



ARBEITSBERICHT NAB 23-15

GAST Gas Flow Test
Data Report

April 2025

**Nagra | National Cooperative for the
Disposal of Radioactive Waste**

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Note: The enclosures are only included in the digital version of this report (PDF) and can be found under the paper clip symbol.

List of Acronyms

AV	Automatic valve
C	Compressibility [m^3/Pa]
CV	Check valve
DAS	Data acquisition system
DMT	Diffusion module test
DP	Differential pressure
DPSP	Double piston syringe pump
EBS	Engineered barrier system
GAST	Gas-Permeable Seal Test
GB	Granular bentonite
GFT	Gas Flow Test
GPT1	Gas Property Test performed in 2018 (see NAB 18-42)
GTS	Grimsel Test Site
G-WX	Gas-to-water exchange
HI	(constant) head injection
HIS	Recovery after constant head injection shut-in
IARF	Infinite acting radial flow
ml/min	Millilitre per minute at temperature (16 °C) and pressure
mln/min	Normal milliliter per minute at STP conditions
NAB	Nagra Work Report (<i>Nagra Arbeitsbericht</i>)
NC	Magnetic automatic valve
NV	Needle valve
PI	Pulse injection
PW	Pulse withdrawal
RI	Constant rate injection
RW	Constant rate withdrawal
S/B	Sand/bentonite
SDM	Solexperts diffusion module
STP	Standard temperature and pressure ($T = 273.15 \text{ K}$; $P = 101.325 \text{ kPa}$) ¹
SV	Safety valve
ULD	Upper left duct
URD	Upper right duct
W-GX	Water-to-gas exchange

¹ Definition according to Mass Flow Online B.V. (2024)

1 Introduction

1.1 Objectives of the report

The Gas-Permeable Seal Test (GAST) at the Grimsel Test Site (GTS) is a field experiment to demonstrate the gas permeability of the 80/20% sand/bentonite (S/B) mixture under realistic scale and boundary conditions. After an extended period of system saturation and characterisation, multiple gas injection and gas flow experiments were performed.

This report describes operational activities and the data recorded during the performance of the gas flow test (GFT) and covers the reporting period from 01 January 2022 to 31 December 2023. It is part of the scientific documentation of the GAST project, which is briefly outlined in Sections 2.1 and 2.2. This report provides essential background information and details about the GFT performance to facilitate understanding and interpretation of the recorded data. Nagra (2025) present further analyses and preliminary interpretations of the recorded data and observations.

1.2 Structure of the report

The report is organised as follows:

- Chapter 1 describes the report objectives and its structure.
- Chapter 2 summarises the GAST and the system description.
- Chapter 3 provides a short description of the emplaced materials and the instrumentation layout. All the upgrades of the equipment to perform the gas injections are reported as well.
- Chapter 4 focuses on the performance of the gas flow test. The field activities are detailed and related data and observations are described.
- Chapter 5 outlines the database and discusses changes with respect to previous GAST databases.
- Chapter 6 discusses data calibrations and preliminary analyses to provide an input/output calibrated flow balance and presents index test analyses.
- Chapter 7 summarises the main results and conclusions.
- Enclosures A to N provide detailed logbooks of the field activities, sensor specifications and calibration sheets, and a complete sequence of data plots.

2 The GAST

2.1 Objectives of experiment and report

The main aims of the GAST are (Rüedi et al. 2012):

- The demonstration of the effective functioning of gas-permeable seals at a realistic scale and with realistic boundary conditions
- The validation and, if necessary, improvement of current conceptual models for the resaturation and gas invasion processes into sand/bentonite (S/B) seals
- The determination of up-scaled gas/water transport parameters of S/B seals (e.g. two-phase flow parameters for large-scale models)

Secondary objectives (and by-products of the experiment) include the evaluation of in-situ emplacement techniques with the necessary quality assurance measures, and the application of novel monitoring methods.

The GAST was emplaced in the WT tunnel at the GTS. The as-built description of the GAST and provision of evidence for secondary objectives is fully documented in Rüedi et al. (2012).

A short description of the GAST components, sensors and saturation evolution from the emplacement (April 2012) to shortly after a leakage event on 28.01.14, when a rapid depressurisation of the engineered barrier system (EBS) occurred, is given in Lanyon & Senger (2015). After investigation of the leak, additional sealing was performed in the summer of 2015 and saturation of the GAST EBS restarted in September 2015. The first gas property test (GPT1) was performed between January and April 2018 and essentially demonstrated the technical feasibility to perform controlled gas injections (Lanyon & Herbert 2019). A short period of post-gas testing up to June 2018 was followed by resaturation and pressure equilibration (Lanyon et al. 2022).

The present data report documents the monitoring data in the period January 2022 to December 2023, which includes a preparation period (January – April 2022), and the large-scale gas injection test performed May 2022 – September 2023. This test was named Gas-Flow Test (GFT) because the focus was not only on the injection of gas into the S/B seal but also on the establishment of a gas flow between the two sand filters.

These data provide the foundation for the interpretation report (Nagra 2025), which demonstrates the achievement of the above-mentioned objectives.

2.2 GAST system description

This section gives a short description of the system prior to the start of the GFT (May 2022). Fig. 2-1 shows simplified vertical cross-sections of the GAST showing the instrumentation Sections S01 – S17 and Levels L1 – L8. Instruments are arranged on a grid that is defined by these sections and levels. Consequentially, data are typically displayed along sections or levels.

The main components of the GAST system are:

- An 8-m-long 80/20% S/B body providing the core of the gas-permeable seal section (light green in Fig. 2-1). The S/B mixture was emplaced at an initial water content of about 10% and then compacted into 10-cm-thick layers with an average dry density of 1.65 Mg/m³ (Rüedi et al. 2012).
- Granular bentonite surrounding the S/B in a 25-cm-thick ring space and a 95-cm-thick headspace (blue in Fig. 2-1).

- Sand filters at S02 and S14 for water and gas injection (orange in Fig. 2-1)
- Bentonite block walls sealing the ends of the filters from the concrete wall at the end of the tunnel and the concrete plug (pink in Fig. 2-1)
- Concrete plug confining the seal section (grey in Fig. 2-1a) and containing two upper instrumentation pass-throughs (upper ducts, green in Fig. 2-1a), carrying lines from the instrumentation at the tunnel surface
- Stainless steel riser system with distribution heads collecting lines and cables per section/level (green in Fig. 2-1)
- A main duct carrying lines and cables from the instrumentation beneath the plug in a square-section slot (green in Fig. 2-1)

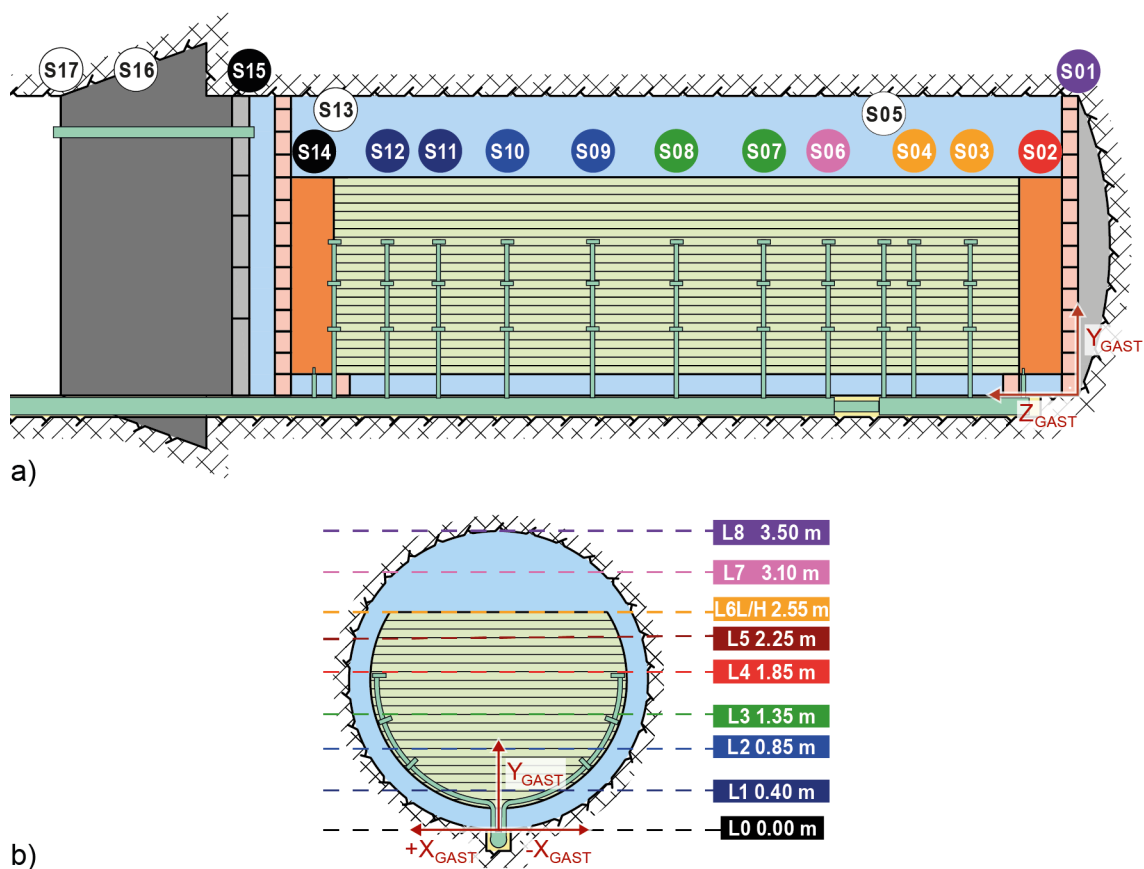


Fig. 2-1: GAST instrumentation layout a) sections and b) levels, as-built showing approximate routing of lines and cables to the risers

Sections S01 (wall at the tunnel end), S02 (filter), S14 (filter), S15 (back wall of plug), S16 (plug centre) and S17 (front wall of plug) do not have instrument risers.

