore storage and skin effects were used for routine evaluation of the tests.

The transient analysis was performed using a special version of the test analysis software AQTESOLV, which enables both visual and automatic type curve matching. The quantitative transient evaluation is generally carried out as an iterative process of manual type curve matching and automatic matching. For the injection period, a model presented by Hurst, Clark and Brauer, 1969 /2/ is used for estimating transmissivity and skin factor.

The storativity was set to a fixed value of 10^{-6}, according to the instruction SKB MD 320.004. The model uses the effective wellbore radius concept to account for non-zero skin factors.

For evaluating transient recovery data, the Dougherty-Babu, 1984 /3/ model was applied. This model also uses the effective wellbore radius concept to account for non-zero skin factors. The wellbore storage is treated as the water level change in a fictive stand pipe connected to the section. The wellbore storage can be calculated from the fictive radius of this pipe, denoted casing radius in AQTESOLV, see below. The nomenclature used in AQTESOLV is listed in Appendix 3. The model was used to estimate values of transmissivity, skin factor and the wellbore storage coefficient (represented by the fictive casing radius r(c)), cf Equation 5-2.

Some tests showed fracture responses (a slope of 0.5 in a log-log plot) and fracture models were then also used for the transient analysis. Both the models by Gringarten-Witherspoon, 1972 /4/ and Ozkan-Raghavan, 1991a /5/ and 1991b /6/ for a vertical fracture and Gringarten-Ramey, 1974 /7/ for a horizontal fracture were employed. In these cases, the test section length was used to convert K and S_s to T and S, respectively, after analysis by fracture models. The quotient K_x/K_y of the hydraulic conductivity in the x and the y-direction, respectively, was assumed to be 1.0 (one). Type curve matching provided values of K_x and L_f, where L_f is the theoretical fracture length.

The different transient estimates of transmissivity, in general from the pseudo-radial flow regimes during flow and recovery period, respectively, were compared and examined. One of these was chosen as the best representative value of transient transmissivity of the formation adjacent to the test section. This value is denoted T_T. In cases with more than one pseudo-radial flow regime during the injection or recovery period, the first one is assumed as the most representative for the hydraulic conditions in the rock close to the tested section. In most cases, the transient estimates of transmissivity from the injection period were considered more representative than those from the recovery period. The recovery responses were often strongly affected by wellbore storage and generally no pseudo-radial flow regime was reached. In addition, pseudo-stationary flow often occurred during the recovery period.

Finally, a representative value of transmissivity of the section, T_R, was chosen from T_T and T_M. For tests approaching a pseudo-spherical or pseudo-stationary flow by the end of the test, the steady-state evaluation (T_M) was in some cases considered the best estimate of transmissivity, (i.e. $T_R = T_M$). Whenever the flow rate by the end of the injection period (Q_p) was too low to be defined, and thus neither T_T nor T_M could be estimated, the most representative value of transmissivity for the test section was considered to be the estimated lower measurement limit for Q/s (i.e. T_R = Q/s-measl-L).

Estimated values of the borehole storage coefficient, C, based on actual borehole geometrical data and assumed fluid properties are shown in Table 5-2. The net water volume in the test section, V_w, has in Table 5-2 been calculated by subtracting the volume of equipment in the test section (pipes and thin hoses) from the total volume of the test section. For an isolated test section, the wellbore storage coefficient, C, may be calculated as /8/:

$$C = V_w \times c_w = L_w \times \pi \times r_w^2 \times c_w \tag{5-1}$$

V_w = water volume in test section (m^3)

r_w = nominal borehole radius (m)

L_w = section length (m)

c_w = compressibility of water (Pa^{-1})

Table 5-2. Calculated net values of the wellbore storage coefficient C for injection tests with different section length, based on the actual geometrical properties of the borehole and equipment configuration in the test section.

Borehole	r_w (m)	L_w (m)	Volume of test section (m^3)	Volume of equipment in section (m^3)	V_w (m^3)	C (m^3/Pa)
KFM03A	0.0385	100	0.466	0.058	0.408	1.9×10^{-10}
KFM03A	0.0385	20	0.093	0.012	0.081	3.7×10^{-11}
KFM03A	0.0385	5	0.023	0.003	0.020	9.3×10^{-12}

When appropriate, estimation of the actual borehole storage coefficient C in the test sections was also made from the recovery period, based on the early borehole response with 1:1 slope in the log-log diagrams. The coefficient C was calculated only for tests with a well-defined line of slope 1:1 in the beginning of the recovery period. In the most conductive sections, this period occurred during very short periods at early test times. The latter values may be compared with the net values of C based on geometry (Table 5-2).

Furthermore, when using the model by Dougherty-Babu, 1984, a fictive casing radius, r(c), is obtained from the parameter estimation. This value can then be used for calculating C as /8/:

$$C = \frac{\pi \cdot r(c)^2}{\rho \cdot g} \tag{5-2}$$

Although this calculation was not done regularly and the results are not presented in this report, the calculations corresponded in most cases well with the value of C obtained from the line of slope 1:1 in the beginning of the recovery period.

The estimated values of C from the tests may differ from the net values in Table 5-2 based on geometry. For example, the effective compressibility for an isolated test section may sometimes be higher than the water compressibility due to e.g. packer compliance, resulting in increased C-values.

5.4.2 Pressure interference below selected test sections

During the injections tests in sections 941–946 m, 941–961 m, 986–991 m and 971–991 m, significant responses were observed in the borehole intervals below the test sections, i.e. the interval between the lower packer and the bottom of the borehole. These pressure interferences were also evaluated qualitatively regarding flow regimes and quantitatively regarding hydraulic parameters. The qualitative analysis is similar to that described for the injection tests.

In the quantitative analysis of the pressure interferences during the flow periods in the sections below the tested sections, the transient flow rate records from the tested sections during the injection tests were used as variable flow rate conditions. The recovery periods were, however, analysed with methods for constant flow rate tests using the Agarwal equivalent time as described in the previous section.

Firstly, a combined analysis, using the head changes in both the test and the observation sections simultaneously, was made for the flow and recovery periods. Secondly, individual analyses of the pressure interferences in each observation section were made for the flow and recovery period of the tests.

5.5 Nonconformities

The test program in KFM03A was carried out according to the Activity Plan AP PF 400-04-26 with the following exceptions:

- While lowering the 100 m section, the down-hole cable was damaged. Therefore, the planned test in the 892–992 m section was not performed (as decided by the activity leader).
- The test in the 989–994 m interval could not be performed due to problems lowering the test section. The problems may have been caused by drill cuttings at the bottom of the borehole. Instead, a test was performed in the 987–992 m interval (as decided by the activity leader).
- The temperature sensor in the injection water at the ground surface was out of order during the injection tests in KFM03A.
- The 5 m section in the intervals tests at 646–651 m, 651–656 m, 656–661 m, 681–686 m, 686–691 m and 691–696 m might have been performed 0.10 m further down in the borehole than planned due to a misreading of a length correction mark.
- Two additional tests were performed at positions that were not included in the test orders. These tests were performed in the 348–353 m interval (5 m test section) and in the interval 518–538 m (20 m test section).
- During the injection tests in the sections 941–946 m, 941–961 m, 971–991 m and 986–991 m, there were significant pressure responses in the borehole interval below the test section. These interferences were analysed with respect to T and S (as decided by the activity leader).

6 Results

6.1 Nomenclature and symbols

The nomenclature and symbols used for the results of the injection tests in KFM03A are in accordance with the Instruction for analysis of injection and single-hole pumping tests SKB MD 320.004. Additional symbols used are explained in the text and in Appendix 6. Symbols used by the AQTESOLV software are explained in Appendix 3.

6.2 Routine evaluation of the single-hole injection tests

6.2.1 General test data

General test data with selected pressure and flow data from all tests are listed in Appendix 2.1 and 2.2, respectively.

6.2.2 Measurement limit for flow rate and specific flow rate

The estimated standard lower measurement limit for the flow rate for injection tests with PSS is c 1 mL/min (1.7×10^{-8} m^3/s). However, if the flow rate for a test was close to, or below, the standard lower measurement limit, a test-specific estimate of the lower measurement limit was used. The test-specific lower limit was based on the measurement noise before and after the injection period. The decisive factor for the varying lower measurement limit is not identified, but it might be of both technical and hydraulic character. For most injections tests in KFM03A, the actual lower measurement limit of the flow rate was estimated and ranged from 4×10^{-9} m^3/s to 1.7×10^{-8} m^3/s. The lower measurement limit for transmissivity is defined in terms of the specific flow rate (Q/s).

The minimum specific flow rate corresponds to the estimated lower measurement limit for the flow rate together with the actual injection pressure during the test, see Table 6-1. The intention during this test campaign was to use a standard injection pressure of 200 kPa (20 m water column). However, for some test sections, the actual injection pressure was considerably different. A higher injection pressure is often a result of the test section being of low hydraulic conductivity. However, none of the tests were carried out with an injection pressure above 300 kPa. A low injection pressure is often due to either the test section being highly conductive or the test section being of low conductivity. The latter might cause the pressure in the section to increase due to packer expansion before injection start. For seven of the tests, the injection pressure was below 100 kPa. Three of those sections were highly conductive and four of them of low conductivity. The estimated lower measurement limit for the specific flow rate in KFM03A ranged from 1.9×10^{-10} m^2/s to 8.9×10^{-10} m^2/s, except for three of the tests in highly conductive sections which had a considerably higher limit (~ 1×10^{-8} m^2/s) due to low injection pressure (~ 12 kPa).

Whenever the final flow rate (Q_p) was not defined (i.e. not clearly above the measurement noise before and after the injection period), the estimated lower measurement limit for specific flow rate was based on the estimated lower measurement limit for the specific test and a standard injection pressure of 20 m. This is done in order to avoid excessively high estimates of the specific flow rate for these low conductivity sections, which would have been the result if the actual injection pressure had been used (since the actual pressure often was significantly less than 20 m, see above).

The lower measurement limits for the flow rate correspond to different values of steady-state transmissivity, T_M, depending on the section lengths used in the factor C in Moye's formula, as described in the Instruction for analysis of injection and single-hole pumping tests, SKB MD 320.004, see Table 6-1.

Table 6-1. Estimated lower measurement limit for specific flow rate (Q/s) and steady-state transmissivity for different injection pressures, measurement scales and estimated lower measurement limits for flow rate for the injection tests in borehole KFM03A.

Borehole	r_w (m)	L_w (m)	Q-measl-L (m^3/s)	Injection pressure (kPa)	Q/s-measl-L (m^2/s)	Factor C in Moye's formula	T_M-measl-L (m^2/s)
KFM03A	0.0385	100	1.7E–08	100	1.6E–09	1.30	2.1E–09
KFM03A	0.0385	100	1.7E–08	200	8.2E–10	1.30	1.1E–09
KFM03A	0.0385	100	1.7E–08	300	5.5E–10	1.30	7.1E–10
KFM03A	0.0385	100	1.2E–08	100	1.1E–09	1.30	1.5E–09
KFM03A	0.0385	100	1.2E–08	200	5.7E–10	1.30	7.4E–10
KFM03A	0.0385	100	1.2E–08	300	3.8E–10	1.30	5.0E–10
KFM03A	0.0385	100	5.0E–09	100	4.9E–10	1.30	6.4E–10
KFM03A	0.0385	100	5.0E–09	200	2.5E–10	1.30	3.2E–10
KFM03A	0.0385	100	5.0E–09	300	1.6E–10	1.30	2.1E–10
KFM03A	0.0385	20	1.7E–08	100	1.6E–09	1.04	1.7E–09
KFM03A	0.0385	20	1.7E–08	200	8.2E–10	1.04	8.5E–10
KFM03A	0.0385	20	1.7E–08	300	5.5E–10	1.04	5.7E–10
KFM03A	0.0385	20	1.2E–08	100	1.1E–09	1.04	1.2E–09
KFM03A	0.0385	20	1.2E–08	200	5.7E–10	1.04	6.0E–10
KFM03A	0.0385	20	1.2E–08	300	3.8E–10	1.04	4.0E–10
KFM03A	0.0385	20	5.0E–09	100	4.9E–10	1.04	5.1E–10
KFM03A	0.0385	20	5.0E–09	200	2.5E–10	1.04	2.6E–10
KFM03A	0.0385	20	5.0E–09	300	1.6E–10	1.04	1.7E–10
KFM03A	0.0385	5	1.7E–08	100	1.6E–09	0.82	1.3E–09
KFM03A	0.0385	5	1.7E–08	200	8.2E–10	0.82	6.7E–10
KFM03A	0.0385	5	1.7E–08	300	5.5E–10	0.82	4.5E–10
KFM03A	0.0385	5	1.2E–08	100	1.1E–09	0.82	9.4E–10
KFM03A	0.0385	5	1.2E–08	200	5.7E–10	0.82	4.7E–10
KFM03A	0.0385	5	1.2E–08	300	3.8E–10	0.82	3.1E–10
KFM03A	0.0385	5	5.0E–09	100	4.9E–10	0.82	4.0E–10
KFM03A	0.0385	5	5.0E–09	200	2.5E–10	0.82	2.0E–10
KFM03A	0.0385	5	5.0E–09	300	1.6E–10	0.82	1.3E–10

The practical upper measurement limit for the PSS system is estimated at a flow rate of c 30 L/min (5×10^{-4} m^3/s) and an injection pressure of c 1 m. Thus, the upper measurement limit for the specific flow rate is 5×10^{-4} m^2/s. However, the practical upper measurement limit may vary, depending on e.g. depth of the test section (friction losses in the pipe string).

6.2.3 Length corrections

The down-hole equipment contains a level indicator located c 3 m below the lower packer in the test section, see Figure 4-3. The level indicator transmits a signal each time a reference mark in the borehole is passed. In KFM03A, reference marks were milled in the borehole wall at (with few exceptions) every 50 m.

During the injection tests in KFM03A with the PSS, length reference marks were detected as presented in Table 6-2.

Table 6-2. Detected reference marks during the injection tests in KFM03A.

Borehole length (m)	Detected during the injection tests in 100 m sections	Detected during the injection tests in 20 m sections	Detected during the injection tests in 5 m sections
110	yes	yes	yes
150	yes	yes	yes
200	yes	yes	yes
250	yes	yes	yes
300	yes	yes	yes
350	yes	yes	yes
403	yes	yes	yes
453	no	yes	yes
500	no	yes	yes
550	no	yes	yes
600	no	yes	yes
650	no	yes	yes
700	no	yes	yes
750	no	yes	yes
800	no	yes	yes
850	no	yes	yes
900	no	yes	yes

As seen from Table 6-2, length marks were only detected down to 403 m during the injection tests in 100 m sections. At the detection of the 403 m length mark with the 100 m section test setup, the level indicator stopped working properly, probably due to deposition from the borehole water clogging the moving parts in the level indicator. At each mark, the length scale for the injection tests was adjusted according to the reported length to the reference mark.

The length correction at 650 m for 5 and 20 m sections deviated by 0.10 m. This was probably due to that the mark was not correctly measured with the 5 m section. This affected the tests in the interval of 646–651 m, 651–656 m, 656–661 m, 681–686 m, 686–691 m and 691–696 m. These tests were probably performed at a position 0.10 m lower than planned.

The largest difference between the reported and measured lengths at the reference marks during the injection tests was 0.11 m, at the 800 m reference mark. The difference between two consecutive measurements over a 100 m borehole interval was 0.07 m or less in all cases, except for the measurement at 650 m with a 5 m section. A comparison of the measurements performed with different section lengths results in a maximum difference of 0.02 m, not including the measurement at 650 m.

Since the length scale was adjusted in the field every time a reference mark was passed, and since the difference between consecutive marks was small, it was not found worthwhile to make any further adjustments after the measurements, e.g. by linear interpolation between reference marks.

6.2.4 General results

A summary of the results of the routine evaluation of the injection tests in different scales in KFM03A is presented, test by test, in Table 6-3. Selected test diagrams are presented in Appendix 3. In general, one linear diagram showing the entire test sequence together with lin-log and log-log diagrams from the injection and recovery periods, respectively, are presented. The quantitative analysis was performed from such diagrams using the AQTESOLV software. From tests with a flow rate below the estimated lower measurement limit for the specific test, only the linear diagram is presented.

The dominating transient flow regimes during the injection and recovery periods, respectively, as interpreted from the qualitative test evaluation, are listed in Table 6-3 and further commented on in Section 6.2.5.

For some tests, particularly from the recovery period, a type curve fit is displayed in the diagrams in Appendix 3, despite that the parameters from the fit are judged as not representative and are thus neither included in Table 6-3 nor in the result tables for SICADA. For these tests, the type curve fit is presented only to illustrate that an assumption of pseudo-radial flow regime is not justified, indicated by the high apparent value for the skin factor. Instead, a pseudo-spherical flow regime is likely to dominate for these tests, as commented in the diagrams and in Section 6.2.5. For tests showing only wellbore storage and tests approaching a pseudo-stationary flow, no unique transient evaluation is possible. In such cases, no type curve matching was done.

In the quantitative evaluation, the steady-state transmissivity (T_M) was calculated by Moye's formula. Transient evaluation was conducted, whenever possible, both on the injection and recovery periods (T_f and T_s, respectively). However, for many low conductivity sections, no unique transient evaluation could be made from the recovery period (only wellbore storage response). Transient evaluation was performed for all tests for which a significant flow rate, Q_p, could be identified, see Section 6.2.2.

The value judged as the most reliable from the transient evaluation of the tests was selected as T_T. The associated value for the skin factor is listed in Table 6-3. Since a fairly well-defined time interval with pseudo-radial flow in most cases could be identified from the injection period, the transmissivity calculated from this period is in most cases considered as the most reliable transient analysis for the injection tests in KFM03A. In addition, the transient evaluation of transmissivity from the injection period was for most of the tests also judged to be the most representative estimate of transmissivity, T_R. The approximate start and stop times used for the transient evaluation are also listed in Table 6-3. For those tests where transient evaluation was not possible or not considered representative, T_M was chosen as the representative transmissivity value, T_R. If Q_p was below the actual estimated measurement limit, the representative transmissivity value, T_R, was assumed less than the estimated Q/s-measl-L, see Section 6.2.2.

In some cases, two transmissivity values could be calculated from the tests, at early and at later times, respectively. It is then assumed that the first transmissivity value represents a region close to the borehole, whereas the later value may represent a larger volume of the rock.

