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Äspö Hard Rock Laboratory

Prototype Repository

Tracer dilution tests during operation phase, test campaign 2

Kristoffer Gokall Norman
Peter Andersson

Geosigma AB

February 2007

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

Äspö Hard Rock Laboratory

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Author	Date
Kristoffer Gokall-Norman Peter Andersson	2007-02-27
Checked by	Date
Eva Wass	
Ingvar Rhén	2007-08-25
Lars-Erik Johannesson	2007-08-31
Approved	Date
Anders Sjöland	2007-09-07

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Abstract

The Prototype Repository project is focused on testing and demonstrating the function of the SKB deep repository system. Activities aimed at contributing to development and testing of the practical, engineering measures required to rationally perform the steps of a deposition sequence are also included in the project but are also part of other projects.

This report describes the second tracer dilution test campaign during the operation period of the Prototype Repository, after the closing of the Prototype Repository tunnel. The purpose was to estimate groundwater flow and will function as a full scale reference for comparison with results from modeling and prior assumptions.

The test campaign consisted of tracer dilution tests in 16 different borehole sections. Each test consisted of approximately 15-55 min tracer injection time (except for one section where the injection time was extended due to low circulation flow rate) and about 1-3 days dilution test time depending on the transmissivity of the test section. The data interpretation also included estimates of the local hydraulic gradients in the vicinity of the borehole sections.

Sammanfattning

Huvudsyftet med Prototypförvaret är att testa och demonstrera funktionen av en del av SKB:s djupförvarssystem. Aktiviteter som syftar till utveckling och försök till praktiska och ingenjörsmässiga lösningar som krävs för att på ett rationellt sätt kunna stegvis utföra deponeringen av kapslar med kärnbränsle, är inkluderade i projektet för Prototypförvaret men även i andra projekt.

Rapporten beskriver den andra utspädningskampanjen med spårämnen under Prototypförvarets driftperiod efter det att dräneringen av tunneln stängts. Syftet är att mäta grundvattenflöden som kommer att fungera som fullskaliga referenser vid modellering och antaganden om flödesfördelningen i berget.

I testkampanjen mättes 16 testsektioner med utspädningsmetoden. Varje test genomfördes så att ett spårämne injicerades under en period av ca 15-55 minuter (utom för en sektion där injektionstiden förlängdes p.g.a. lågt cirkulationsflöde) med en påföljande provtagningsperiod av sektionsvatten under ungefär 1-3 dygn. Utvärderingen inkluderade också en uppskattning av den lokala hydrauliska gradienten intill borrhålet.

Executive summary

The Prototype Repository project is focused on testing and demonstrating the function of the SKB deep repository system. Activities aimed at contributing to development and testing of the practical, engineering measures required to rationally perform the steps of a deposition sequence are also included in the project but are also part of other projects.

This report describes the second tracer dilution campaign during the operation period of the Prototype Repository, after the closing of the Prototype Repository tunnel. The purpose was to estimate the groundwater flows and will function as a full scale reference for comparison with results from modeling and prior assumptions.

The test campaign consisted of tracer dilution tests in 16 different sections. Each test consisted of approximately 15-55 min tracer injection time, depending on the volume of the injected test section, followed by a 1–3 days dilution time, during which water sampling from the test section was performed. The injection time for one of the test sections was extended due to a lower circulation flow.

The dilution method is based on a tracer being injected into the test section with a constant flow rate during simultaneous circulation/mixing until a homogeneous tracer concentration is reached in the system. When groundwater flows through the section the tracer will be diluted. The groundwater flow is calculated as a function of the decreasing tracer concentration with time as shown in the equation below as well as in *Figure 1*.

$$\ln (c/c_0) = -(Q_{bh}/V) \cdot \Delta t$$

By plotting $\ln (c/c_0)$ versus Δt, and by knowing the borehole volume V, Q_{bh} may then be obtained from the slope of the straight line. If c_0 is constant it is sufficient to use $\ln c$ in the plot instead of $\ln (c/c_0)$, cf. *Figure 1*.

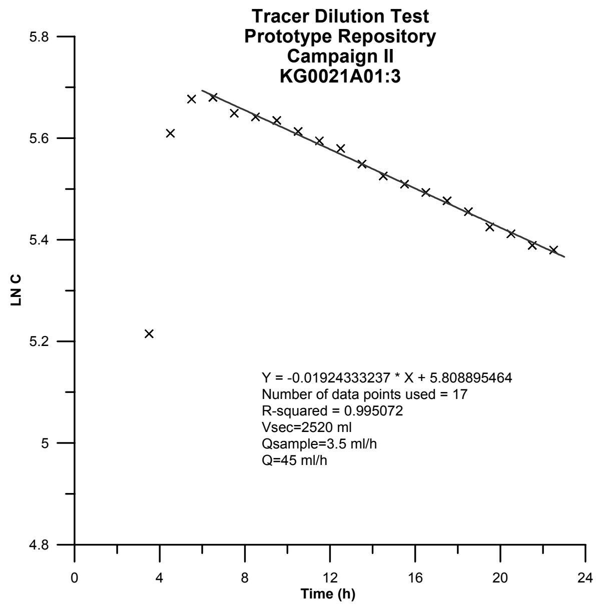

Figure 1. *Example of a tracer dilution test diagram.*

Apart from the period between 2004-11-01 and 2004-12-06, the Prototype Repository tunnel has been drained. Generally speaking, the pressure in the vicinity of the tunnel has decreased since the construction of the tunnel which is likely to lead to a decreasing hydraulic gradient.

There were no major pressure disturbances during the tests and no interference between the sections was observed with two exceptions: In borehole *KA3546G01* there was an indication of a cross-connection between section 2 and 3. Also there were signs of interference between sections *KA3546G01:2* and *KA3552G01:2*.

The magnitude of flow is governed by the local transmissivity of the borehole section and the hydraulic gradient. Prevailing flow rates in Prototype Repository vary between 0.4-60 ml/h, excluding sections believed to suffer from packer system leakage.

As expected, most of the non-leaking sections included in the test exhibit a lower flow than was measured during the last dilution campaign, presumably due to the generally lower pressure levels that are prevailing in the rock surrounding the Prototype repository tunnel compared to the conditions during test campaign 1. The flow rates had decreased between 20 to 97% since the last campaign.

Two sections (*KA3550G01:2* and *KA3544G01:*2), with suspected packer leakage were also measured and the leakage was confirmed. No real flow could be estimated from these sections since the determined values represent leakage rather than flow through fractures intersecting the sections. In addition, no measurements could be done in section *KA3566G02:2* due to gas being trapped inside the section.

Estimated local gradients vary between 0.01 and 62 m/m for the 14 non-leaking sections. The two leaking sections exhibit large values, as expected.

Table 1. Results from tracer dilution tests in the Prototype Repository, a comparison between campaign 1 and 2.

Test section	$Q_{natural}$, camp. 1 (ml/h)	$Q_{natural}$ camp. 2 (ml/h)	Flow decrease (%)	Accuracy camp. 2 ± (ml/h) [2]		Comments
KA3539G:2	56	43	23	4	3	
KA3542G01:3	223	38	83	2	2	
KA3542G02:2	9.0	5.9	35	0.1	5	
KA3544G01:2	(384)	(181)	(53)	4	5	Packer system leakage
KA3546G01:2	(15) [1]	8.2	46	1	2	
KA3548A01:3	90	60	34	4	3	
KA3550G01:2	(255)	(260)	(-2.0)	29	7	Packer system leakage
KA3552G01:2	12	4.6	62	0.6	0.2	
KA3554G01:2	66	23	66	3	2	
KA3554G02:4	8.4	6.4	24	0	2	
KA3563G:4	14	0.4	97	0.1	0.3	
KA3566G01:2	19	11	41	0.8	0.5	Extended test duration
KA3566G02:2	3.1	-	-	-	-	Not measured due to gas in test section
KA3572G01:2	6.0	2.0	67	0.2	0.4	Extended test duration
KA3574G01:3	3.8	1.6	59	0.8	0.2	Extended test duration
KG0021A01:3	56	45	20	18	0.2	
KG0048A01:3	7.8	4.2	46	0.6	0.1	Extended test duration

[1] Valve leakage during the dilution of campaign 1.
[2] The uncertainty of the calculated flow constitutes of two parts. In the first column the uncertainty due to the volume approximation is described. The second column reports the uncertainty contributed by the fortuitous aspect of the graph fitting, which is the base for the flow rate calculations. The uncertainties can be considered independent and may be added together.

Table 2. Results of tracer dilution tests in the Prototype Repository, a comparison between campaign 1 and 2.

Test section	I Gradient camp. 1 (m/m)	I Gradient camp. 2 (m/m)	Decrease (%)	Comments
KA3539G:2	0.1	0.1	-7	
KA3542G01:3	13.1	1.8	86	
KA3542G02:2	18.9	23	-23	
KA3544G01:2	94.8	(45)	53	Packer system leakage
KA3546G01:2	24.9 [1)]	16	38	
KA3548A01:3	1.5	1.3	15	
KA3550G01:2	105.9	(108)	-2	Packer system leakage
KA3552G01:2	2.7	10	-286	
KA3554G01:2	0.2	0.1	62	
KA3554G02:4	1.3	1.1	17	
KA3563G:4	0.2	0.01	92	
KA3566G01:2	267.1	62	77	Extended test duration
KA3566G02:2	0.7	-	-	Not measured due to gas in test section (camp. 2)
KA3572G01:2	3.1	1.0	67	Extended test duration
KA3574G01:3	18.8	7.7	59	Extended test duration
KG0021A01:3	0.1	0.1	-13	
KG0048A01:3	0.2	0.1	41	Extended test duration

[1)] Valve leakage during the dilution of campaign 1.

Contents

1 Background

1.1 Äspö Hard Rock Laboratory

In order to prepare for siting and licensing of a spent fuel repository, SKB has constructed an underground research laboratory. In the autumn of 1990, SKB began the construction of Äspö Hard Rock Laboratory, Äspö HRL, near Oskarshamn in the south-eastern part of Sweden. A 3.6 km long tunnel was excavated in crystalline rock down to a depth of approximately 460 m. The laboratory was completed in 1995 and research concerning the disposal of nuclear waste in crystalline rock has been carried out since then.

1.2 Prototype repository

The Äspö Hard Rock Laboratory is an essential part of the research, development and demonstration work performed by SKB in preparation for construction and operation of the deep repository for spent fuel. Within the scope of the SKB program for RD&D 1995, SKB has decided to carry out a project with the designation “Prototype Repository Test”. The aim of the project is to test important components in the SKB deep repository system in full scale and in a realistic environment.

The Prototype Repository Test is focused on testing and demonstrating the function of the SKB deep repository system. Activities aimed at contributing to the development and testing of the practical, engineering measures required to rationally perform the steps of a deposition sequence are also included. However, efforts in this direction are limited, since these matters are addressed in the Demonstration of Repository Technology project and to some extent in the Backfill and Plug Test.

1.2.1 General objectives

The Prototype Repository should simulate as many aspects as possible of a real repository, regarding for example geometry, materials and rock environment. The Prototype Repository is a demonstration of the integrated function of the repository components. Results will be compared with models and assumptions tested for their validity.

The major objectives for the Prototype Repository are:

- To test and demonstrate the integrated function of the repository components under realistic conditions in full scale and to compare results with models and assumptions.
- To develop, test and demonstrate appropriate engineering standards and quality assurance methods.
- To simulate appropriate parts of the repository design and construction process.
- The objective for the operation phase program is to monitor processes and properties in the canister, buffer material, backfill and near-field rock mass.

2 Objective

The objective of the tracer dilution tests during test campaign 2 is to measure the groundwater flow through 17 borehole sections in the Prototype Repository during natural conditions. The results will be compared to results from similar tests performed during drained conditions in October-November 2004 (Gröhn et al., 2005). The measurements will function as a full scale reference for comparison with results from modeling and prior assumptions.

3 Scope

Tracer dilution tests were performed in 16 borehole sections in the Prototype Repository tunnel. One of the sections intended for testing could not be used due to gas being trapped inside the test section, cf. Table 3-1. The tested intervals and basic test data are listed in Table 3-1.

Table 3-1. List of borehole test sections included in the second tracer dilution test campaign in November and December of 2006.

Borehole	Section	Start of test	Test stop
KA3539G:2	15.85 – 17.6	2006-12-07 17:37	2006-12-08 13:06
KA3542G01:3	18.6 – 20.3	2006-12-11 15:50	2006-12-12 16:27
KA3542G02:2	25.6 – 27.2	2006-12-06 17:50	2006-12-07 17:27
KA3544G01:2	8.9 – 10.65	2006-12-13 15:44	2006-12-14 15:28
KA3546G01:2	6.75 – 8.3	2006-11-29 19:29	2006-11-30 11:17
KA3548A01:3	8.8 – 10.75	2006-11-28 11:54	2006-11-29 17:08
KA3550G01:2	5.2 – 7.3	2006-12-12 16:44	2006-12-13 15:36
KA3552G01:2	4.35 - 6.05	2006-11-30 11:45	2006-12-01 08:34
KA3554G01:2	22.6 – 24.15	2006-11-23 15:00	2006-11-24 13:24
KA3554G02:4	10.5 – 12.2	2006-12-05 16:54	2006-12-06 17:46
KA3563G:4	1.5 – 3	2006-12-04 16:09	2006-12-05 16:44
KA3566G01:2	20- 21.5	2006-12-14 15:42	2006-12-18 15:16
KA3566G02:2 1)	16 – 18	-	-
KA3572G01:2	2.7 – 5.3	2006-12-01 08:47	2006-12-04 15:57
KA3574G01:3	1.8 – 4.1	2006-11-24 13:38	2006-11-27 20:00
KG0021A01:3	35 – 36	2006-12-18 15:29	2006-12-19 15:47
KG0048A01:3	32.8 – 33.8	2006-12-08 14:15	2006-12-11 15:00

1) Section not tested due to gas in test section.

The results of the tests are presented in Chapter 6.

4 Equipment

4.1 Description of equipment

The 17 characterisation boreholes in the Prototype Repository involved in the dilution tests are instrumented with 1-4 inflatable packers, isolating 1-5 borehole sections each (Rhén et al., 2001). All isolated borehole sections are connected, via polyamide tubes, to pressure transducers placed in the G-tunnel. The transducers are connected to the HMS-system at Äspö HRL by means of data loggers (Datascan). The sections used for tracer dilution tests are equipped with two additional polyamide tubes with an inner diameter of 4 mm. These are used for injection, sampling and circulation of tracer solution in the borehole section. The borehole sections are also equipped with volume reducers (dummies) made of polyamide.

A schematic drawing of the dilution test equipment used in the Prototype Repository is shown in Figure 4-1. The basic idea is to have an internal circulation in the borehole section. The circulation makes it possible to obtain a homogeneous tracer concentration in the borehole section and to sample the tracer concentration outside the borehole in order to monitor the dilution rate with time.

Circulation is controlled by a pump with variable speed (A) and measured by a flow meter (B). Tracer injections are made with a HPLC plunger pump (C) and sampling is made by continuously extracting a small volume of water from the system through a flow controller (constant leak) to a fractional sampler (D). Pictures of the equipment are shown in Figure 4-2.

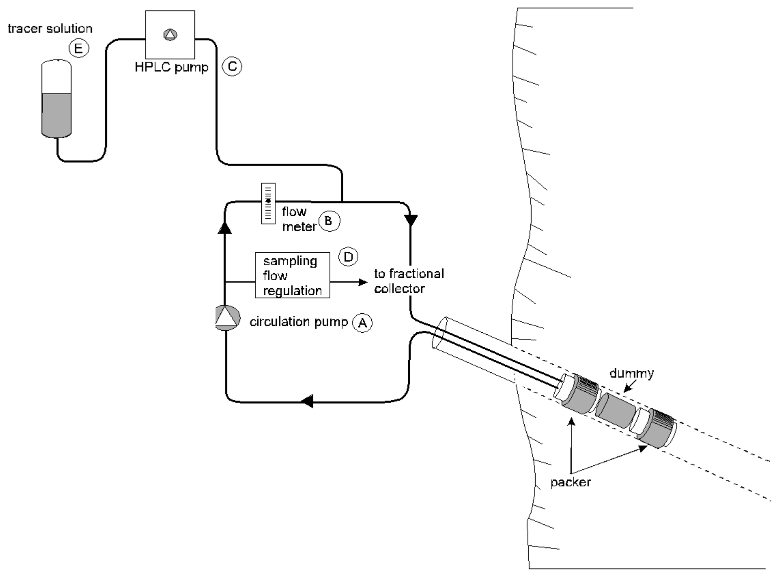

Figure 4-1. *Schematic drawing of the tracer injection/sampling system used in the Prototype Repository. The tracer is actually injected before the flow meter.*

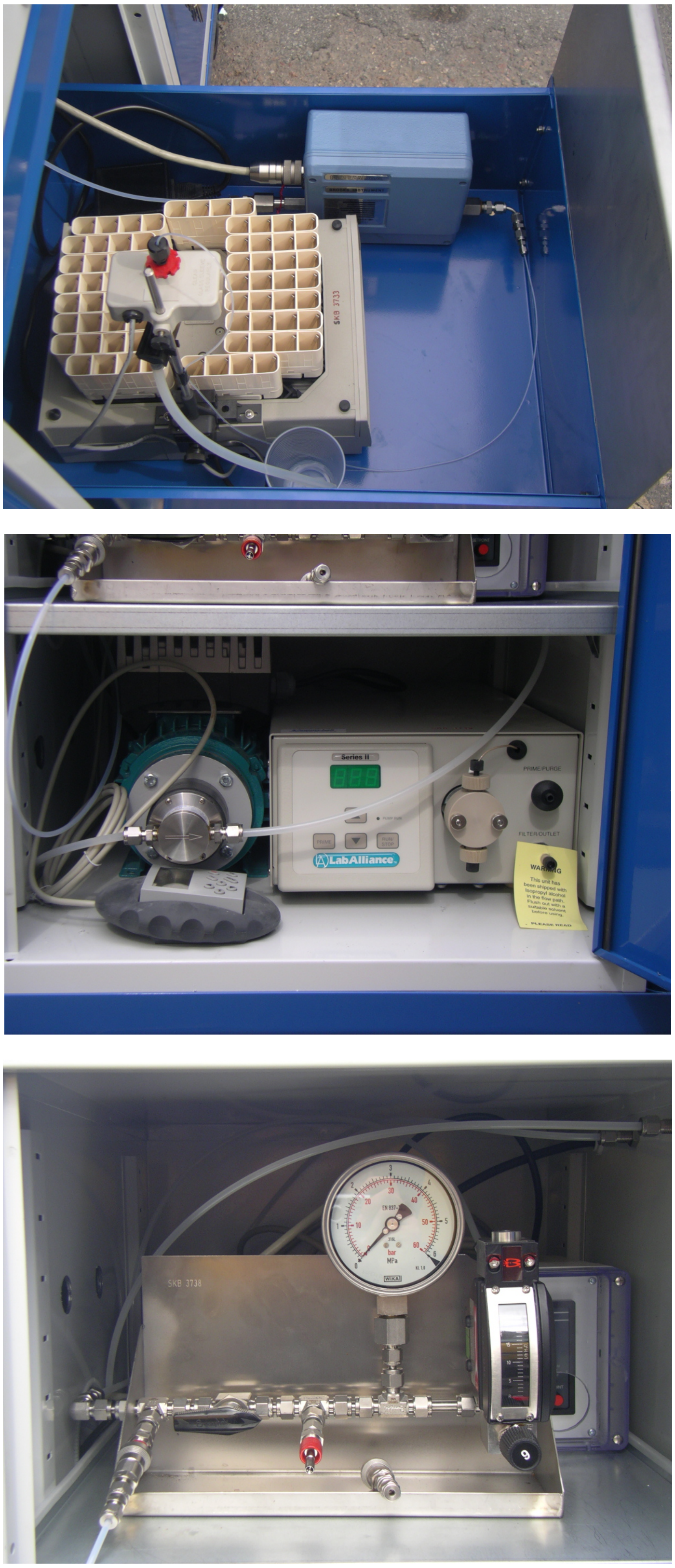

Figure 4-1. *Equipment from the dilution test: flow controller and fractional sampler (upper picture), circulation- and injection pump (middle) and the circulation board with flow meter and manometer (lower picture).*

4.2 Tracers used

The tracers used were two fluorescent dye tracers, Uranine (Sodium Fluorescein) from Merck (purum quality) and Amino G Acid from Aldrich (techn. quality). These tracers have been used extensively in the TRUE-1, TRUE Block Scale and TRUE Continuation tracer and dilution tests (Andersson et al., 2002, 2004). The tracers have been found to be conservative (non-reactive) in Äspö bedrock conditions.