The main components of the GAST system are listed in Tab. 2-1 together with their estimated volume, porosity and initial saturation. There are uncertainties on the volumes, porosity and initial saturation as set out in Appendix B of Lanyon & Senger (2015).

Tab. 2-1: GAST EBS component pore volumes. Sand/bentonite was emplaced as a series of layers numbered 1 – 28

The sand/bentonite for a layer was emplaced and then compacted in situ.²

Material	Component	Volume [m ³]	Porosity [%]	Pore volume [m ³]	Initial saturation [%]	Water needed [m ³]
Sand/ gravel	Filter	5.74	39	2.25	0.1	2.25
Bentonite blocks	Walls	3.66	37	1.36	68	0.44
Granular bentonite	Wall	2.89	46	1.32	31	0.91
	Ring space	15.90	46	7.28	31	5.04
	Headspace	19.00	46	8.80	30	6.15
	Total	37.79		17.40		12.11
Sand/ bentonite	Layer 1 – Layer 28	45.89	35 – 38	16.01 – 17.45	45 – 51	7.82 – 9.65

The GAST was equipped with a large number of sensors to monitor the saturation behaviour during water injections and gas transport in the subsequent gas injection phases. Additional sensors monitor the hydraulic effects in the host rock as well as the curing and any deformation of the concrete plug. Tab. 2-2 summarises the instrumentation and the abbreviations for sensor types. Full characteristics and coordinates of the instrumentation are found in Rüedi et al. (2012). All sensors are named according to type, section (position along tunnel) and level (elevation). The naming convention is as follows:

TTT_Sss_LL-n, where *TTT* is the type (Tab. 2-2), *ss* is the section number (01 – 17), *l* is the level number (0 – 8) and *n* is the number when there is more than one sensor at the same section and level. For example, TPW_S08_L4-2 is the second total pressure cell on the tunnel wall in Section 08 at Level 4.

A collection of detailed cross-sections showing the amount and location of sensors at each section can be found in Enclosure A.

A number of sensors were lost during saturation and leakage repair (see Tab. 2-2 for an overview). However, an early risk assessment (Lanyon et al. 2022) concluded that the original instrumentation is valuable but not essential for a successful GFT.

² The volumes for the granular bentonite and sand/bentonite differ slightly from those given in Lanyon & Senger (2015) as the headspace has now been taken to consist of all the volume above 2.55 m and as the “inclined layers” (or dog ears), previously assumed to be sand/bentonite, are now included within the headspace granular bentonite volume.

Tab. 2-2: GAST sensor type and counts as installed, and operational at the start of the GFT

Sensor	Type	Quantity installed ^(*)	Operational as of 2022
Pore pressure external (transducer linked by hydraulic line to screen in S/B body or filter)	PPE	39	39
Port lines in filter	PL	10	7 ^(a)
Total pressure cells on tunnel wall	TPW	20	19
Total pressure cells at L6 interface S/B-GB	TPB	3	0 ^(b)
Volumetric water content probes (time domain reflectometry probe)	TDP/TDL	38	33 ^(c)
Seismic sensors in S/B (seismic tomography system)	SE	34	0 ^(b)
Psychrometers	PS	30	0 ^(b)
Relative humidity and temperature sensors	RH/T	20 RH/20 T ^(d)	2 RH/2 T ^(e)
Temperature sensors	PT1000	3	0 ^(b)
Displacement sensors on plug surface	DI	4	4
Acoustic emission sensors on plug surface	AE	12	15 ^(f)
Well-head sensors	PPE/PT1000	6/1 ^(g)	6/1
Flowmeters	FRW	3	See Sect. 3.2
Pressure sensors external	PRE	3	
Pressure sensor	Water column	1	

(*) After as-built report (Rüedi et al. 2012).

(a) Three port lines clogged (see Lanyon et al. 2022).

(b) All sensors disconnected (see Rösli et al. 2018).

(c) 5 sensors failed (p.c. S. Schläger 2022).

(d) 18 out of 20 installed sensors were operational after the installation (Rüedi et al. 2012).

(e) 2 sensors with both RH and T channel still record data.

(f) 3 additional sensors were installed on 18 August 2021.

(g) For well-head installation, see van Meir et al. (2017).

2.3 The Gas Flow Test

The Gas Flow Test (GFT) was performed to demonstrate that the gas permeability of an S/B seal is sufficiently large to meet the expectations for a gas-permeable seal in the repository. Gas tests were performed with three different mixtures of conservative gases (see Section 3.1 for details):

- Gas Mix #1: N₂ with He as tracer
- Gas Mix #2: N₂ with He, Ar and Xe as tracers
- Pure N₂ to remove the tracers after a gas test

Chemically non-reactive, and hence conservative, noble gases were preferred to avoid any bio- or geochemical reactions with the geomaterials and in the porewater solution. Also, the requirement to ensure safe operation over an extended testing period of up to 2 years guided the selection of noble gases.

Tracer gases were employed to assess the gas phase arrival during the various test phases. Since the GPT1 was executed with pure N₂, adding a significant concentration of He was considered appropriate for the GFT to identify the newly injected gas from any potential gas background composition. Gas Mix #2 was composed of three noble gases and N₂ to investigate effects of atomic mass, and hence solubility and diffusion, on the arrival times of the different tracers. An elevated He concentration was designed for Gas Mix #2 to ensure a clear signal after the expected increased background of He after the injection of Gas Mix #1. Cleaning phases using N₂ between tracer gas injections were used to purge tracers from the gas-accessible pore space. Tab. 2-3 provides an overview of the test phases and the gas mixes used.

This report covers the observation period between 01 January 2022 and 31 December 2023. This period includes a preparation phase from January to mid-March 2022. The actual GFT experiments are grouped in ten phases, each with a main testing and operational purpose. The first phase started on 15 March 2022, the last one (Phase 10) with the shut-in on 01 September 2023. Phase 11 is dedicated to the removal of gas from the system.

Tab. 2-3: GFT phases

Start date and time	GFT phase	Section (*)
01.01.22	Preparation phase	4.1
15.03.22 13:39	Phase 1: Filter water exchange/pulse testing	4.1
02.05.22 08:00	Phase 2: Water-gas exchange (W-GX) with Gas Mix #1	4.2
06.05.22 11:22	Phase 3: Stepwise increase in gas pressure	4.3
12.05.22 12:50	Phase 4: Stabilisation of gas flow	4.3
15.06.22 08:34	Phase 5: Sampling in stable gas flow path	4.3
01.12.22 07:05	Phase 6: Flush flow path with pure N ₂	4.4
22.02.23 13:21	Phase 7: Pressure gradient adjustment	4.4
18.04.23 07:20	Phase 8: Injection of Gas Mix #2	4.5
29.06.23 12:16	Phase 9: Flush flow path with pure N ₂	4.6
01.09.23 11:00	Phase 10: Shut-in and step-rate tests	4.7
01.11.23 10:00	Phase 11: Reverse flow, S02 G-WX, gas extraction	4.8
16.01.24 12:04	Start of resaturation (S02 injection)	-

(*) Corresponding section for each phase in which the fieldwork and data are presented.

3 Gas Flow Test: injected fluids and test equipment

3.1 Injected fluids and gases

Several fluids were employed and injected at GAST during the experimental operations described in this report. Here, a summary of the fluids is reported, with the aim to create a reference baseline of respective dissolved gas compositions.

Tap water was employed for early saturation of S02 and S14 between 17 September 2015 and 22 March 2021. Since 06 September 2016, the tap water was filled in a 300-l tank, and a dosage pump was used for injection. Between 22 March 2021 and 17 August 2021, two tanks, filled with BOUS 85.003 water and pressurised with Nitrogen N₂, were used for injection in S02 and S14. Since 17 August 2021, BOADUS 96.001 water has been directly used for injection in S02 and S14 (Tab. 3-1). The pressure was adjusted by a pressure reduction valve and by a pressure controller (Fig. 3-1). Literature data on dissolved gases in Grimsel borehole water are reported in Tab. 3-2, along with a BOADUS sample collected during the membrane module testing (Tab. 3-2, see Enclosures J, K and L for full details on sampling collection and analytical results). Due to a lower total gas amount and a higher Ar relative concentration, this latter BOADUS sample is suspected to be biased with sampling artefacts. In addition, the potential effects on the gas composition of the tap/BOADUS water collection in a tank with successive pressurisation by means of an N₂ piston cannot be assessed based on the available information.

Tab. 3-1: Overview of GAST water supply

Period from	Period to	Water supply	Injection method	References
17.09.15	22.03.21	GTS tap water	Direct or dosage pump	Van Meir et al. (2017), Rösli et al. (2019) Rösli et al. (2020)
22.03.21	17.08.21	BOUS 85.003	Tank pressurised with N ₂	
Since 17.08.21		BOADUS 96.001	Direct	

Tab. 3-2: Gas composition of borehole water samples at Grimsel

Tot.: total amount of dissolved gases in cm³_{STP}/kg. The relative composition in [%] was calculated from dissolved species abundance for samples where a direct measurement of a gas phase was not possible (numbers in italics). Empty fields: measurements not performed; “n.d.”: below the detection limit.

Sample	Start of collection	Sampling date	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	O ₂	N ₂
			[%]	[cm ³ _{STP} /kg]					[%]			
Borehole BOMI 87.009 (Fernandez 2019)				2.2E-3	0.44	2.1E-3	19.6	n.d.	<i>n.d.</i>	<i>n.d.</i>	<i>n.d.</i>	<i>n.d.</i>
Borehole BOMI 87.008 (Fernandez 2019)				3.4E-3	0.40	0.02	16.2	16.7	<i>n.d.</i>	<i>2.4</i>	<i>0.1</i>	<i>97.0</i>
Borehole BOEM 85.012 (Fernandez 2019)				n.d.	0.41	n.d.	17.6	18.1	<i>n.d.</i>	<i>2.3</i>	<i>n.d.</i>	<i>97.2</i>
BOADUS (DMT#1) (*)	21.03.22 13:58	21.03.22 13:58	100	n.d.	0.62	n.d.	3.2	3.8	<i>n.d.</i>	<i>16.3</i>	<i>n.d.</i>	<i>84.2</i>

(*) Due to a lower total gas amount and higher Ar relative concentration, this sample is suspected to be biased with sampling artefacts.