The results of the routine evaluation of the injection tests in borehole KFM03A are also compiled in appropriate tables in Appendix 6, to be stored in the SICADA database.

For the evaluation of the test data, no corrections of the measured flow rate and absolute pressure data (e.g. due to barometric pressure variations or tidal fluctuations) have been made. For short-time single-hole tests, such corrections are generally not needed, unless very small pressure changes are applied. No subtraction of the barometric pressure from the measured absolute pressure has been made, since the length of the test periods are short relative to the time scale for barometric pressure changes. In addition, pressure differences rather than the pressure magnitudes are used by the evaluation.

Drilling records were checked in order to identify possible interference with test data from drilling in nearby boreholes. These records showed that drilling of HFM20 and HFM21 (approximately 700 m north west of drilling site DS1, see Figure 1-1) was in progress during 2004-05-08 to 2004-06-07 and drilling of KFM06A (at drilling site DS6, see Figure 1-1) started at 2004-06-15. However, the injection tests in KFM03A are assumed to be unaffected by these activities due to the long distance between the boreholes.

In Figure 6-1, a comparison of calculated transmissivities in 5 m sections from steady-state evaluation (T_M) and transmissivity values from the transient evaluation (T_T) is shown. The agreement between the two populations is considered good. The lower measurement limit of transmissivity in 5 m sections for a flow rate of 1 mL/min and an injection pressure of 200 kPa is indicated in the figure.

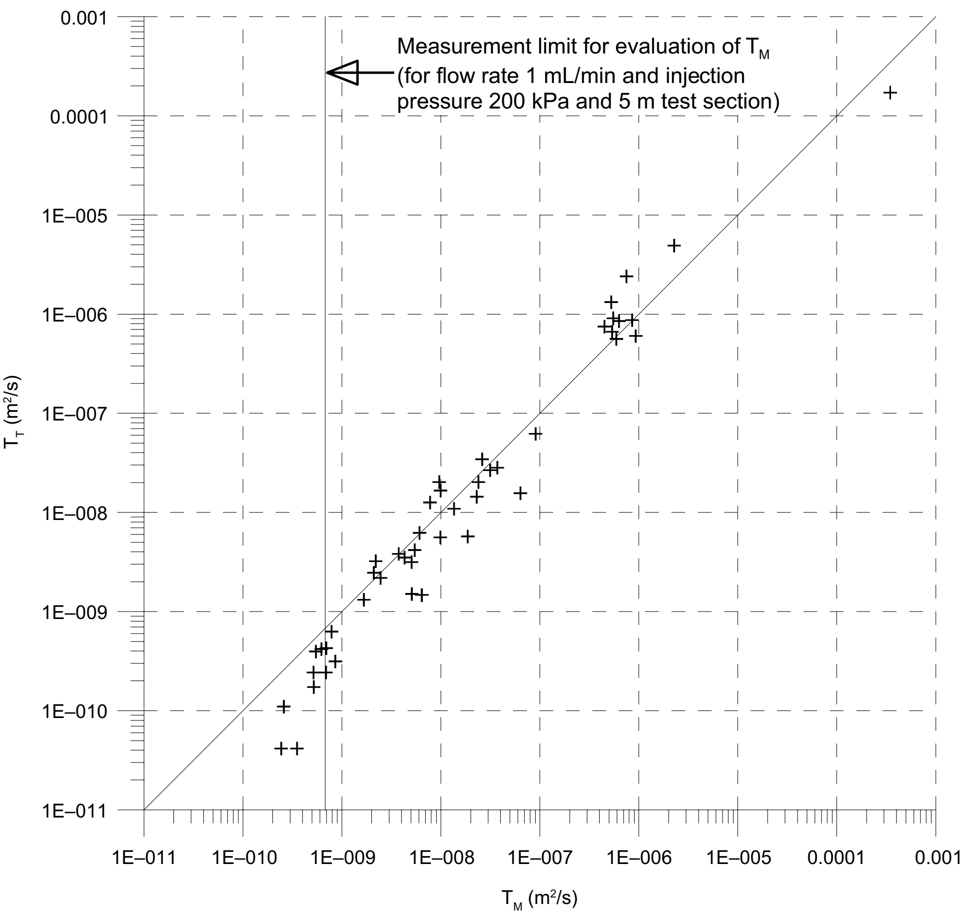

Figure 6-1. *Estimated transmissivities in 5 m sections from steady-state (T_M) and transient (T_T) evaluation.*

The wellbore storage coefficient, C, was calculated from the straight line with a unit slope in the log-log diagrams from the recovery period, see Table 6-3. The coefficient C was only calculated for tests with a well-defined line of unit slope in the beginning of the recovery period. In the most conductive sections, this period occurred during very short intervals at very early times and is not visible in the diagrams. In sections with a very low transmissivity, the estimates of C may be uncertain due to difficulties in defining an accurate time for the start of the recovery period. Furthermore, the resolution of the pressure sensors causes the recovery to be quite scattered in sections of low transmissivity. The values of C presented in Table 6-3 may be compared with the net values of C in Table 5-2 (based on geometry).

The number of tests with a well defined line of unit slope for which it was possible to calculate C was as follows, 100 m tests; 4 out of 8, 20 m tests; 20 out of 46, and 5 m tests; 27 out of 103. Table 6-3 shows that there is, in general, a good agreement between the calculated C values from the tests and those listed in Table 5-2, although the calculated values from the tests tend to be higher. The test in the section between 811–816 m resulted in a higher estimate of C than tests in other intervals. The 100 m and 20 m tests that straddle the interval 811–816 m also result in higher estimates of C than the other test intervals. No reasonable explanation has been found for the significantly higher wellbore storage coefficient estimated from the test in the interval of 811–816 m. When constructing 95% confidence intervals (using a t-distribution) from calculated values of C from the tests, the values of C listed in Table 5-2 are within these confidence intervals. When constructing 95% confidence intervals (using a t-distribution), but excluding the tests covering the interval of 811–816 m, the values of C listed in Table 5-2 are lower than the lower confidence interval limit for 20 m and 5 m tests.

Table 6-3. Summary of the routine evaluation of the single-hole injection tests in borehole KFM03A.

Secup (m)	Seclow (m)	Test start YYYYMMDD hh:mm	b (m)	Flow regime [1] injection	recovery	Q/s-measl-L (m²/s)	Q/s (m²/s)	T_M (m²/s)	T_f (m²/s)	T_s (m²/s)	T_T (m²/s)	T_R [2] (m²/s)	ξ (–)	dt_1 (s)	dt_2 (s)	C (m³/Pa)
106.00	206.00	20040517 17:11	100	PLF –> PRF –> PSF	PLF –> PSF	7.77E–10	1.99E–07	2.59E–07	7.70E–08	6.49E–08	6.49E–08	6.49E–08		0	200	
201.00	301.00	20040517 20:08	100	PRF	WBS	6.60E–10	3.80E–09	4.95E–09	1.31E–09	1.61E–09	1.31E–09	1.31E–09	–2.2	80	1,800	2.44E–10
301.00	401.00	20040517 23:16	100		PRF –> PSF	1.38E–08	4.24E–04	5.52E–04	4.98E–04	3.72E–04	3.72E–04	3.72E–04	–4.5	10	800	
401.00	501.00	20040518 15:45	100	PSF	PSS –> NFB?	8.16E–10	1.34E–06	1.75E–06				1.75E–06				
501.00	601.00	20040518 18:58	100	PRF	WBS –> PRF	8.28E–10	3.41E–08	4.44E–08	2.00E–08	2.11E–08	2.00E–08	2.00E–08	–1.9	70	1,800	2.80E–10
601.00	701.00	20040518 22:07	100	PRF/PSF?	PSS	8.20E–10	1.05E–06	1.37E–06	2.61E–06		2.61E–06	2.61E–06	7.5	80	1,800	
701.00	801.00	20040519 08:38	100	PRF	WBS	8.37E–10	5.52E–09	7.19E–09	2.29E–09	3.66E–09	2.29E–09	2.29E–09	–2.1	90	1,800	2.24E–10
801.00	901.00	20040524 07:47	100	PRF	WBS	7.72E–10	5.28E–08	6.88E–08	2.52E–08	2.63E–08	2.52E–08	2.52E–08	–2.8	200	1,800	1.45E–09
106.00	126.00	20040525 10:46	20	PRF1? –> PRF2	PLF –> PSF	8.20E–10	1.11E–07	1.16E–07	9.50E–08	3.54E–08	9.50E–08	9.50E–08	–0.8	200	1,200	
121.00	141.00	20040525 13:11	20	PLF –> PRF –> PSF	(PLF) –> PRF –> PSF	8.00E–10	1.37E–07	1.43E–07	5.10E–08	5.41E–08	5.10E–08	5.10E–08	–3.5	80	500	
141.00	161.00	20040525 14:44	20		WBS	3.50E–10						3.50E–10				
161.00	181.00	20040601 12:52	20	(PRF)	WBS	3.14E–10	7.86E–10	8.22E–10	2.02E–10	9.32E–11	2.02E–10	2.02E–10	–1.4	10	600	5.94E–11
181.00	201.00	20040525 16:46	20		WBS	3.50E–10						3.50E–10				
201.00	221.00	20040525 18:19	20		WBS	1.90E–10	2.37E–10	2.48E–10				2.48E–10				1.02E–10
221.00	241.00	20040525 19:53	20		WBS	2.31E–10	2.31E–10	2.42E–10	1.55E–11		1.55E–11	2.42E–10	–1.6			1.13E–10
241.00	261.00	20040525 21:11	20	PRF	WBS	7.79E–10	1.77E–09	1.86E–09	6.62E–10	1.53E–10	6.62E–10	6.62E–10	–1.5	60	400	6.45E–11
261.00	281.00	20040525 22:44	20	PRF	WBS	3.82E–10	7.48E–10	7.83E–10	1.73E–10	1.75E–10	1.73E–10	1.73E–10	–1.7	30	1,200	5.31E–11
281.00	301.00	20040526 06:30	20	PRF	WBS	3.78E–10	7.83E–10	8.19E–10	1.70E–10	5.89E–11	1.70E–10	1.70E–10	–2.1	10	1,200	5.64E–11
301.00	321.00	20040526 08:05	20	PRF	WBS –> (PRF)	8.03E–10	5.89E–09	6.16E–09	2.67E–09	3.78E–09	2.67E–09	2.67E–09	–1.7	100	1,200	6.24E–11
321.00	341.00	20040526 09:50	20	PLF??	WBS –> PRF	8.34E–10	4.61E–09	4.83E–09	1.00E–09	2.29E–09	2.29E–09	2.29E–09	–1.5	80	700	9.13E–12
341.00	361.00	20040526 11:30	20	PRF –> PSF	PLF –> (PRF) –> PSF	7.98E–10	1.13E–06	1.19E–06	6.35E–07	4.96E–07	6.35E–07	6.35E–07	–3.5	30	600	
361.00	381.00	20040526 13:50	20	PRF –> NFB	PSS	8.09E–10	2.08E–06	2.18E–06	2.66E–06		2.66E–06	2.66E–06	–0.5	100	300	

Secup (m)	Seclow (m)	Test start YYYYMMDD hh:mm	b (m)	Flow regime 1) injection	recovery	Q/s-measl-L (m^2/s)	Q/s (m^2/s)	T_M (m^2/s)	T_f (m^2/s)	T_s (m^2/s)	T_T (m^2/s)	T_R 2) (m^2/s)	ξ (–)	dt_1 (s)	dt_2 (s)	C (m^3/Pa)
381.00	401.00	20040526 16:00	20	PSF –> (PRF) –> PSF	(PRF)	1.24E–08	3.93E–04	4.11E–04	2.04E–04	3.32E–04	3.32E–04	3.32E–04	–4.8	10	600	
401.00	421.00	20040526 18:43	20	PRF?	WBS –> (PRF)	8.16E–10	7.79E–09	8.15E–09	3.34E–09	8.67E–09	8.67E–09	8.67E–09	2.2	10	800	6.25E–11
421.00	441.00	20040526 20:58	20	(PRF)	WBS	3.13E–10	3.13E–10	3.27E–10	4.21E–11		4.21E–11	3.27E–10	–0.5	100	1,000	7.13E–11
441.00	461.00	20040526 23:12	20	PSF	PSS	8.18E–10	2.06E–06	2.15E–06				2.15E–06				
461.00	481.00	20040527 07:43	20	PRF –> NFB	WBS –> PRF	8.25E–10	8.78E–09	9.18E–09	5.19E–09	1.08E–08	1.08E–08	1.08E–08	2.2	300	700	4.52E–11
481.00	501.00	20040527 09:18	20	PRF	PRF	8.22E–10	3.67E–08	3.84E–08	2.95E–08	2.40E–08	2.95E–08	2.95E–08	–0.5	100	1,200	
501.00	521.00	20040527 10:53	20	PRF –> PSF	WBS –> PSF	8.18E–10	8.19E–09	8.57E–09	5.31E–09		5.31E–09	5.31E–09	–0.2	150	400	
518.00	538.00	20040527 13:14	20	PRF	PRF1 –> (PRF2)	8.20E–10	2.58E–08	2.70E–08	1.18E–08	1.51E–08	1.18E–08	1.18E–08	–2.3	100	1,200	
521.00	541.00	20040527 15:30	20	PRF	PRF1 –> PRF2	8.19E–10	2.61E–08	2.73E–08	1.55E–08	1.66E–08	1.55E–08	1.55E–08	–1.6	100	1,200	
541.00	561.00	20040601 19:57	20			2.50E–10						2.50E–10				
561.00	581.00	20040601 21:52	20	(PRF) –> PSF	WBS	2.83E–10	2.83E–10	2.97E–10	3.15E–11		3.15E–11	3.15E–11	–2.0	20	200	8.49E–11
581.00	601.00	20040602 06:07	20	PRF –> PSF	WBS –>	7.94E–10	2.31E–09	2.42E–09	1.78E–09	4.20E–09	1.78E–09	1.78E–09	0.5	80	800	4.95E–11
601.00	621.00	20040602 07:40	20			2.50E–10						2.50E–10				
621.00	641.00	20040602 08:56	20			3.00E–10						3.00E–10				
641.00	661.00	20040602 10:02	20	PSF/PRF	PSS	6.57E–10	1.04E–06	1.09E–06	2.09E–06		2.09E–06	2.09E–06	5.0	50	1,200	
661.00	681.00	20040602 11:28	20			4.00E–10						4.00E–10				
681.00	701.00	20040602 13:38	20	PRF –> NFB?	WBS –>	8.54E–10	4.59E–09	4.80E–09	4.33E–09	5.00E–10	4.33E–09	4.33E–09	–1.4	50	150	5.72E–11
701.00	721.00	20040602 15:28	20			3.00E–10						3.00E–10				
721.00	741.00	20040602 17:08	20	PRF> PFL?	WBS –> PRF –> PFL	8.86E–10	5.07E–09	5.30E–09	4.18E–09	4.17E–09	4.18E–09	4.18E–09	–0.7	10	100	4.42E–11
741.00	761.00	20040602 18:58	20	(PRF)	WBS	3.72E–10	3.72E–10	3.89E–10	5.43E–11			3.89E–10				1.43E–11
761.00	781.00	20040602 21:43	20	PRF	WBS	8.19E–10	1.14E–09	1.19E–09	4.94E–10		4.94E–10	4.94E–10	–0.5	30	1,200	5.92E–11
781.00	801.00	20040603 06:02	20			2.50E–10						2.50E–10				
801.00	821.00	20040603 07:35	20	PRF	WBS	6.54E–10	6.14E–08	6.43E–08	2.49E–08	3.56E–08	2.49E–08	2.49E–08	–3.1	200	1,200	1.60E–09

Secup (m)	Seclow (m)	Test start YYYYMMDD hh:mm	b (m)	Flow regime 1) injection	recovery	Q/s-measl-L (m²/s)	Q/s (m²/s)	T_M (m²/s)	T_f (m²/s)	T_s (m²/s)	T_T (m²/s)	T_R 2) (m²/s)	ξ (–)	dt_1 (s)	dt_2 (s)	C (m³/Pa)
821.00	841.00	20040603 09:07	20	PRF	WBS	2.63E–10	4.64E–10	4.86E–10	1.54E–10		1.54E–10	1.54E–10	–1.5	40	1,200	3.59E–11
841.00	861.00	20040603 10:40	20		WBS	3.50E–10						3.50E–10				
861.00	881.00	20040603 12:52	20	(PRF)	WBS	3.40E–10	5.30E–10	5.55E–10	5.85E–11		5.85E–11	5.85E–11	–2.0	300	800	6.37E–11
881.00	901.00	20040603 14:27	20			3.50E–10						3.50E–10				
901.00	921.00	20040603 16:03	20			2.50E–10						2.50E–10				
921.00	941.00	20040603 17:30	20			4.00E–10						4.00E–10				
941.00	961.00	20040603 18:55	20	PRF	PRF1 –> PRF2	8.04E–10	9.68E–07	1.01E–06	5.91E–07	7.55E–07	5.91E–07	5.91E–07	–3.3	100	1,200	
961.00	981.00	20040603 20:47	20			4.50E–10						4.50E–10				
971.00	991.00	20040603 22:51	20	PRF	PRF	8.20E–10	7.51E–07	7.85E–07	5.50E–07	5.52E–07	5.50E–07	5.50E–07	–2.4	80	1,200	
104.00	109.00	20040622 13:37	5	PRF	WBS –> PSF?	8.46E–10	3.17E–08	2.61E–08	3.44E–08	3.05E–08	3.44E–08	3.44E–08	1.3	50	1,200	7.96E–11
106.00	111.00	20040607 05:53	5	PRF	WBS –> PSF?	8.17E–10	2.90E–08	2.40E–08	2.02E–08	2.85E–08	2.02E–08	2.02E–08	–0.8	30	800	7.11E–11
111.00	116.00	20040607 07:34	5	PRF? PSF?	WBS –> PSS	6.70E–10	1.17E–08	9.62E–09	2.02E–08		2.02E–08	2.02E–08	4.7	20	300	2.96E–11
116.00	121.00	20040607 08:58	5	PSF –> PSS	PSF –> PSS	8.20E–10	1.94E–07	1.61E–07	6.57E–07	3.34E–07		1.61E–07				
121.00	126.00	20040607 10:26	5	PRF –> PSF	PLF –> PRF? –> PSF	8.20E–10	7.71E–08	6.37E–08	1.56E–08	2.70E–08	1.56E–08	1.56E–08	–3.7	20	120	
126.00	131.00	20040607 12:28	5	PRF –> NFB	PRF –> PSF	8.16E–10	1.10E–07	9.06E–08	6.20E–08	1.01E–07	6.20E–08	6.20E–08	–2.8	30	300	
131.00	136.00	20040607 14:01	5	PRF/PSF	WBS –> PSF	7.09E–10	2.67E–09	2.20E–09	3.22E–09		3.22E–09	2.20E–09	3.2	100	800	2.14E–11
136.00	141.00	20040607 15:49	5	PLF –> PRF?	PLF	7.22E–10	6.17E–09	5.10E–09	1.50E–09	5.93E–10	1.50E–09	1.50E–10	–2.8	300	800	
161.00	166.00	20040607 18:21	5			3.50E–10						3.50E–10				
166.00	171.00	20040607 20:32	5			4.00E–10						4.00E–10				
171.00	176.00	20040607 22:09	5	PRF	WBS –> (PRF)	3.08E–10	8.42E–10	6.95E–10	4.27E–10	4.21E–10	4.27E–10	4.27E–10	–0.4	20	1,200	1.95E–11
176.00	181.00	20040608 06:08	5			3.00E–10						3.00E–10				
241.00	246.00	20040608 07:44	5			3.50E–10						3.50E–10				
246.00	251.00	20040608 08:54	5			3.00E–10						3.00E–10				