5 Execution

5.1 Preparations

The preparations included functionality checks of the equipment. The testing equipment had also been serviced and calibrated at the Geosigma engineering workshop in Librobäck, Uppsala, just prior to the test campaign. It was also important to check that no other activities which may cause pressure disturbances occurred in the neighbourhood of the test area.

Protocols were prepared for tracer injection and sampling. Tracer stock solutions were prepared at the Geosigma laboratory in Uppsala.

5.2 Performance of the dilution tests

The test campaign involved 17 different borehole sections, identical to campaign 1, performed in October-November 2004, cf. Table 3-1. Based on values of transmissivity, (Rhén I., Forsmark T., 2001) and (Forsmark T., 2007), and borehole volumes, listed in Appendix 3, as well as the results from previous dilution tests in campaign 1, the test duration for each section was estimated at 24 hours except for the most low-transmissive fractures where the test duration was increased to approximately 72 hours. For exact dates and times of each test, see Table 3-1.

One of the sections intended for testing could not be measured due to gas in the test section and results are therefore only presented from 16 sections in this report.

The dilution method is based on a tracer being injected into the section with a constant flow rate during simultaneous circulation/mixing, until a homogeneous tracer concentration is reached in the system. For the Uranine tracer, this was achieved by injecting a 50 ppm tracer solution during a time period equivalent to the time it takes to circulate one section volume. During the tracer injection, the sampling flow rate is the same as the injection flow rate in order to avoid any pressure changes in the test section. The injection rate to circulation rate was set to 1/100 implying that the start concentration in the borehole should be about 0.5 ppm for the Uranine tracer. When using the Amino-G tracer, the concentration of the injected solution was 100 ppm aiming at a start concentration in the test section of 1.0 ppm. The higher start concentration of Amino-G solution is used to avoid background noise in the analyzing process.

When groundwater flows through the section the tracer will be diluted. The groundwater flow is calculated as a function of the decreasing tracer concentration with time, cf. Chapter 5.4.

As a complement, pressure was monitored (Äspö Hydro Monitoring System) in each of the tested boreholes in order to investigate any potential interferences or pressure disturbances during the performed dilution tests.

Table 5-1 summarises the test set-ups including calculated transmissivities (from previous investigations) and volumes. Locations of the boreholes in the Prototype Repository are shown in Figure 5-1 in both vertical and plan view.

Table 5-1. Data on test sections used in the Prototype Repository tracer dilution tests. T- values, transmissivity values, from (Rhén I., Forsmark T., 2001) and (Forsmark T., 2007), based on tests performed prior to the dilution measurements. In a few cases, no new tests have been conducted since campaign 1 and in those cases the same value is used in campaign 2 as well.

Bh section	Secup	Seclow	T (campaign 1) (m^2/s)	T (campaign 2) (m^2/s)	$V_{section+tubing}$ (dm^3)	Comments
KA3539G:2	15.85	17.6	1.0E-06	7.2E-07	7.66	IPR07-02
KA3542G01:3	18.6	20.3	3.1E-08	3.8E-08	7.68	IPR07-02
KA3542G02:2	25.6	27.2	8.7E-10	4.6E-10	7.49	IPR07-02
KA3544G01:2	8.9	10.65	7.4E-09	7.4E-09	7.69	Packer system leakage, IPR07-02
KA3546G01:2	6.75	8.3	1.1E-09	9.6E-10	6.83	IPR07-02
KA3548A01:3	8.8	10.75	1.1E-07	8.6E-08	8.29	IPR07-02
KA3550G01:2	5.2	7.3	4.4E-09	4.4E-09	9.05	Packer system leakage, IPR01-65
KA3552G01:2	4.35	6.05	8.1E-09	8.0E-10	7.36	IPR07-02
KA3554G01:2	22.6	24.15	4.9E-07	4.4E-07	7.19	IPR07-02
KA3554G02:4	10.5	12.2	1.2E-08	1.1E-08	7.60	IPR07-02
KA3563G:4	1.5	3	1.7E-7	5.1E-08	3.78	IPR07-02
KA3566G01:2	20	21.5	1.3E-10	3.3E-10	4.08	IPR07-02
KA3566G02:2	16	18	8.7E-09	8.7E-09	4.15	IPR01-65
KA3572G01:2	2.7	5.3	3.5E-09	3.5E-09	3.99	IPR07-02
KA3574G01:3	1.8	4.1	3.7E-10	3.7E-10	4.09	IPR01-65
KG0021A01:3	35	36	8.0E-07	5.7E-07	2.52	IPR07-02
KG0048A01:3	32.8	33.8	8.0E-08	7.4E-08	2.47	IPR07-02

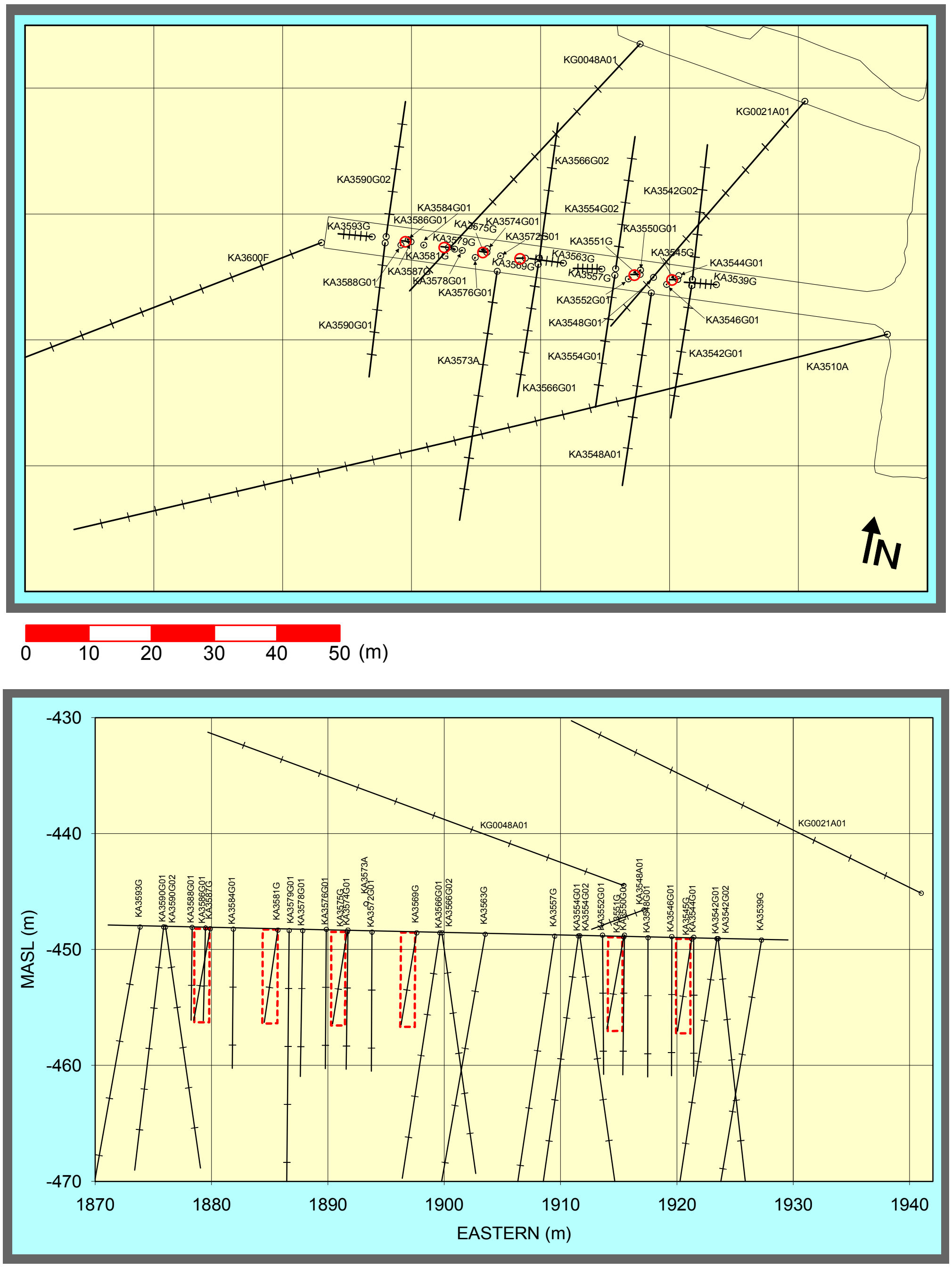

Figure 5-1. Plan view (upper) and vertical view (below) of the location of the boreholes in the Prototype Repository. In the plan view the G-tunnel, where the equipment was set up, is shown in the upper part of the picture.

5.3 Laboratory analyses

Samples were analysed for dye tracer content at the Geosigma Laboratory using a Jasco FP 777 Spectrofluorometer. For practical reasons, some of the analyses were performed at the BASLAB laboratory on the CLAB premises. At BASLAB a Turner Biosystems TD-700 fluorometer was used.

5.4 Evaluation and interpretation

5.4.1 Tracer dilution tests

Flow rates were calculated from the decay of tracer concentration versus time by means of dilution with natural unlabelled groundwater, cf. Gustafsson (2002). The so-called "dilution curves" were plotted as the natural logarithm of concentration versus time. Theoretically, a straight-line relationship exists between the natural logarithm of the relative tracer concentration (c/c_0) and time (Δt):

$$\ln (c/c_0) = -(Q_{bh}/V) \cdot \Delta t \qquad (5\text{-}1)$$

where Q_{bh} (m^3/s) is the groundwater flow rate through the borehole section and V (m^3) is the volume of the borehole section. By plotting ln (c/c_0) versus Δt, and by knowing the borehole volume V, Q_{bh} may then be obtained from the slope of the straight line. If c_0 is constant it is sufficient to use ln c in the plot.

The sampling procedure with a constant flow of 3-4 ml/h also creates a dilution of tracer. This flow rate is therefore subtracted from the value obtained from eq. 5-1.

5.4.2 Hydraulic gradient

Hydraulic gradients are roughly estimated from Darcy´s law where the gradient *(I)* is calculated as the function of the Darcy velocity *(v)* with the conductivity *(K):*

$$I = \frac{v}{K} = \frac{Q_{bh} \cdot L_{bh}}{\alpha \cdot A \cdot T_{bh}} = \frac{Q_{bh} \cdot L_{bh}}{2 \cdot d_{bh} \cdot L_{bh} \cdot T_{bh}} \qquad (5\text{-}2)$$

where Q_{bh} is the groundwater rate through the borehole section , L_{bh} is the length of the borehole section, T_{bh} the transmissivity of the section, A the cross section area between the packers and d_{bh} the borehole diameter which for the boreholes in the Prototype Repository is 76 mm.

The contraction factor α depends on the interference of the flow field in the fracture plane locally surrounding the borehole. For a homogeneous rock with the fracture cutting the borehole axis in 90^{o} the contraction factor α is equal to 2 according to Gustafsson (2002). Since the rock is mostly heterogeneous and the angles in the sections are not always 90^{o}, the calculation of the hydraulic gradient must be considered a rough estimate.

5.4.3 Nonconformities

- Section KA3566G02:2 was not tested. Gas was trapped inside the test section, and even though several attempts to escape the gas from the section were made, it was not possible to rid the section of enough gas to enable testing.

- During the dilution test in section KA3548A01:3 the circulation pump did not function properly. It was not possible to maintain the desired flow rate. Due to this the injection time was prolonged to make up for the lower flow rate.

6 Results and interpretation

6.1 Hydraulic conditions

During the first test campaign, the Prototype Repository tunnel was drained and the groundwater flow in each of the 17 sections therefore represented the situation with an enhanced hydraulic gradient (Gröhn et al., 2005). Apart from a short period between 2004-11-01 and 2004-12-06, the Prototype Repository tunnel has been constantly drained. Since the construction of the Prototype Repository tunnel the water pressure in the rock surrounding the tunnel has, generally speaking, decreased. It was considered likely that the ground water flow would decrease as time passed and more particularly, since the last dilution tests during campaign 1.

In Table 6-1 a comparison between the approximate prevailing pressure conditions in the tested borehole sections during campaign 1 and 2 are presented. It is clear that sections exhibiting relatively low pressure (c. 200-500 kPa) during the first campaign, have experienced an increasing pressure. Conversely, all sections with a high pressure during the first campaign, demonstrate a pressure decrease. These results indicate that the general pressure decrease that is an effect of the HRL-tunnel construction, have a larger impact on pressure than the local influence from the Prototype Repository.

There were no major pressure disturbances observed during the tests. It seems however, cf. Figure A2-3, that there is some interference between sections KA3546G01:2 and KA3552G01:2, indicating that these sections may be hydraulically connected.

Table 6-1. Approximate prevailing pressure conditions in the test sections included in the dilution tests. Comparison between campaign 1 and campaign 2.

Test section	Pressure, campaign 1 (kPa)	Pressure, campaign 2 (kPa)	Pressure change (kPa)	I, Gradient campaign 2 (m/m)	Comments
KA3539G:2	2010	1450	-560	0.1	
KA3542G01:3	3270	2435	-835	1.8	
KA3542G02:2	2320	1845	-475	23	
KA3544G01:2	200	660	460	45	Packer system leakage
KA3546G01:2	380	750	370	16	
KA3548A01:3	3360	2490	-870	1.3	
KA3550G01:2	200	670	470	108	Packer system leakage
KA3552G01:2	460	790	330	10	
KA3554G01:2	3630	2730	-900	0.1	
KA3554G02:4	1940	1320	-620	1.1	
KA3563G:4	340	750	410	0.01	
KA3566G01:2	1770	1130	-640	62	
KA3566G02:2	2780	-	-	-	Not measured due to gas in test section
KA3572G01:2	420	500	80	1.0	
KA3574G01:3	180	320	140	7.7	
KG0021A01:3	3000	2270	-730	0.1	
KG0048A01:3	3310	2530	-780	0.1	Extended injection time due to low circulation flow

6.2 Dilution tests

The evaluated flow rates in the sections from the dilution tests performed during both campaign 1 and 2 are presented in Table 6-2. In Table 6-3 the hydraulic gradients are presented, also from campaign 1 as well as campaign 2. Tracer injection data are listed in Table 6-4. The tests generally yield results that are consistent with the expectations and the data quality is fairly good. There are some circumstances regarding the tests or uncertainties concerning the calculation of the groundwater flow that need to be commented on:

In Table 6-2 the accuracy of the calculated flow is reported. It is divided in two parts. The first column addresses the uncertainty due to volume calculations. In Table 6-4 there is a comparison between the calculated injection concentration (based on known volumes) and analysed tracer concentration in the different sections included in the tests. The difference between these two parameters provides a measure of uncertainty of the volume calculations which in turn are directly proportional to the calculated flow rates. In the second column, the uncertainty from the graph fitting is given. Since the slope of the tracer dilution diagrams (Appendix 1), is the basis for the flow rate calculations and there is an aspect of subjective selection included in this process, an uncertainty has been appointed to the fitting procedure. The uncertainty is an approximation based on different choices of points to include in the graph fitting calculations. In most cases the real uncertainty due to graph fitting is expected to be smaller than reported.

In some of the tests, a higher dilution rate can be observed in the early time data. This is most probably an effect of the pressure disturbance created when attaching the dilution equipment. Early time data is therefore generally omitted in the test evaluation, cf. Appendix 1.

All of the non-leaking sections display flows that are lower than in the results from the previously performed investigation (Gröhn et al., 2005). The flow has decreased between 20% and up to 97% compared to campaign 1, cf. Table 6-2. The average decrease is 50%. A lower flow is consistent with the expectations since the general pressure conditions in the surrounding rock have decreased in time.

The exact length of the tubing from each section is not known. This will introduce some uncertainty in the volume calculations. Calculated volumes of the section between packers are however very accurate. A good check of the accuracy of the volume determination is to compare the theoretical concentration of tracer in the borehole section at the start of the test to the actually measured one. The data presented in Table 6-4 shows that there is a reasonably good agreement in 12 of the sections.

One of the four sections where the measured concentration differs from the theoretical concentration has a packer leakage (KA3550G01:2) which explains the discrepancy.

Section KG0021A01:3 has a very small volume which makes it important to have the correct tubing length thus, the volume, and consequently also the flow may be erroneously estimated. If the measured concentration in the section is correct, it implies a section volume that is about 72% larger than reported (corresponding to a concentration decrease of c. 42%). It should be noted that in the previous dilution measurements, performed during campaign 1 (Gröhn et al., 2005), very similar results were reached. This may be an indication of the effective section volume actually being larger than has previously been reported. As a consequence of this the flow rate through the section may also be about 72 % larger than reported in Table 6-2.

Also sections KA3574G01:3 and KA3563G:4 demonstrate inconsistencies between theoretical and actual tracer concentration indicating that the volumes may be wrongly estimated.

The uncertainty of the analyses of the tracers is ± 2% based on replication measurement made by Geosigma Laboratory (the same measurements have not been performed for the equipment at CLAB). This affects the fits of the dilution graphs (logarithm of concentration versus time) in sections having very slow dilution (low flow). Dilution graphs from all 16 measured sections are presented in Appendix 1 with uncertainty presented as R-squared, see also Table 6-2. The fits are generally good, 11 of the 16 tests show R^2-values larger than 0.8, but in sections having low flow rates (approximately <10 ml/h) the uncertainty increases. It is evident that even analyses of sections with a low flow, produce good fits if the testing time is long enough, cf. Table 6-2. It is likely that some of the sections showing a less good fit would benefit from longer testing periods.

The measurement limit of the groundwater flow is set to 3 ml/h since the sampling of the water during the test is approximately 3-4 ml/h. This also increases the uncertainty for the determination of low flow rates (<10 ml/h). Sections KA3544G01:2 and KA3550G01:2 were expected to have a packer system leakage and this was confirmed during the performed tracer dilution tests. The flow in KA3544G01:2 was, however, not as large as in previous tests. The groundwater flow rates are still much higher than in the other sections, and also higher than would be expected for natural conditions. This indicates leakage of water to neighboring sections.

6.3 Hydraulic gradient

The hydraulic gradients of the test sections are presented in Table 6-3. Note that these are rough estimated based on several assumptions, as discussed in Chapter 5.4.2, and should not be used as exact data. The estimated gradients vary between 0.01 and 62 m/m for 15 of the 16 sections (including one of the leaking sections at 45 m/m). The two leaking sections exhibit large values, as expected. The gradients are generally high (>1 m/m) except for a few sections at rather long distance from the tunnel (KA3539G:2, KA3554G01:2, KG0021A01:3 and KG0048A01:3). One may expect that gradients increase towards the tunnel and thus, that sections having low pressures also would display high gradients. This also seems to be the case, c.f. Table 6.1. However, there are a few exceptions that either have large estimated gradients although they are located at some distance from the tunnel, KA3542G02:2 and KA3566G01:2, or has a low gradient, although being close to the tunnel, KA3563G:4. The exact reasons for these anomalous gradients are not known but may be a combination of uncertainties related to the determination of groundwater flow, transmissivity and the gradient itself, as discussed in Chapter 5.4.2.

Table 6-2. Results from tracer dilution tests in the Prototype Repository, a comparison between campaign 1 and 2. Tubing is included in the specified section volume.