Three different tracer mixes were available for injection during the GFT:

- Gas Mix #1
- Gas Mix #2
- Pure nitrogen (N₂)

The nominal compositions of the three gases are shown in Tab. 3-3, and producers' certificates are enclosed in Enclosures B.5 and B.6. Laboratory results from samples taken on site are presented in Sections 4.3.7.1, 4.4.7.1, 4.5.6.1 and 4.6.7.1.

Tab. 3-3: Nominal gas composition used in the GFT

	N ₂ [%Vol]	He [%Vol]	Ar [%Vol]	Xe [%Vol]	Ref.
Gas Mix #1	98.0	2.0	-	-	Encl. B.5
Gas Mix #2	74.9	10.0	15.0	0.1	Encl. B.6
Pure N ₂	100	-	-	-	-

3.2 Surface equipment and flow control

Preliminary tests as part of the GPT1 indicated limitations of the original instrumentation (e.g. Rösli et al. 2019, Lanyon & Herbert 2019). Quantitative analyses of gas flow tests would require more specialised test equipment, for example to allow for controlled gas extraction and sampling. The following requirements for test equipment were set for the GFT:

- Controlled injection (by rate or pressure) of different gas mixes across a wide range of gas flow rates,
- Controlled extraction (by rate or pressure) and sampling of gas/water mix with measurement of gas/water ratios,
- Sampling of extracted fluids (water, gas/water mix or gas) for the measurement of fluid composition and free gas phases,
- Online monitoring of the qualitative trends in the gas phase composition at extraction keeping the extraction line under pressure,
- Sampling of in-situ fluids from PPEs for the measurement of dissolved and free gas phases in the S/B,
- Online monitoring of any gas leakage to the WT tunnel,
- Online monitoring of plug movements and plug integrity.

The layout of the backfitted and upgraded surface equipment as of the end of Phase 9 is shown in Fig. 3-1. Adjustments to the instrumentation layout are discussed in specific sections in Chapter 4. The equipment on the injection side as developed for the GPT1 (Rösli et al. 2019) was largely appropriate for the planned gas injections. The injection gas source was connected to PL_S02_L6L-2 for gas injection and the extraction side to PL_S02_L1 for water/gas extraction during the water gas exchange and fluid sampling.

The extraction side, on the other hand, was significantly upgraded. The combination of syringe pumps and a large-volume gas-water separator provided the necessary robustness and pressure control to perform long-term gas tests. Installation of a diffusive gas-water separator module (Solexperts diffusion module, SDM in Fig. 3-1 and also referred to as membrane module in Fig. 3-10) facilitated inline gas sampling and real-time gas monitoring of the gas phase in the separator using a field-type mass spectrometer. For the GFT, the extraction side was connected to the PL_S14_L1 port.

Intermittent fluid samplings and component failures resulted in minor system changes during the performance of the GFT. The detailed layouts of the surface equipment for each injection phase are shown in the Sections 4.3.3, 4.4.3, 4.5.3 and 4.6.3. These layouts document the flow control during each phase in full detail.

The instruments were connected with stainless steel lines of 6/4 mm outer diameter (OD)/inner diameter (ID) diameter using Swagelok fittings. Port lines from the surface equipment to the injection and extraction filters (PL type) were implemented as 9.63/7.81 mm (OD/ID) stainless steel lines. Tightness tests were consistently performed after each exchange of test components to minimise leakage and assure high-quality measurements.

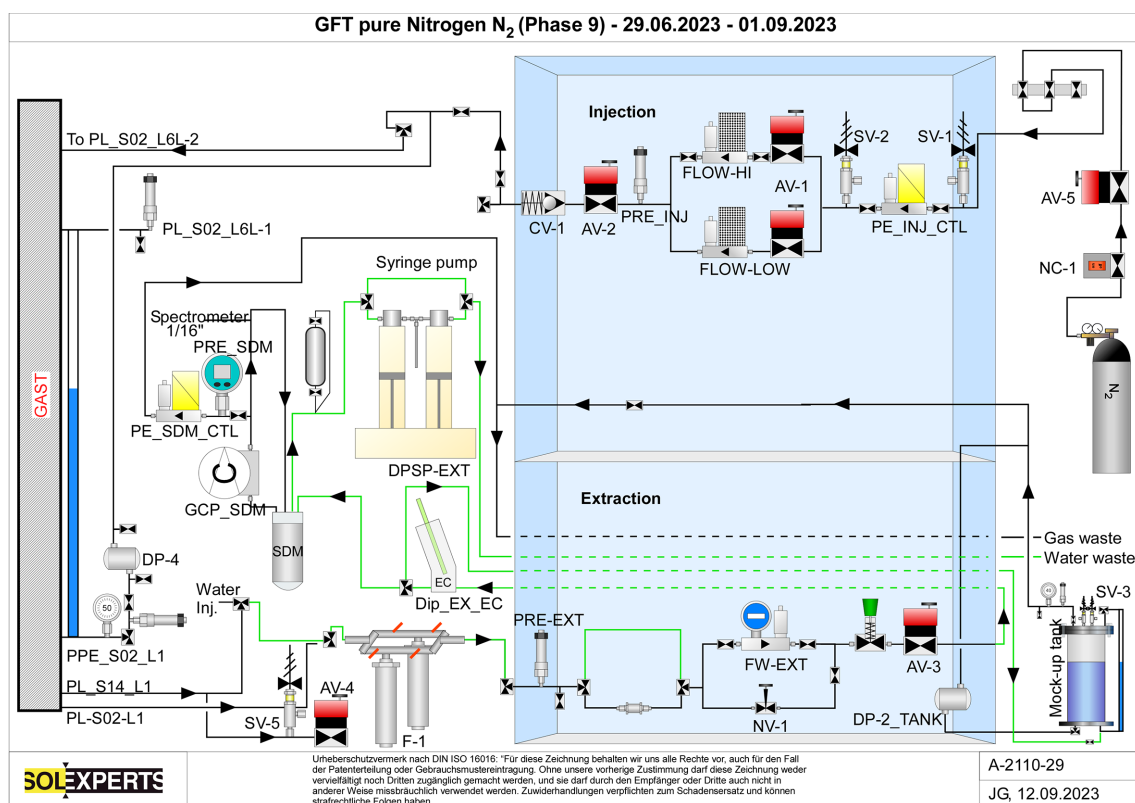


Fig. 3-1: Example of surface equipment used for the GFT as of the end of Phase 9

Detailed specifications of the used surface equipment are given in Tab. 3-4. The calibration certificates for the equipment installed or calibrated during the period of this report are given in Enclosure C. The connection of the sensors to the GAST data acquisition system (DAS channel) and modifications during the period of this report are documented in Enclosure D.

Tab. 3-4: Specifications of surface equipment

Code	Instrument	Purpose	Technical specification
N ₂	N ₂ bottle	Gas source	Pressure 200 bar equipped with N ₂ reduction valve type W 24 X 1/14" right thread, outflow port dimension G 1/4", DN 6.
AV-1	Automatic valves 1-1 and 1-2	Activating either high flow (FLOW-HI) or low flow (FLOW-LOW) controller	Electrical motor valve. Voltage 24 VDC, 90° rotation angel fixed on 2-way valve. The valves are activated by GeoMonitor using defined limits for each sensor
AV-2	Automatic valve 2	Shut-in in case of failure on the injection side and protection of the GAST system.	Electrical motor valve. Voltage 24 VDC, 90° rotation angel fixed on 2-way valve. The valve is activated by GeoMonitor after defined limits are reached
AV-3	Automatic valve 3	Shut-in on the extraction side if extraction pressure is too low	Electrical motor valve. Voltage 24 VDC, 90° rotation angel fixed on 2-way valve. The valve is activated by GeoMonitor after defined limits are reached
AV-4	Automatic valve 4	Automatic pressure release valve	Electrical motor valve. Voltage 24 VDC, 90° rotation angel fixed on 2-way valve. The valve is activated by GeoMonitor after defined limits are reached
AV-5	Automatic valve 5	Automatic pressure release valve at the gas bottle	Electrical motor valve. Voltage 24 VDC, 90° rotation angel fixed on 2-way valve. The valve is activated by GeoMonitor after defined limits are reached
CV-1	Check valve	Prevent backflow from the filter in case the injection side pressure is lower than the S02 pressure	Stainless steel 413 bar check valve with 6 mm tube fitting
Dip_EX_EC	Electric conductivity	Dipole test: Flow-through electric conductivity of extraction water	Type: Hamilton Conducell Parameter: Conductivity 4-pole Range: 1 µS/cm to 300 mS/cm Pressure: 0 to 20 bar
DUCT_LEFT_O2	Oxygen sensor	O ₂ level at upper duct left	Type: Greisinger Oxy 3690 Parameter: O ₂ vol. concentration Range: 0 – 100% Resolution: 0.1% FS

Tab. 3-4: Cont.