Secup (m)	Seclow (m)	Test start YYYYMMDD hh:mm	b (m)	Flow regime [1)] injection	recovery	Q/s-measl-L (m²/s)	Q/s (m²/s)	T_M (m²/s)	T_f (m²/s)	T_s (m²/s)	T_T (m²/s)	T_R [2)] (m²/s)	ξ (–)	dt_1 (s)	dt_2 (s)	C (m³/Pa)
251.00	256.00	20040608 09:53	5	PRF	WBS –> ?	7.74E–10	1.04E–09	8.61E–10	3.14E–10	7.12E–10	3.14E–10	3.14E–10	–1.3	100	1,200	2.86E–11
256.00	261.00	20040608 11:20	5			3.50E–10						3.50E–10				
261.00	266.00	20040608 13:20	5		WBS	3.55E–10	3.55E–10	2.93E–10	4.84E–11			2.93E–10				4.79E–11
266.00	271.00	20040608 14:48	5	(PRF)	WBS> PRF	2.35E–10	6.30E–10	5.20E–10	1.04E–10	1.73E–10	1.73E–10	1.73E–10	–1.2	10	600	1.71E–11
271.00	276.00	20040608 16:27	5			3.50E–10						3.50E–10				
276.00	281.00	20040608 17:42	5			2.50E–10						2.50E–10				
281.00	286.00	20040608 18:50	5			3.00E–10						3.00E–10				
286.00	291.00	20040608 20:05	5			3.00E–10						3.00E–10				
291.00	296.00	20040608 21:21	5	(PRF)	WBS –> PSF?	2.67E–10	7.52E–10	6.20E–10	4.18E–10		4.18E–10	4.18E–10	0.5	10	500	1.72E–11
296.00	301.00	20040608 23:11	5	PLF	WBS	2.99E–10	4.26E–10	3.52E–10	4.16E–11	4.55E–12	4.16E–11	4.16E–11	–2.4	10	1,200	3.40E–11
301.00	306.00	20040609 07:14	5			3.00E–10						3.00E–10				
306.00	311.00	20040609 08:13	5	(PRF)	WBS	2.96E–10	2.96E–10	2.44E–10	4.16E–11	1.65E–12	4.16E–11	4.16E–11	–1.2	10	1,200	4.28E–11
311.00	316.00	20040609 09:38	5	PRF	PRF	7.48E–10	6.14E–09	5.07E–09	3.15E–09	3.45E–09	3.15E–09	3.15E–09	–1.2	100	1,000	
316.00	321.00	20040609 11:02	5	PRF	WBS –> ?	3.76E–10	6.61E–10	5.46E–10	3.96E–10	2.48E–09	3.96E–10	3.96E–10	0.1	20	1,200	1.79E–11
321.00	326.00	20040609 13:20	5	PRF –> PSF	WBS –> ?	3.49E–10	6.26E–10	5.17E–10	2.43E–10	7.07E–09	2.43E–10	2.43E–10	–0.1	100	1,200	1.83E–11
326.00	331.00	20040609 14:50	5	PRF –> NFB	WBS –> NFB	7.64E–10	2.54E–09	2.10E–09	2.46E–09	2.10E–09	2.46E–09	2.46E–09	0.5	10	100	1.42E–11
331.00	336.00	20040609 16:27	5	PRF	WBS –> PRF	7.46E–10	6.59E–09	5.44E–09	4.17E–09	4.38E–09	4.17E–09	4.17E–09	–0.5	100	700	
336.00	341.00	20040609 18:20	5		WBS	2.82E–10	2.82E–10	2.33E–10				2.33E–10				3.82E–11
341.00	346.00	20040609 20:01	5			3.50E–10						3.50E–10				
346.00	351.00	20040609 21:25	5			4.00E–10						4.00E–10				
348.00	353.00	20040609 22:46	5			3.00E–10						3.00E–10				
351.00	356.00	20040609 23:53	5			2.50E–10						2.50E–10				
356.00	361.00	20040610 06:52	5	PLF? –> PRF –> PSF	PLF –> PRF –> PSF	7.88E–10	1.13E–06	9.31E–07	6.00E–07	5.20E–07	6.00E–07	6.00E–07	–3.7	30	400	
361.00	366.00	20040610 08:18	5	PRF –> NFB	PSS	8.25E–10	5.43E–07	4.48E–07	7.46E–07		7.46E–07	7.46E–07	0.6	70	300	
366.00	371.00	20040610 09:48	5	PRF –> NFB	PSS	8.17E–10	6.71E–07	5.54E–07	9.06E–07		9.06E–07	9.06E–07	1.3	70	400	

Secup (m)	Seclow (m)	Test start YYYYMMDD hh:mm	b (m)	Flow regime [1)] injection	recovery	Q/s-measl-L (m^2/s)	Q/s (m^2/s)	T_M (m^2/s)	T_f (m^2/s)	T_s (m^2/s)	T_T (m^2/s)	T_R [2)] (m^2/s)	ξ (–)	dt_1 (s)	dt_2 (s)	C (m^3/Pa)
371.00	376.00	20040610 11:14	5	PRF –> NFB	PSS	8.21E–10	7.65E–07	6.32E–07	8.50E–07		8.50E–07	8.50E–07	–0.8	60	300	
376.00	381.00	20040610 13:28	5	PRF/PSF	PSF –> PSS	8.21E–10	6.39E–07	5.27E–07	1.32E–06		1.32E–06	1.32E–06	5.6	130	1,200	
381.00	386.00	20040610 15:04	5	PRF	PSF –> PSS	8.17E–10	6.52E–07	5.38E–07	6.62E–07		6.62E–07	6.62E–07	–0.6	100	600	
386.00	391.00	20040610 16:43	5	PRF	PLF –> PRF> PSF	1.33E–08	4.20E–04	3.46E–04	3.50E–04	1.71E–04	1.71E–04	1.71E–04	–7.2	50	500	
391.00	396.00	20040610 18:33	5	PSF/PSS	PSF –> PSS	8.20E–10	4.49E–08	3.70E–08	2.62E–07	1.59E–07		3.70E–08		200	1,200	
396.00	401.00	20040610 20:31	5	PRF	WBS	7.84E–10	7.80E–09	6.44E–09	1.47E–09		1.47E–09	1.47E–09	–3.3	100	1,200	2.82E–10
401.00	406.00	20040610 22:10	5			3.00E–10						3.00E–10				
406.00	411.00	20040611 06:08	5	PRF	WBS –> PRF	8.25E–10	1.65E–08	1.36E–08	1.09E–08	3.18E–08	1.09E–08	1.09E–08	–1.0	70	800	
411.00	416.00	20040611 07:40	5	PRF	WBS –> PRF	8.21E–10	4.55E–09	3.76E–09	3.81E–09	5.34E–09	3.81E–09	3.81E–09	0.7	50	1,200	1.89E–11
416.00	421.00	20040611 09:06	5			3.07E–10	3.07E–10	2.53E–10				2.53E–10				
441.00	446.00	20040611 10:49	5			2.50E–10						2.50E–10				
446.00	451.00	20040611 13:06	5	PSF	WBS –> PSF	8.29E–10	1.36E–09	1.12E–09				1.12E–09				2.79E–11
451.00	456.00	20040611 14:35	5	PRF/PSF	PSS –> NFB	8.15E–10	2.76E–06	2.28E–06	4.90E–06		4.90E–06	2.28E–06	3.4	50	200	
456.00	461.00	20040611 16:23	5			4.00E–10						4.00E–10				
461.00	466.00	20040611 17:41	5	PRF	WBS –> PSF –> PLF?	8.17E–10	1.20E–08	9.87E–09	5.59E–09	9.82E–09	5.59E–09	5.59E–09	–2.0	80	600	1.66E–11
466.00	471.00	20040611 19:17	5			3.50E–10						3.50E–10				
471.00	476.00	20040601 20:31	5		WBS	3.00E–10						3.00E–10				
476.00	481.00	20040611 21:53	5			3.00E–10						3.00E–10				
481.00	486.00	20040611 22:50	5			3.50E–10						3.50E–10				
486.00	491.00	20040614 06:01	5			2.50E–10						2.50E–10				
491.00	496.00	20040614 07:09	5			3.00E–10						3.00E–10				
496.00	501.00	20040614 08:13	5	PRF	PRF	8.23E–10	3.81E–08	3.15E–08	2.96E–08	2.66E–08	2.66E–08	2.66E–08	–1.1	40	400	
501.00	506.00	20040614 09:45	5			3.50E–10						3.50E–10				
506.00	511.00	20040614 10:39	5			3.50E–10						3.50E–10				
511.00	516.00	20040614 12:56	5	PRF –> PSF	WBS –> (PRF)	8.15E–10	2.98E–09	2.46E–09	2.18E–09	3.08E–09	2.18E–09	2.18E–09	0.6	50	400	2.48E–11

Secup (m)	Seclow (m)	Test start YYYYMMDD hh:mm	b (m)	Flow regime [1] injection	recovery	Q/s-measl-L (m^2/s)	Q/s (m^2/s)	T_M (m^2/s)	T_f (m^2/s)	T_s (m^2/s)	T_T (m^2/s)	T_R [2] (m^2/s)	ξ (–)	dt_1 (s)	dt_2 (s)	C (m^3/Pa)
516.00	521.00	20040614 14:25	5	PSF	WBS –> PSS	8.23E–10	1.20E–08	9.93E–09	1.66E–08		1.66E–08	9.93E–09	4.0	100	1,200	
521.00	526.00	20040614 15:55	5			3.00E–10						3.00E–10				
526.00	531.00	20040614 17:01	5			2.50E–10						2.50E–10				
531.00	536.00	20040614 17:52	5	PRF	PRF1 –> PRF2	8.30E–10	2.79E–08	2.30E–08	1.44E–08	2.80E–08	1.44E–08	1.44E–08	–2.0	40	1,200	
536.00	541.00	20040614 19:16	5			3.00E–10						3.00E–10				
541.00	546.00	20040614 20:09	5			2.50E–10						2.50E–10				
581.00	586.00	20040614 21:16	5			3.00E–10						3.00E–10				
586.00	591.00	20040614 22:09	5			2.50E–10						2.50E–10				
591.00	596.00	20040614 23:03	5	PRF	WBS –>	6.52E–10	2.02E–09	1.67E–09	1.31E–09	1.65E–09	1.31E–09	1.31E–09	–0.3	30	1,200	1.60E–11
596.00	601.00	20040615 06:26	5		WBS	3.00E–10						3.00E–10				
641.00	646.00	20040615 08:07	5	PSF	PSS	8.05E–10	9.10E–07	7.51E–07	2.40E–06		2.40E–06	7.51E–07				
646.00	651.00	20040615 09:43	5			4.00E–10						4.00E–10				
651.00	656.00	20040615 10:45	5			3.50E–10						3.50E–10				
656.00	661.00	20040615 13:08	5			3.00E–10						3.00E–10				
681.00	686.00	20040615 16:28	5			2.50E–10						2.50E–10				
686.00	691.00	20040615 17:18	5			3.00E–10						3.00E–10				
691.00	696.00	20040615 22:37	5	PRF –> NFB	WBS –> PRF –> NFB	8.20E–10	7.40E–09	6.11E–09	6.22E–09	7.34E–09	6.22E–09	6.22E–09	–0.6	70	300	5.11E–11
696.00	701.00	20040616 06:33	5			2.50E–10						2.50E–10				
721.00	726.00	20040616 07:50	5	PRF –> NFB	PRF –> NFB	8.23E–10	5.21E–09	4.30E–09	3.50E–09	5.07E–09	3.50E–09	3.50E–09	–1.6	60	200	
726.00	731.00	20040616 09:59	5			2.50E–10						2.50E–10				
731.00	736.00	20040616 10:55	5			2.50E–10						2.50E–10				
736.00	741.00	20040616 12:50	5			3.00E–10						3.00E–10				
761.00	766.00	20040616 15:09	5			3.00E–10						3.00E–10				
766.00	771.00	20040616 16:09	5			3.00E–10						3.00E–10				
771.00	776.00	20040616 17:06	5	(PRF)	WBS –> PSF?	2.97E–10	8.38E–10	6.92E–10	2.43E–10		2.43E–10	2.43E–10	–1.0	70	1,200	1.72E–11

Secup	Seclow	Test start	b	Flow regime [1]		Q/s-measl-L	Q/s	T_M	T_f	T_s	T_T	T_R [2]	ξ	dt_1	dt_2	C
(m)	(m)	YYYYMMDD hh:mm	(m)	injection	recovery	(m^2/s)	(m^2/s)	(m^2/s)	(m^2/s)	(m^2/s)	(m^2/s)	(m^2/s)	(–)	(s)	(s)	(m^3/Pa)
776.00	781.00	20040616 18:29	5	(PRF)	WBS> ?	2.61E–10	3.14E–10	2.59E–10	1.10E–10		1.10E–10	1.10E–10	–0.4	50	1,200	1.83E–11
801.00	806.00	20040616 20:02	5	PRF	WBS –> PRF	8.30E–10	4.51E–08	3.73E–08	2.82E–08	9.10E–08	2.82E–08	2.82E–08	–1.7	80	1,200	1.03E–10
806.00	811.00	20040616 21:31	5			2.50E–10						2.50E–10				
811.00	816.00	20040616 22:23	5	PRF	WBS	6.48E–10	2.27E–08	1.87E–08	5.71E–09		5.71E–09	5.71E–09	–3.4	200	1,200	1.49E–09
816.00	821.00	20040616 23:47	5			3.50E–10						3.50E–10				
941.00	946.00	20040617 07:30	5	PRF –> PLF	PSF –> PLF	8.03E–10	1.04E–06	8.56E–07	8.69E–07	1.57E–06	8.69E–07	8.69E–07	–2.2	40	500	
946.00	951.00	20040617 09:03	5	PRF	WBS	4.45E–10	9.53E–10	7.87E–10	6.28E–10	8.25E–10	6.28E–10	6.28E–10	0.5	30	600	1.91E–11
951.00	956.00	20040617 10:45	5			3.00E–10						3.00E–10				
956.00	961.00	20040618 06:27	5			3.00E–10						3.00E–10				
971.00	976.00	20040618 07:33	5			2.50E–10						2.50E–10				
976.00	981.00	20040618 08:29	5			3.00E–10						3.00E–10				
981.00	986.00	20040618 09:36	5			2.50E–10						2.50E–10				
986.00	991.00	20040618 10:47	5	PRF	PRF	8.16E–10	7.19E–07	5.94E–07	5.62E–07	5.35E–07	5.62E–07	5.62E–07	–2.1	80	1,200	
987.00	992.00	20040618 15:18	5	PRF	WBS –> PSS	6.30E–10	9.41E–09	7.76E–09	1.26E–08		1.26E–08	1.26E–08	3.4	200	1,200	

[1] The acronyms in the column "Flow regime" are as fol□
flow (PSS) and apparent no-flow boundary (NFB). The flow regime definitions are further discussed in Section 6.2.5 below

[2] For the tests were Q_p was not detected, T_R was assumed equal to the estimated Q/s-measl-L.

6.2.5 Comments on the tests

Short comments on each test follow below. Flow regimes and hydraulic boundaries re in the text referred to as:

WBS = Wellbore storage

PRF = Pseudo-radial flow regime

PLF = Pseudo-linear flow regime

PSF = Pseudo-spherical flow regime

PSS = Pseudo-stationary flow regime

NFB = No-flow boundary

As discussed in Section 5.4, the flow regimes were mainly interpreted from the log-log plots of flow rate and pressure together with the corresponding derivatives. WBS is identified as a straight line of unit slope. PRF corresponds to a visible period of a horizontal derivative. PLF may at the beginning of the tests be reflected by a straight line of slope 0.5 or less in the log-log diagrams, both for the measured variable (flow rate or pressure) and the derivative. A true PSF is reflected by a straight line with a slope of –0.5 for the derivative. However, other slopes may indicate transitions to PSF or PSS. The latter flow regime corresponds to almost stationary conditions with a derivative approaching zero. Due to the limited resolution of the flow meter and pressure sensor, the derivative may at some times erroneously indicate a horizontal line by the end of periods with PSS.

106–206 m

The injection period indicates a PLF transitioning to a PRF and a PSF by the end of the period. The recovery period indicates a PLF transitioning to a PSF. Type curve fitting with single fracture models results in an apparent fracture length of c 7 m for both periods. Type curve fits with models assuming PRF also resulted in consistent transmissivity values, although the value considered most representative is from a fit with a single fracture model on recovery data.

201–301 m

Due to a drift in the gas pressure regulator, the pressure in the test section was not constant during the injection period but decreased c 4 kPa. Still, a well-defined PRF is indicated from c 80 s and throughout the injection period. The recovery only indicates WBS and a transition period.