Test section	V (dm^3)	$Q_{natural}$, camp. 1 (ml/h)	$Q_{natural}$ camp. 2 (ml/h)	Flow decrease (%)	Accuracy camp. 2 ± (ml/h) [2]		Regression coefficient	Comments
KA3539G:2	7.66	56	43	23	4	3	0.94	
KA3542G01:3	7.68	223	38	83	2	2	0.87	
KA3542G02:2	7.49	9.0	5.9	35	0.1	5	0.60	
KA3544G01:2	7.69	(384)	(181)	(53)	4	5	0.99	Packer system leakage
KA3546G01:2	6.83	(15) [1]	8.2	46	1	2	0.48	
KA3548A01:3	8.29	90	60	34	4	3	0.93	
KA3550G01:2	9.05	(255)	(260)	(-2.0)	29	7	0.99	Packer system leakage
KA3552G01:2	7.36	12	4.6	62	0.6	0.2	0.67	
KA3554G01:2	7.19	66	23	66	3	2	0.95	
KA3554G02:4	7.60	8.4	6.4	24	0	2	0.58	
KA3563G:4	3.78	14	0.4	97	0.1	0.3	0.76	
KA3566G01:2	4.08	19	11	41	0.8	0.5	1.00	Extended test duration
KA3566G02:2	4.15	3.1	-	-	-	-	-	Not measured due to gas in test section
KA3572G01:2	3.99	6.0	2.0	67	0.2	0.4	0.99	Extended test duration
KA3574G01:3	4.09	3.8	1.6	59	0.8	0.2	0.97	Extended test duration
KG0021A01:3	2.52	56	45	20	18	0.2	1.00	
KG0048A01:3	2.47	7.8	4.2	46	0.6	0.1	0.96	Extended test duration

[1] Valve leakage during the dilution of campaign 1.
[2] The uncertainty of the calculated flow constitutes of two parts. In the first column the uncertainty due to the volume approximation is described. The second column reports the uncertainty contributed by the fortuitous aspect of the graph fitting, which is the base for the flow rate calculations. The uncertainties can be considered independent and may be added together.

Table 6-3. Results from tracer dilution tests in the Prototype Repository, a comparison between campaign 1 and 2.

Test section	I Gradient (camp. 1) (m/m)	I Gradient (camp. 2) (m/m)	Decrease (%)	Comments
KA3539G:2	0.1	0.1	-7	
KA3542G01:3	13.1	1.8	86	
KA3542G02:2	18.9	23	-23	
KA3544G01:2	94.8	(45)	53	Packer system leakage
KA3546G01:2	24.9	16	38	
KA3548A01:3	1.5	1.3	15	
KA3550G01:2	105.9	(108)	-2	Packer system leakage
KA3552G01:2	2.7	10	-286	
KA3554G01:2	0.2	0.1	62	
KA3554G02:4	1.3	1.1	17	
KA3563G:4	0.2	0.01	92	
KA3566G01:2	267.1	62	77	Extended test duration
KA3566G02:2	0.7	-	-	Not measured due to gas in test section (camp. 2)
KA3572G01:2	3.1	1.0	67	Extended test duration
KA3574G01:3	18.8	7.7	59	Extended test duration
KG0021A01:3	0.1	0.1	-13	
KG0048A01:3	0.2	0.1	41	Extended test duration

[1)] Valve leakage during the dilution of campaign 1.

Table 6-4. Comparison of calculated injection concentration (based on known volumes) and analysed tracer concentration from dilution tests in Prototype Repository.

Test section	Tracer	Calculated C_0 in test section (mg/l)	Analysed C_0 in test section (mg/l)	Comments
KA3539G:2	Uranine	0.49	0.54	
KA3542G01:3	Uranine	0.50	0.53	
KA3542G02:2	Uranine	0.50	0.51	
KA3544G01:2	Amino-G acid	1.00	1.02	Packer system leakage
KA3546G01:2	Uranine	0.50	0.56	
KA3548A01:3	Uranine	0.51	0.54	
KA3550G01:2	Amino-G acid	1.00	0.88	Packer system leakage
KA3552G01:2	Uranine	0.50	0.56	
KA3554G01:2	Uranine	0.51	0.45	
KA3554G02:4	Uranine	0.51	0.51	
KA3563G:4	Uranine	0.49	0.68	
KA3566G01:2	Amino-G acid	0.98	1.06	
KA3566G02:2	-	-	-	Not measured due to gas in test section
KA3572G01:2	Uranine	0.50	0.55	
KA3574G01:3	Uranine	0.49	0.25	
KG0021A01:3	Uranine	0.50	0.29	
KG0048A01:3	Uranine	0.51	0.44	Extended injection time due to low circulation flow

6.4 Supporting data

The pressure data from each section during the tests are displayed in Appendix 2. These data are collected from the HMS. In Figure A2-1 through A2-3, pressure curves from all sections included in the dilution test, for the duration of the entire test campaign, are presented. In these diagrams, a possible interference between sections may be discovered. In Figure A2-4 through A2-19, pressure curves for each section, at the time of each individual dilution test, are shown. There are no major pressure disturbing activities observed during the period. However, a few of the sections show pressure changes related to the tracer dilution tests. In section KA3566G01:2 the displayed pressure exhibit a rather erratic behavior and the pressure is increasing for the duration of the test. The pressure in the test section prior to the start of the test is approximately 50 kPa lower than the pressure in the test section after the test is finished and the circulation line is closed again.

Figures *A2-20* through *A2-35* display the pressure of all sections in every individual borehole that was included in the dilution tests. These diagrams can be used to identify possible hydraulic connections between different sections of the same borehole. There seems to be some interference in some of the boreholes. No major disturbances however, with the exception of borehole KA3546G01 where section 3 appears to be strongly affected by pressure changes in section 2 (where the dilution test was performed).

A general observation is that in most sections of low transmissivity ($T<10^{-8}$ m^2/s), there is a decreasing pressure of between 10-90 kPa in the section. This is due to the constant sampling rate of 2-4 ml/h that affect the pressure in these low transmissive sections, but not notably in the high transmissive sections. The sampling flow rate has been subtracted from the results.

7 Discussion and conclusions

The determination of flow rates using the tracer dilution method was performed under prevailing gradients and represents the groundwater flow through each of the 16 sections during natural conditions. There was no major pressure disturbance during the tests and no interference between the sections was observed with two exceptions: In borehole KA3546G01 there is an indication of a cross-connection between section 2 and 3. Also there are signs of interference between sections KA3546G01:2 and KA3552G01:2.

The magnitude of flow is governed by the local transmissivity of the borehole section and the hydraulic gradient. During prevailing gradient conditions, flow rates in the Prototype Repository vary by between 0.4 and 60 ml/h (c.f. Table 6-2) and there is a fairly good correlation between transmissivity and flow rate, as shown in Figure 7-1.

No groundwater flow could be calculated for KA3550G01:2 and KA3544G01:2 since the determined values represent leakage rather than flow through fractures intersecting the section. In addition, no measurements could be completed in section KA3566G02:2 due to gas being trapped inside the test section.

As expected, most of the non-leaking sections included in the test exhibit a lower flow than was measured during the last dilution campaign, presumably due to the generally lower pressure levels that are prevailing in the rock surrounding the Prototype repository tunnel compared to the conditions during test campaign 1. The flow rates had decreased between 20 to 97% since the last campaign.

Many of the low flowing sections would presumably benefit from longer measuring times in order to get more certain estimates of flow rate.

One may expect that gradients increase towards the tunnel and thus, that sections having low pressures also would display high gradients. This also seems to be the case, c.f. Table 6.1. However, there are a few exceptions that either have large estimated gradients although they are located at some distance from the tunnel, KA3542G02:2 and KA3566G01:2, or has a low gradient, although being close to the tunnel, KA3563G:4. The exact reasons for these anomalous gradients are not known but may be a combination of uncertainties related to the determination of groundwater flow, transmissivity and the gradient itself, as discussed in Chapter 5.4.2.

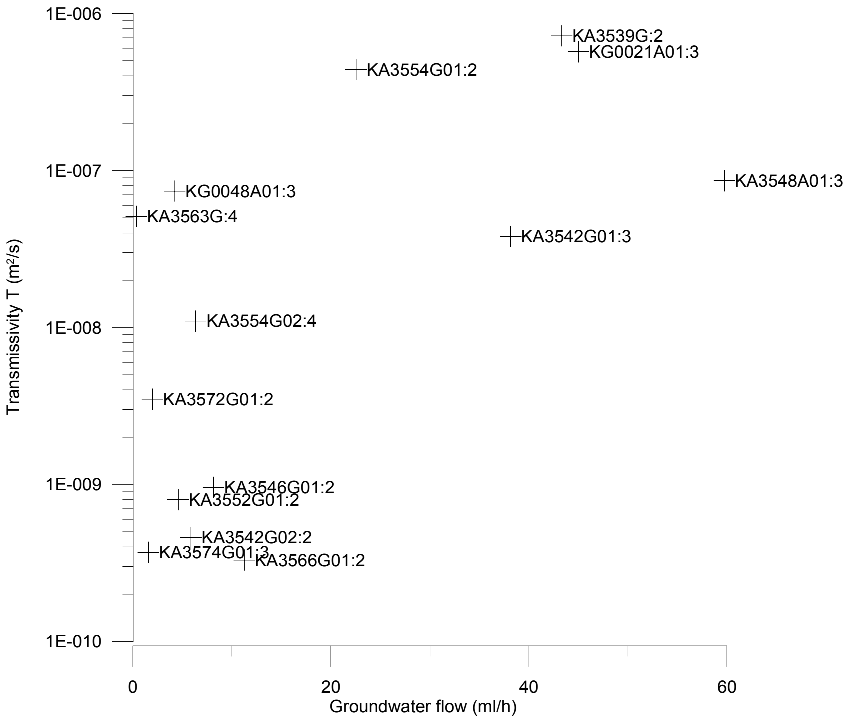

Figure 7-1. *Logarithm of transmissivity versus groundwater flow rate for the sections measured in the tracer dilution test, campaign 2 (leaking sections excluded).*

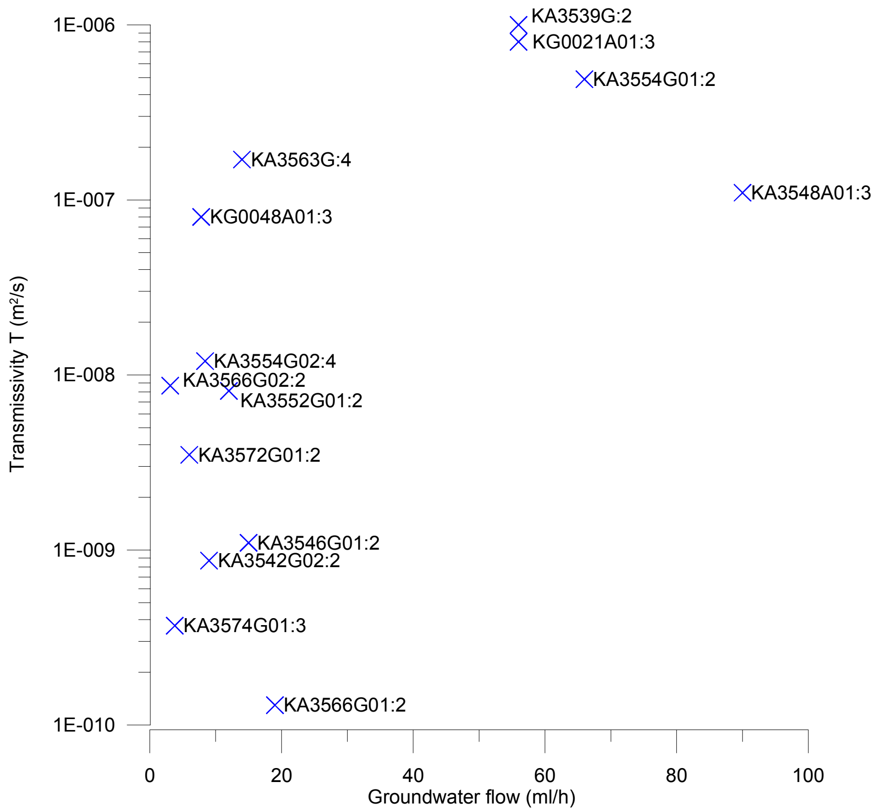

Figure 7-2. *Logarithm of transmissivity versus groundwater flow rate for the sections measured in the tracer dilution test, campaign 1 (leaking sections excluded).*

8 References

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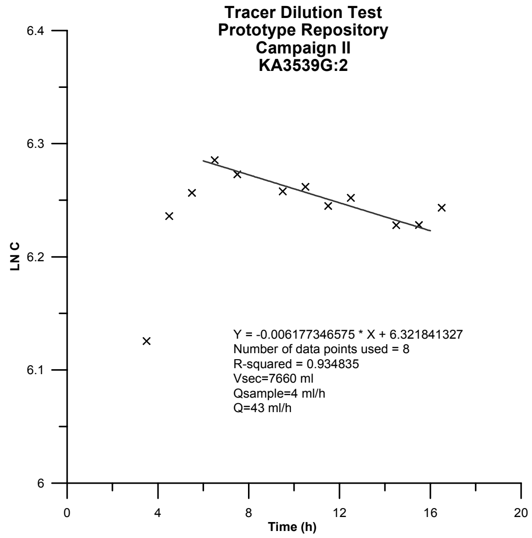
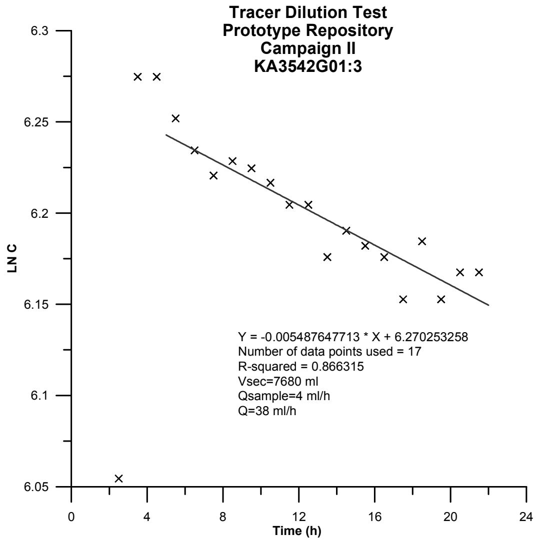
Svensk Kärnbränslehantering AB.

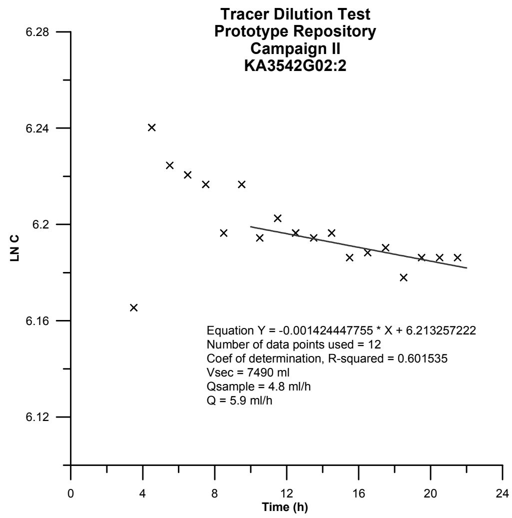
9 Appendices

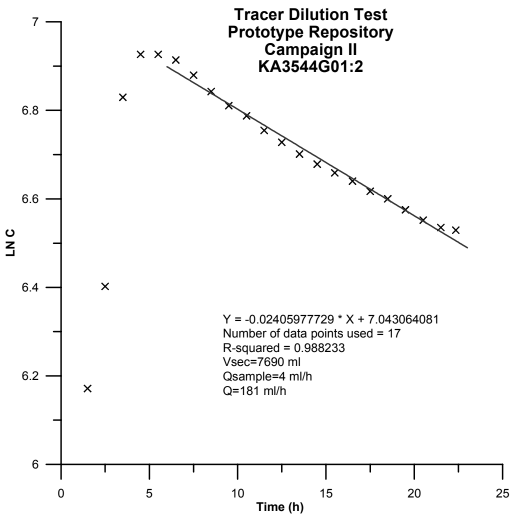
Appendix 1

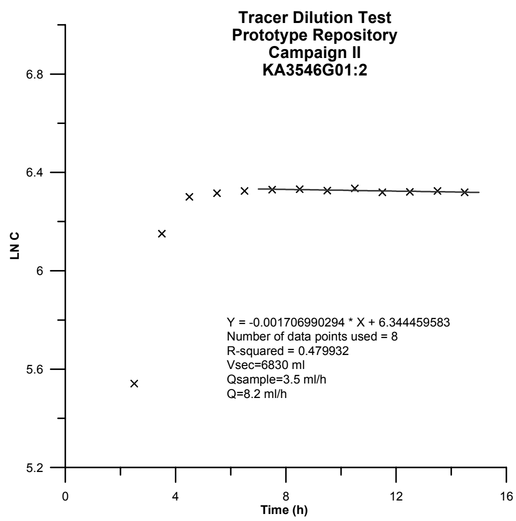
Tracer dilution diagrams

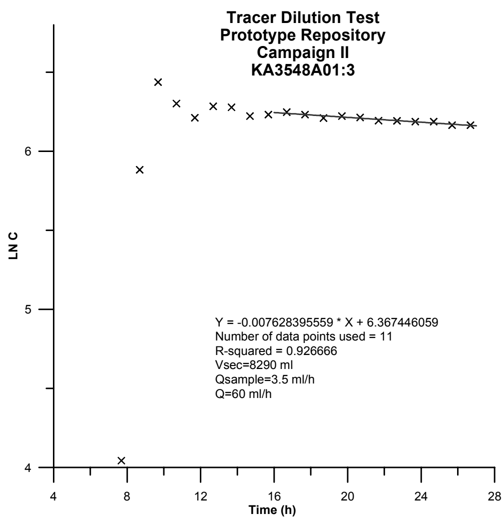


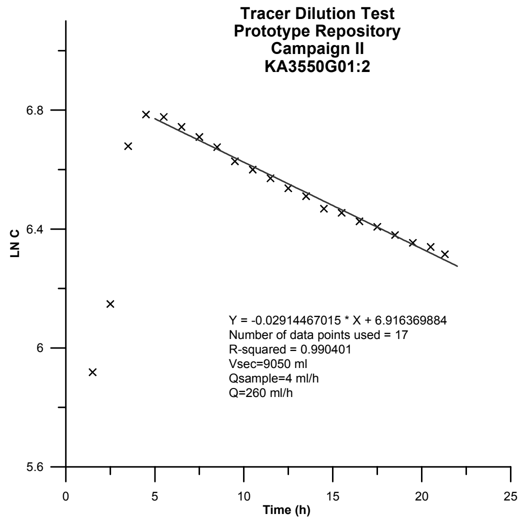


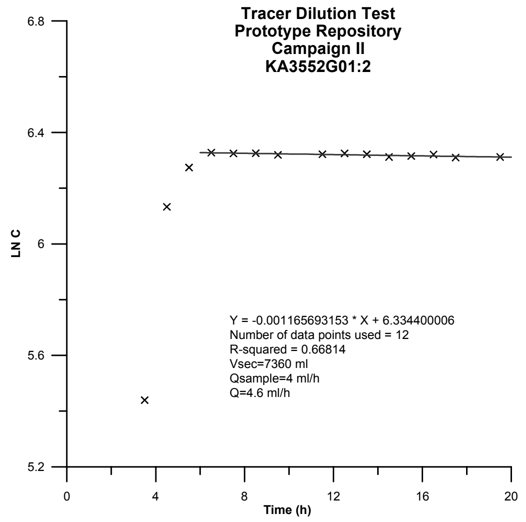









Tracer Dilution Test
Prototype Repository
Campaign II
KA3550G01:2
Y = -0.02914467015 * X + 6.916369884
Number of data points used = 17
R-squared = 0.990401
Vsec=9050 ml
Qsample=4 ml/h
Q=260 ml/h
LN C
Time (h)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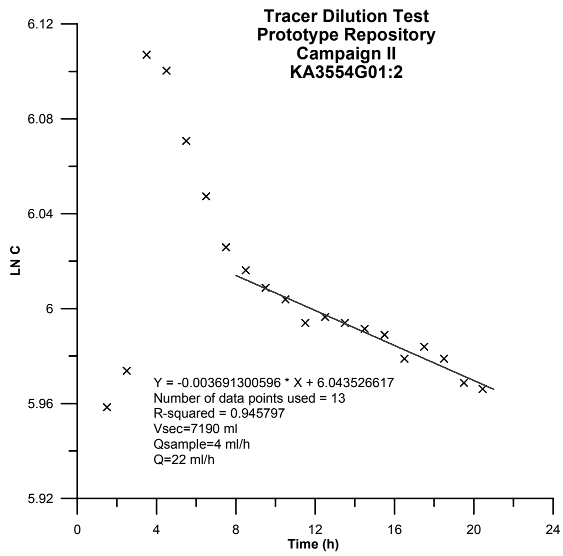
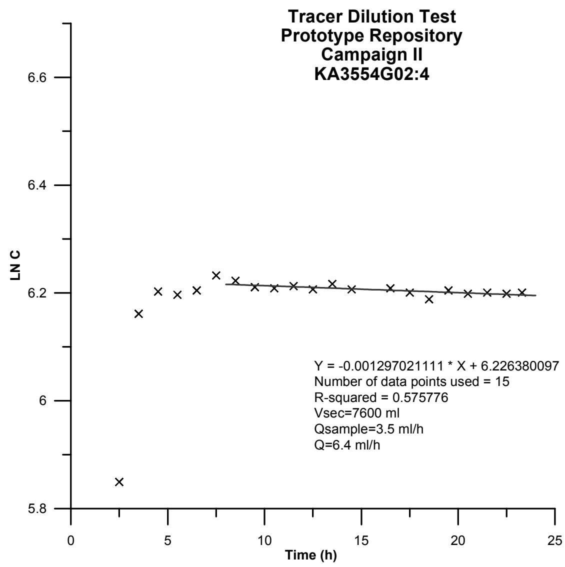
Prototype Repository
Campaign II
KA3552G01:2
Y = -0.001165693153 * X + 6.334400006
Number of data points used = 12
R-squared = 0.66814
Vsec=7360 ml
Qsample=4 ml/h
Q=4.6 ml/h
LN C
Time (h)