Code	Instrument	Purpose	Technical specification
DUCT_RIGHT_O2	Oxygen sensor	O ₂ level at upper duct right	Type: Greisinger Oxy 3690 Parameter: O ₂ vol. concentration Range: 0 – 100% Resolution: 0.1% FS
DP-2	Differential pressure sensor	Water level measurement in the extraction tank during water/gas exchange	Type: Rosemount 3051C Range: 0 – 1,000 mm Accuracy: 0.05% FS
DP-4	Differential pressure sensor	Water level measurement in S02 filter during water/gas exchange and long-term gas injection	Type: Keller PD-33X Range 0 – 3,000 mm Accuracy: 0.002% FS
DPSP	Double piston syringe pump	Upstream constant pressure water/gas extraction, sampling, PI tests	Type ISCO Teledyne 500d Syringe pump, used in double or single piston configuration Medium: water/gas Flow rate range: 0.001 – 200 ml/min Pressure range: 0 – 100 bar
EX_EC	Electric conductivity	W-GX: Flow-through electric conductivity of extraction water	Type: Hamilton Conducell Parameter: Conductivity 4-pole Range: 1 µS/cm – 300 mS/cm Pressure: 0 to 20 bar
F-1	Filter device	Filter for extracted water	Double filter device, possibility to switch between the 2 filters for cleaning and replacement. Filter mesh 45 µm, total volume: 6.124 l, one side ~3 l (determined on 24.01.18, NAB 18-42)
FG-EXT	Gas flow controller	Downstream gas extraction flow rate measurement	Downstream gas extraction (after the tank) • Type: Vögtlin RED-Y • Medium: N₂ • Range: 50 – 5,000 mln/min • Pressure range upstream: 1.013 bar • Pressure range downstream: 0 bar • dP up to 1.013 bar • Accuracy: 1%

Tab. 3-4: Cont.

Code	Instrument	Purpose	Technical specification
FLOW-HI	Gas flow controller	Upstream gas injection flow rate measurement	High flow • Type Bronkhorst EL-FLOW • Medium: N₂ • Range: 28 – 1,400 mln/min • Pressure range upstream: 10 – 31 bar • dP 1 bar Accuracy: 0.5% of real value + 0.1% FS
FLOW-LOW	Gas flow controller	Upstream gas injection flow rate measurement for rates between 1 and 100 mln/min	Low flow • Type: Bronkhorst EL-FLOW • Medium: N₂ • Range: 1 – 100 mln/min • Pressure range upstream: 10 bar • dP up to 10 bar Accuracy: 1% of real value +0.2% FS
FG_INJ_MASS	Mass flow controller	Upstream mass injection flow rate measurement	Mass flow • Type: CODA Alicat • Density accuracy: ± 5.0 kg/m³ • Range: 15 – 300 g/h • Pressure range upstream: 103.42 bar • dP up to 41.4 bar • $\pm 0.6\%$ of reading or $\pm 0.2\%$ of FS, whichever is greater
FW-EXT	Water flow meter	Downstream water extraction flow rate measurement.	Downstream flow measurement without control • Type: Bronkhorst ES-FLOW • Medium: Water (GAST filter water) • Range: 7 – 350 ml/min • Accuracy: 0.2% of real value • Pressure 1.25 – 30 bar
GCP-SDM	Gas circulation pump (membrane pump)	Homogenisation of diffused gas	Type: KNF IP20-T Range: 15 l/min Pressure 4 bar max
	Mock-up tank	Gas-water separator on extraction side	Dimensions: Length: 920 mm, ID 600 mm, total volume ~260 L. Pressure 20 bar max. Construction by Aitemin for GMT project

Tab. 3-4: Cont.

Code	Instrument	Purpose	Technical specification
NC-1	Automatic valve	Shut-in gas supply during power failure	- Type: magnetic valve - Switch function: normally closed - Power supply: 24 V Pressure: 90 bar max
PE_EXT_CTL	Pressure controller	Upstream pressure regulation for controlled gas extraction pressure to avoid fast exchange	- Type Bronkhorst EL-PRESS - Medium: N₂ - Range: 0.4 – 20 bar - Flow rate range: 1 – 50 mln/min - Accuracy: 0.5% FS Pressure control range: 4 – 20 bar
PE_INJ_CTL	Pressure controller	Downstream pressure regulation for controlled gas injection pressure inside the filter	- Type Bronkhorst EL-PRESS - Medium: N₂ - Range: 0.6 – 30 bar - Flow rate range: 28 – 1,400 mln/min - Accuracy: 0.5% FS Pressure control range: 7.5 – 30 bar
PE_SDM_CTL	Pressure controller	Upstream pressure regulator in the gas circulation loop of the diffusion module	- Type Bronkhorst EL-PRESS - Medium: N₂ - Control: Upstream - Range: 0.0 – 1.5 bar Accuracy: 0.5% FS
PRE-EXT	P-sensor extraction	Pressure measurement downstream and comparison between pressures on the extraction side and at the filter PL_S02_L1.	Keller PAA 33X Range 0 – 30 bar
PRE-INJ	Pressure sensor (P-sensor injection)	Pressure measurement upstream. Monitoring pressure on injection side during shut-in	Keller PAA 33X Range 0 – 30 bar
PRE_SDM	Pressure sensor	Pressure of gas circulation loop of the diffusion module	Keller PAA 33X Range 0 – 3 bar
SDM	Diffusion module	Flow-through diffusive gas/water separator	Type: Solexperts diffusion module Method: Gas diffusion through membrane surface Surface area 100 cm ²
SV-1	Safety valve	Pressure relief in case of high pressure from the N2 bottle	Mechanical valve with adjustable spring
SV-2	Safety valve	Pressure relief in case of high pressure from the pressure controller	Mechanical valve with adjustable spring

Tab. 3-4: Cont.

Code	Instrument	Purpose	Technical specification
SV-3	Safety valve	Two valves for pressure relief in case of high pressure inside the tank	Mechanical valves with adjustable spring. Each valve is adjusted at different pressure
SV-4	Safety valve	Pressure relief in case of high pressure in the well head	Mechanical valves with adjustable spring.
SV-5	Safety valve	Pressure relief in case of high pressure	Mechanical valves with adjustable spring.
WORK_SPACE_O2	Oxygen sensor	O ₂ level in working area	Type: Greisinger Oxy 3690 Parameter: O ₂ vol. concentration Range: 0 – 100% Resolution: 0.1% FS
NV-1	Needle valve	Manual gas outflow control on extraction side	Stainless steel bonnet needle valve 0.37 Cv, 6 mm fitting tube
	UPS battery	Backup power in case of power failure	
NV-1	Control unit and equipment	Connection and control of the flow controllers and the pressure controllers	E-8000 digital unit, dedicated power supply, cables, RJ45 isolators and terminators and RS232 interface
	Lines and connections	Built according to the setup	Lines, 2-way valves, T-pieces and fittings

3.2.1 Syringe pumps

Single and double piston syringe pumps were used for injection and extraction purposes during the testing period. The specifications of the syringe pumps are given in Tab. 3-5. The installation dates are included in Tab. 3-6. The syringe pumps were used in double-piston or single-piston configuration. An uninterrupted flow rate can only be achieved with the double-piston configuration (DPSP), as the second piston takes over when the first is filled up and needs to be emptied (in extraction mode).

Tab. 3-5: Specifications of syringe pumps

Product details	Teledyne ISCO SyriXus 500D / 500X	Teledyne ISCO SyriXus 260D
Volume of injection chamber	500 ml	260 ml
Range of injection rate	0.001 – 204 ml/min	0.001 – 107 ml/min
Range of injection pressure	0 – 100 bar	0 – 100 bar
Refill of syringe pump	By electro valves	By electro valves
Adjustment of injection pressure	By pressure transducers and electro valves	By pressure transducers and electro valves
Data sheet	Enclosure G.1	Enclosure G.2

Tab. 3-6: Use of syringe pumps

Manufacturer	Installation date	Purpose
Teledyne ISCO-500D	Since 20.12.21	Dipole test, extraction from S14, pulse injection (PI), sampling
Teledyne ISCO-260D	26.01.23	Sampling
Teledyne ISCO-500X	06.04.23	Sampling

(*) First installed on 09 March 2023, repaired by the manufacturer and reinstalled on 06 April 2023.

3.2.2 Injection flow measurements

During the GFT, the gas injection flow rate was measured with the two gas flow meters FLOW_LOW with a range of 1 – 100 mln/min and FLOW_HI with a range of 28 – 1,400 mln/min. The low range flow meter was only used during Phase 3 between 06 and 12 May 2022 at the beginning of GFT Gas Mix #1.

Between 26 January and 30 March 2023 (Phases 6 and first part of 7), the mass flow controller FG_INJ_MASS was installed to measure the injection flow rate. During this period, the flow controller FLOW_HI was removed for recalibration with N₂ (Tab. 3-7) and new calibration with Gas Mix #2 (Tab. 3-8).

At the end of the gas injections (Phase 9), the flow controller FLOW-HI was again backward calibrated in September 2023 for both for Gas Mix #2 and for N₂ (Tab. 3-9). All calibration sheets by the manufacturer Bronkhorst are included in Enclosure C.

Tab. 3-7: Bronkhorst backward (as-found) calibration of FLOW-HI for N₂ (March 2023)

Customer flow	Equivalent flow	Reference flow	Measured deviation	Measurement uncertainty
N ₂	Air	Air	Reading	Reading
mln/min	mln/min	mln/min		
1,399.9	1,421	1,395.5	1.82%	0.40%
699.91	710.89	694.61	2.34%	0.40%

Tab. 3-8: Bronkhorst calibration of FLOW-HI for Gas Mix #2 (September 2023)

Customer flow	Equivalent flow	Reference flow	Measured deviation	Measurement uncertainty
Gas Mix #2	Air	Air	Reading	Reading
mln/min	mln/min	mln/min		
1,399.9	1,315.2	1,321.2	-0.46%	0.40%
700.09	658.56	660.21	-0.25%	0.40%

Tab. 3-9: Bronkhorst backward (as-found) calibration of FLOW-HI for N₂ (September 2023)

Customer flow	Equivalent flow	Reference flow	Measured deviation	Measurement uncertainty
N ₂	Air	Air	Reading	Reading
mln/min	mln/min	mln/min		
1,399.9	1,425.6	1,419.1	0.46%	0.40%
699.91	713.28	711.81	0.21%	0.40%

The data measured by the flow controller FLOW-HI were corrected to correspond to the actual injected gas. The factors for the injection of the Gas Mix #1 were calculated with the FLUIDAT software (pers. comm. Lanyon 2024), as no calibration was available. The other conversion factors were based on the calibrations as received by Bronkhorst.