301–401 m

This section is of very high conductivity and, as a result, a relatively long time was required for achieving a constant head. Furthermore, it was not possible to obtain a constant head of 200 kPa due to limited flow capacity of the test system. The final constant head was only 13 kPa. Due to the large variations in the flow rate, it was not possible to identify any flow regimes during the injection period. During the recovery period, a PRF is indicated, although the small pressure change in combination with pressure sensor resolution causes the recovery derivative to be rather noisy. By the end of the recovery period a transition to PSF (leaky flow) is indicated.

401–501 m

The first attempt to perform a test in this section was interrupted due to a short power failure. The packers were kept expanded from the first to the second test attempt. The second test was performed successfully. During pressure stabilisation (before the test section was sealed off), two short pressure increases are seen in the linear overview plot. They are caused by accidental water leakage down through the pipe string (the system was still set up for injection after the power failure). The injection period indicates a PSF, as illustrated by the apparently strong skin factor obtained from the type curve fit. The recovery period indicates a PSS approaching a possible NFB by the end of the period. The type curve fit on recovery data is shown only to illustrate that an assumption of PRF is not reasonable.

501–601 m

Both the injection and the recovery period indicates a PRF. Type curve matching gives consistent results for the injection and the recovery period. The beginning of the recovery period is dominated by WBS effects.

601–701 m

Injection period indicates a PRF, although a high apparent skin factor indicates tendencies towards PSF. The recovery period is interpreted as PSS (values with negative derivative represent noise). No unique transient evaluation is possible for the recovery period.

701–801 m

A PRF flow regime is indicated for the injection period. The recovery period is dominated by WBS and a transition period.

801–901 m

The injection period indicates a PRF. The recovery period indicates only WBS followed by a transition period.

106–126 m

During the injection period, a transition from a possible PRF flow regime with a lower transmissivity to a PRF regime with higher transmissivity is indicated, although the first flow of these is not well defined. The recovery period indicates a PLF transitioning to a PSF. Type curve matching with a fracture model assuming PLF results in a fictive fracture length of c 5 m for the recovery period. Type curve matching on recovery data was also performed with a model assuming PRF. The judged best transient evaluation of transmissivity is from type curve matching on the second PRF during the injection period.

121–141 m

After an initial PLF regime, a transition to PRF is indicated from c 100 s and to PSF by the end of the injection period. Estimation of the most representative value of transmissivity was made from the injection period with a model assuming PRF. In addition, an interpretation was also made with a model assuming PLF (vertical fracture model). Type curve fitting resulted in a fictive fracture length of 5.9 m. During recovery, a short period with PLF dominated in the beginning of the recovery. From c 50 s a transition to PRF is indicated transitioning to PSF by the end of the recovery period. A model assuming PRF was used for parameter estimation. The fracture model did not give a satisfactory type curve fit using the assumed specific storativity.

141–161 m

No transient evaluation is possible since the flow rate was below the measurement limit during the injection period. The recovery period indicates only WBS. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. As a result, the transmissivity value considered most representative for this section is Q/s-measl-L. The pressure did not recover more than 4 m from the injection head of 24.65 m during the injection period.

161–181 m

Qp is considered significant despite that it is below 1 mL/min and a PRF is assumed for the injection period. The recovery period indicates only WBS. The pressure did not recover more than 13 m from a head change of 22.27 m during the injection period.

181–201 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L is considered as most representative transmissivity value for this section. The recovery period indicates only WBS. The pressure did not recover more than 2 m from the head change of 21.34 m during the injection period.

201–221 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L is considered as the most representative transmissivity value for this section. The recovery phase shows only WBS. Pressure did not recover more than 4 m from 21.09 m drawdown.

221–241 m

Despite a flow rate below 1 mL/min, the flow rate is considered significant, although no flow regime is indicated. The recovery period shows only WBS. The pressure did not recover more than 4 m from the head change of 21.65 m during the injection period.

241–261 m

There was a slight decrease in pressure during the later part of the injection period. However a PRF is indicated. The recovery period indicates only WBS with a transition period. The pressure did not recover more than 18 m from the head change of 21.43 m during the injection period.

261–281 m

Despite a flow rate below 1 mL/min, reliable measurements of Q are available and, thus, stationary and transient evaluation is possible. Although flow rate data are scattered, a PRF is indicated by the end of the injection period. The recovery period only indicates WBS and a transition period.

281–301 m

Despite a flow rate below 1 mL/min, reliable measurements of Q are available and, thus, stationary and transient evaluation is possible. Although flow rate data are scattered, a PRF is indicated by the end of the injection period. The recovery period only indicates WBS and a transition period.

301–321 m

Due to a drift in the gas pressure regulator, the pressure in the test section decreased by c 5 kPa during the injection period. As a result, the reciprocal flow rate derivative increases by the end of the injection period, giving the appearance of a NFB. Still, the injection period indicates a PRF and the recovery period indicates WBS transitioning to a possible PRF.

321–341 m

Due to a drift in the gas pressure regulator, the pressure in the test section decreased by c 4 kPa during the injection period. As a result, reciprocal flow rate was disturbed throughout the injection period. The pressure drift caused an increasing trend in the derivative that may not be representative for the rock formation. Still, with consideration taken to the pressure drift, a PRF is interpreted as the dominating flow regime during the injection period. The recovery period is dominated by WBS during the first 30 seconds. A PRF is indicated from c 80 seconds and throughout the recovery period. A transient evaluation of the recovery period is considered the most representative transmissivity value due to the pressure drift during the injection period.

341–361 m

The injection period indicates a PRF transitioning to a PSF by the end of the period. Type curve matching with a fracture model during the injection period results in a transmissivity value close to the one estimated from a model assuming PRF. The type curve fit with the fracture model results in a fictive fracture length of c 7 m. During the beginning of the recovery period, a PLF is indicated transitioning to a short possible PRF and to a PSF by the end of the recovery period. The results are consistent with those from the injection period. The type curve fit for the recovery period with a fracture model results in a fictive fracture length of c 8 m. The type curve fit on the PRF from the injection period is considered as the most representative estimate of transmissivity.

361–381 m

The injection period indicates a PRF from c 100 to c 300 s. After c 300 s, NFB effects are indicated. The recovery is almost instantaneous and rapidly transitioning to PSS.

381–401 m

Due to the very high transmissivity of this section and the limited flow capacity of the injection system, only a constant head of c 13 kPa could be maintained in the section. Thus, the test is of rather low quality. The injection period indicates an initial PSF, followed by a short period of possible PRF and another period of PSF. The recovery period indicates a transition to a possible PRF towards the end. No clear WBS effects are seen during recovery.

401–421 m

A possible PRF is indicated by the end of the injection period, although data are very scattered. WBS followed by a transition to a possible PRF is indicated during the recovery period.

421–441 m

Transient evaluation is uncertain since the flow rate was very low (below 1 mL/min) during the injection period; a PRF is assumed but not clearly indicated. The recovery period indicates only WBS. The pressure did not recover more than 13 m from a total of 22.27 m during the recovery period.

441–461 m

Unstable pressure regulation was observed during the first 160 s due to a large pressure decrease across the regulation valve. PSF/PSS is indicated for both the injection and the recovery period. No transient evaluation is possible with a model assuming PRF. The type curve fit for the injection period data is shown only to demonstrate the apparently large positive skin which implies that a PRF is not present.

461–481 m

For reasons unknown there was an unusual amount of noise in the flow registration. This results in a noisy derivative during the injection period. Nevertheless, a PRF is indicated with a possible transition into a NFB at c 700 s. Recovery is dominated by WBS during the first 10 s. A transition is indicated from c 10 s to c 200 s. followed by a PRF from c 200 s to the end of the recovery.

481–501 m

A PRF is indicated after c 100 s and throughout the injection period. During the recovery period, a transition from WBS is indicated during first c 150 s. A PRF is indicated from c150 s to the end of the recovery period.

501–521 m

Due to unstable/noisy flow during injection, the evaluation of flow regimes is uncertain. However, an intermediate period with PRF from c 150 to 400 s is weakly indicated, transitioning to PSF by the end of the injection period. The transient evaluation of transmissivity is consistent with the stationary estimation (Moye). Only a transition period from WBS is indicated during the recovery phase.

518–538 m

The injection period indicates a PRF. The recovery period indicates a PRF with a transition to a possible second PRF with slightly lower transmissivity.

521–541 m

The injection period indicates a PRF. The recovery period indicates a PRF with a transition to another PRF with slightly lower transmissivity by the end of the period.

541–561 m

This test section has a very low conductivity. Since the flow rate was below the measurement limit, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low co

561–581 m

This test section has a very low conductivity and the scattered flow rate data do not clearly indicate any flow regimes, although a PRF is assumed, transitioning to a PSF by the end of the injection period. The recovery period only indicates WBS (1:1 straight line).

581–601 m

The injection period indicated a PRF, transitioning to a PSF by the end of the period. The recovery period indicates WBS followed by a transition period. The pressure recovery was almost complete, 20 m of 21 m.

601–621 m

The test time was shortened (in accordance with the activity plan AP PF 400-04-26) since the flow rate was below Q-measl-L. Thus, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section.

621–641 m

The test time was shortened (in accordance with the activity plan AP PF 400-04-26) since the flow rate was below Q-measl-L. Thus, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section.

641–661 m

The injection period indicates a PSF or possibly a PRF flow regime by the end of the period. The recovery period indicates PSS by the end and, thus, no reliable transient evaluation of transmissivity from the recovery period is possible.

661–681 m

The test time was shortened (in accordance with the activity plan AP PF 400-04-26) since the flow rate was below Q-measl-L. Thus, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section.

681–701 m

Due to a drift in the gas pressure regulator, the pressure in the test section decreased c 5 kPa during the injection period. The flow rate was below 1 mL/min but still definable. A PRF is indicated during the first phase (after c 50 s) of the injection period, transitioning to an apparent no-flow boundary. The latter might be an effect caused by the drift in the gas regulator. The recovery period shows WBS with a transition period.

701–721 m

This test section is of very low conductivity. Since the flow rate was below the detection limit, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section.

721–741 m

Due to a drift in the gas pressure regulator, the pressure in the test section was decreasing with c 4 kPa during the injection period. With consideration taken to the pressure drift, a PRF is the dominating flow regime during the injection period. The initial 30 s during the recovery period are dominated by WBS. A transition is indicated from c 30 to 120 s when a short period of PRF is indicated. NFB is indicated at 300 s to the end of the recovery period.

741–761 m

This test section has a very low conductivity and no reliable transient evaluation is possible. The recovery period only indicates WBS.

761–781 m

Due to the low flow rate, data registration is noisy during the test. However, a PRF is considered to be the dominating flow regime during the injection period. The recovery period is dominated by WBS the first 300 s. After 300 s, a transition period is indicated.

781–801 m

This test section has a very low conductivity. Since the flow rate was below the measurement limit, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The recovery measurements only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

801–821 m

The initial phase of the injection period shows a disturbance probably related to gas in the injection system. While performing this test, the injection system showed tendencies of being more compressible than usual. After the test was finished, gas was found in the injection system which explained the high compressibility in the system. The injection period indicates a PRF and the recovery period indicates WBS with a transition period by the end of the period.

821–841 m

The flow rate was below 1 mL/min, but reliable values of Q are available and thus stationary and transient evaluation is possible. Although flow rate data are scattered, a PRF is indicated during the injection period. The recovery period only indicates WBS.

841–861 m

The test section has a very low conductivity. Since the flow rate was below the measurement limit, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed WBS.

861–881 m

The flow rate was below 1 mL/min, but reliable values of Q are available and thus stationary and transient evaluation is possible. Although flow rate data are scattered, a transition to a PRF is assumed during the injection period. The recovery period only indicates WBS.

881–901 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered most representative transmissivity value for this section.

901–921 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

921–941 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

941–961 m

The pressure in the section below the test section was affected significantly during the injection. The pressure in the section below increased by c 40 kPa during the injection period. The injection period indicates a well-defined PRF. The recovery period indicates an early PRF of short duration transitioning to another PRF by the end of the recovery period.

961–981 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

971–991 m

The pressure in the section below the test section was affected significantly during the injection. The pressure in the section below increased by c 60 kPa during the injection period. The injection period and the recovery period both indicate a well-defined PRF. This test shows a strong resemblance with the test in section 941–961 m, indicating the possibility of a hydraulic connection between the two intervals.

104–109 m

Although the data are scattered, a PRF is assumed during the main part of the injection period. By the end of the injection period, the automatic control system was switched off and, as a result, the flow rate and the injection pressure decreased. This resulted in a flow rate decrease which might be mistaken for an apparent NFB by the end of the injection period. The recovery period indicates WBS followed by a transition period, possibly to a PSF.

106–111 m

The injection period indicates a PRF. The recovery period indicates WBS of short duration followed by a transition period, possibly to a PSF by the end of the recovery period.

111–116 m

Due to a drift in the gas pressure regulator, the pressure in the test section decreased by c 7 kPa during the injection period. This resulted in a flow rate decrease which might be mistaken for an apparent NFB by the end of the injection period. Still, a PRF is indicated at intermediate time during the injection period, but it may also be interpreted as a transition from PSF to the increasing derivative by the end of the injection period. The initial recovery period is dominated by WBS transitioning to PSS. No unique transient evaluation can be made for the recovery period.

116–121 m

Both the injection period and the recovery period indicate a PSF transitioning to PSS. No unique and reliable transient evaluation is possible. Type curve matching with models assuming PRF results in an apparent high positive skin factor.

121–126 m

The injection period indicates a PRF transitioning to a PSF. The recovery period indicates a PLF transitioning to a PSF by the end of the period. A possible short PRF is indicated between the PLF and the PSF during the recovery period.

126–131 m

The injection period indicates a PRF followed by NFB effects by the end. The recovery period indicates a PRF transitioning to a PSF.

131–136 m

The injection period indicates an intermediate regime between PRF and PSF, i.e. slightly PSF. A type curve fit with a model assuming PRF results in reasonable estimates of transmissivity and skin factor. On the other hand, the reciprocal flow rate derivative has a slope of c –0.5, thus indicating PSF. The recovery period indicates WBS transitioning to PSF.

136–141 m

Due to a drift in the gas pressure regulator, the pressure in the test section decreased c 3 kPa during the first minutes of the injection period. Both the injection and the recovery period indicate a PLF in the beginning of the periods. During the injection period a possible PRF was indicated transitioning to a PSF. The head did not recover more than 18 m of 23 m during the recovery period.

161–166 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase indicating that the section is of such low conductivity that packer expansion effects still were affecting the section.

166–171 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

171–176 m

The injection period indicates a PRF. The recovery period indicates WBS transitioning to near PRF.

176–181 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

241–246 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

246–251 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

251–256 m

Although the injection period data are scattered, a PRF is indicated. The recovery period is dominated by WBS effects and a transition period.

256–261 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

261–266 m

There was a detectable final flow of c 0.5 mL/min. No unique transient evaluation of the recovery period was possible. WBS is dominating throughout the recovery period.

266–271 m

Although injection period data are scattered, a PRF period is weakly indicated. WBS transitioning to PRF is indicated during the recovery period.

271–276 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered the most representative transmissivity value for this section.

276–281 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered the most representative transmissivity value for this section.

281–286 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered most representative transmissivity value for this section.

286–291 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered most representative transmissivity value for this section.

291–296 m

A PRF is weakly indicated during the injection period, although this interpretation is uncertain due to noisy flow rate data. The recovery period is dominated by WBS with a transition indicated after 100 s. No unique transient evaluation is possible for the recovery period.

296–301 m

Due to a drift in the gas pressure regulator, the pressure in the test section decreased by c 2 kPa during the injection period. The injection period indicates a PLF. Type curve matching by a model assuming a single fracture on the early phase of the injection period results in a fictive fracture length of c 11 m. The interpretation of a fracture response is also supported by the negative skin factor estimated from the type curve match on later data with a model assuming PRF. The recovery data and derivative do not show an exact slope of neither 1 nor 0.5. The actual slope is somewhere in between, although closer to 1. The recovery data are interpreted as WBS effects.

301–306 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

306–311 m

The section has a very low conductivity. Still, the flow rate was definable throughout the injection period. Due to the low conductivity and thus low flow rate, the reciprocal flow rate data and derivative are very scattered. For the injection period, a near-PRF is assumed. For the recovery period, only WBS effects are seen.

311–316 m

Due to a drift in the gas pressure regulator, the injection pressure decreased c 5 kPa during the injection period. Nevertheless, a well-defined PRF is indicated during both the injection and the recovery period.

316–321 m

The injection period indicates a PRF. The recovery period is dominated by WBS effects and a transition period to a possible PSF. The type curve fit of recovery data is shown only to illustrate that an assumption of PRF results in an apparent strong positive skin, thus indicating that the assumption of PRF is not justified.

321–326 m

The section has a low conductivity and as a result, flow rate data and derivative are very scattered. During the injection period, a PRF transitioning to a PSF is assumed. During the recovery period, only WBS effects and a transition period to a possible PSF are seen. The type curve fit on recovery data is only to illustrate that an assumption of PRF results in an apparent strong positive skin, thus indicating that the assumption of PRF is not justifiable.

326–331 m

Due to a drift in the gas pressure regulator, the pressure in the test section decreased c 3 kPa during the first minutes of the injection period. The injection period indicated an early PRF followed by apparent no-flow boundary effects. The recovery indicates WBS with a transition period followed by a weakly indicated apparent no-flow boundary by the end. The head recovery was almost complete.

331–336 m

Due to a drift in the gas regulator, the pressure in the section decreased c 2.5 kPa during the test. The injection phase indicates a PRF, and the recovery period indicates WBS transitioning to a PRF. The head recovery was almost complete.

336–341 m

The section has a low conductivity and no reliable transient evaluation is possible. The recovery period only indicates WBS.

341–346 m

The test time was shortened, in accordance with the activity plan AP PF 400-04-08 since the flow rate was not detectable. Thus, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section.

346–351 m

The test time was shortened, in accordance with the activity plan AP PF 400-04-08 since the flow rate was not detectable. Thus, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section.

348–353 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

351–356 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed WBS effects.

356–361 m

The injection period indicates a possible early PLF of short duration, transitioning to a PRF followed by a PSF. The recovery period indicates an early PLF, transitioning to a short PRF regime and to a PSF by the end of the recovery period.

361–366 m

The injection pump capacity oscillated during the test which highly affected the test performance. Both the flow rate and the injection pressure were oscillating throughout the injection period. Still, the injection period indicates a PRF followed by indications of an apparent NFB by the end of the period. The recovery was almost instant, and quickly approached PSS.