Tracer Dilution Test
Prototype Repository
Campaign II
KA3554G01:2
Y = -0.003691300596 * X + 6.043526617
Number of data points used = 13
R-squared = 0.945797
Vsec=7190 ml
Qsample=4 ml/h
Q=22 ml/h
LN C
Time (h)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Campaign II
KA3554G02:4
Y = -0.001297021111 * X + 6.226380097
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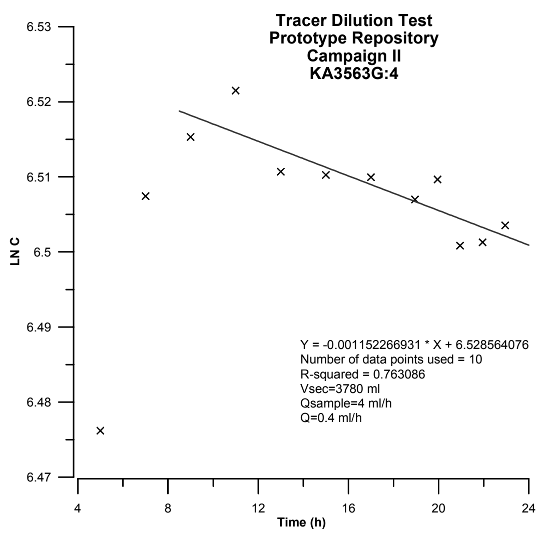
R-squared = 0.575776
Vsec=7600 ml
Qsample=3.5 ml/h
Q=6.4 ml/h
LN C
Time (h)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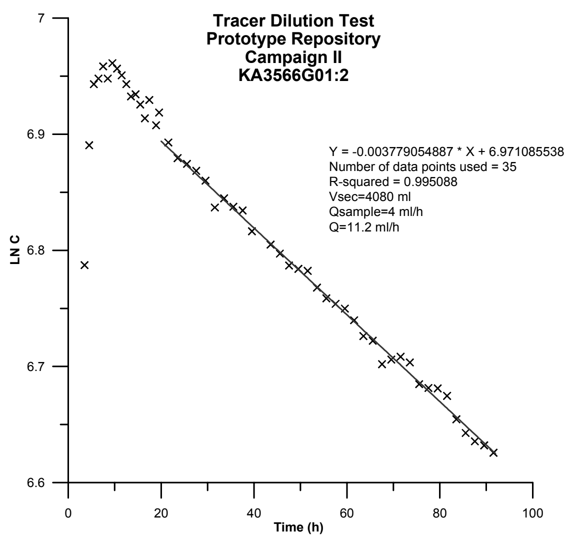
Vsec=3780 ml
Qsample=4 ml/h
Q=0.4 ml/h
LN C
Time (h)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Campaign II
KA3566G01:2
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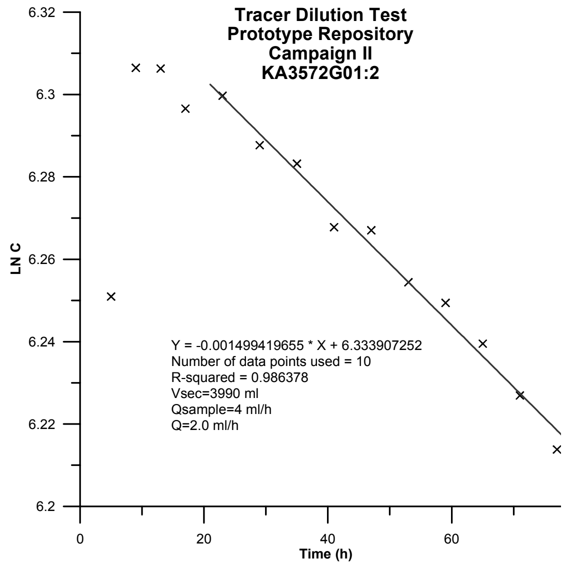
Q=11.2 ml/h
LN C
Time (h)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Campaign II
KA3572G01:2
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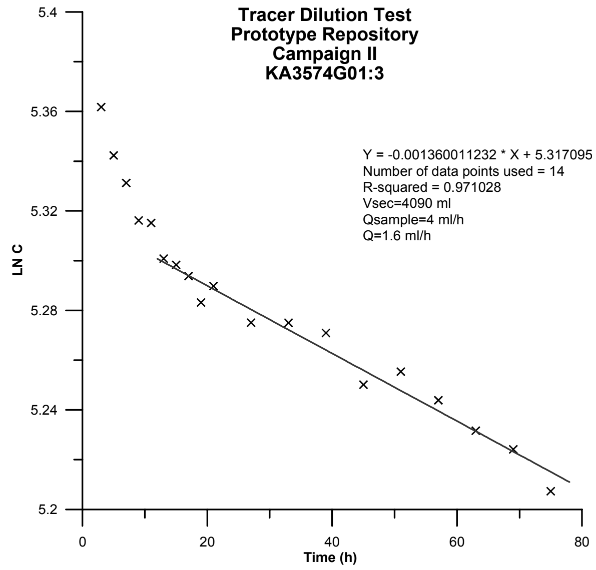
Number of data points used = 10
R-squared = 0.986378
Vsec=3990 ml
Qsample=4 ml/h
Q=2.0 ml/h
LN C
Time (h)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Campaign II
KA3574G01:3
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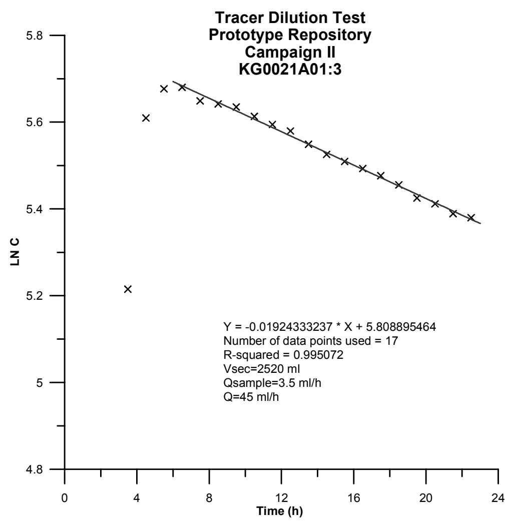
Number of data points used = 14
R-squared = 0.971028
Vsec=4090 ml
Qsample=4 ml/h
Q=1.6 ml/h
LN C
Time (h)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Prototype Repository
Campaign II
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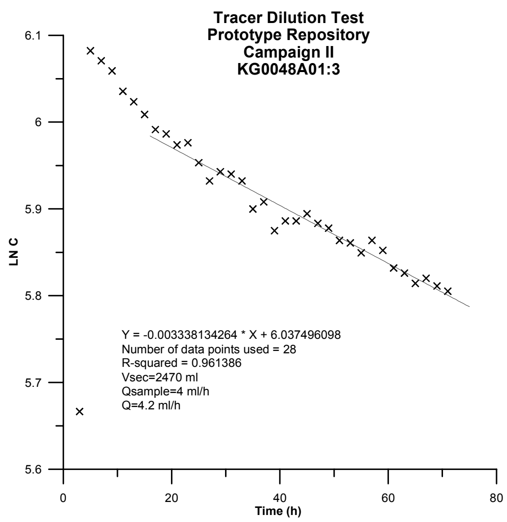
Qsample=3.5 ml/h
Q=45 ml/h
LN C
Time (h)


Tracer Dilution Test
Prototype Repository
Campaign II
KG0048A01:3
Y = -0.003338134264 * X + 6.037496098
Number of data points used = 28
R-squared = 0.961386
Vsec=2470 ml
Qsample=4 ml/h
Q=4.2 ml/h
LN C
Time (h)

Appendix 2

Pressure data from included test sections

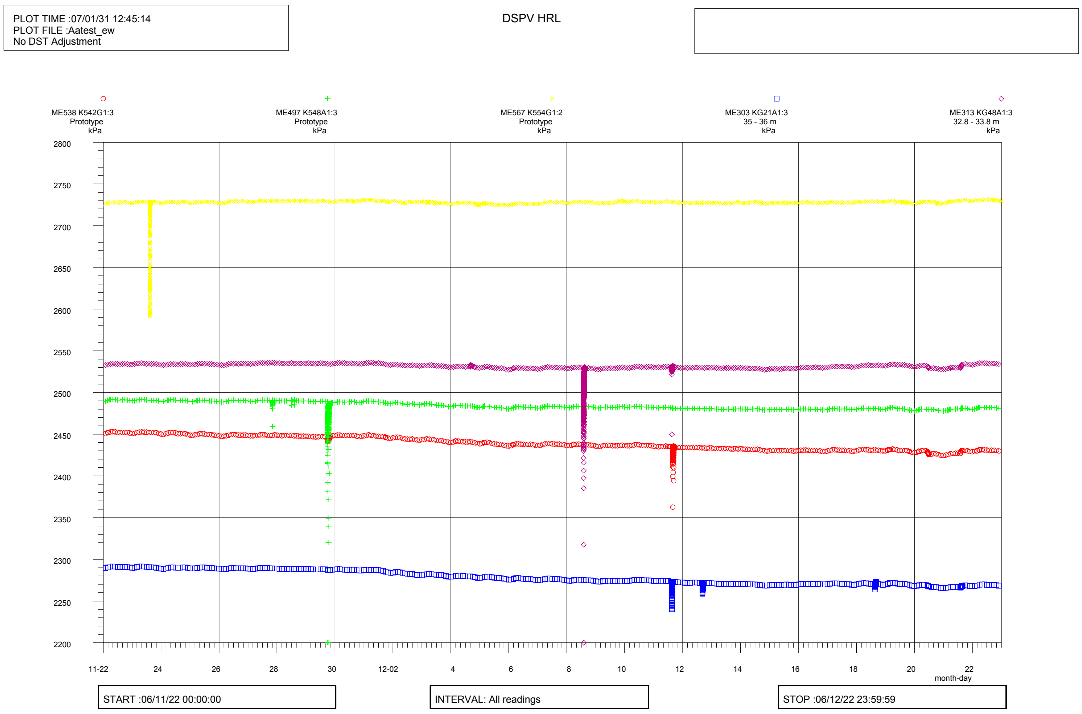


Figure A2-1. Plot showing the pressure in selected sections included in the dilution test during the duration of the entire test.

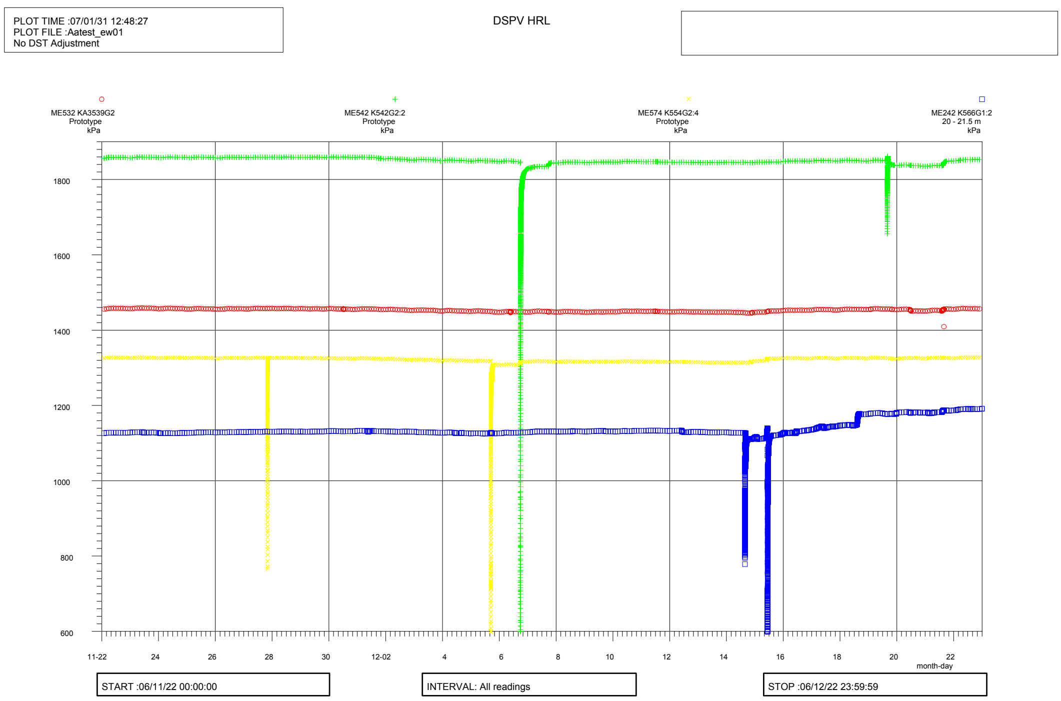


Figure A2-2. Plot showing the pressure in selected sections included in the dilution test during the duration of the entire test.

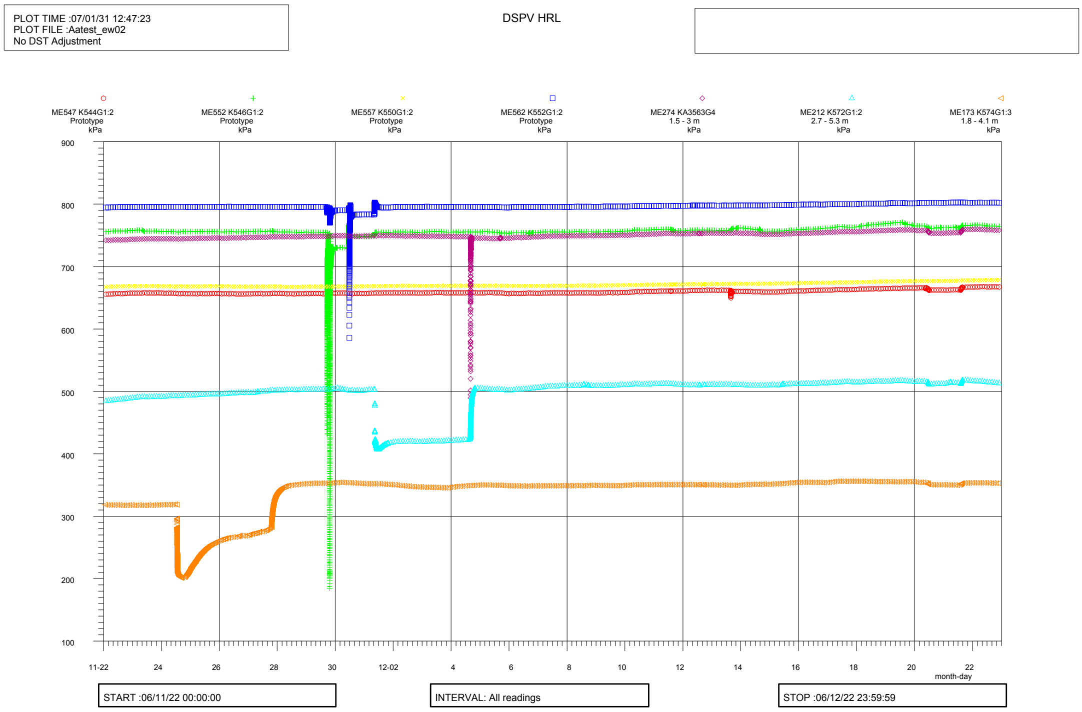


Figure A2-3. *Plot showing the pressure in selected sections included in the dilution test during the duration of the entire test.*

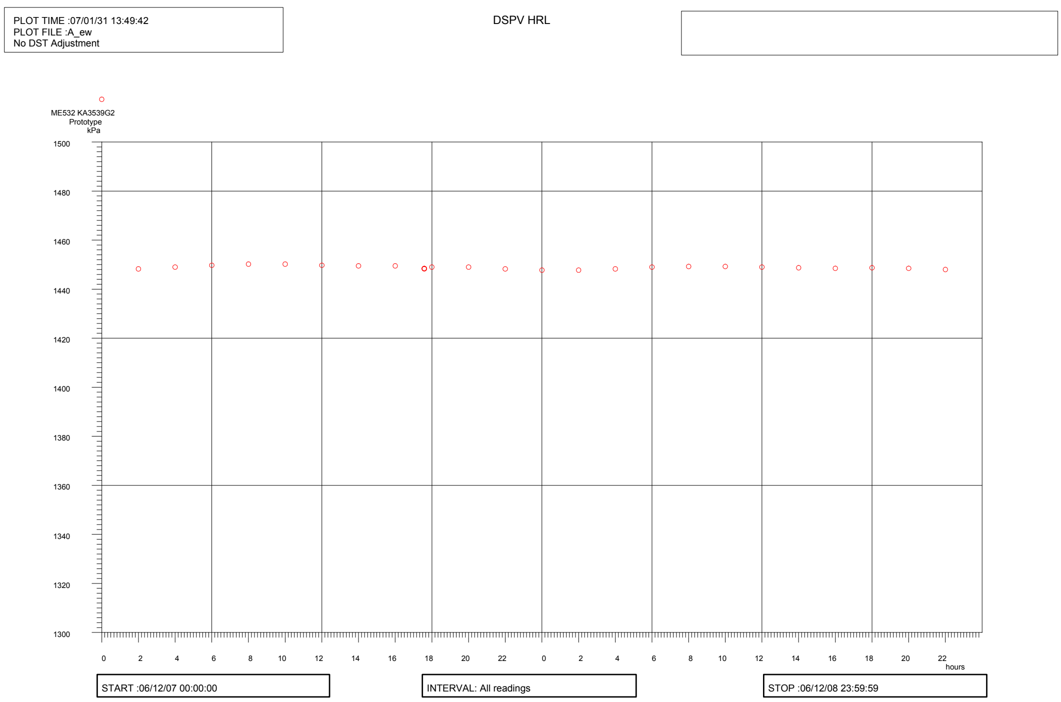


Figure A2-4. *Plot showing the pressure in KA3539G:2 during the performed dilution test in that section.*