Tab. 3-10: Conversion factors for the injection flow controller due to calibration

Start	End	Gas (*)	Data	Calibration factor	Gas conversion factor
02.05.20 08:00	01.12.22 07:05	Gas Mix #1 (Phases 2 to 5)	FLOW_HI	0.98	1.007
01.12.20 07:05	26.01.23 08:40	N ₂ (Phase 6)	FLOW_HI	0.98	1.00
26.01.20 08:40	26.01.23 13:47	N ₂ (Phase 6)	FG_INJ_MASS	13.3	1.00
26.01.20 13:47	30.03.23 07:41	N ₂ (Phases 6 and 7)	FG_INJ_MASS	13.3	1.00
30.03.20 07:41	11.04.23 08:36	N ₂ (Phase 7)	FLOW_HI	1.00	0.9232
11.04.20 08:36	18.04.23 07:20	N ₂ (Phase 7)	FLOW_HI	1.00	0.9232
18.04.20 07:20	29.06.23 12:16	Gas Mix #2 (Phase 8)	FLOW_HI	1.004	1.00
29.06.20 12:16	01.09.20 11:00	N ₂ (Phase 9)	FLOW_HI	1.004	0.9232

(*) For definition of the phases, see Tab. 2-3.

3.2.3 Extraction flow measurements

The two sensors FW_EXT and FG_EXT were used to measure the extraction flow rate during the water-gas exchange in Section S02.

During the GFT, the extraction flow rate was mainly measured with the syringe pump DPSP in single or double configuration. The DPSP was installed on 06 May 2022. The syringe pump measures the total extraction volume and the extraction flow rate. To measure the amount of water in the extraction flow rate, the mock-up tank was connected to the extraction side on 31 May 2022. The mock-up tank is equipped with a differential pressure sensor to measure the water level in the mock-up tank and to calculate the resulting water flow rate. Between 15 June and 16 August 2022, the syringe pumps were used for sampling. Between 16 August 2022 until 09 March 2023, the extraction flow rate was measured with a single piston syringe pump. As the single piston must be regularly emptied, the measured extraction flow rate is rather noisy.

3.3 GAST instrumentation

This section summarises the instrumentation of the GAST system, which was installed during construction. It includes the internal instrumentation, sensors for concrete plug monitoring, the borehole monitoring and the environmental sensors for operational safety. The data acquisition system is also outlined.

3.3.1 Internal sensors

According to Tab. 2-2, the internal instrumentation includes the 39 pore pressure sensors (PPE in Sections S02 – S15), 20 total pressure cells on the wall (TPW in Sections S01, S06, S08, S10 and S15), 3 internal total pressure sensors (TPB in Sections S06, S08 and S10), 20 relative humidity (RH in L7 and L8) including temperature sensors (RH-T), 30 3-rod TDR sensors for point measurements of volumetric water content probes (TDP, S03-S12), 8 ribbon-type TDR sensors for filter water level observations (TDL in S13), and 30 psychrometers (PS in S03-S12). Installation details are given in Rüedi et al. (2012). The psychrometers were cut and sealed on 16 June 2016 because of possible leakage of water into the well head (Van Meir et al. 2017). Most of the relative humidity sensors recorded out-of-range values or were defective by 01 January 2022.

An overview of the layout of the experiment with the instrumented sections and the approximated heights above gallery floor for each level is shown in Fig. 3-2. The detailed instrumentation of each section is displayed in Enclosure A. Essential sensor specifications and recording settings during the observation period are given in Tab. D-1 in Enclosure D.

Furthermore, temperature sensors were installed in the plug (S16) to monitor the concrete curing temperature, but later disconnected. Section S05 was equipped with 34 regularly spaced piezoelectric sensors to perform seismic tomography. These sensors were shortcut and lost during well-head installation (Van Meir et al. 2017).

Finally, the plug stability is monitored by four displacement sensors at the plug surface (S17). Additionally, 15 acoustic emission sensors on the plug surface (S17) are analysed for crack development inside the concrete or concrete/host rock interface.

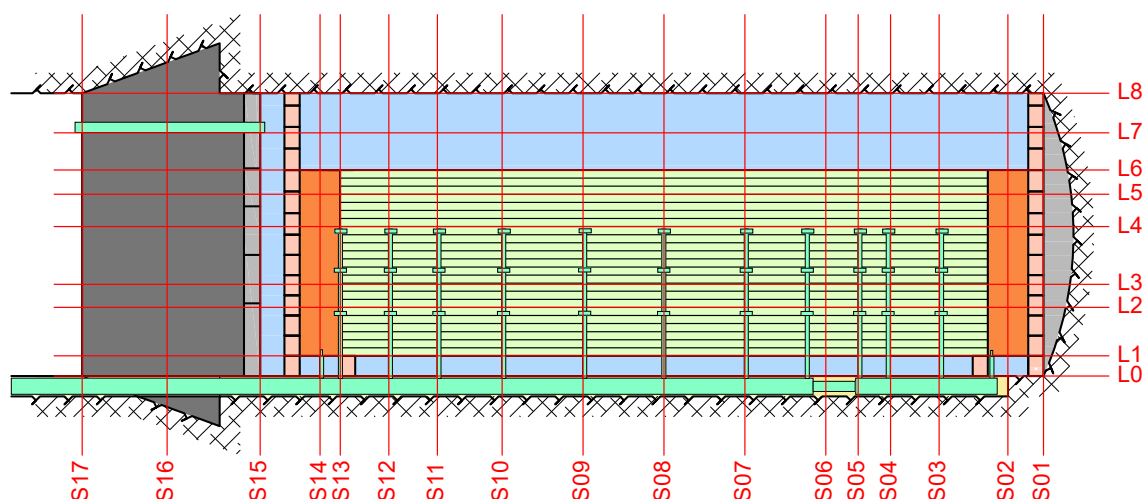


Fig. 3-2: Schematic layout with grid indicating sections (S01 – S17) and levels (L0 – L8)

Light green: sand/bentonite, orange: sand/gravel filters, blue: granular bentonite, dark grey: plug, green: ducts

3.3.2 Environmental sensors

On 01 October 2021, three oxygen sensors were installed at the GAST site, one at each upper duct and one in the working area. The oxygen sensors are part of the alarm system for the GFT. Before operating in alarm mode, the sensors were automatically calibrated with the integrated calibration mode on 24 August 2023. Afterwards, the alarm mode was activated. The corresponding data plot is included in Fig. N-16.

3.3.3 Borehole sensors

During the GAST installation, three boreholes located below and at the back of the GAST in the WT tunnel were equipped with single packer systems to monitor the borehole pressure and assess any impact of the test on the hydraulic regime of the host rock. The borehole SB 80.003, closely bypassing the GAST tunnel, was equipped with a 4-fold packer system. The names and location of these boreholes are shown in Enclosure A.3-1. The corresponding data plots are included in Fig. N-17 and Fig. N-18.

3.3.4 Data acquisition systems

Since 16 March 2015, the internal and the WT tunnel borehole sensors have been recorded with the GAST Solexperts Data Acquisition System (DAS) running the GeoMonitor II software (Van Meir, 2017). On 01 October 2021, the environmental sensors were added. During the period of this report, the scan rate was set to 20 seconds to record sudden events that could occur during the course of the GFT. The data acquisition logbook is included in Enclosure E. The specifications of the sensors connected to the DAS are given in Enclosure D.

Auxiliary data are recorded on other data acquisition systems:

- Sensors installed at borehole SB 80.003 are recorded by the colloid formation and migration (CFM) experiment DAS with a scan rate of 2 min.
- Upper and lower ducts outflow volume and conductivity are recorded on independent data loggers that are operated by the GTS team.
- The acoustic emission system is operated by an independent data acquisition system allowing real-time autolocation of triggered acoustic emissions (Rüedi et al., 2012).

Providing information on operational safety and experiment boundary conditions, these auxiliary data are considered non-essential for understanding the GFT performance and are not presented in this report.

3.4 Sampling

3.4.1 Layout of PL and PPE sampling equipment

Fluid sampling was performed at both filter PL ports and at selected PPE ports. Samples at PL_S14_L1 were taken directly from the DPSP. Sampling from PL_S02_L1 and the PPE ports was performed by connecting a sampler (generally 75 ml for filter samples, 25 ml for PPE samples) and a syringe pump to the sampling port (Fig. 3-3 and Fig. 3-4). Between 15 June 2022 and 09 August 2022, the DPSP previously connected to the S14 extraction port was used for sampling.

On 26 January 2023, an additional single-piston syringe pump (SyriXus 500X) was installed to be used for sampling. On 06 April 2023, a further syringe pump (SyriXus 260D) was installed to take two samples at the same time. The syringe pump data sheets are included in Enclosure G. N₂ was used to flush the sampler and the syringe pump prior to sampling and to pressurise the sampling equipment to avoid marked pressure drops at the corresponding PPE port.