366–371 m

By the end of the injection period, the automatic control system performed an unfortunate change from the larger to the smaller flow meter. This resulted in an apparent increase of the flow rate, probably because the larger flow meter was not perfectly calibrated for these relatively low flow rates. (The change from the larger to the smaller flow meter was made because the flow rate fell below a critical level where the accuracy of the larger flow meter decreases.) Still, the injection period indicates a PRF followed by a transition to an apparent NFB at c 400 s. The recovery is almost instant and only indicates PSS.

371–376 m

The injection period indicates a PRF transitioning to an apparent NFB or PLF. The recovery is instant and only indicates PSS.

376–381 m

The injection period indicates a PRF (or possibly PSF). The recovery period indicates WBS transitioning to PSS.

381–386 m

The injection period indicates a PRF (possibly transitioning to a PSF by the end of the injection period). The recovery period indicates a PSF transitioning to PSS.

386–391 m

The section has a very high conductivity and as a result, the time required for achieving a constant head was long. Furthermore, it was not possible to obtain a constant head of 200 kPa. Instead the head was c 12 kPa. Although the data were very scattered during the injection period, a possible PRF is indicated. During the early phase of the recovery period, a PLF is indicated transitioning to a PRF and a PSF by the end. The recovery was also evaluated using a single-fracture model.

391–396 m

A PSF (or possibly PSS) is indicated during both the injection and the recovery period.

396–401 m

A PRF is indicated during the injection period. The recovery period only indicates WBS.

401–406 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

406–411 m

Although the data are scattered, a PRF is indicated during the injection period. The recovery period indicates WBS in the beginning, transitioning to a PRF.

411–416 m

Although the data are scattered, a PRF is indicated during the injection period. The recovery period indicates WBS transitioning to a PRF.

416–421 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed WBS effects.

441–446 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

446–451 m

The test section has a low conductivity and, as a result, flow rate data and derivative are very scattered. The injection period weakly indicates a PSF (implied also by the apparently strong skin factor resulting from a type curve match with a model assuming PRF). The recovery period indicates WBS transitioning to a PSF.

451–456 m

A PRF (or possibly PSF) is indicated during the injection period. This interpretation is supported by a relatively high skin factor with a model assuming PRF. The recovery period is, after a fast recovery during the first few seconds, dominated by PSS up to c 100 s. A transition to a flow regime with a lower flow dimension (e.g. NFB) is indicated after 100 s to the end of the recovery period. No unique transient evaluation is possible for the recovery period.

456–461 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. In accordance with AP PF 400-04-26, the injection time was shortened since the flow rate was not detectable. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. Pressure was increasing in test section during the recovery period.

461–466 m

An oscillating derivative was observed during the injection period due to scattered flow data. A PRF is indicated from 80 to 600 s or longer during the injection period. After WBS during the early recovery period, a short period of PSF is indicated, transitioning to a flow regime of lower flow dimension, e.g. PLF.

466–471 m

The injection was interrupted after c 11 min due to zero flow. A valve on the pipe string was briefly opened which caused an abrupt drop in injection pressure c 4 min into the injection period. Since the flow rate was not definable, this has no effect on test evaluation. Neither stationary nor transient evaluation was possible.

471–476 m

The injection was interrupted after c 6 min due to zero flow. The entire recovery period was dominated by WBS.

476–481 m

The injection was interrupted after c 6 min due to zero flow. Neither stationary nor transient evaluation is possible.

481–486 m

The injection was interrupted after c 7 min due to zero flow. The pressure increased in the test section during recovery period. Neither stationary nor transient evaluation is possible.

486–491 m

The injection was interrupted after c 6 min due to zero flow. The pressure increased in the test section during therecovery period. Neither stationary nor transient evaluation is possible.

491–496 m

The injection was interrupted after c 5 min due to zero flow. The pressure increased in the test section during the recovery period. Neither stationary nor transient evaluation is possible.

496–501 m

A well-defined PRF is indicated during both the injection and the recovery period. The transmissivity considered as the most representative value is based on transient evaluation of the recovery period. This is supported by a good type curve fit and a well-defined PRF.

501–506 m

The injection was interrupted after c 4 min due to zero flow. The pressure increased in the test section during the recovery period. Neither stationary nor transient evaluation is possible.

506–511 m

The injection was interrupted after c 6 min due to zero flow. The pressure increased in the test section during the recovery period. Neither stationary nor transient evaluation is possible.

511–516 m

The initial injection period indicates a transition to a PRF. After c 400 s, a transition to a PSF is weakly indicated. The initial phase of the recovery period is dominated by WBS, followed by a transition to near PRF.

516–521 m

During the injection period, PSF is indicated. During the recovery period, WBS transitioning to PSS is indicated. Thus, T_M is considered the most representative transmissivity value for the section. An approximative transient evaluation was also made for the injection period.

521–526 m

The test time was shortened, in accordance with the activity plan AP PF 400-04-08 since the flow rate was not detectable. Hence, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L is considered the most representative transmissivity value for this section.

526–531 m

The test time was shortened, in accordance with the activity plan AP PF 400-04-08 since the flow rate was not detectable. Since no flow rate was detectable, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L is considered most representative transmissivity value for this section.

531–536 m

A well-defined PRF is indicated during the injection period. Transition from an early PRF to a late PRF is indicated during the recovery period.

536–541 m

The test time was shortened in accordance with the activity plan AP PF 400-04-08 since the flow rate was not detectable. Hence, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L is considered most representative transmissivity value for this section.

541–546 m

The test time was shortened in accordance with the activity plan AP PF 400-04-08 since the flow rate was not detectable. Hence, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L is considered most representative transmissivity value for this section.

581–586 m

The test time was shortened in accordance with the activity plan AP PF 400-04-08 since the flow rate was not detectable. Hence, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L is considered most representative transmissivity value for this section.

586–591 m

The test time was shortened in accordance with the activity plan AP PF 400-04-08 since the flow rate was not detectable. Hence, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L is considered most representative transmissivity value for this section.

591–596 m

A well-defined PRF is indicated during the injection phase. A short WBS followed by a transition is indicated during the recovery period.

596–601 m

The test time was shortened in accordance with the activity plan AP PF 400-04-08 since the flow rate was not detectable. Hence, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L is considered most representative transmissivity value for this section.

641–646 m

The injection period indicates a PSF. The recovery period only indicates a PSS.

646–651 m

The test time was shortened in accordance with the activity plan AP PF 400-04-08 since the flow rate was not detectable. Hence, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L is considered most representative transmissivity value for this section.

651–656 m

The test time was shortened in accordance with the activity plan AP PF 400-04-08 since the flow rate was not detectable. Hence, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L is considered most representative transmissivity value for this section.

656–661 m

The test time was shortened in accordance with the activity plan AP PF 400-04-08 since the flow rate was not detectable. Hence, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L is considered most representative transmissivity value for this section.

681–686 m

This test section has a very low conductivity. The pressure in the test section increased c 400 kPa during the pressure stabilisation before start of injection. Due to the very high pressure increase, no injection was performed to avoid an excessively high relative pressure difference across packers. Because of the above mentiond reasons, Q/s-measl-L is considered the most representative transmissivity value for this section.

686–691 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

691–696 m

Both the injection and the recovery period indicate a PRF transitioning to an apparent NFB.

696–701 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

721–726 m

Both the injection and the recovery period indicate a PRF transitioning to an apparent NFB.

726–731 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

731–736 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

736–741 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

761–766 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

766–771 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

771–776 m

The section has a low conductivity. Still, the flow rate was definable throughout the injection period. Due to the low conductivity and thus low flow rate, the reciprocal flow rate data and derivative are very scattered. For the injection period, a PRF is weakly indicated. The recovery period indicates WBS transitioning to possible PSF. No unique transient evaluation is possible on the recovery period.

776–781 m

The section has a low conductivity. Still, the flow rate was definable throughout the injection period. Due to the low conductivity and thus low flow rate, the reciprocal flow rate data and derivative are very scattered. For the injection period, a PRF is assumed but not clearly indicated. For the recovery period, only WBS effects and a transition period are seen.

801–806 m

The injection period indicates a well-defined PRF. The initial recovery period indicates WBS transitioning to a possible PRF. By the end of the recovery period, only slight effects of an apparent NFB are indicated. Type curve fitting on later recovery data, (where a PRF or possibly a PSF is indicated) with a model assuming PRF, results in an apparently high positive skin factor which implies that an assumption of PRF may not be valid.

806–811 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

811–816 m

PRF is dominating during the injection period. A negative skin factor and an inferior type curve fit may suggest a flow regime of lower dimension. WBS is dominating throughout the recovery period. No unique transient evaluation can be made for the recovery period.

816–821 m

The injection was interrupted after c 3 min due to zero flow. Neither stationary nor transient evaluation is possible.

941–946 m

A pressure increase of c 40 kPa in the section below the test section during the injection period indicates a hydraulic connection across the lower packer. A PRF is indicated during the first 500 s of the injection period, followed by a transition to a flow regime of lower dimension, e.g. apparent NFB or PLF. During the first phase of the recovery period, PSF occurs, transitioning to a flow regime of lower dimension, e.g. apparent NFB or PLF.

946–951 m

Although flow data are scattered with a noisy derivative, PRF is indicated during the injection period. WBS is dominating the recovery period, making an evaluation of this period difficult.

951–956 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

956–961 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

971–976 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

976–981 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

981–986 m

The test section has a very low conductivity. Since the flow rate was not detectable, neither steady-state nor transient evaluation of transmissivity was possible. Hence, in accordance with AP PF 400-04-26, the injection time was shortened. As a result, Q/s-measl-L was considered to be the most representative transmissivity value for this section. The period of measured recovery only showed a pressure increase, indicating that the section is of such low conductivity that packer expansion affects the pressure throughout the period.

986–991 m

Both the injection and the recovery period indicates a well-defined PRF. During the injection period, the pressure increased by c 100 kPa in the section below the test section, indicating a good hydraulic connection between the two sections.

987–992 m

Although the data are scattered, a PRF is indicated during the injection period. The recovery period only indicates WBS and a transition to PSS. The instant recovery might be a result of a hydraulic short-cut around the upper packer caused by to the fracture intersecting the borehole at c 986.2 m

6.2.6 Flow regimes

As discussed in the Section 6.2.5, several recovery periods were dominated by wellbore storage effects and no pseudo-radial flow period was reached. On the other hand, some time interval of pseudo-radial flow could in most cases be identified from the injection period. A summary of the frequency of identified flow regimes on different scales is presented in Table 6-4, which shows all identified flow regimes. I.e. if a certain flow period indicates a pseudo-radial flow regime transitioning to a pseudo-spherical flow regime, this flow period contributes to one observation of pseudo-radial and one observation of pseudo-spherical flow. The numbers within parenthesis denote the number of tests where the actual flow regime is the only one present.

It should be noted that the interpretation of flow regimes is only tentative and based on visual inspection of the data curves. The number of tests with a pseudo-linear flow regime may be underestimated for the injection period due to the fact that a certain time is required for achieving constant pressure in the beginning of the test.

Table 6-4. Interpreted flow regimes during the injection tests in KFM03A.

Section length (m)	Number of tests	Number of tests with definable Q_p	Injection period					Recovery period					
			PLF	PRF	PSF	PSS	NFB	WBS	PLF	PRF	PSF	PSS	NFB
5	103	52	4 (1)	43 (26)	13 (2)	2 (0)	7 (0)	33 (14)	6 (1)	17 (3)	16 (0)	12 (4)	4 (0)
20	46	33	3 (1)	29 (17)	8 (1)	0 (0)	3 (0)	23 (18)	4 (0)	13 (3)	4 (0)	3 (3)	0 (0)
100	8	8	1 (0)	6 (5)	3 (1)	0 (0)	0 (0)	4 (3)	1 (0)	2 (0)	2 (0)	2 (1)	1 (0)

Table 6-4 shows that a period of pseudo-radial flow could be identified from the injection period in at least 80% of the tests with a definable final flow rate. For the recovery period, the corresponding result is only c 32%

For almost half of the tests, more than one flow regime could be identified. The most common transitions were from pseudo-radial to pseudo-spherical flow during the injection period and from wellbore storage to pseudo-radial flow during the recovery period.

Another observation is that the number of tests with a pseudo-stationary flow regime was significantly higher for the recovery period of the tests. The reason for this is not clear.

6.3 Transmissivity values on different scales

The transmissivity values considered the most representative, T_R, from the injection tests in the tested sections of 100 m, 20 m and 5 m length, respectively, are shown in Figure 6-2. This figure demonstrates a good agreement between results obtained from tests on different scales. A consistency check of the transmissivity values on the different scales was made by summation of calculated values from smaller scales (20 m and 5 m) and comparing with the estimated values in longer sections (100 m and 20 m).

In Table 6-5, estimated transmissivity values in 100 m and 20 m test sections according to steady-state (T_M) and most representative evaluation (T_R) are listed together with summed transmissivities in 20 m and 5 m sections over the corresponding 100 m and 20 m sections. In addition, the corresponding sum of transmissivities from the difference flow logging in 5 m sections (SUM T_D) is displayed for each section.

In Table 6-5, all transmissivity values considered the most representative (T_R) below the measurement limit (Q_p could not be defined) have been assigned the estimated lower measurement value of Q/s according to Q/s-measl-L in Section 5.4. Furthermore, in Table 6-5, all values of transmissivity from the steady-state evaluation (T_M) below the measurement limit (Q_p could not be defined) have been assigned the estimated lower measurement value (Q/s-measl-L) for the specific test. The measurement limit values are included in the summed values in Table 6-5. This leads to overestimated values of the summed transmissivities. This is particularly true for the summed transmissivities from the difference flow logging in 5 m sections, due to the increased lower measurement limit for these tests, see /1/.

In Figure 6-3, transmissivity values considered as the most representative for 100 m and 20 m sections (T_R–100 m and T_R–20 m, respectively) are plotted versus the sum of the transmissivity values considered the most representative in 5 m sections in the corresponding intervals (SUM T_R–5 m). The lower measurement limit of T_M for the different section lengths (Q_p = 1 mL/min and an assumed pressure difference of 200 kPa) together with the cumulative measurement limit for the sum of 5 m sections are also shown in the figure.

Figure 6-3 indicates a good agreement between measured transmissivity values in longer sections and summed transmissivity values in corresponding 5 m sections for the injection tests. The deviation towards the lower limit is caused by the fact that values at the measurement limit (Q/s-measl-L) are accumulated in the summation process which most likely results in overestimated values of SUM T_R–5 m.

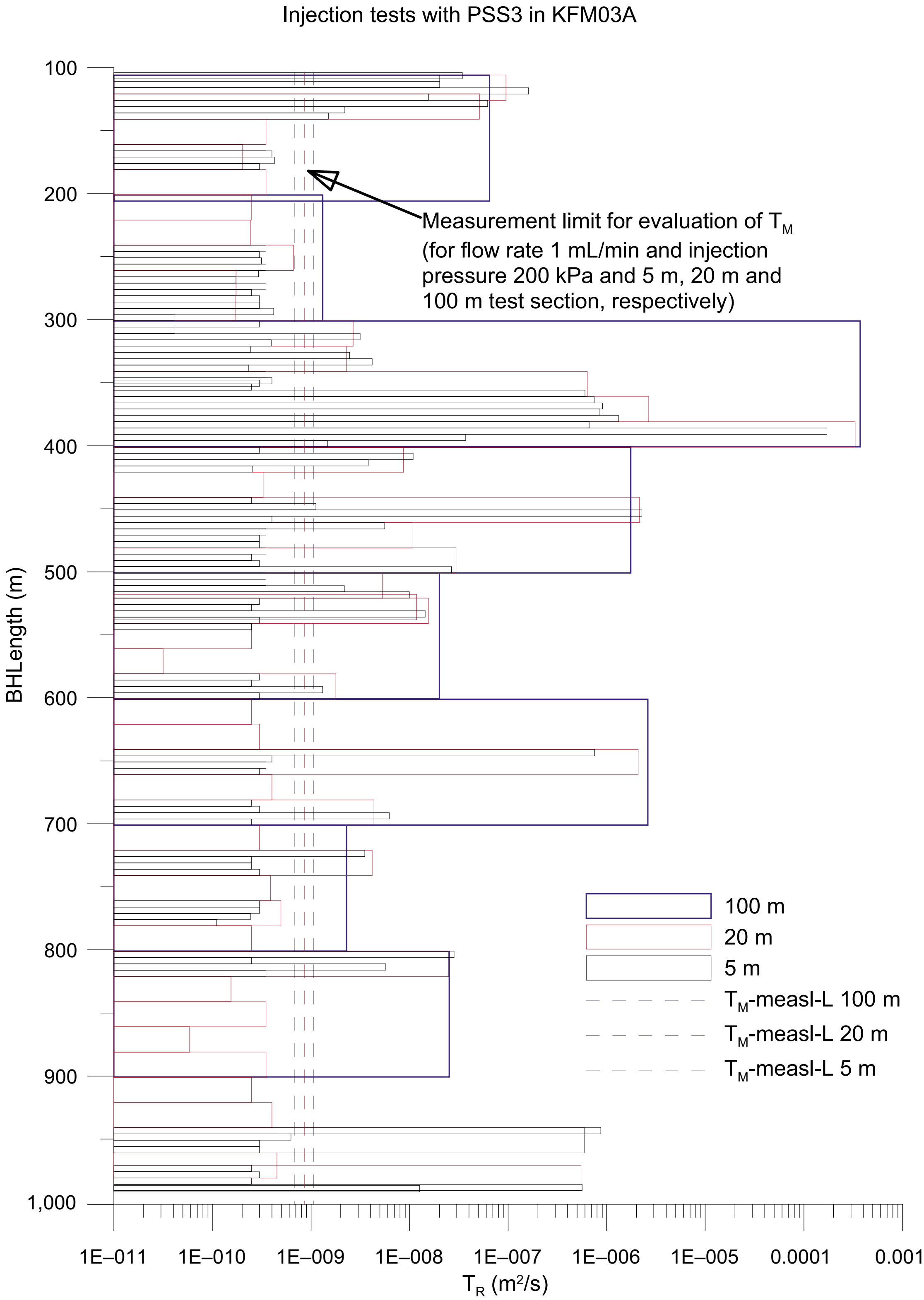

Figure 6-2. *Estimated best representative transmissivity values (T_R) for sections of 100 m, 20 m and 5 m length in borehole KFM03A. Estimated transmissivity values for the lower measurement limit from stationary evaluation (T_M-measl-L) (flow rate 1.7×10^{-8} m³/s and injection pressure 200 kPa) for different test section lengths are also shown.*

Table 6-5. Estimated transmissivity values in 100 m and 20 m test sections together with summed up transmissivity values in 20 m and 5 m sections in the corresponding borehole intervals from the injection tests in KFM03A. In addition, the corresponding sum of transmissivity values from the difference flow logging in 5 m sections is shown.