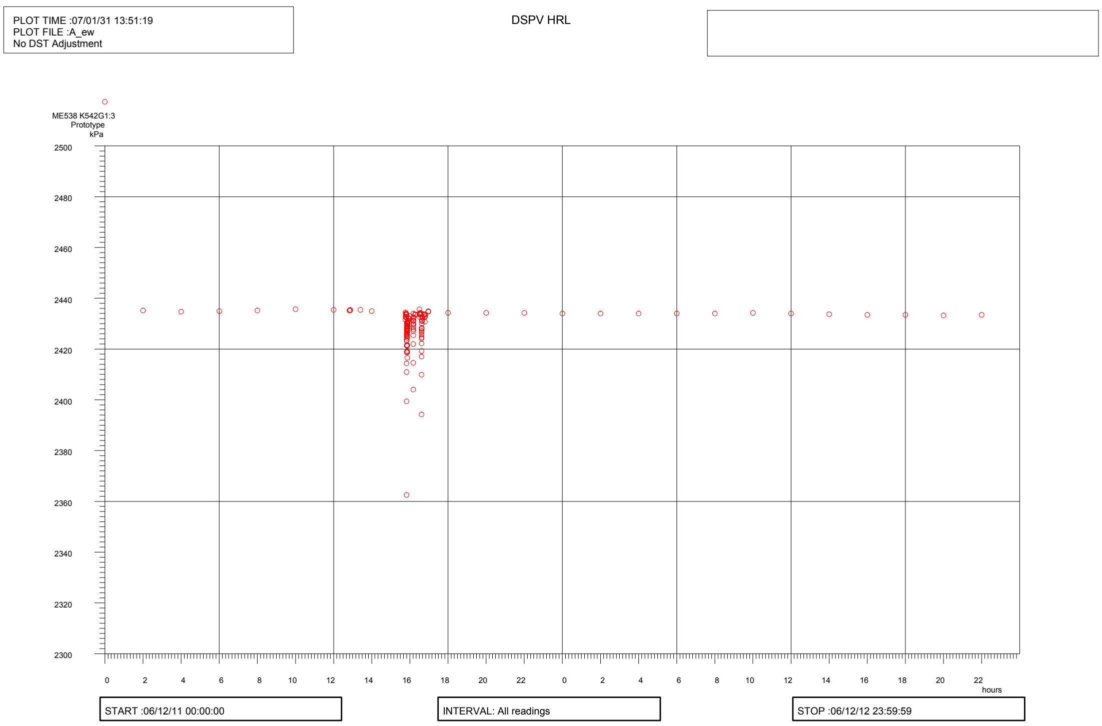


Figure A2-5. *Plot showing the pressure in KA3542G01:3 during the performed dilution test in that section.*

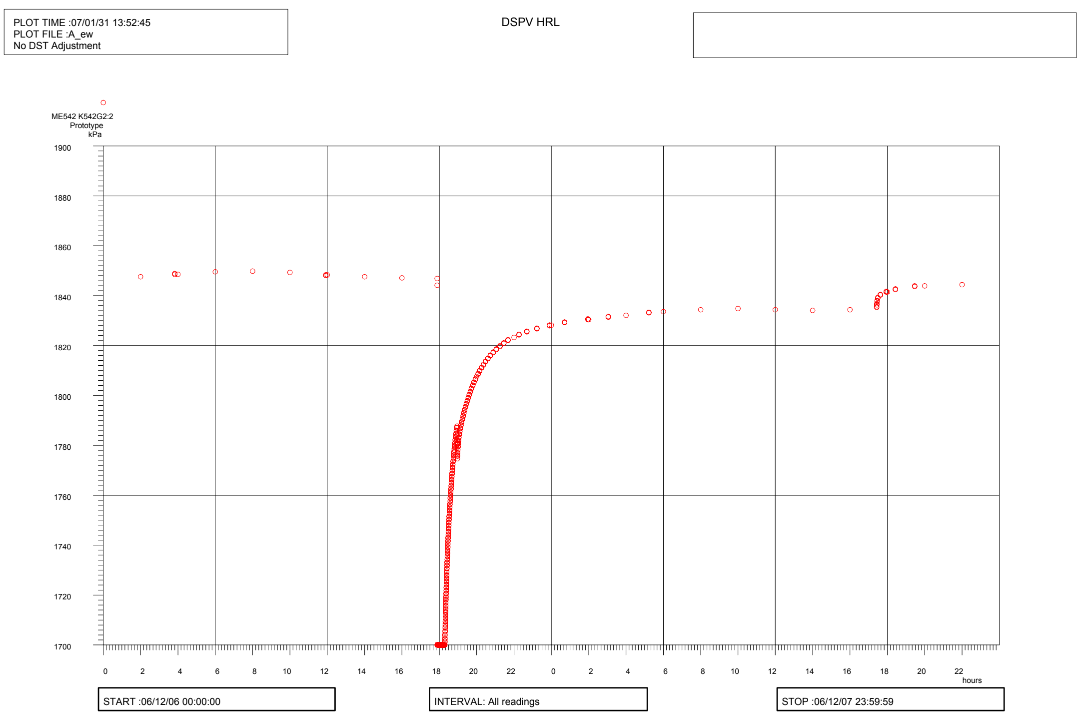


Figure A2-6. *Plot showing the pressure in KA3542G02:2 during the performed dilution test in that section.*

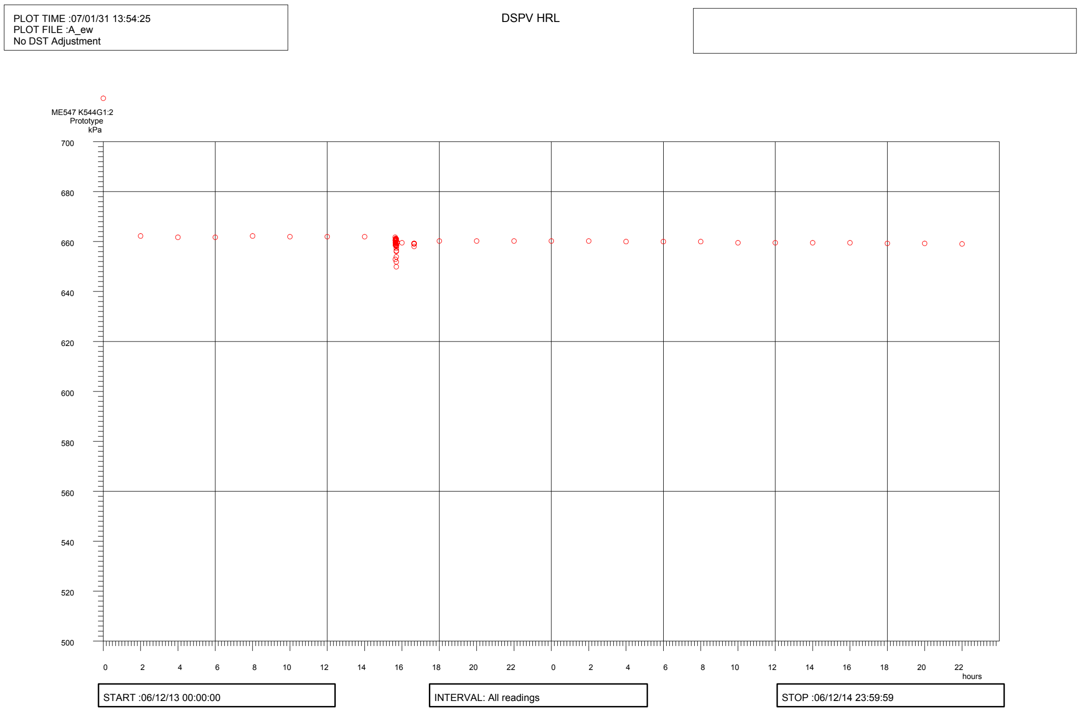


Figure A2:7. *Plot showing the pressure in KA3544G01:2 during the performed dilution test in that section.*

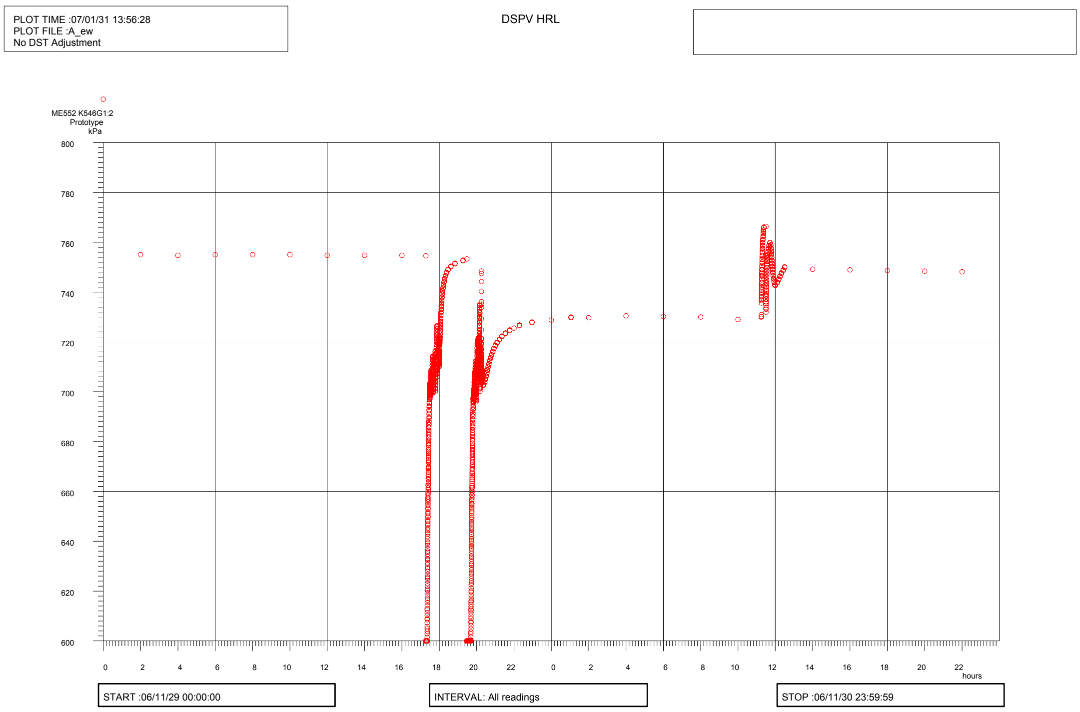


Figure A2-8. *Plot showing the pressure in KA3546G01:2 during the performed dilution test in that section.*

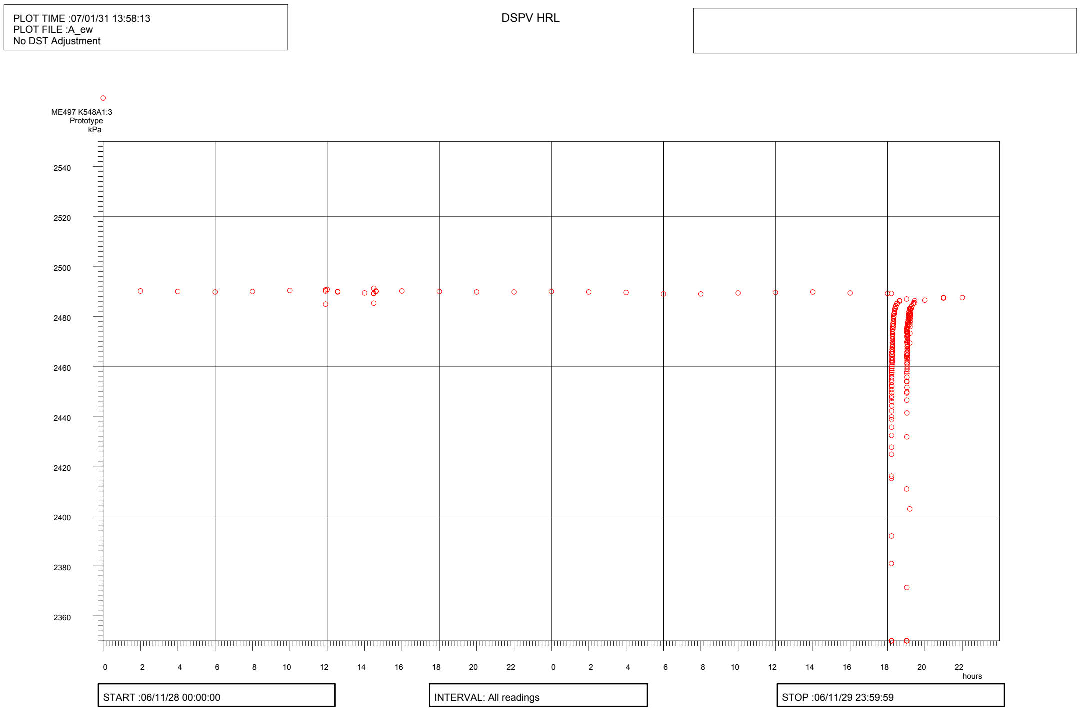


Figure A2-9. *Plot showing the pressure in KA3548A01:3 during the performed dilution test in that section.*

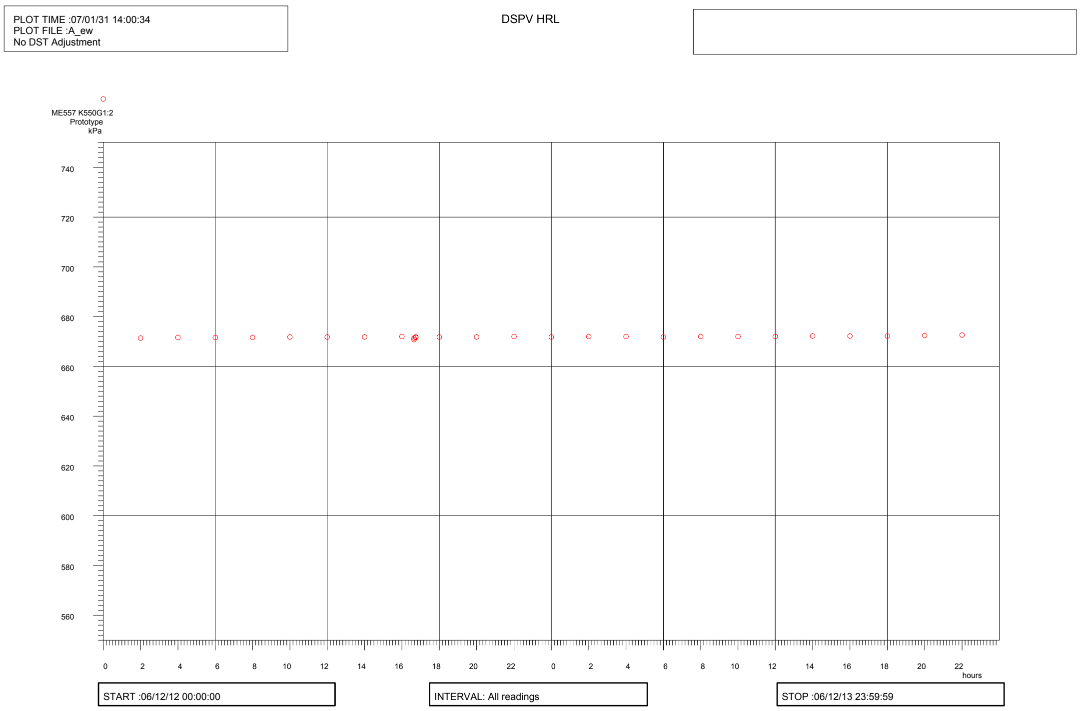


Figure A2-10. *Plot showing the pressure in KA3550G01:2 during the performed dilution test in that section.*

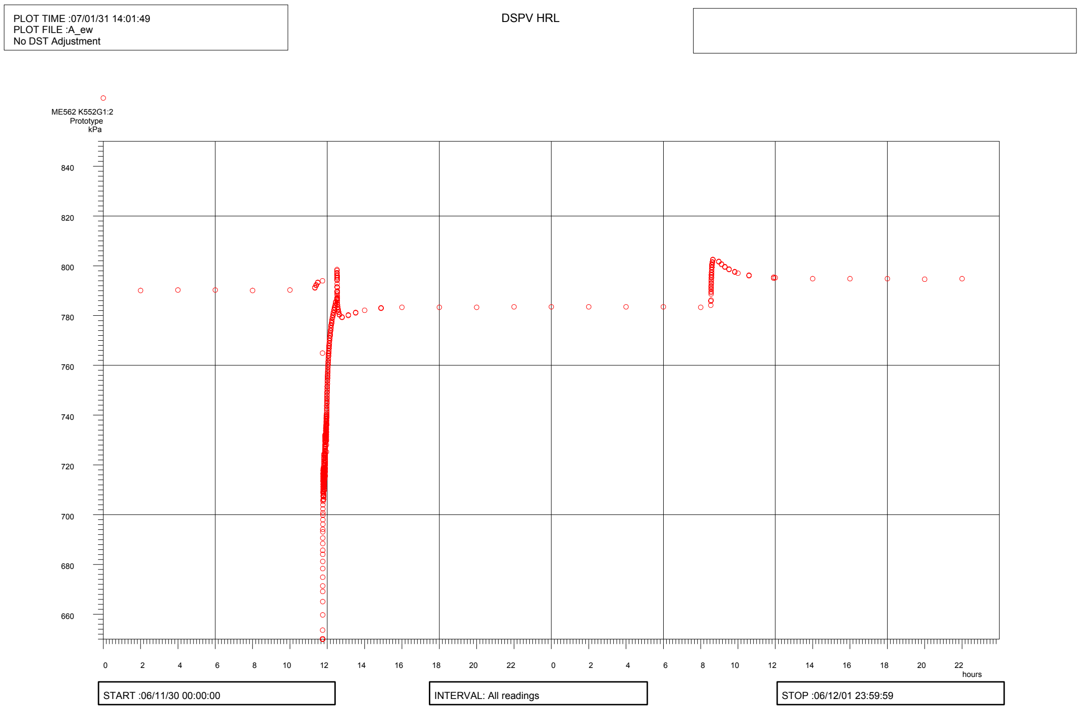


Figure A2-11. *Plot showing the pressure in KA3552G01:2 during the performed dilution test in that section.*

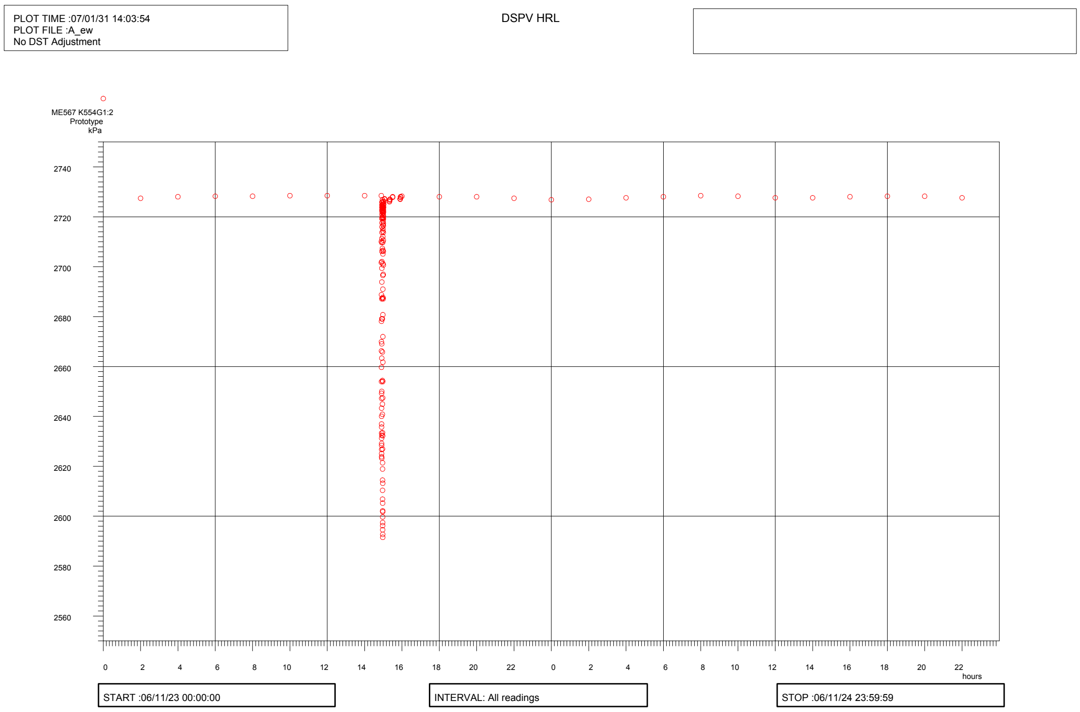


Figure A2-12. *Plot showing the pressure in KA3554G01:2 during the performed dilution test in that section.*