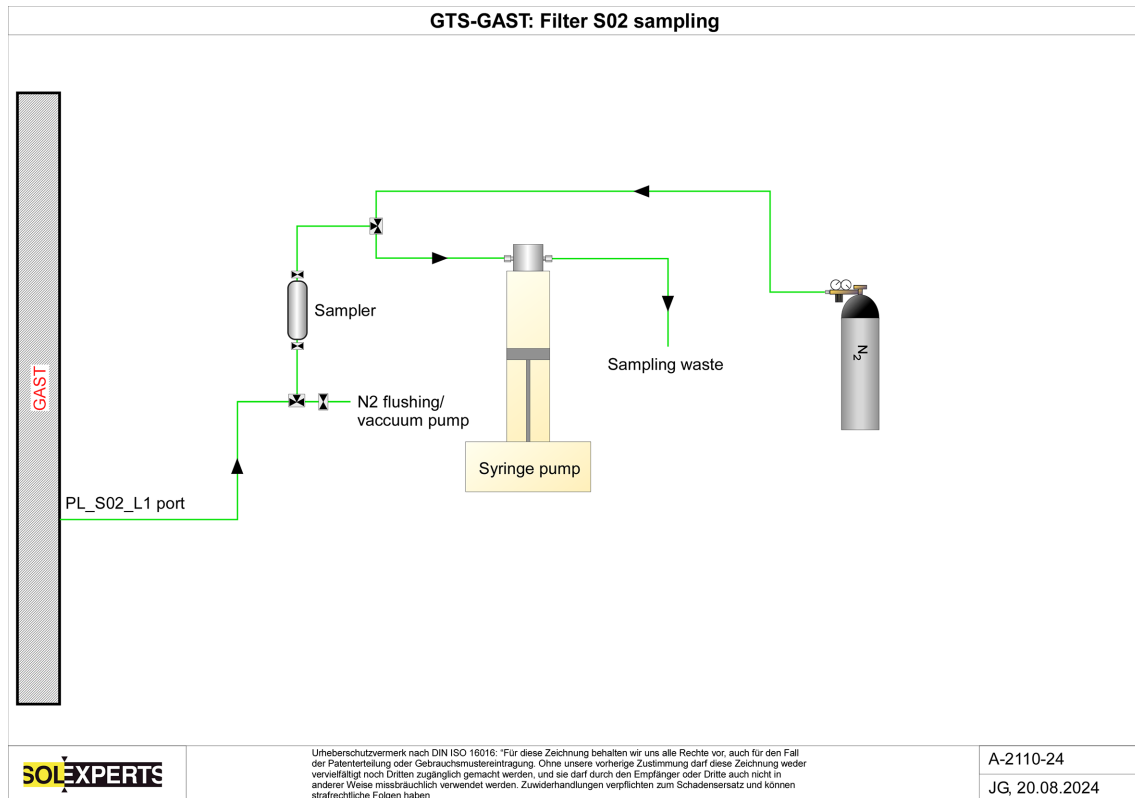


Fig. 3-3: Schematic layout of sampling equipment for S02

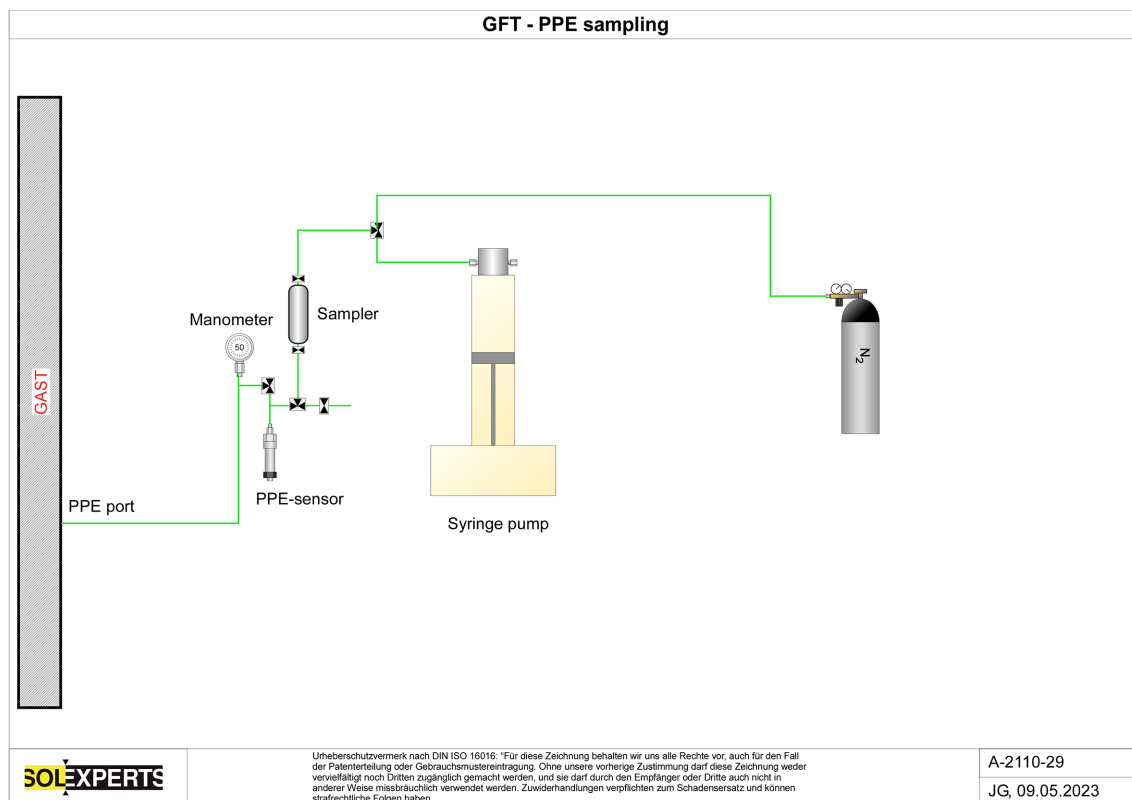


Fig. 3-4: Schematic layout of PPE sampling equipment with on syringe pump

To collect PL_S14_L1 samples for off-site analyses, the samplers were placed upstream with respect to the membrane module to avoid artefacts/biases due to the gas exchange expected to occur through the semi-permeable membrane.

Sampling cylinders specifically designed and tested (see Enclosures B.3 and B.4 for the 25 ml and 75 ml cylinder test reports) to be as He-tight as possible were acquired by Entracers GmbH from Arbor Fluidtec AG. Two sets of cylinders were purchased: 10 cylinders with an inner volume of about 25 ml, and 15 cylinders with an inner volume of about 75 ml.

Each sampler consisted of two Swagelok SS-4H bellows-sealed valves sealing a stainless-steel cylinder (either Swagelok item SS-4CD-TW-25 or SS-4TA-1-4). Different sampler volumes were considered to allow adaptations of the sampling strategy depending on the flow rates of the fluids emitted from the experiment.

In general, the samplers were evacuated prior to the connection to the extraction lines, or alternatively pre-pressurised with N₂ in case of sampling of lines with low flow rates, in order not to significantly depressurise the experiment. Details and exceptions are listed in Enclosure K. The weights of the sampler before and after the sample acquisition were determined to estimate the amounts of liquid and gas phases inside the samplers. The timing of the sample collection was decided based on the possibility to perform fieldwork according to the safety conditions and on the volume of fluids required to flush the samplers. The duration of sample collection aimed at fully flushing the cell volume three times prior to sampler collection, and at least once for the sampling of lines yielding low flow rates.

The samples collected from GAST were analysed by Hydroisotop GmbH (Germany) by means of gas chromatography using a thermal conductivity detector (GC-TCD) and flame ionisation detector (GC-FID), preceded by stripping with a carrier gas in case of analyses of water samples

to assess the composition of dissolved gases. The respective results are presented and discussed in Chapter 4. It should be noted that, lacking an estimate of individual analytical errors for each measured gas, the analytical uncertainty for N_2 was assigned to be 4% while for all other gas species, the uncertainty was assigned as 15%. Such percentages are declared by the laboratory as 2σ analytical uncertainty.

3.5 On-site gas monitoring system

The present section describes the installation of a miniRUEDI portable mass spectrometer system (Brennwald et al. 2016, Tomonaga et al. 2019) to monitor the breakthrough and tailing of tracer gases at the GAST extraction port PL_S14_L1 (coupled with Solexperts' membrane module). Additionally, miniRUEDI served as on-site monitoring tool for the gas composition in proximity to the concrete plug to detect any potential leaks of tracer gases from the experiment plug.

The miniRUEDI portable mass spectrometer system allows quantification of the partial pressures of e.g. He, Ar, Kr, H_2 , CH_4 , N_2 , O_2 , and CO_2 with an uncertainty of approximately 1 – 3% (Brennwald et al. 2016).

The miniRUEDI used for the gas monitoring at the GAST was tailored to allow:

- Flexible sniffing in the vicinity of the GAST plug where potential gas emissions could occur,
- The assessment of the breakthrough of the injected gases at filter line PL_S14_L01 based on the determination of the gas composition in the membrane module provided by Solexperts AG.

The membrane module manufactured by Solexperts AG allows gas exchange between the fluids (i.e., liquid and gas phases) extracted from filter S14 and a headspace (i.e., where only a free gas phase is present) through a semi-permeable membrane. As the semi-permeable membrane does not allow water to enter the headspace volume, the miniRUEDI can be connected to the headspace to determine the gas composition of the fluids from filter S14 without the risk of clogging the capillary system with macroscopic water droplets.

Usually, the miniRUEDI inlet capillaries have an outer diameter of 1/16" and an inner diameter of 0.004" (VICI TSS104) and extend from the VICI inlet selector valve to the measurement position for about 1 m. As the closest location for the installation of the portable mass spectrometer in the GAST niche was initially estimated to be about 5 m from the plug, the length of the standard inlet capillaries was clearly not adequate for the intended gas monitoring. The inlet capillaries, together with the approximately 10-m-long main capillary connecting the VICI inlet selector valve to the chamber of the mass spectrometer, reduce the sample gas pressure from the atmospheric pressure range to the required high-vacuum range ($\sim 1E-8$ bar). Such pressure has been shown to yield maximum overall sensitivity while not exceeding the linear operation range of the quadrupole mass spectrometer (Stanford Research Systems RGA-200) with a gas flow of about $0.06 \text{ cm}_{STP}^3/\text{min}$. The total length of the inlet capillaries plus the main capillary as well as their inner diameter limit the gas flow entering the mass spectrometer chamber. Thus, a capillary with a larger inner diameter (i.e., offering a lower resistance to the gas flow) was required to extend the length of the inlet capillaries.