Borehole idcode	Secup inj test (m)	Seclow inj test (m)	L_w (m)	T_M inj tests (m^2/ s)	T_R inj tests (m^2/s)	SUM T_M (20 m) inj tests (m^2/s)	SUM T_R (20 m) inj tests (m^2/s)	SUM T_M (5 m) inj tests (m^2/s)	SUM T_R (5 m) inj tests (m^2/s)	Secup diff-flow log (m)	Seclow diff-flow log (m)	SUM-T_D (5 m) diff-flow log (m^2/s)
KFM03A	106.00	206.00	100	2.59E–07	6.49E–08	2.61E–07	1.47E–07	n m 5 m	n m 5 m	105.82	205.85	8.60E–07
KFM03A	201.00	301.00	100	4.95E–09	1.31E–09	3.95E–09	1.49E–09	n m 5 m	n m 5 m	200.85	300.88	8.09E–07
KFM03A	301.00	401.00	100	5.52E–04	3.72E–04	4.15E–04	3.35E–04	3.50E–04	1.76E–04	300.88	400.97	1.78E–04
KFM03A	401.00	501.00	100	1.75E–06	1.75E–06	2.21E–06	2.20E–06	n m 5 m	n m 5 m	400.97	500.98	6.71E–06
KFM03A	501.00	601.00	100	4.44E–08	2.00E–08	6.56E–08	3.47E–08	n m 5 m	n m 5 m	500.98	601.10	5.56E–08
KFM03A	601.00	701.00	100	1.37E–06	2.61E–06	1.09E–06	2.09E–06	n m 5 m	n m 5 m	601.10	701.19	2.63E–06
KFM03A	701.00	801.00	100	7.19E–09	2.29E–09	7.43E–09	5.61E–09	n m 5 m	n m 5 m	701.21	801.39	1.12E–07
KFM03A	801.00	901.00	100	6.88E–08	2.52E–08	6.60E–08	2.58E–08	n m 5 m	n m 5 m	801.40	901.57	1.39E–07
KFM03A	106.00	126.00	20	1.16E–07	9.50E–08			2.58E–07	2.17E–07	105.82	125.82	1.49E–07
KFM03A	121.00	141.00	20	1.43E–07	5.10E–08			1.62E–07	8.13E–08	120.82	140.82	2.09E–07
KFM03A	141.00	161.00	20		3.50E–10			n m 5 m	n m 5 m	140.83	160.84	1.65E–07
KFM03A	161.00	181.00	20	8.22E–10	2.02E–10			1.75E–09	1.48E–09	160.84	180.85	1.65E–07
KFM03A	181.00	201.00	20		3.50E–10			n m 5 m	n m 5 m	180.85	200.85	1.63E–07
KFM03A	201.00	221.00	20	2.48E–10	2.48E–10			n m 5 m	n m 5 m	200.85	220.86	1.63E–07
KFM03A	221.00	241.00	20	2.42E–10	2.42E–10			n m 5 m	n m 5 m	220.86	240.88	1.63E–07
KFM03A	241.00	261.00	20	1.86E–09	6.62E–10			1.86E–09	1.31E–09	240.88	260.90	1.62E–07
KFM03A	261.00	281.00	20	7.83E–10	1.73E–10			1.41E–09	1.07E–09	260.90	280.89	1.61E–07
KFM03A	281.00	301.00	20	8.19E–10	1.70E–10			1.57E–09	1.06E–09	280.89	300.88	1.61E–07
KFM03A	301.00	321.00	20	6.16E–09	2.67E–09			6.15E–09	3.89E–09	300.88	320.89	1.61E–07
KFM03A	321.00	341.00	20	4.83E–09	2.29E–09			8.29E–09	7.10E–09	320.89	340.90	1.62E–07
KFM03A	341.00	361.00	20	1.19E–06	6.35E–07			9.32E–07	6.01E–07	340.91	360.93	1.56E–06
KFM03A	361.00	381.00	20	2.18E–06	2.66E–06			2.16E–06	3.82E–06	360.93	380.95	5.59E–06
KFM03A	381.00	401.00	20	4.11E–04	3.32E–04			3.47E–04	1.72E–04	380.96	400.97	1.70E–04

Borehole idcode	Secup inj test (m)	Seclow inj test (m)	L_w (m)	T_M inj tests (m^2/ s)	T_R inj tests (m^2/s)	SUM T_M (20 m) inj tests (m^2/s)	SUM T_R (20 m) inj tests (m^2/s)	SUM T_M (5 m) inj tests (m^2/s)	SUM T_R (5 m) inj tests (m^2/s)	Secup diff-flow log (m)	Seclow diff-flow log (m)	SUM-T_D (5 m) diff-flow log (m^2/s)
KFM03A	401.00	421.00	20	8.15E–09	8.67E–09			1.79E–08	1.52E–08	400.97	420.97	2.16E–08
KFM03A	421.00	441.00	20	3.27E–10	3.27E–10			n m 5 m	n m 5 m	420.98	440.98	5.17E–09
KFM03A	441.00	461.00	20	2.15E–06	2.15E–06			2.28E–06	2.28E–06	440.98	460.97	6.65E–06
KFM03A	461.00	481.00	20	9.18E–09	1.08E–08			1.08E–08	6.54E–09	460.97	480.98	1.08E–08
KFM03A	481.00	501.00	20	3.84E–08	2.95E–08			3.24E–08	2.75E–08	480.98	500.98	2.10E–08
KFM03A	501.00	521.00	20	8.57E–09	5.31E–09			1.31E–08	1.28E–08	500.98	520.99	1.41E–08
KFM03A	518.00	538.00	20	2.70E–08	1.18E–08			n m 5 m	n m 5 m			
KFM03A	521.00	541.00	20	2.73E–08	1.55E–08			2.39E–08	1.52E–08	521.00	541.03	2.64E–08
KFM03A	541.00	561.00	20		2.50E–10			n m 5 m	n m 5 m	541.04	561.07	5.05E–09
KFM03A	561.00	581.00	20	2.97E–10	3.15E–11			n m 5 m	n m 5 m	561.08	581.10	5.06E–09
KFM03A	581.00	601.00	20	2.42E–09	1.78E–09			2.52E–09	2.16E–09	581.10	601.10	5.06E–09
KFM03A	601.00	621.00	20		2.50E–10			n m 5 m	n m 5 m	601.10	621.11	5.06E–09
KFM03A	621.00	641.00	20		3.00E–10			n m 5 m	n m 5 m	621.11	641.12	5.04E–09
KFM03A	641.00	661.00	20	1.09E–06	2.09E–06			7.52E–07	7.52E–07	641.13	661.14	2.57E–06
KFM03A	661.00	681.00	20		4.00E–10			n m 5 m	n m 5 m	661.15	681.16	2.20E–08
KFM03A	681.00	701.00	20	4.80E–09	4.33E–09			6.91E–09	7.02E–09	681.17	701.19	2.22E–08
KFM03A	701.00	721.00	20		3.00E–10			n m 5 m	n m 5 m	701.21	721.26	2.23E–08
KFM03A	721.00	741.00	20	5.30E–09	4.18E–09			5.10E–09	4.30E–09	721.27	741.30	2.23E–08
KFM03A	741.00	761.00	20	3.89E–10	3.89E–10			n m 5 m	n m 5 m	741.31	761.33	2.23E–08
KFM03A	761.00	781.00	20	1.19E–09	4.94E–10			1.55E–09	9.53E–10	761.34	781.36	2.25E–08
KFM03A	781.00	801.00	20		2.50E–10			n m 5 m	n m 5 m	781.37	801.39	2.23E–08
KFM03A	801.00	821.00	20	6.43E–08	2.49E–08			5.66E–08	3.45E–08	801.40	821.42	4.94E–08
KFM03A	821.00	841.00	20	4.86E–10	1.54E–10			n m 5 m	n m 5 m	821.43	841.46	2.23E–08
KFM03A	841.00	861.00	20		3.50E–10			n m 5 m	n m 5 m	841.47	861.50	2.24E–08
KFM03A	861.00	881.00	20	5.55E–10	5.85E–11			n m 5 m	n m 5 m	861.51	881.54	2.24E–08
KFM03A	881.00	901.00	20		3.50E–10			n m 5 m	n m 5 m	881.55	901.57	2.24E–08

Borehole	Secup	Seclow	L_w	T_M	T_R	SUM T_M (20 m)	SUM T_R (20 m)	SUM T_M (5 m)	SUM T_R (5 m)	Secup	Seclow	SUM-T_D (5 m)
	inj test	inj test		inj tests	inj tests	inj tests	inj tests	inj tests	inj tests	diff-flow log	diff-flow log	diff-flow log
idcode	(m)	(m)	(m)	(m^2/ s)	(m^2/s)	(m^2/s)	(m^2/s)	(m^2/s)	(m^2/s)	(m)	(m)	(m^2/s)
KFM03A	901.00	921.00	20		2.50E–10			n m 5 m	n m 5 m	901.57	921.57	2.23E–08
KFM03A	921.00	941.00	20		4.00E–10			n m 5 m	n m 5 m	921.57	941.58	2.23E–08
KFM03A	941.00	961.00	20	1.01E–06	5.91E–07			8.58E–07	8.70E–07	941.59	961.60	3.96E–07
KFM03A	961.00	981.00	20		4.50E–10			n m 5 m	n m 5 m	961.60	981.61	2.23E–08
KFM03A	971.00	991.00	20	7.85E–07	5.50E–07			5.95E–07	5.63E–07	971.61	991.62	2.40E–07

[1] partly overlapping sections
n m = not measured

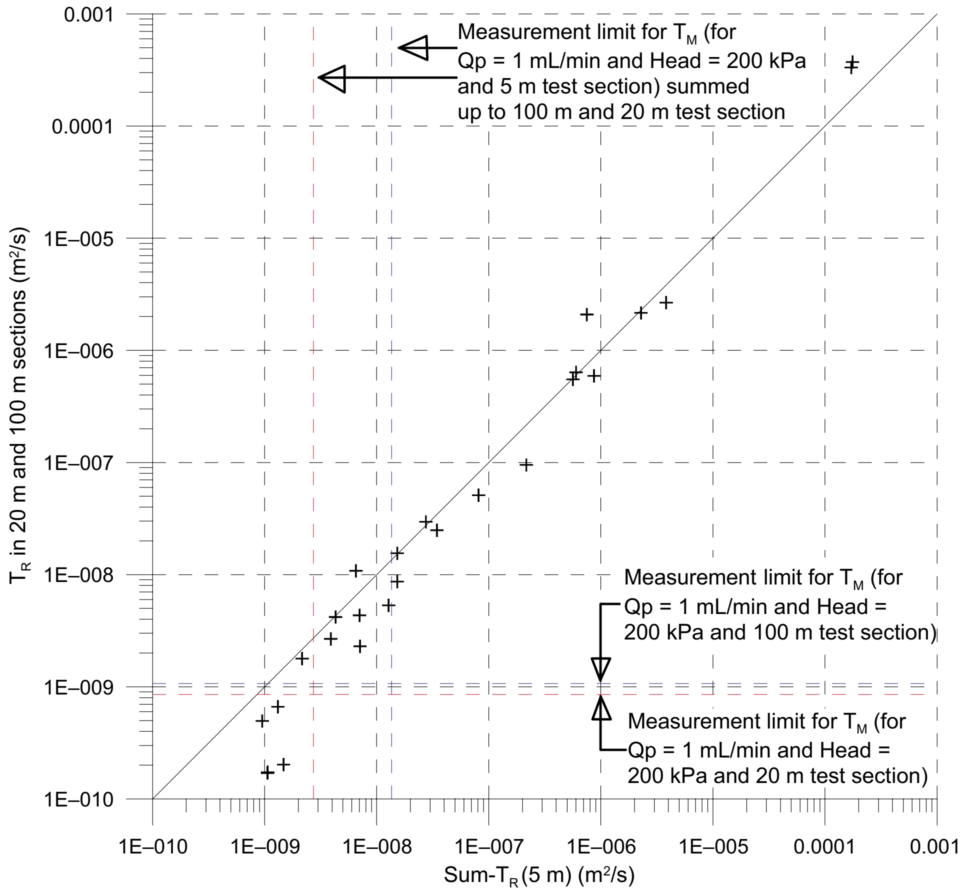

Figure 6-3. *Transmissivity values considered most representative (T_R) for 100 m and 20 m sections versus the sum of most representative transmissivity values (T_R) in 5 m sections in the corresponding borehole intervals from the injection tests in KFM03A.*

6.4 Comparison with results from the difference flow logging

In Figure 6-4, a direct comparison is made of calculated steady-state (T_M) and most representative transmissivity values (T_R) from the injection tests in 5 m sections with the calculated transmissivity values in the corresponding 5 m sections from the previously performed sequential difference flow logging in KFM03A /1/. The difference flow logging was performed at a drawdown of c 7 m and 2.3 m in the borehole (at pumping rates of c 108 L/min and 29 L/min, respectively). The presented measurement limit for the difference flow logging is the practical lower measurement limit (varying along the borehole) /1/. In the summation of the transmissivities from the 5 m sections, the estimated values on the lower (practical) measurement limit are included.

Figure 6-4 indicates good agreement between the estimated transmissivity values from the injection tests and the difference flow logging, respectively. It should, however, be noted that the two methods differ regarding assumptions and associated uncertainties. Potential uncertainties for difference flow logging results are discussed in /9/ and for injection tests in /10/.

Three ranges of the lower limits for transmissivity values were estimated for the difference flow logging in KFM03A, approximately at 4.1×10^{-8} m²/s, 5.6×10^{-9} m²/s and 1.3×10^{-9} m²/s.

These limits are significantly higher than the corresponding measurement limits for the injection tests in KFM03A. This is clearly seen in Figure 6-4 as a difference between T_D, T_M, and T_R respectively, particularly for low transmissivity values. Divergences between injection tests and difference flow logging may also result from small differences in the positions of the test sections in the borehole. In sections 381–386 m and 391–396 m the injection tests indicated much higher conductivity, than the difference flow logging. The section in-between (386–391 m) indicated a high conductivity which may explain the difference between the two measurement methods for the surrounding sections.

In Figure 6-5, a comparison is made of estimated steady-state transmissivity values from the injection tests in 100 m and 20 m test sections with summed transmissivity values for 5 m sections from the difference flow logging (SUM T_D(5 m)) in the corresponding intervals in borehole KFM03A. The latter sums are shown in Table 6-5. Figure 6-5 may be compared with Figure 6-3 only for the injection tests.

Figure 6-5 shows that the estimated transmissivity values from the injection tests in 100 m and 20 m sections are distributed over a much wider range than the sum of transmissivity values from the difference flow logging. This is partly a result of the lower measurement limit being included in the sum for the difference flow logging. These results are consistent with the results in Figure 6-4.

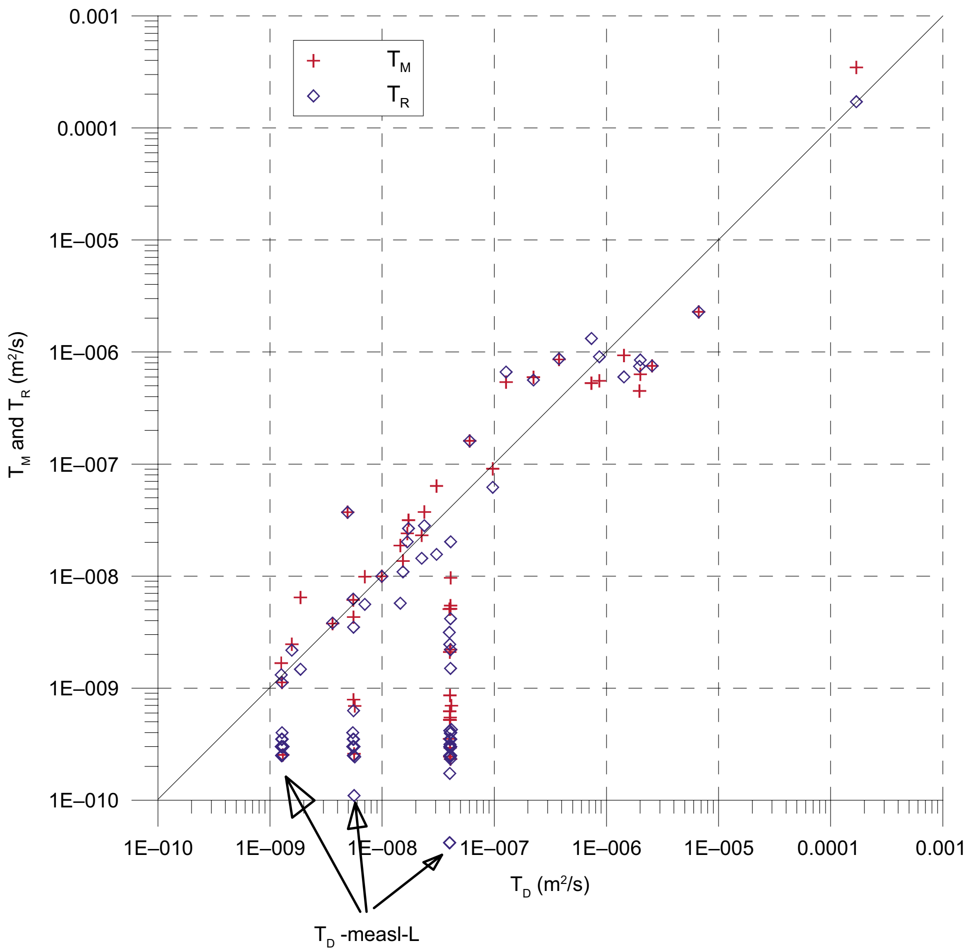

Figure 6-4. *Comparison of estimated steady-state (T_M) and most representative (T_R) transmissivity values from the injection tests in 5 m sections with estimated transmissivity values in the corresponding 5 m sections from the previous difference flow logging (T_D) in KFM03A.*