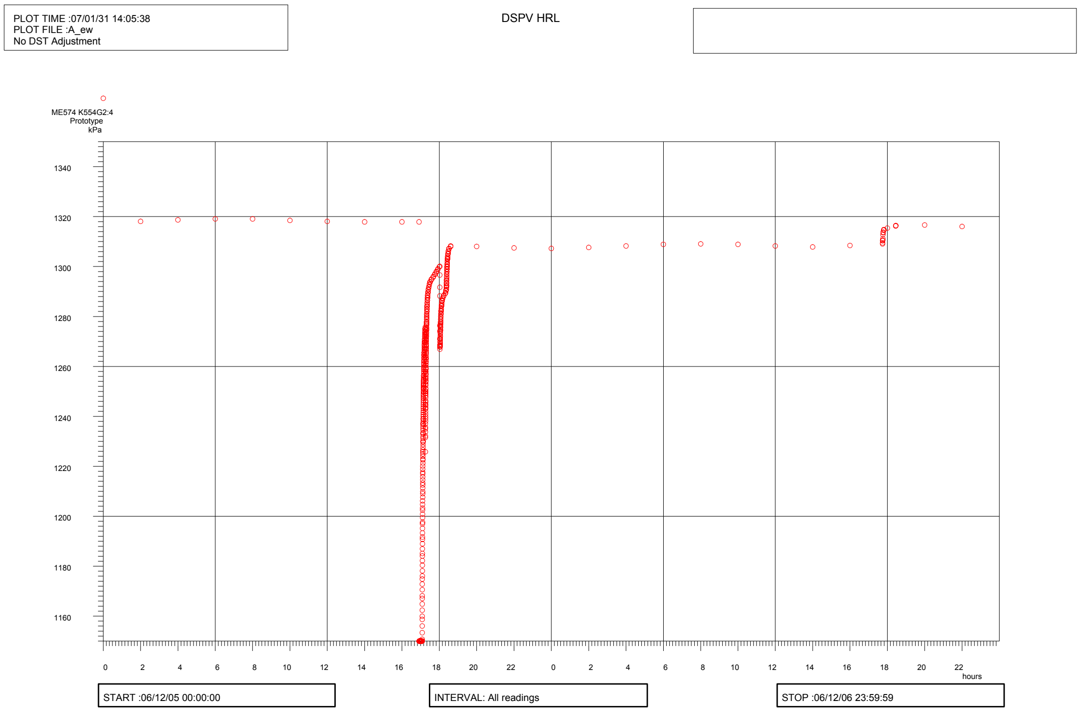


Figure A2-13. *Plot showing the pressure in KA3554G02:4 during the performed dilution test in that section.*

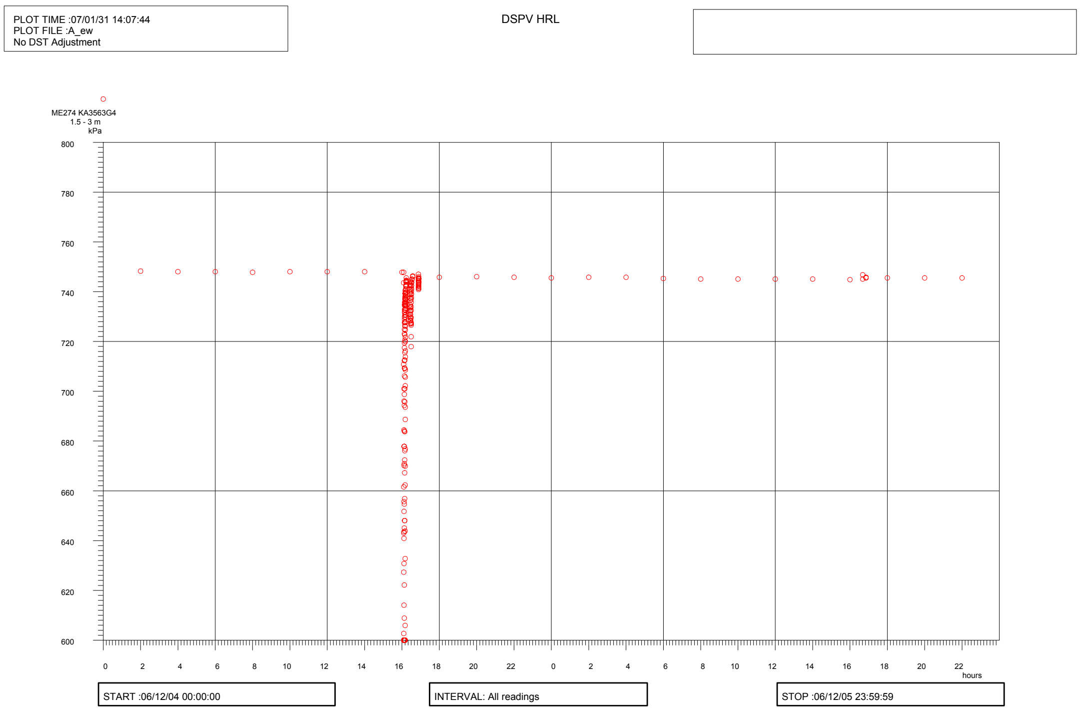


Figure A2-14. *Plot showing the pressure in KA3563G:4 during the performed dilution test in that section.*

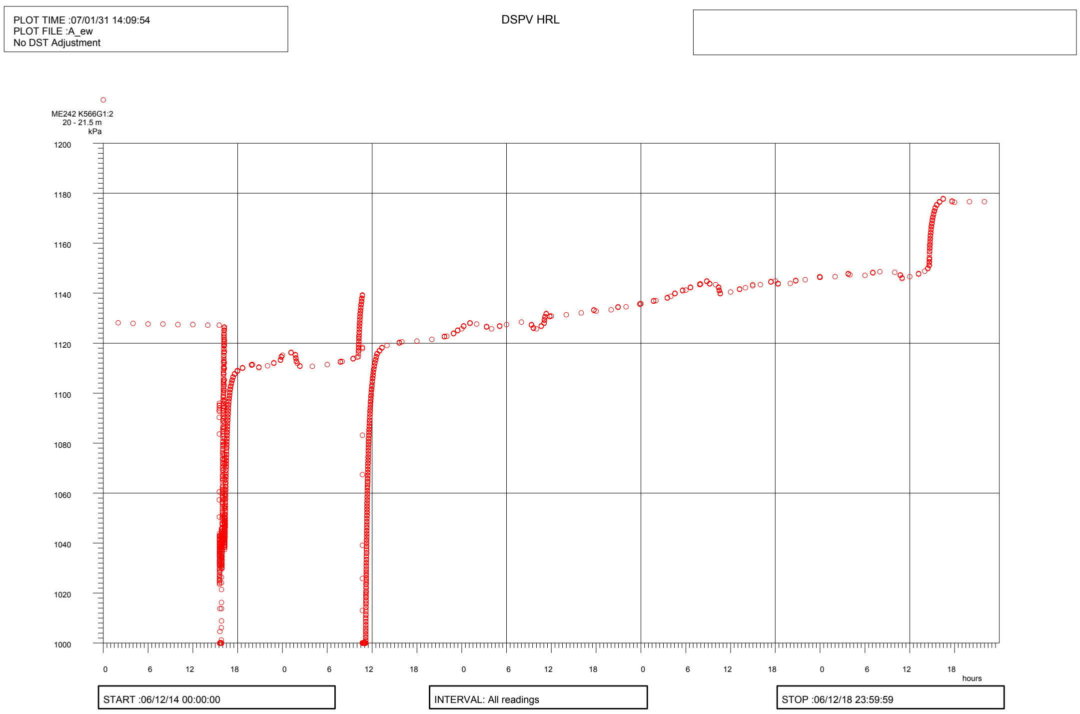


Figure A2-15. *Plot showing the pressure in KA3566G01:2 during the performed dilution test in that section.*

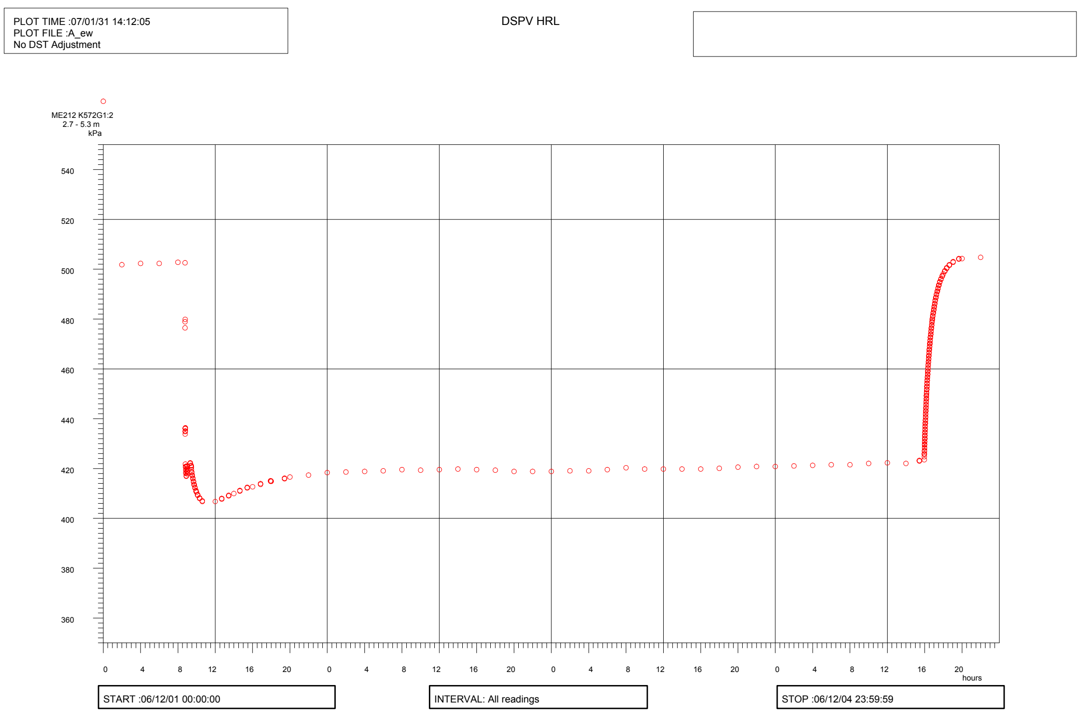


Figure A2-16. *Plot showing the pressure in KA3572G01:2 during the performed dilution test in that section.*

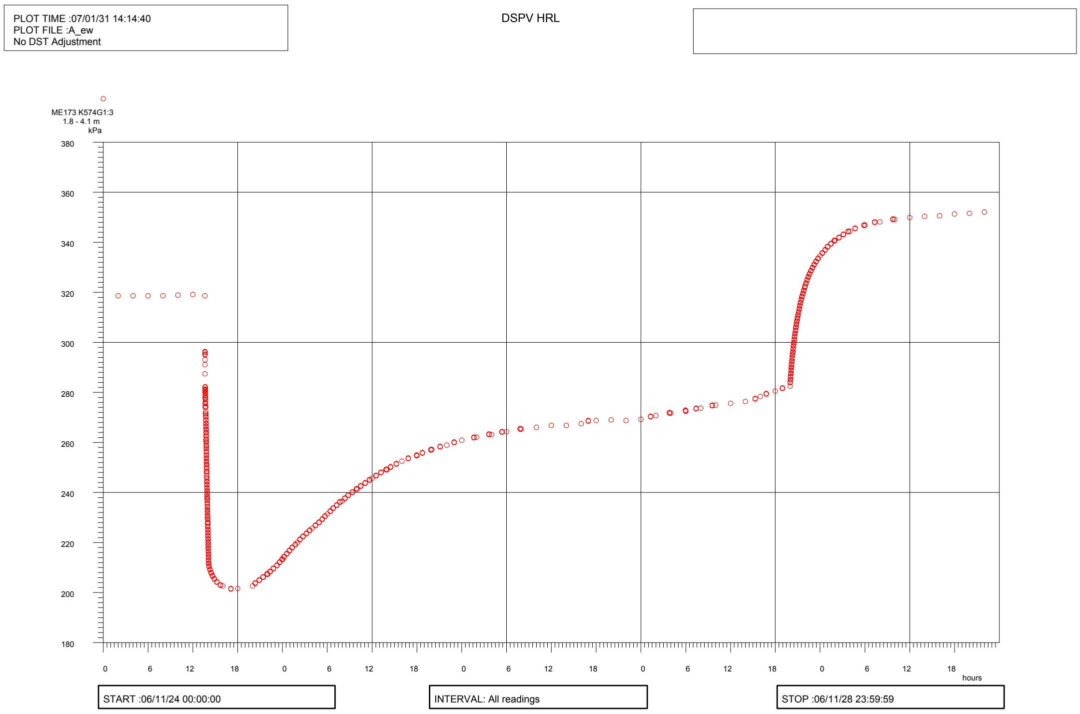


Figure A2-17. *Plot showing the pressure in KA3574G01:3 during the performed dilution test in that section*

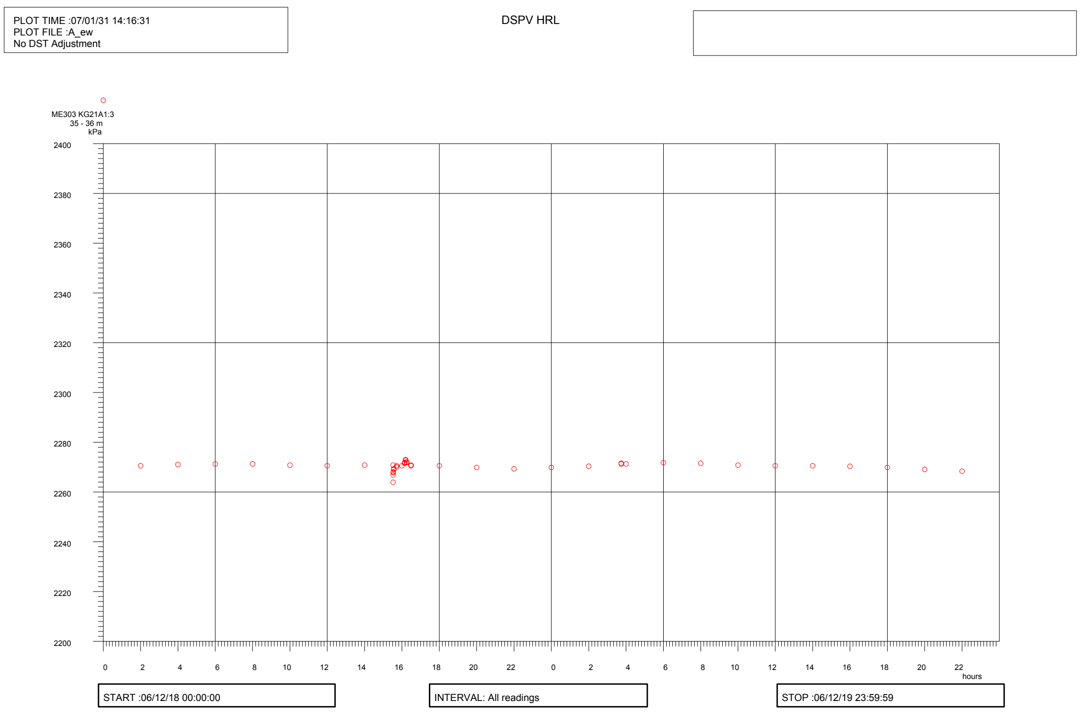


Figure A2-18. *Plot showing the pressure in KG0021A01:3 during the performed dilution test in that section.*

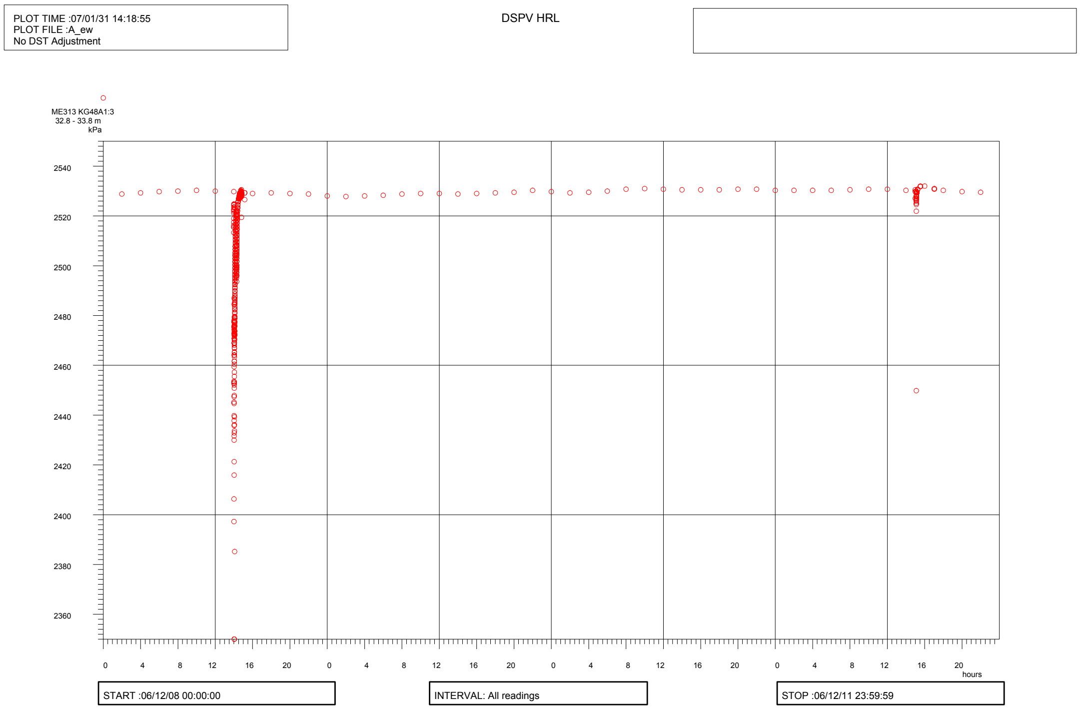


***Figure A2-19.** Plot showing the pressure in KG0048A01:3during the performed dilution test in that section*

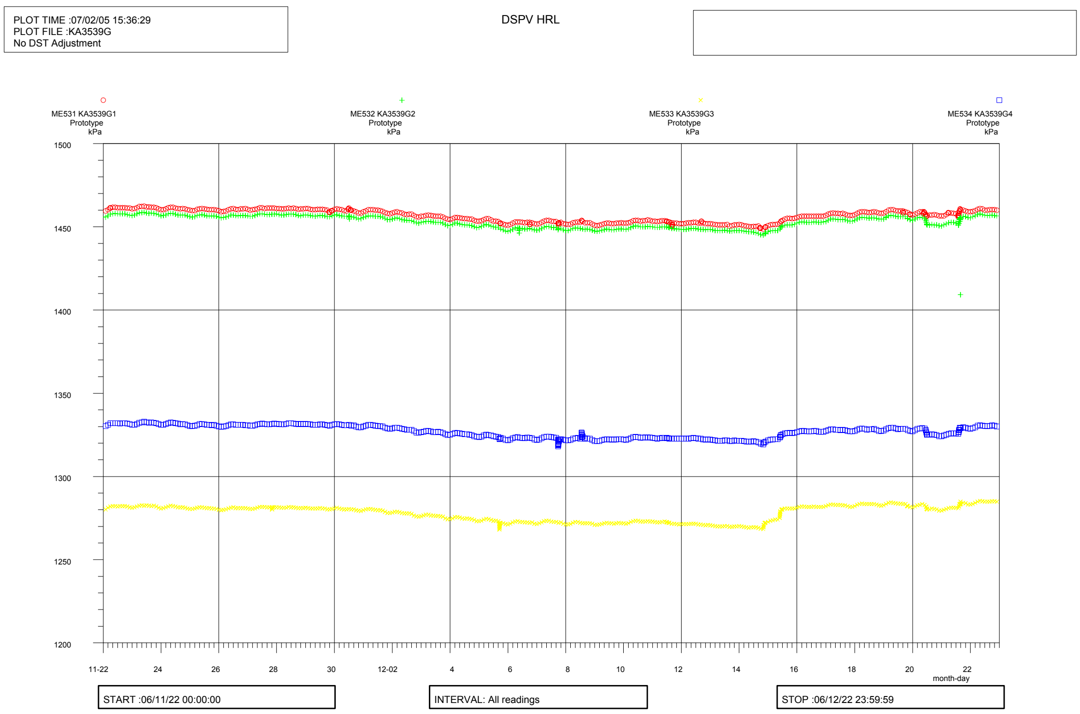


***Figure A2-20.** Plot showing the pressure in all sections of KA3539G for the duration of the entire dilution test period.*