Three stainless-steel capillaries with an inner diameter of 0.005" (VICI TSS105) and a length of about 12 m were used to replace the standard inlet capillaries. The chosen length was deemed to be long enough to allow a flexible deployment of the capillaries at three positions in the vicinity of the GAST plug for sniffing purposes (i.e., the detection of a free gas phase exiting the experiment). The main TSS104 capillary of the miniRUEDI was trimmed (i.e., shortened) in a stepwise manner to reach the typical intensity range of $\sim 1E-9$ A for N_2 (measured at a mass (m) to charge (z) ratio $m/z = 28$) determined in ambient air using the 12-m-long TSS105 capillaries

for the gas inlet. The typical capillary purge time (i.e., the time required for the sample gas to pass through the capillary system before entering the mass spectrometer chamber) of a standard miniRUEDI system is about 120 – 140 s. Based on the inlet of a CO₂ pulse, the purge time of the miniRUEDI with the TSS105 inlet capillaries was estimated to be about 300 s.

The remaining three inlet selector valve positions (out of the six available on the standard VICI valve used on miniRUEDI systems) were used for:

- The measurement of the gas composition in the headspace of the membrane module by Solexperts AG,
- Calibration (for the respective gas composition see Tab. 3-11), and
- Residual gas (blank) determination (i.e., the assessment of the intensities for each gas when the inlet is closed, and the chamber of the mass spectrometer system is evacuated; see Brennwald et al. 2016)

As the main capillary of the miniRUEDI was shortened to allow the use of extended capillaries (TSS105), the TSS104 capillaries connecting the membrane module and the calibration bag had to be prolonged to reach the same intensity range for N₂ as measured with the TSS105 inlet capillaries. The use of the TSS104 capillary allows keeping the standard purge time of 120 – 140 s and, thus, to minimise the amount of gas extracted from both the calibration bag and the membrane module.

Based on the tailoring of the miniRUEDI described above, no additional gas circulation system was needed for the observation of the gas composition at different sniffing points close to the GAST plug or at the membrane module. The highest temporal resolution of the measurements was estimated to be about 1.5 h for each sample inlet.

3.5.1 miniRUEDI installation

3.5.1.1 Initial setup

The miniRUEDI was installed at the GTS on 13 January 2022 on a table on the right-hand side of the GAST niche at a distance of about 3 – 4 m from the experiment plug and about 1 m from the well head (see Fig. 3-5). The fieldwork logs as well as the hardware documentation can be found in Enclosures H.1 and H.2.

Before running any measurements, the membrane pump of the miniRUEDI was turned on to check for unwanted interferences between the running pump and the acoustic emission survey system of GAST. As no alarm was triggered by the vibrations of the membrane pump, the extended inlet capillaries were attached along the wall of the GAST niche following cables, tubing, and capillaries already present on the right-hand side of the drift and temporarily fixed in the vicinity of the upper right duct (URD).

The connection of the miniRUEDI computing unit to the internet for remote operation was set and tested successfully. The miniRUEDI system was therefore launched. After tuning of the system based on atmospheric air from the calibration bag located on the inner side of the lid of the instrument case, two blank measurements were conducted.



Fig. 3-5: On 13 January 2022, the miniRUEDI acquired by Entracers GmbH was installed at the GTS close to the GAST plug

To increase the chances of detecting gas leakages from the upper right duct (URD) and the upper left duct (ULD), the installation of protectors was proposed to minimise the influence of the active ventilation system of the niche (e.g., dilution of injected gases with atmospheric air). To this end, the capillaries/cables exiting the plug were enclosed by plastic cylinders with the ends towards the GAST niche being enclosed with foam-like material (Fig. 3-6 and Fig. 3-7). In the lower part of the cylinders towards the GAST plug, openings were drilled to serve as outflows for the water dripping from the ducts. A third cylinder (Fig. 3-8) was used to protect the third sniffing capillary to be set around the plug middle with the help of a tripod-like system.

On the same day, a prototype protector for the URD was produced and installed with no major issues. Considering the geometrical constraints of the used PVC cylinder as well as the risk of clogging the miniRUEDI inlet capillaries with macroscopic water dripping from the ducts, holes in the upper part of the protectors were planned to host the 1/4" fittings (Swagelok SS100-R-4BT) present at the end of each inlet capillary.

3.5.1.2 Capillary installation

The emplacement of the sniffing capillaries in the vicinity of the GAST plug was done on 20 January 2022. PVC protectors were firmly fixed at the URD and the ULD using metal brackets (Fig. 3-6 and Fig. 3-7). Tape was used to seal the cylinder openings. The 1/4" miniRUEDI fittings with the connected 1/16" inlet capillaries were carefully fixed in the pre-drilled holes in the topmost part of the protectors, avoiding any contact with the tubing exiting from the duct.

The final connections to the VICI valve of the miniRUEDI were set as follows:

- Inlet 1: air calibration bag
- Inlet 2: upper right duct (URD)
- Inlet 3: upper left duct (ULD)
- Inlet 4: adjustable position (starting at the middle of the GAST plug)
- Inlet 5: PL_S14_L1 extraction line with Solexperts AG membrane module (see next section)
- Inlet 6: sealed port for blank determination

The composition of the gas in the air calibration bag (Calibrated Instruments, 5 L) reflected the atmospheric air composition as shown in Tab. 3-11.

A quantitative analysis of H₂, CH₄, and CO₂ would require a connection to the respective calibration bag. However, as the standard VICI valve of the miniRUEDI has only six positions in total, no additional bag could be installed. Therefore, a protocol adaptation was made to allow at least a qualitative appreciation of concentration changes of these uncalibrated gas species (i.e., assessment of relative changes by setting arbitrary calibration volume fractions of 6E-7 for H₂, 1.9E-6 for CH₄, and 4E-4 for CO₂). A test run was made to check the protocol functionality, including the processing of the data.

It should be noted that for Gas Mix #2 injection, the measurements of He, Ar, and Xe were calibrated using an additional bag containing the gas mix itself set on Inlet 6 of the miniRUEDI (i.e., blanks were determined manually by closing the main valve of the instrument on site). For details on Gas Mix #2 and its use to calibrate the miniRUEDI analyses, please refer to Section 3.5.1.4.

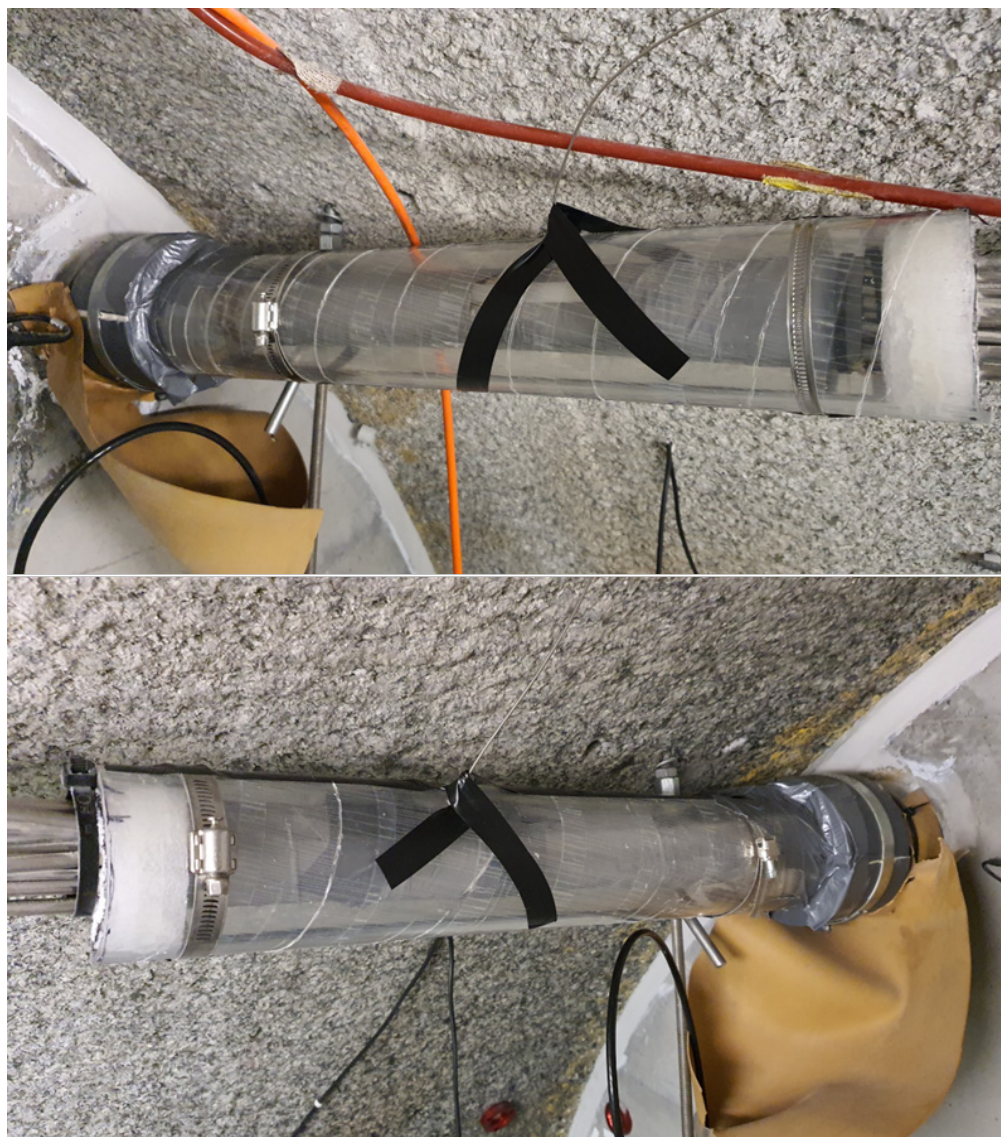


Fig. 3-6: On 20 January 2022, PVC protectors were installed around the URD (top panel) and the ULD (bottom panel)

Tab. 3-11: Composition of atmospheric air in the air calibration bag
See also Ozima & Podosek (2002).