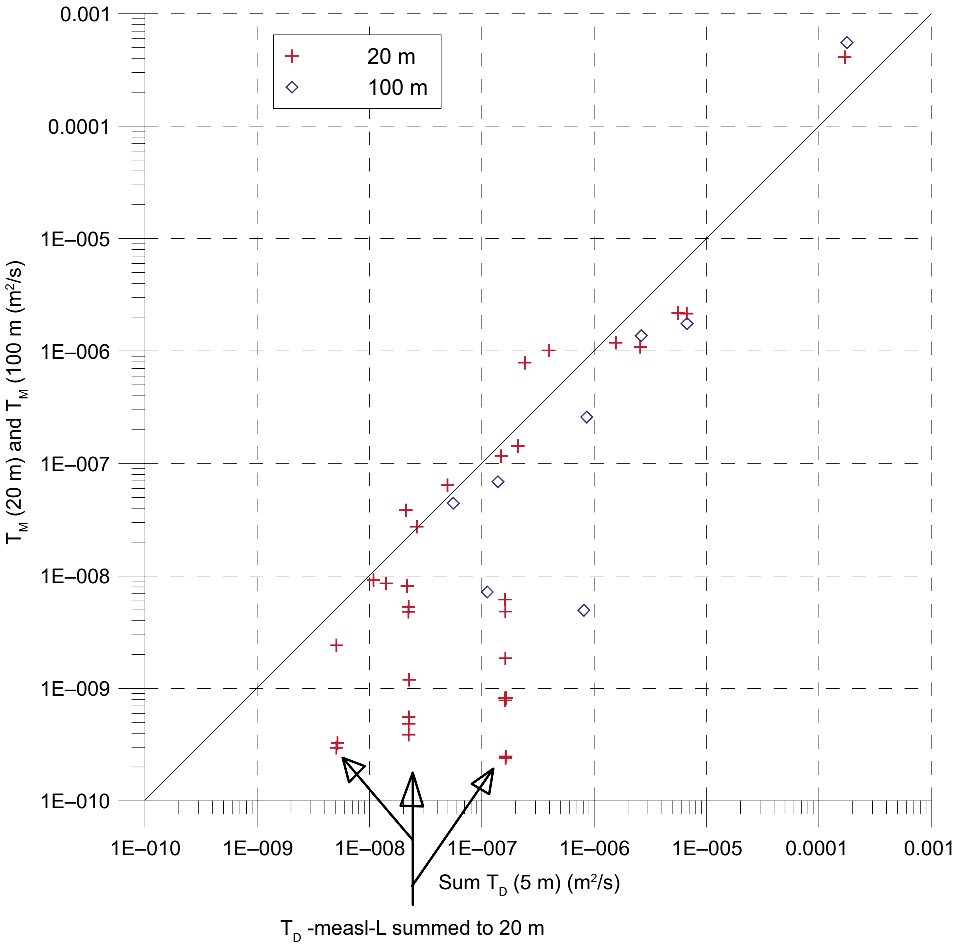

Figure 6-5. *Comparison of estimated steady-state transmissivity values from injection tests in 20 m and 100 m sections with summed transmissivity values in 5 m sections in the corresponding borehole intervals from difference flow logging in KFM03A.*

6.5 Basic statistics of hydraulic conductivity distributions

Some basic statistical parameters were calculated for the steady-state hydraulic conductivity (K_M) distributions in different scales (100 m, 20 m and 5 m) from the injection tests in borehole KFM03A. The hydraulic conductivity is obtained by dividing the hydraulic transmissivity by the section length. Results from tests where Q_p was below the estimated measurement limit were not included in the statistical analyses of K_M. Therefore, the same basic statistical parameters were derived for the transmissivity considered most representative, divided by the section length (T_R/L_w), including all tests. In the statistical analysis, the logarithm (base 10) of K_M and T_R/L_w was used. Selected results are shown in Table 6-6. It should be noted that the statistics for the different section lengths is based on different borehole intervals.

Table 6-6. Basic statistical parameters for steady-state hydraulic conductivity (K_M) and transmissivity considered most representative, divided by section length (T_R/L_w) in different measurement scales in borehole KFM03A. L_w = section length, m = arithmetic mean, s = standard deviation.

Borehole	Parameter	Unit	L_w = 100 m	L_w = 20 m	L_w = 20 m	L_w = 5 m	L_w = 5 m
KFM03A	Measured borehole interval	m	106–901 [2)]	106–901 [3)]	901–991 [4)]	106–901	901–992 [5)]
	Number of tests	–	8	40	5	94	9
	No of tests below E.L.M.L.[1)]	–	0	10	3	46	5
	m ($Log_{10}(K_M)$)	Log_{10} (m/s)	–8.55	–9.29	–7.35	–8.66	–8.08
	s ($Log_{10}(K_M)$)	–	1.63	1.50	0.08	1.32	1.48
	m ($Log_{10}(T_R/L_w)$)	Log_{10} (m/s)	–8.85	–9.86	–9.47	–9.50	–9.28
	s ($Log_{10}(T_R/L_w)$)	–	1.82	1.52	1.76	1.24	1.47

1) Number of tests where Qp could not be defined (E.L.M.L. = estimated lower measurement limit)

2) Sections 106.00–206.00 and 201.00–301.00 partly overlapping

3) Sections 106.00–126.00 and 121.00–131.00 partly overlapping

4) Sections 961.00–981.00 and 971.00–991.00 partly overlapping

5) Sections 986.00–991.00 and 987.00–992.00 partly overlapping

6.6 Comparison of results from different hydraulic tests in KFM03A

In Table 6-7, a comparison of estimated transmissivity values from different hydraulic tests in KFM03A is presented. It should be observed that the summed transmissivity values for the injection tests only include the tests actually performed for each section length. However, the most conductive sections are measured.

Table 6-7 shows that the results of the different hydraulic test methods performed in borehole KFM03A give consistent results. The total transmissivity of the borehole (106–991 m) is dominated by the interval between 386–391 m.

Table 6-7. Comparison of calculated transmissivity values from different hydraulic tests in borehole KFM03A (n m = not measured).

Hydraulic test method	Sum of T (m^2/s)	Borehole interval and length of interval (m)		
		106.00–901.00	901.00–991.00	100.80–997.02
Injection tests	$\sum T_M$ (100 m)	5.56E–04	n m	
	$\sum T_R$ (100 m)	3.76E–04	n m	
	$\sum T_M$ (20 m)	4.19E–04	1.80E–06	
	$\sum T_R$ (20 m)	3.40E–04	1.14E–06	
	$\sum T_M$ (5 m)	3.54E–04	1.45E–06	
	$\sum T_R$ (5 m)	1.80E–04	1.43E–06	
Difference flow logging	$\sum T_D$ (5 m)			1.90E–04
	$\sum T_{Df}$ (flow anomalies)			1.88E–04
Pumping test in conjunction with difference flow logging	T_M			4.24E–04 [1)]

[1)] The pumping test includes the entire non-cased borehole, 11.96–1,001.19 m. A conductive zone is present at c 60 m.

6.7 Pressure interferences below test sections

The results of the evaluation of the pressure interferences in selected borehole intervals below test sections, during the injection tests in section 941–946 m, 941–961 m, 971–991 m and 986–991 m, are presented below.

The difference flow logging in KFM03A /1/ showed that there are several relatively highly conductive fractures in the borehole interval below c 940 m. The most dominating fractures were located at c 944.2 m and c 986.2 m (fractures 1 and 2, respectively). Conductive fractures were also identified at lower positions in the borehole, see Table 6-8. The position and orientation (strike and dip) of these fractures have been determined from the corresponding BIPS-images /11/. The BIPS-aperture represents the thickness of the fracture in the BIPS images. The fractures are generally filled with fracture minerals. Table 6-8 indicates that the conductive fractures form an interconnected network of sub-horizontal and sub-vertical fractures in this borehole interval.

To illustrate the geometrical configuration of these fractures, 3D-images of the fractures together with the positions of the actual test sections and the interval below have been prepared for each test. The extensions of the fractures are unknown and thus only fictive in the images.

Table 6-8. Geometrical and hydraulic properties of the most conductive fractures in the borehole interval below 940 m in KFM03A, as identified from the difference flow logging and the BIPS-mapping.

Fracture no	DIFF – corrected length to fracture (m)	BIPS – corrected length to fracture (m)	Strike (°)	Dip (°)	T_D (m^2/s)	BIPS-Aperture (mm)
1	944.2	944.3	249	32	3.28E–7	6
2	986.2	986.5	30	82	1.89E–7	5
3	992.9	992.9	41	74	4.22E–8	2
4	993.8	993.7	56	78	4.85E–8	2.5
5	994.0	994.1	88	32	1.76E–8	1

6.7.1 Pressure interference below test section 941–946 m

The results of the injection test in section 941–946 m are presented in Section 6.2.4–5. A significant pressure response (c 40 kPa) was observed in the borehole interval 947–1,001 m below the test section during the injection test.

Table 6-8 shows that the test section 941–946 m is only intersected by the conductive, sub-horizontal fracture at c 944.2 m (fracture 1). The borehole interval below the test section is intersected by the sub-vertical fractures 2–4 at c 986.2 m, 992.9 m and 993.8 m, respectively. It is likely that the latter fractures transmitted the observed pressure interferences. This is further illustrated in Figure 6-6. A simple schematic extrapolation of the outcrop of the sub-vertical fracture 2 near the ground surface is shown in Figure 6-7.

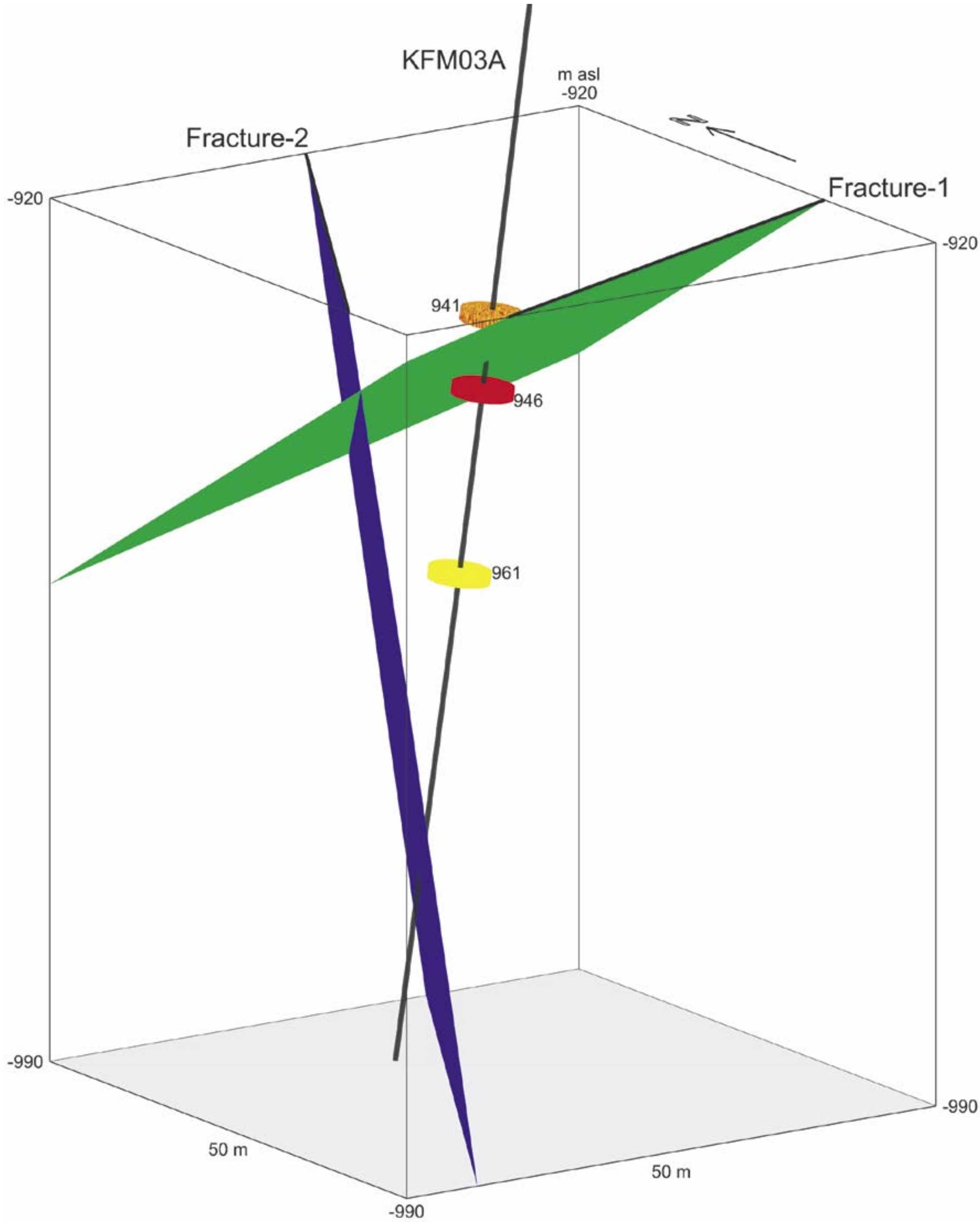

__Figure 6-6.__ Three-dimensional image of the two major conductive fractures below 940 m, as interpreted from the difference flow logging results in borehole KFM03A. Also shown are the positions of the test sections 941–946 m and 941–961 m and the intervals below the test sections.

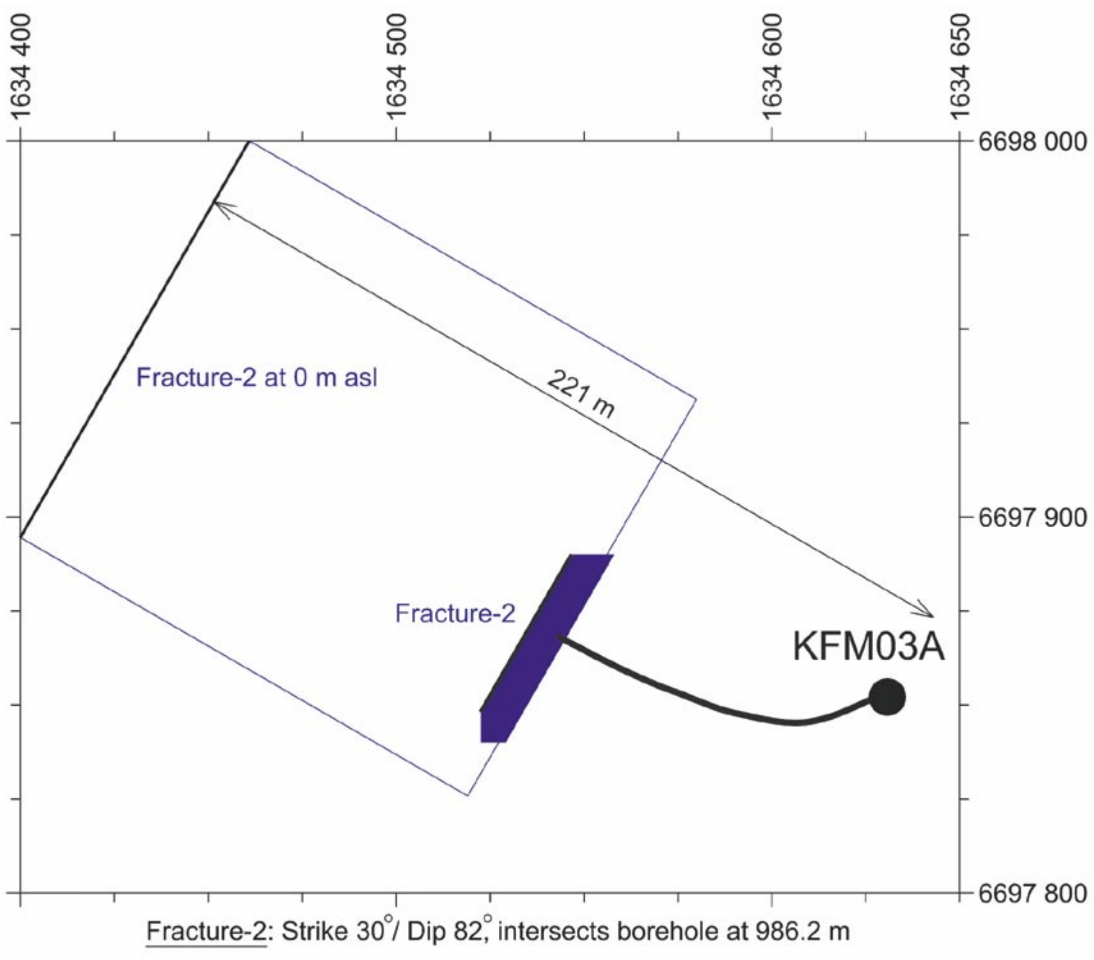

Figure 6-7. *Schematic extrapolation of the outcrop of the interpreted sub-vertical conductive fracture intersecting KFM03A at c 986.2 m, according to the difference flow logging in this borehole.*

The injection head in the test section together with the corresponding pressure interferences (pressure increase and subsequent recovery) in the borehole interval below the test section are shown in the figures in Appendix 4. The analysis of the pressure interference is presented in Section 5.4. General test data from the observation section below the tested section are shown in Table 6-9.

Table 6-9. General test and pressure data from observation section 947–1,001 m during the injection test in section 941–946 m in KFM03A.

General test data			
Borehole	KFM03A		
Test type*	2		
Observation section (open borehole/packed-off section)	947–1,001 m		
Test No	1		
Field crew	T Svensson and K Gokall Norman, Geosigma AB		
Test equipment system	PSS		
General comment	Injection test in section 941–946 m		
	Nomen-clature	**Unit**	**Value**
Borehole length	L	m	1001.19
Casing length	L_c	m	11.96 (ID 0.200 m)
Observation section- secup	Secup	m	947.00
Observation section- seclow	Seclow	m	1,001.19
Observation section length	L_w	m	54.19
Observation section diameter	$2\times r_w$	mm	77
Test start (start of pressure registration)		yymmdd hh:mm	20040617 07:30
Packer expanded		yymmdd hh:mm	20040617 07:31
Start of flow period		yymmdd hh:mm:ss	20040617 08:09:45
Stop of flow period		yymmdd hh:mm:ss	20040617 08:30:21
Test stop (stop of pressure registration)		yymmdd hh:mm	20040617 08:52
Total flow time	t_p	min	21
Total recovery time	t_F	min	20

Pressure data in observation section 947–1,001 m in KFM03A	**Nomen-clature**	**Unit**	**Value**
Absolute pressure in observation section before start of flow period	p_i	kPa	9,374.93
Absolute pressure in observation section before stop of flow period	p_p	kPa	9,414.55
Absolute pressure in observation section at stop of recovery period	p_F	kPa	9,397.98
Maximal pressure change in observation section during flow period	s_p	kPa	39.62

* 2: Interference test

Interpretation of flow regimes

Table 6-3 shows that the interpreted flow regimes in the tested section 941–946 m were pseudo-radial flow, transitioning to pseudo-linear during the flow period and pseudo-spherical, transitioning to pseudo-linear (or apparent no-flow boundary) during the recovery period. These interpretations were made on the transient flow rate (injection period) and pressure data (recovery period).