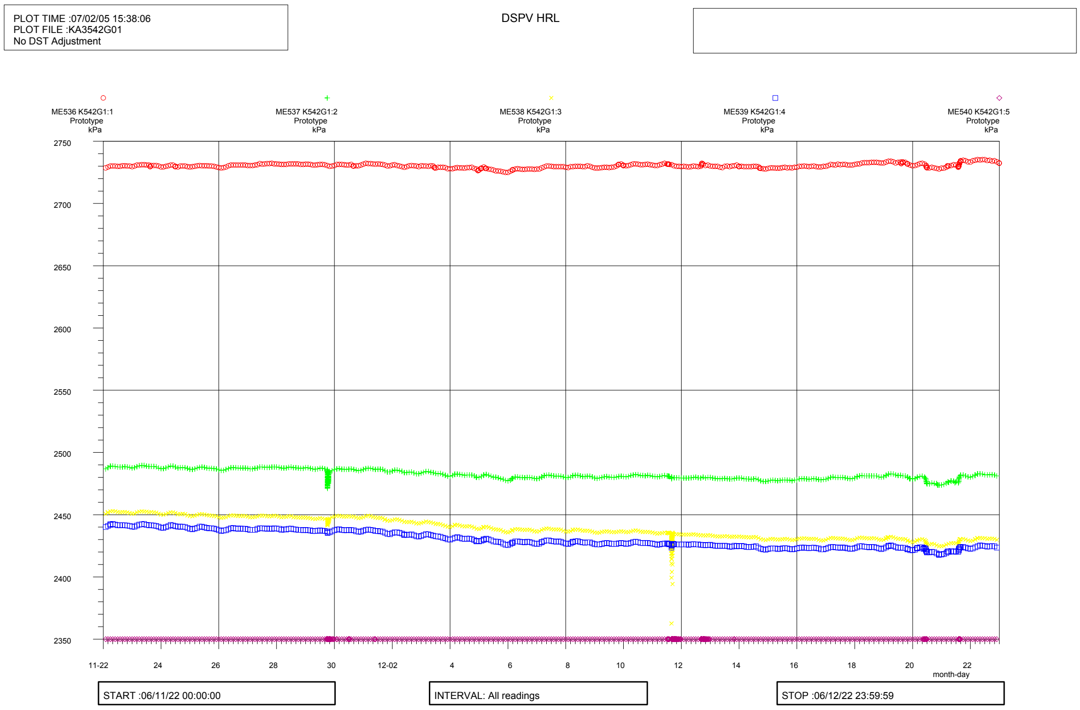


__Figure A2-21.__ Plot showing the pressure in all sections of KA3542G01 for the duration of the entire dilution test period.

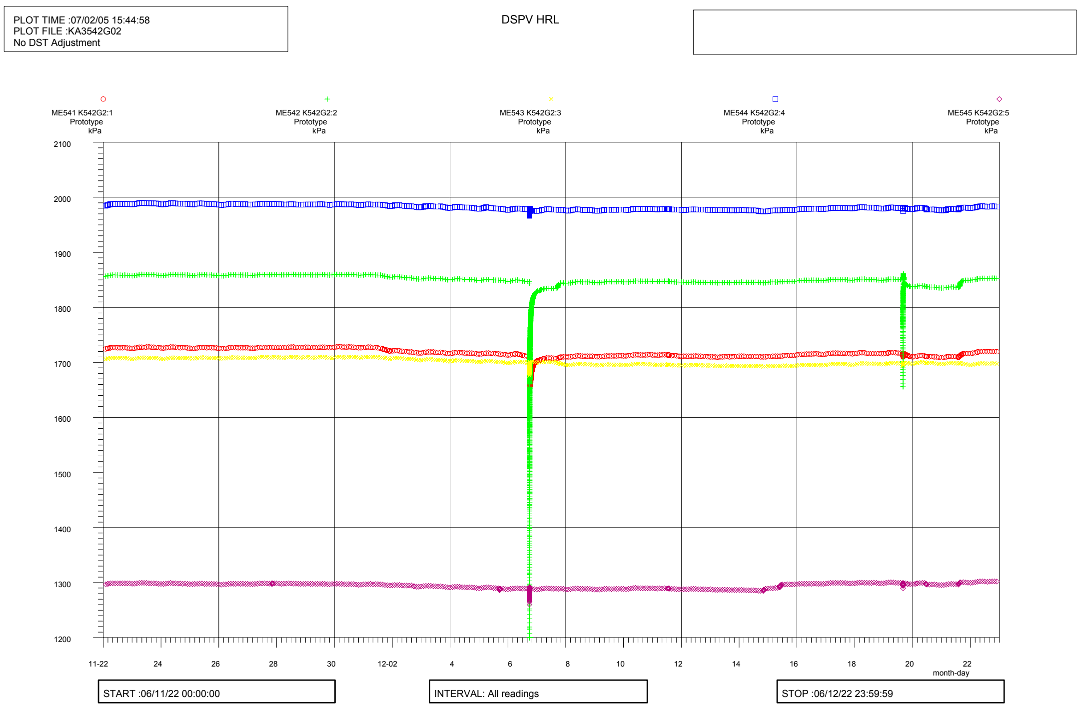


__Figure A2-22.__ Plot showing the pressure in all sections of KA3542G02 for the duration of the entire dilution test period.

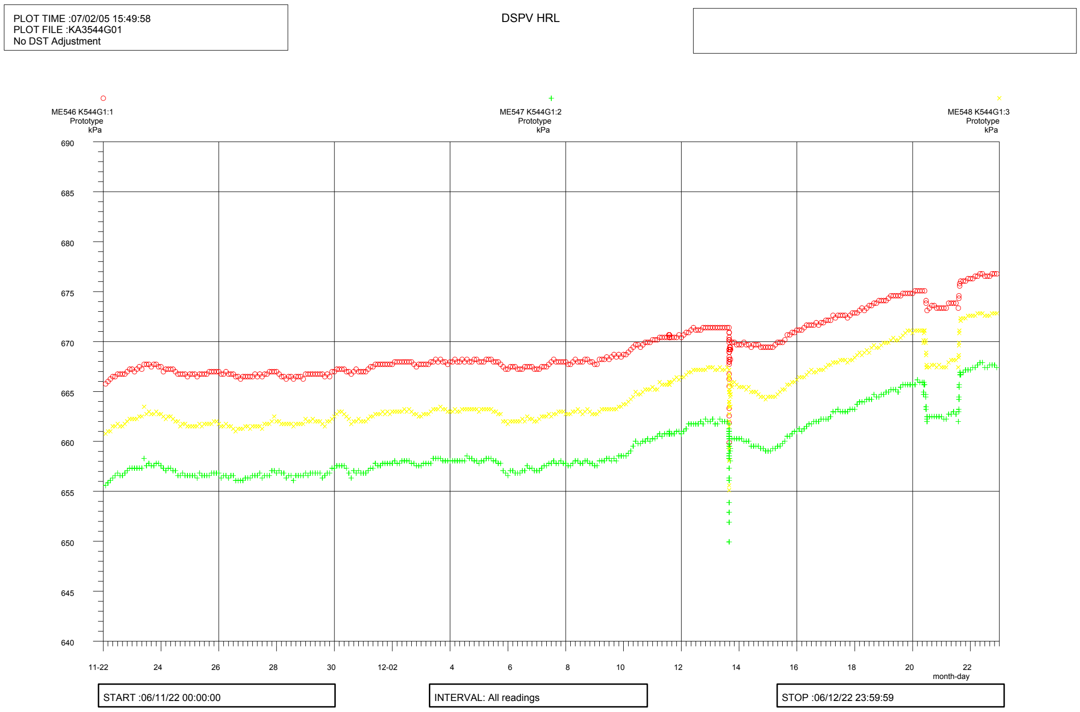


Figure A2-23. *Plot showing the pressure in all sections of KA3544G01 for the duration of the entire dilution test period.*

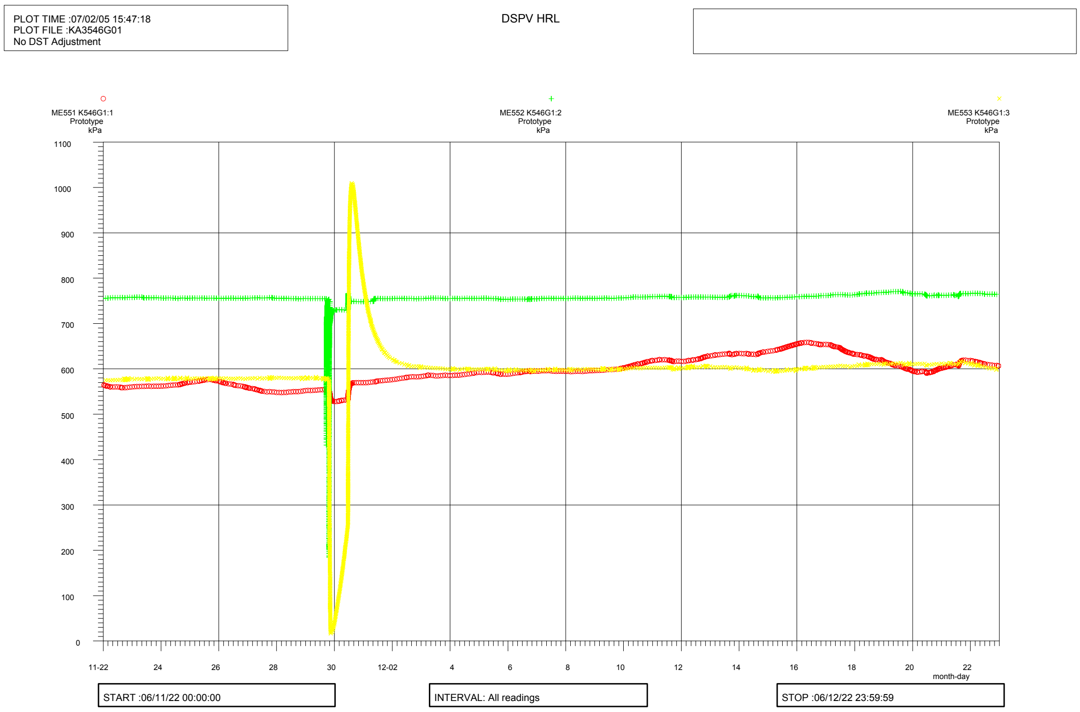


Figure A2-24. *Plot showing the pressure in all sections of KA3546G01 for the duration of the entire dilution test period.*

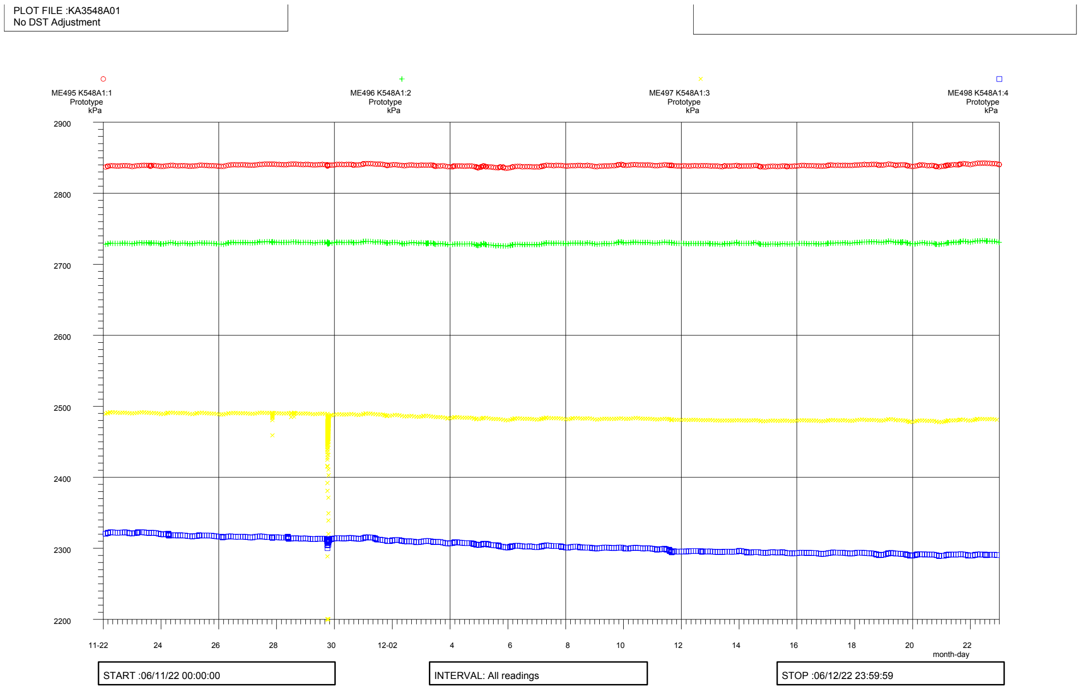


Figure A2-25. *Plot showing the pressure in all sections of KA3548A01 for the duration of the entire dilution test period.*

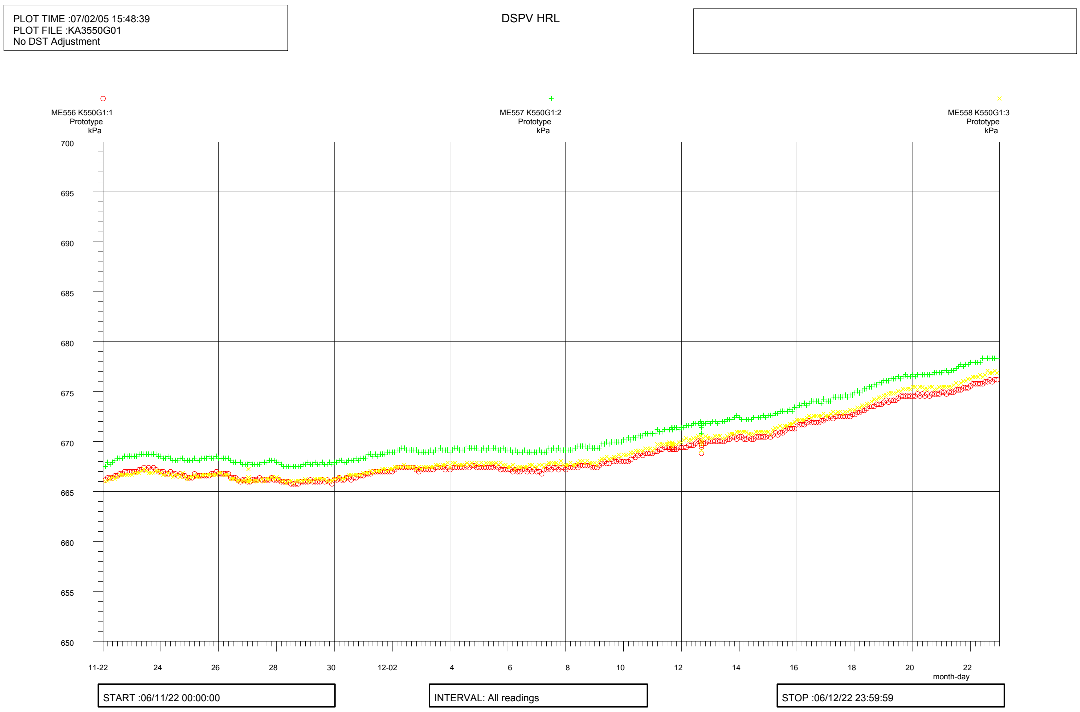


Figure A2-26. *Plot showing the pressure in all sections of KA3550G01 for the duration of the entire dilution test period.*

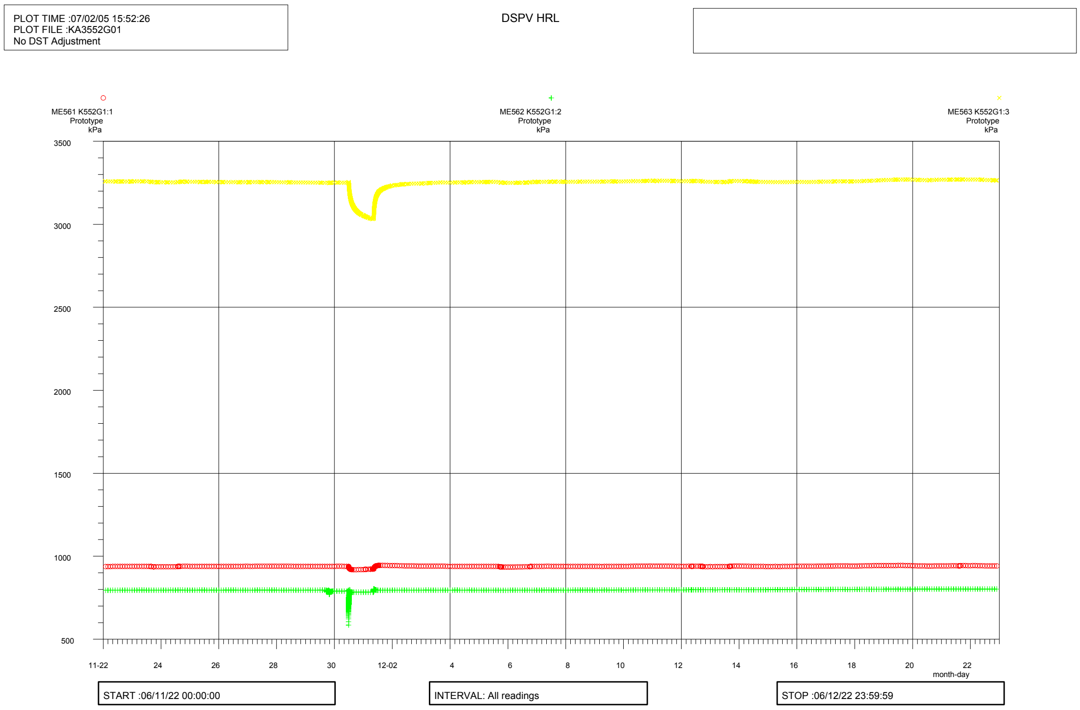


Figure A2-27. *Plot showing the pressure in all sections of KA3552G01 for the duration of the entire dilution test period.*

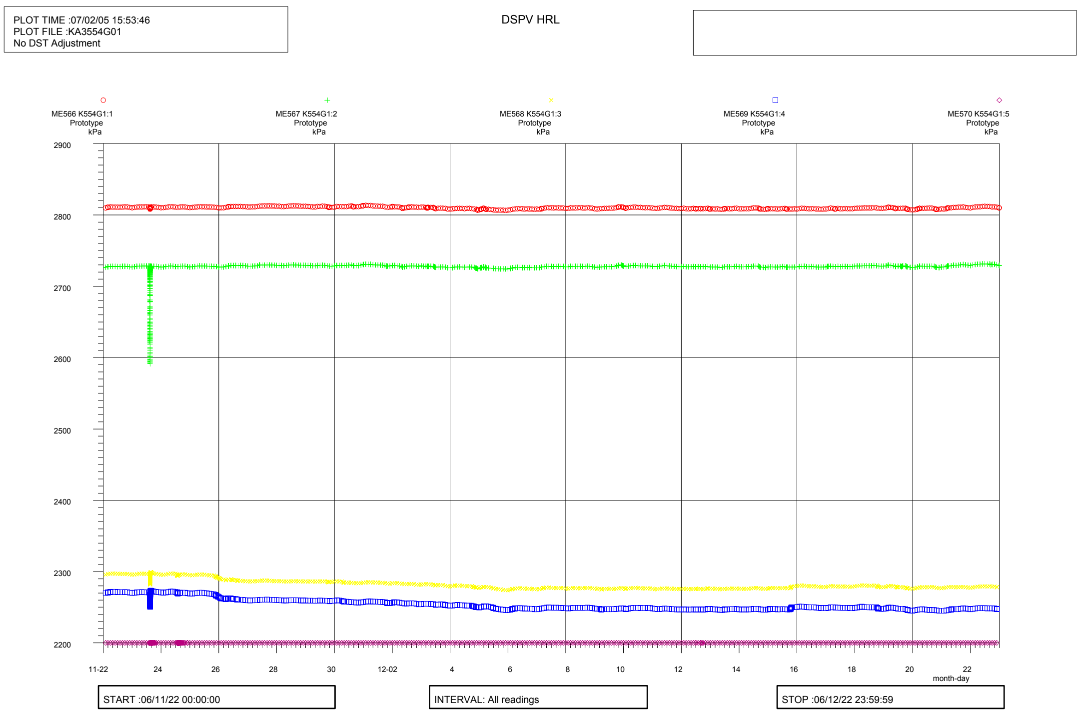


Figure A2-28. *Plot showing the pressure in all sections of KA3554G01 for the duration of the entire dilution test period.*

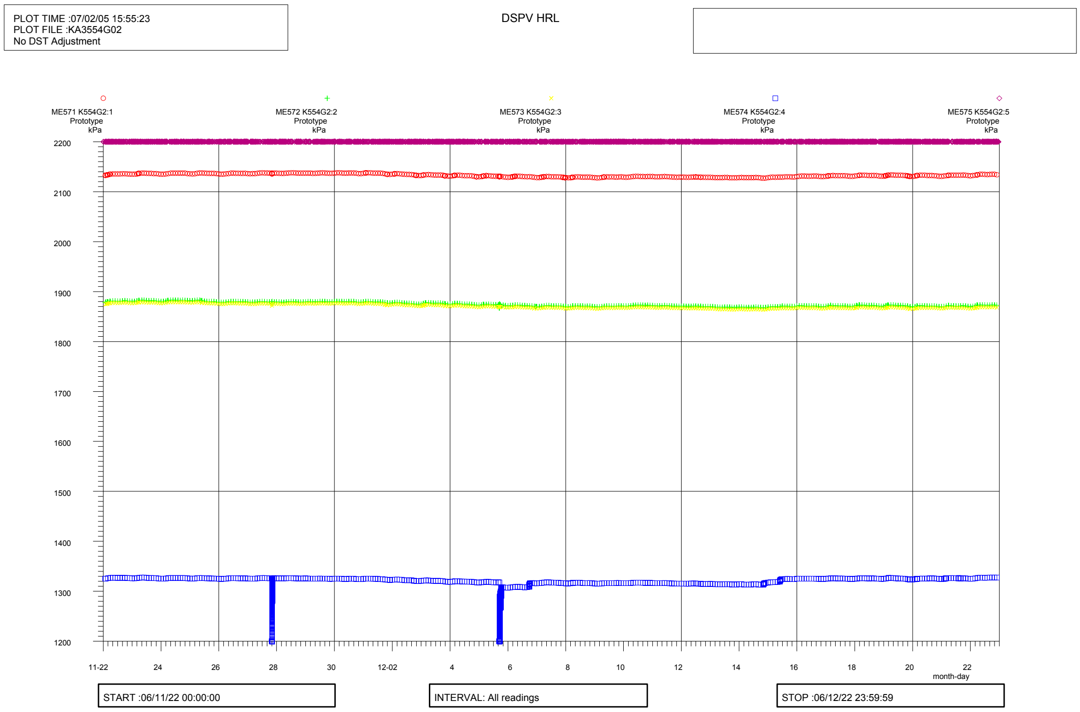


__Figure A2-29.__ Plot showing the pressure in all sections of KA3554G02 for the duration of the entire dilution test period.

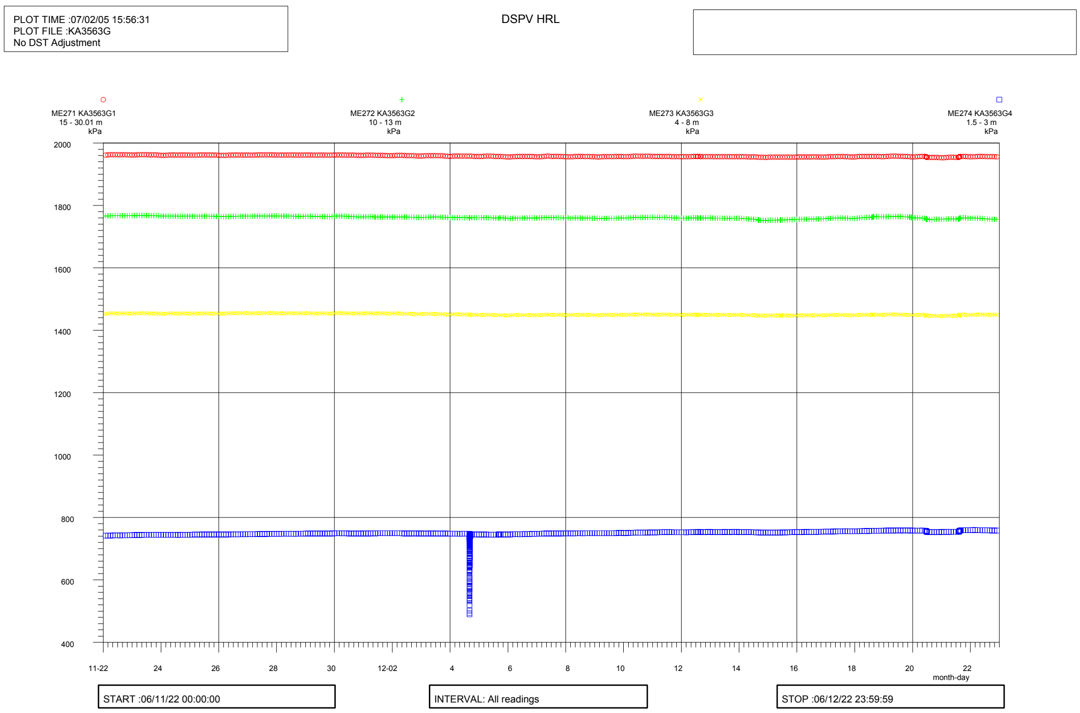


__Figure A2-30.__ Plot showing the pressure in all sections of KA3563G for the duration of the entire dilution test period.

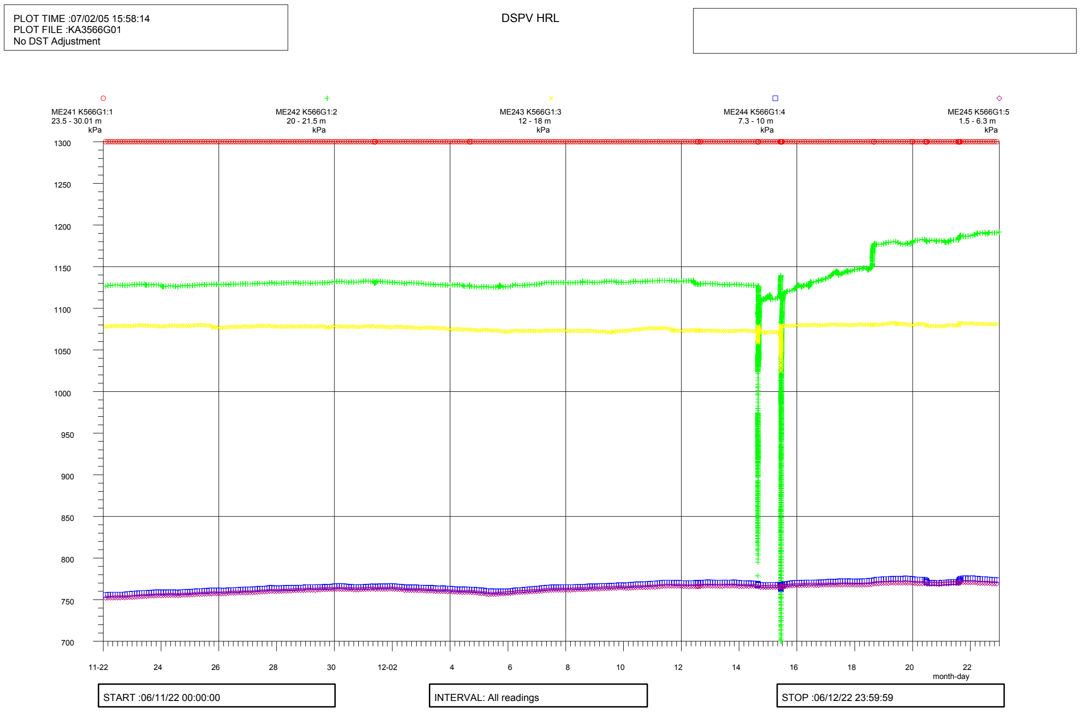


Figure A2-31. *Plot showing the pressure in all sections of KA3566G01 for the duration of the entire dilution test period.*

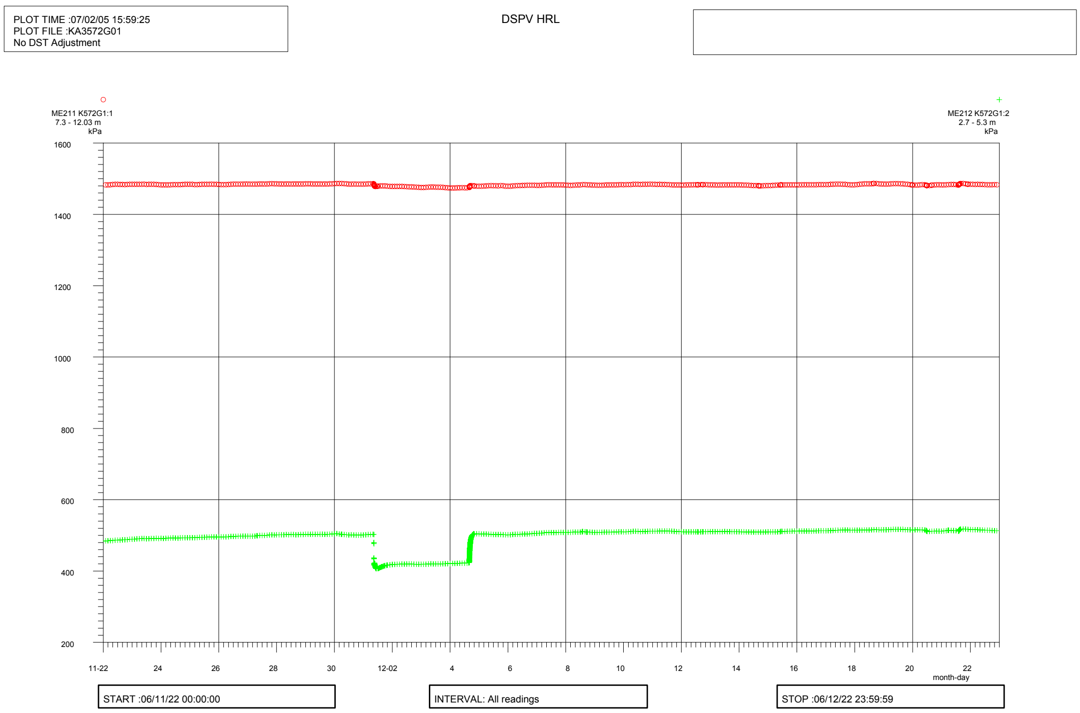


Figure A2-32. *Plot showing the pressure in all sections of KA3572G01 for the duration of the entire dilution test period.*

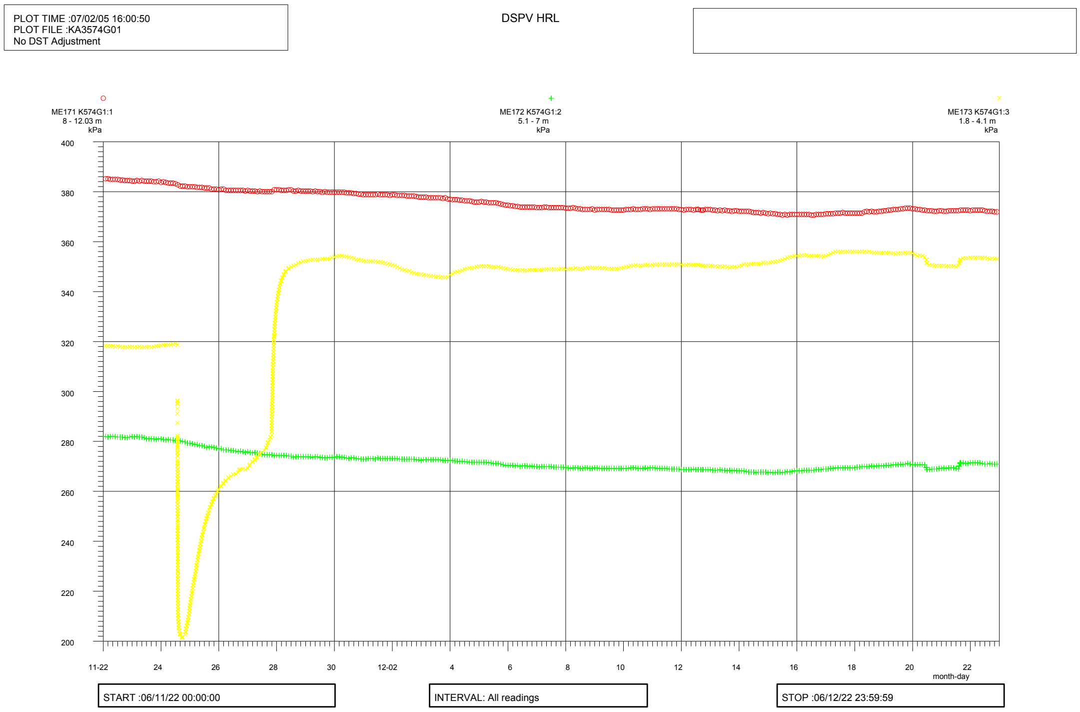


Figure A2-33. *Plot showing the pressure in all sections of KA3574G01 for the duration of the entire dilution test period.*

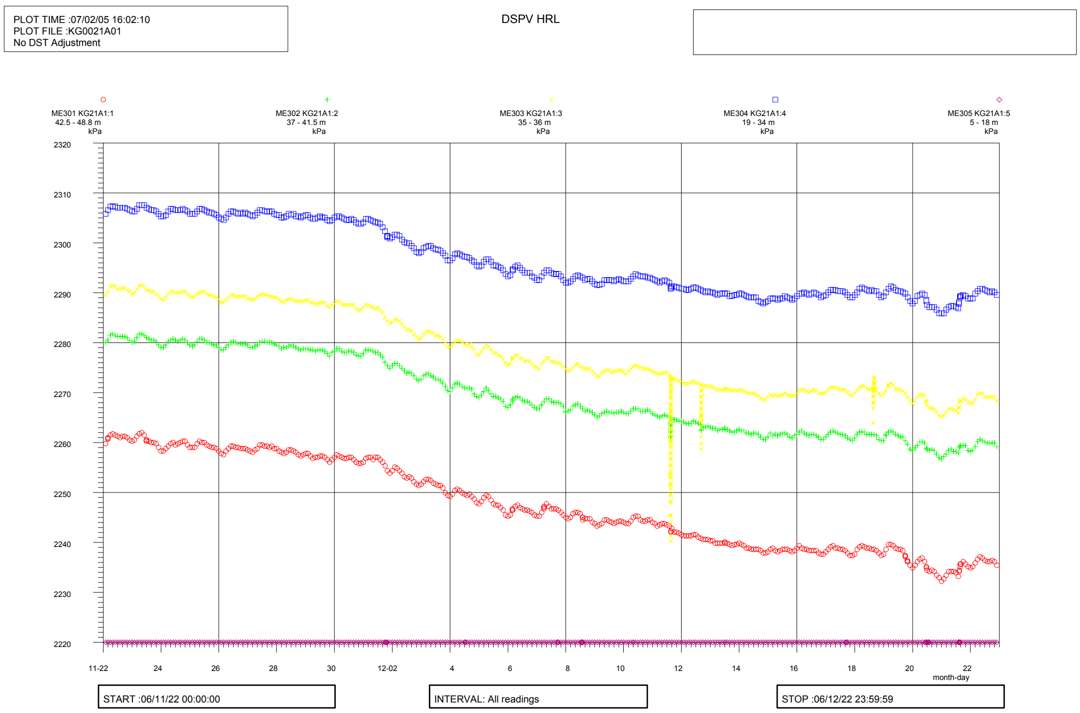


Figure A2-34. *Plot showing the pressure in all sections of KG0021A01 for the duration of the entire dilution test period.*

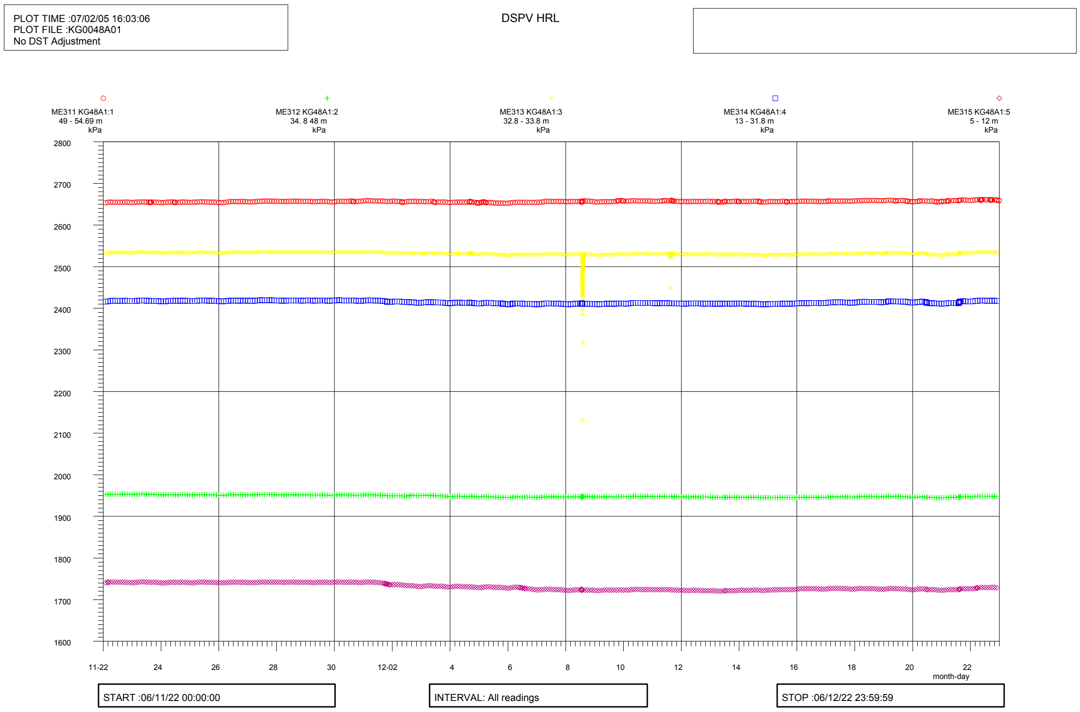


Figure A2-35. *Plot showing the pressure in all sections of KG0048A01 for the duration of the entire dilution test period.*

Appendix 3

Volumes of borehole sections and borehole tubing

Borehole	$V_{section}$ (dm^3)	V_{tubing} (dm^3)	V_{total} (dm^3)
KA3539G:2	5.10	2.56	7.66
KA3542G01:3	4.84	2.84	7.68
KA3542G02:2	4.48	3.01	7.49
KA3544G01:2	5.10	2.59	7.69
KA3546G01:2	4.27	2.56	6.83
KA3548A01:3	5.80	2.49	8.29
KA3550G01:2	6.55	2.50	9.05
KA3552G01:2	4.88	2.48	7.36
KA3554G01:2	4.26	2.93	7.19
KA3554G02:4	4.97	2.63	7.60
KA3563G:4	1.29	2.49	3.78
KA3566G01:2	1.29	2.79	4.08
KA3566G02:2	1.46	2.69	4.15
KA3572G01:2	1.63	2.36	3.99
KA3574G01:3	1.54	2.55	4.09
KG0021A01:3	1.17	1.35	2.52
KG0048A01:3	1.17	1.30	2.47