Figures A4-1 to A4-8 indicate that the pressure interference in the observation section approached a pseudo-radial regime by the end of the injection period, considering the variable flow rate during this period. However, no such regime was developed during the recovery period.

Interpretation of parameters

The transient analysis of the pressure interference was carried out according to the methods described in Section 5.4, mainly based on the identified period with pseudo-radial flow. The results are presented in Appendix 4 and in Table 6-13. Firstly, the combined analysis of the head changes in both sections is shown in Appendix 4. Secondly, individual analyses of pressure interference for the injection and recovery periods of the test are shown in Appendix 4. For the recovery period, only an approximate evaluation was made. Consistent results were obtained from the combined and the individual analyses.

For estimation of storativity in the observation section, the sum of the distances along fracture 1 to its intersection with fracture 2, and the distance from this point to the intersection with the borehole along fracture 2 was used. This distance was estimated at c 49 m using Figure 6-6. The corresponding straight-line distance along the borehole between the fractures is c 42 m.

6.7.2 Pressure interference below test section 941–961 m

The results of the injection test in section 941–961 m are presented in Section 6.2.4–5. A significant pressure response (c 40 kPa) was also in this case observed in the borehole interval below the test section (962–1,001 m).

Table 6-8 shows that the test section 941–961 m is only intersected by the conductive, sub-horizontal fracture at c 944.2 m (fracture 1), i.e. similar to the conditions for the previous test in section 941–946 m. The borehole interval below the test section is also in this case intersected by the sub-vertical fractures 2–4 at c 986.2 m, 992.9 m and 993.8 m. It is likely that the latter fractures transmitted the observed pressure interference. This is further illustrated in Figure 6-6.

The injection head in the test section together with the corresponding pressure interferences (pressure increase and subsequent recovery) in the borehole interval below the test section are shown in the figures in Appendix 4. The analysis of the pressure interference is presented in Section 5.4. General test data from the observation section below the tested section are shown in Table 6-10.

Table 6-10. General test data from observation section 962–1,001 m during the injection test in section 941–961 m in KFM03A.

General test data			
Borehole	KFM03A		
Test type*	2		
Observation section (open borehole/packed-off section)	962–1,001 m		
Test No	1		
Field crew	T Svensson and K Gokall-Norman, Geosigma AB		
Test equipment system	PSS		
General comment	Injection test in section 941–961 m		
	Nomen-clature	**Unit**	**Value**
Borehole length	L	M	1,001.19
Casing length	L_c	M	11.96 (ID 0.200 m)
Observation section- secup	Secup	M	962.00
Observation section- seclow	Seclow	M	1,001.19
Observation section length	L_w	M	39.19
Observation section diameter	$2{\times}r_w$	Mm	77
Test start (start of pressure registration)		yymmdd hh:mm	20040603 18:55
Packer expanded		yymmdd hh:mm	20040603 18:55
Start of flow period		yymmdd hh:mm:ss	20040603 19:37:43
Stop of flow period		yymmdd hh:mm:ss	20040603 19:58:07
Test stop (stop of pressure registration)		yymmdd hh:mm	20040603 20:20
Total flow time	t_p	Min	20
Total recovery time	t_F	Min	20

Pressure data in observation section 962–1,001 m in KFM03A	**Nomen-clature**	**Unit**	**Value**
Absolute pressure in observation section before start of flow period	p_i	kPa	9,527.73
Absolute pressure in observation section before stop of flow period	p_p	kPa	9,564.17
Absolute pressure in observation section at stop of recovery period	p_F	kPa	9,549.26
Maximal pressure change in observation section during flow period	s_p	kPa	36.44

* 2: Interference test

Interpretation of flow regimes

Table 6-4 indicates that the interpreted flow regimes in the tested section 941–961 m were pseudo-radial flow during the injection period, and an early pseudo-radial flow period transitioning to a late pseudo-radial regime during the recovery period. The latter regime may also be interpreted as pseudo-linear (or an apparent no-flow boundary), as for the previous test in section 941–946 m. These interpretations were made on the transient flow rate (injection period) and pressure data (recovery period).

Figures A4-9 to A4-16 indicate that a pseudo-radial regime was approached by the end of the injection period, considering the variable flow rate during this period, similar to the test in section 941–946 m. However, no such regime was developed during the recovery period.

Interpretation of parameters

The transient analyses of the pressure interferences were made according to the methods described in Section 5.4, mainly based on the identified period with pseudo-radial flow. The results are presented in Appendix 4 and in Table 6-13. Firstly, the combined analysis of the head changes in both sections is shown in Appendix 4. Secondly, individual analyses of pressure interference for the injection and recovery periods of the test are shown in Appendix 4. For the recovery period, only an approximate evaluation was made. Consistent results were obtained from the combined and the individual analyses.

For estimation of storativity in the observation section, the same distance (49 m) was used as for the test in section 941-946 m, see Figure 6-6.

6.7.3 Pressure interference below test section 971–991 m

The results of the injection test in section 971–991 m are presented in Section 6.2.4–5. A significant pressure response (c 100 kPa) was observed in the borehole interval below the test section (i.e. 992–1,001 m).

Table 6-8 shows that the test section 971–991 m is intersected only by the conductive sub-vertical fracture at c 986.2 m (fracture 2). The borehole interval below the test section is intersected by the sub-vertical fractures 3–4 at c 992.9 m and 993.8 m, as well as by the sub-horizontal fracture 5 at c 994.0 m. It is likely that the latter fractures transmitted the observed pressure interference. This is further illustrated in Figure 6-8.

The injection head in the test section together with the corresponding pressure interferences (pressure increase and subsequent recovery) in the borehole interval below the test section are shown in the figures in Appendix 4. The analysis of the pressure interference is presented in Section 5.4. General test data from the observation section below the tested section are shown in Table 6-11.

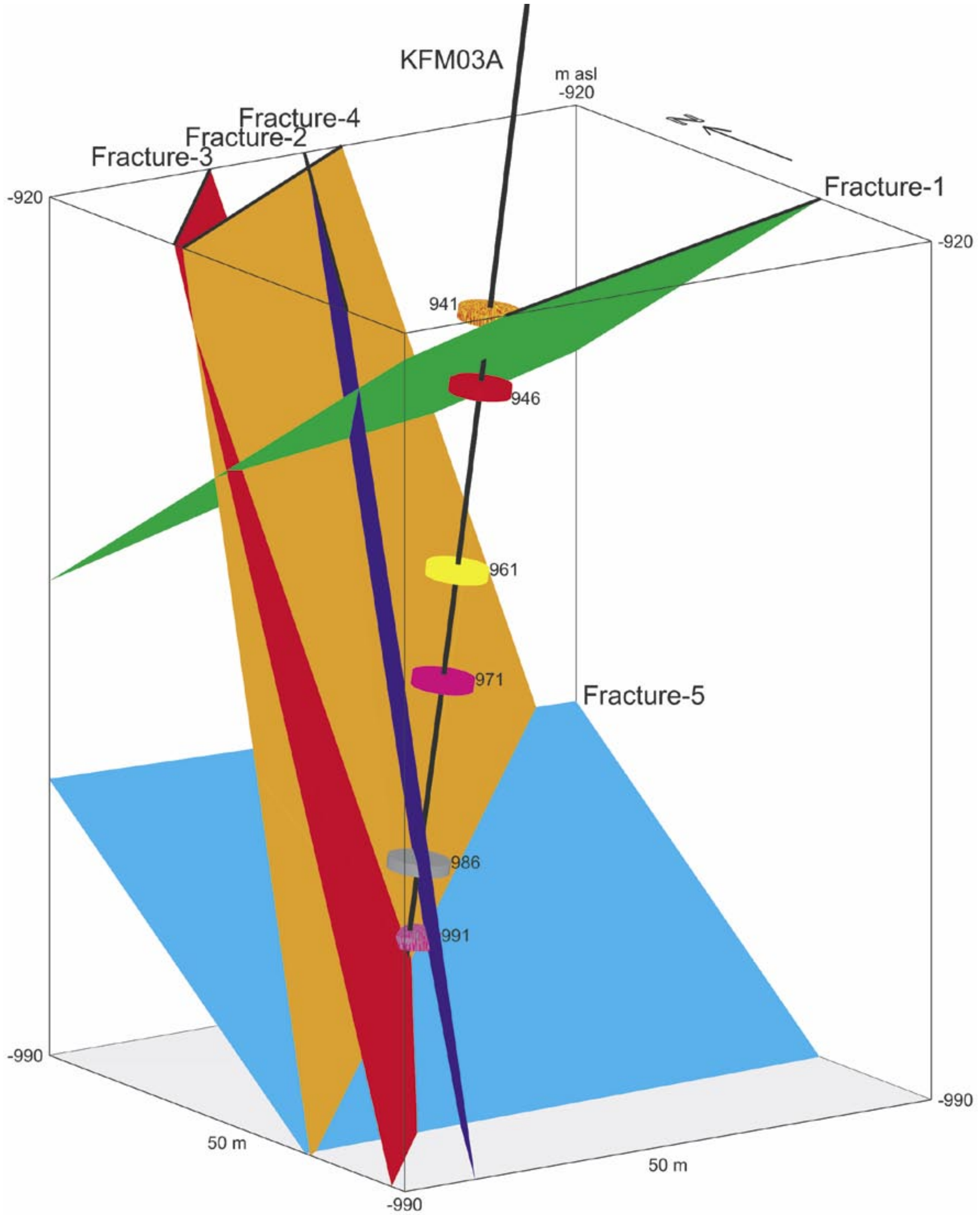

Figure 6-8. *Three-dimensional image of interpreted conductive fractures below 940 m from the difference flow logging in borehole KFM03A together with the positions of all test sections evaluated with respect to pressure interferences.*

Table 6-11. General test data from observation section 992–1,001 m during the injection test in section 971–991 m in KFM03A.

General test data			
Borehole	KFM03A		
Test type*	2		
Observation section (open borehole/packed-off section)	992–1,001 m		
Test No	1		
Field crew	T Svensson and K Gokall-Norman, Geosigma AB		
Test equipment system	PSS		
General comment	Injection test in section 971–991 m		
	Nomen-clature	**Unit**	**Value**
Borehole length	L	M	1,001.19
Casing length	L_c	M	11.96 (ID 0.200 m)
Observation section- secup	Secup	M	992.00
Observation section- seclow	Seclow	M	1,001.19
Observation section length	L_w	M	9.19
Observation section diameter	$2\times r_w$	Mm	77
Test start (start of pressure registration)		yymmdd hh:mm	20040603 22:51
Packer expanded		yymmdd hh:mm	20040603 22:52
Start of flow period		yymmdd hh:mm:ss	20040603 23:27:42
Stop of flow period		yymmdd hh:mm:ss	20040603 23:48:09
Test stop (stop of pressure registration)		yymmdd hh:mm	20040604 00:10
Total flow time	t_p	Min	20
Total recovery time	t_F	Min	20

Pressure data in observation section 992–1,001 m in KFM03A	Nomen-clature	Unit	Value
Absolute pressure in observation section before start of flow period	p_i	kPa	9,825.32
Absolute pressure in observation section before stop of flow period	p_p	kPa	9,929.67
Absolute pressure in observation section at stop of recovery period	p_F	kPa	9,835.26
Maximal pressure change in observation section during flow period	s_p	kPa	104.35

* 2: Interference test

Interpretation of flow regimes

Table 6-4 indicates that the interpreted dominating flow regimes in the tested section 971–991 m were pseudo-radial flow during both the injection and recovery period. These interpretations were made on the transient flow rate (injection period) and pressure data (recovery period).

Figures A4-17 to A4-24 indicate that the pressure interference in the observation section approached a pseudo-radial (or slightly pseudo-spherical) flow regime by the end of the injection and recovery periods, respectively.

Interpretation of parameters

The transient analyses of the pressure interferences were made according to the methods described in Section 5.4, mainly based on the identified period with pseudo-radial flow. The results are presented in Appendix 4 and in Table 6-13. Firstly, the combined analysis of the head changes in both sections is shown in Appendix 4. Secondly, individual analyses of pressure interference for the injection and recovery periods of the test are shown in Appendix 4. Consistent results were obtained from the combined and the individual analyses.

For estimation of storativity in the observation section, the sum of the distances along fracture 2 to its intersection with fracture 5 and the distance from this point to the intersection with the borehole along the latter fracture was used. This distance was estimated at c 8 m from Figure 6-7. The corresponding straight-line distance along the borehole between the fractures is c 7 m.

6.7.4 Pressure interference below test section 986–991 m

The results of the injection test in section 986–991 m are presented in Section 6.2.4–5. Again, a significant pressure response (c 100 kPa) was observed in the borehole interval below the test section (i.e. 992–1,001 m).

Table 6-8 shows that the test section 986–991 m is intersected only by the conductive sub-vertical fracture at c 986.2 m (fracture 2). The borehole interval below the test section is intersected by the sub-vertical fractures 3–4 at c 992.9 m and 993.8 m as well as by the sub-horizontal fracture 5 at c 994.0 m. It is likely that the latter fractures transmitted the observed pressure interference. This is further illustrated in Figure 6-8.

The injection head in the test section together with the corresponding pressure interference (pressure increase and subsequent recovery) in the borehole interval below the test section are shown in the figures in Appendix 4. The analysis of the pressure interference is presented in Section 5.4. General test data from the observation section below the tested section are shown in Table 6-12.

Table 6-12. General test data from observation section 992–1,001 m during the injection test in section 986–991 m in KFM03A.

General test data			
Borehole	KFM03A		
Test type*	2		
Observation section (open borehole/packed-off section)	992–1,001 m		
Test No	1		
Field crew	T Svensson and K Gokall-Norman, Geosigma AB		
Test equipment system	PSS		
General comment	Injection test in section 986–991 m		
	Nomenclature	**Unit**	**Value**
Borehole length	L	m	1,001.19
Casing length	L_c	m	11.96 (ID 0.200 m)
Observation section- secup	Secup	m	992.00
Observation section- seclow	Seclow	m	1,001.19
Observation section length	L_w	m	9.19
Observation section diameter	$2{\times}r_w$	mm	77
Test start (start of pressure registration)		yymmdd hh:mm	20040618 10:47
Packer expanded		yymmdd hh:mm	20040618 10:48
Start of flow period		yymmdd hh:mm:ss	20040618 12:38:02
Stop of flow period		yymmdd hh:mm:ss	20040618 12:58:35
Test stop (stop of pressure registration)		yymmdd hh:mm	20040618 13:20
Total flow time	t_p	min	21
Total recovery time	t_F	min	20
Pressure data in observation section 992–1,001 m in KFM03A	Nomenclature	Unit	Nomenclature
Absolute pressure in observation section before start of flow period	p_i	kPa	9,823.52
Absolute pressure in observation section before stop of flow period	p_p	kPa	9,923.60
Absolute pressure in observation section at stop of recovery period	p_F	kPa	9,833.05
Maximal pressure change in observation section during flow period	s_p	kPa	100.08

* 2: Interference test

Interpretation of flow regimes

Table 6-4 indicates that the interpreted dominating flow regimes in the tested section 986–991 m were pseudo-radial flow during both the injection and recovery period. These interpretations were made on the transient flow rate (injection period) and pressure data (recovery period).

Figures A4-25 to A4-32 indicate that the pressure interference in the observation section approached a rather well-defined pseudo-radial regime, both during the injection and recovery period.

Interpretation of parameters

The transient analyses of the pressure interferences were made according to the methods described in Section 5.4, mainly based on the identified period with pseudo-radial flow. The results are presented in Appendix 4 and in Table 6-13. Firstly, the combined analysis of the head changes in both sections is shown in Appendix 4. Secondly, individual analyses of pressure interference for the injection and recovery periods of the test are shown in Appendix 4. Consistent results were obtained from the combined and the individual analyses.

For estimation of storativity from the observation section, the same distance (8 m) was used as for the test in section 971–991 m, see Figure 6-8.

6.7.5 Summary of pressure interference below test sections

In Table 6-13, a summary of the results of the analyses of the pressure interference below tested sections is presented. Selected results from the corresponding analyses of the tested sections are also shown. The distance r_s is the estimated distance along the assumed pathways along the fractures. Table 6-13 shows that the results of the analyses of data from the test sections and from the pressure interference below the test sections are consistent.

Table 6-13. Summary of the analyses of the pressure interference in the borehole intervals below some of the tested sections in KFM03A.

Test section (m)	Observation section below (m)	Interpreted flow regime	Distance r_s to test section (m)	T_T (m^2/s)	S	S*
941–946		PRF→PLF		8.69×10^{-7}	–	1×10^{-6}
	947–1,001	PRF	49	6.26×10^{-7}	2.45×10^{-7}	
941–961		PRF		5.91×10^{-7}	–	1×10^{-6}
	962–1,001	PRF	49	6.31×10^{-7}	2.37×10^{-7}	
971–991		PRF		5.50×10^{-7}	–	1×10^{-6}
	992–1,001	PRF	8	5.46×10^{-7}	2.40×10^{-7}	
986–991		PRF		5.62×10^{-7}	–	1×10^{-6}
	992–1,001	PRF	8	4.94×10^{-7}	3.20×10^{-7}	

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8 Appendices

Appendix 1	File description table (only on CD)
Appendix 2.1	General test data (only on CD)
Appendix 2.2	Pressure and flow data (only on CD)
Appendix 3	Test diagrams – Injection tests (only on CD)
Appendix 4	Diagrams from pressure interferences (only on CD)
Appendix 5	Borehole technical data (only on CD)
Appendix 6	Sicada tables (only on CD)