Gas species	Volume fraction
^4He	5.24E-6
N_2	0.781
O_2	0.2095
^{40}Ar	9.303E-3
^{84}Kr	6.498E-7



Fig. 3-7: Lower view of the protectors at the ULD (left panel) and the URD (right panel)

3.5.1.3 Membrane module connection

The miniRUEDI system was first connected to the membrane module of Solexperts AG on 04 February 2022. The module allows gas exchange between the pressurised fluid phase (i.e., gaseous, liquid, or a mixture of both) from filter S14 and the module headspace through a semi-permeable membrane.

This approach mimics that of GE-MIMS (gas equilibrium membrane inlet mass spectrometry; see Mächler et al. 2012, Brennwald et al. 2016) where the system strives towards an equilibrium between the (dissolved) gas phase in the fluids from filter PL_S14_L1 and the gas phase in the headspace of the membrane module. In principle, if equilibrium is reached between the headspace and a liquid phase flowing on the other side of the semi-permeable membrane, the concentrations of the dissolved gases can be inferred from the gas partial pressures determined in the headspace using the respective solubility. However, as the properties of the semipermeable membrane are not well constrained (i.e., equilibration times or fractionation processes were not assessed by specific laboratory trials), the quantitative assessment of dissolved gas concentrations is hardly feasible. Nevertheless, the measurement of the gas partial pressures in the membrane module headspace is expected to provide clear insights on the timing of the tracer breakthrough(s) and a qualitative appreciation of the gas dynamics in the experiment.



Fig. 3-8: Protector holding the third sniffing capillary for flexible deployment at different positions at the GAST plug and its vicinity

The 1/4" fitting connected to the miniRUEDI inlet capillary was inserted in the plastic foam, sealing the end of the PVC cylinder.

A miniRUEDI inlet capillary as well as a total gas pressure sensor (Omega PXM409-002BAUSBH; Enclosures B.1 and B.2) were attached to the loop where gases flow from/to the headspace of the membrane module with the help of a gas circulation pump (see Fig. 3-9; see also Fig. 3-1). The pressure sensor was intended as a means to verify the consistency of the miniRUEDI measurements in case of major deviations in the composition of the analysed gases from that of atmospheric air (used as calibration). In addition, the pressure sensor was employed as a safety measure to infer unwanted pressure build-up prior to the inlet of the gases into the miniRUEDI (potentially resulting in damage to the mass spectrometer system).

The total gas pressure in the headspace has been kept 100 mbar above the atmospheric pressure in the GAST niche (about 830 mbar) using an automatic pressure controller. Such pressure difference hampers the inflow of gases from the niche into the membrane module headspace.

A temperature sensor was set on the line carrying the fluids from filter PL_S14_L1 into the membrane module to monitor potential temperature anomalies due to changes in the experimental conditions (Fig. 3-10).

A schematic overview of the final setup as used during the on-site tests of the membrane module is given in Fig. 3-11.

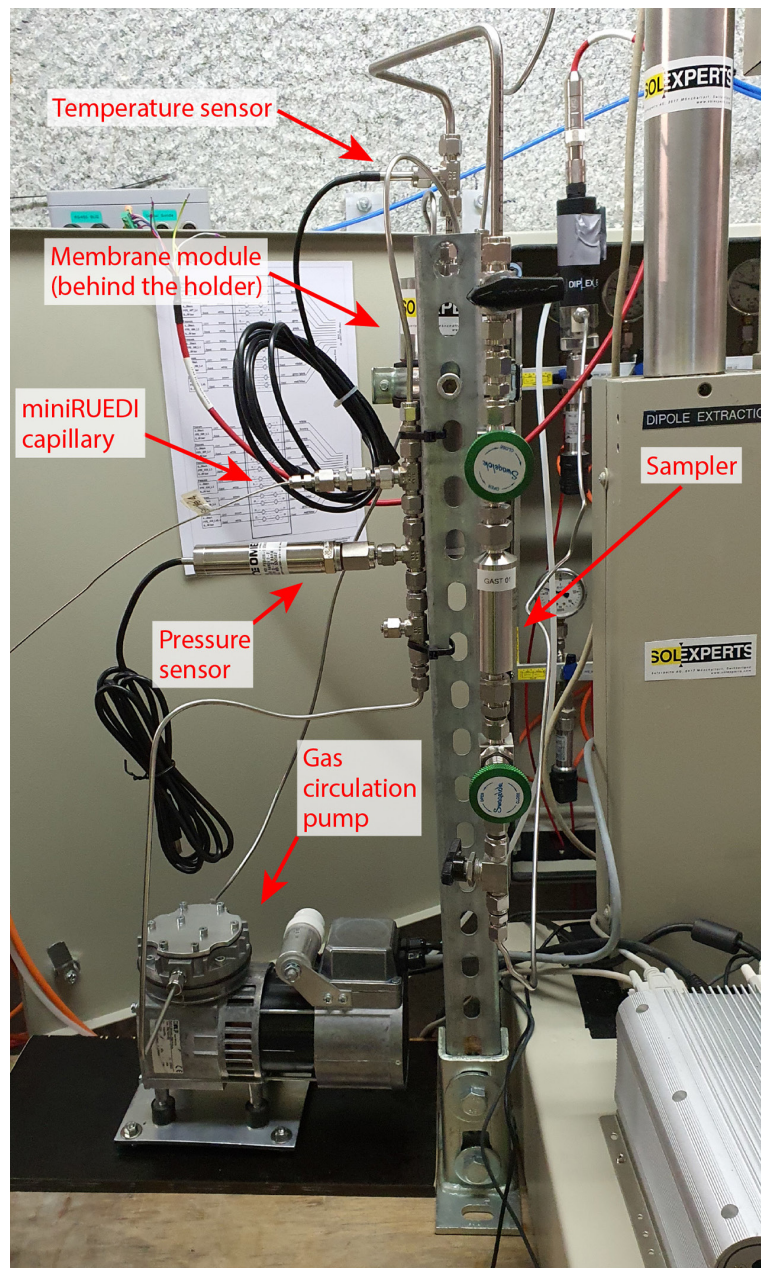


Fig. 3-9: Capillary, pressure sensor, and temperature sensor connected to the membrane module provided by Solexperts AG

On the line carrying the fluids from PL_S14_L1, a 25 ml sampler for off-site analyses is connected upstream of the membrane module.

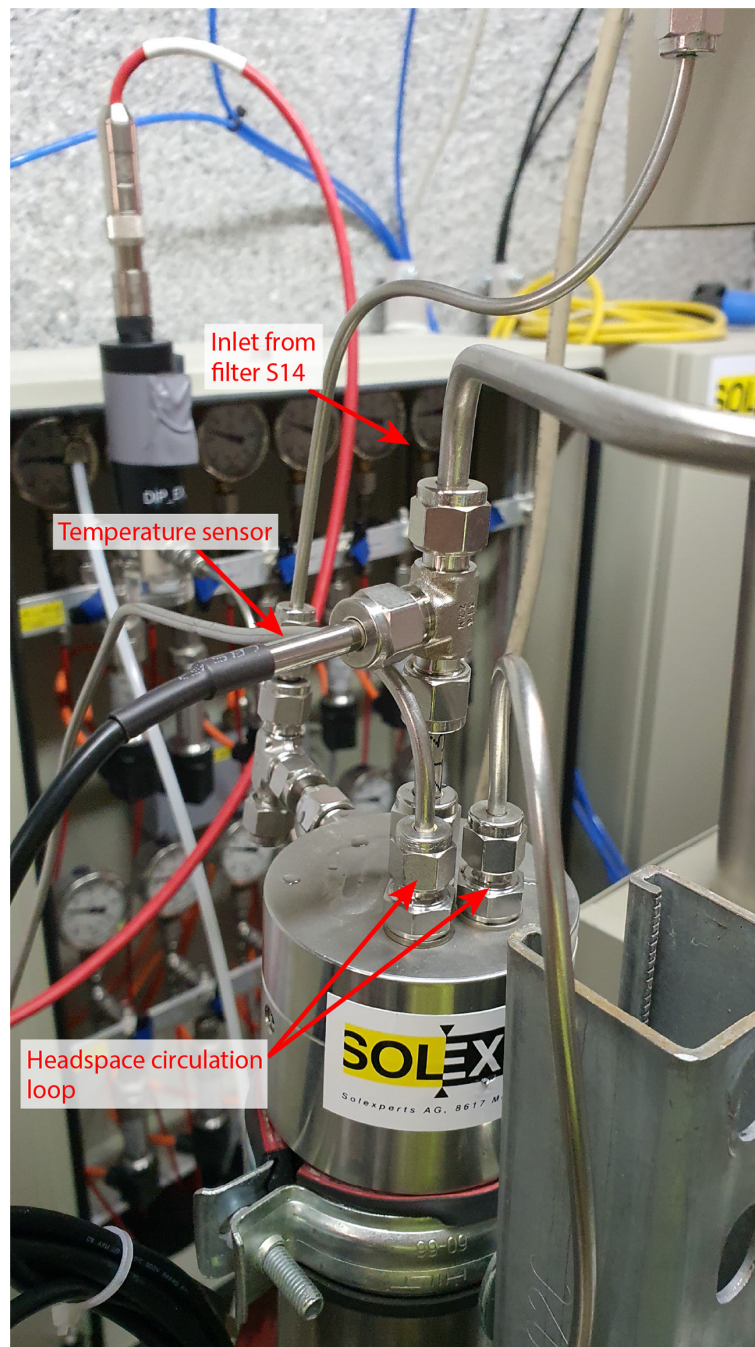


Fig. 3-10: Picture detailing the temperature sensor connected to the fluid inlet at the head of membrane module by Solexperts AG

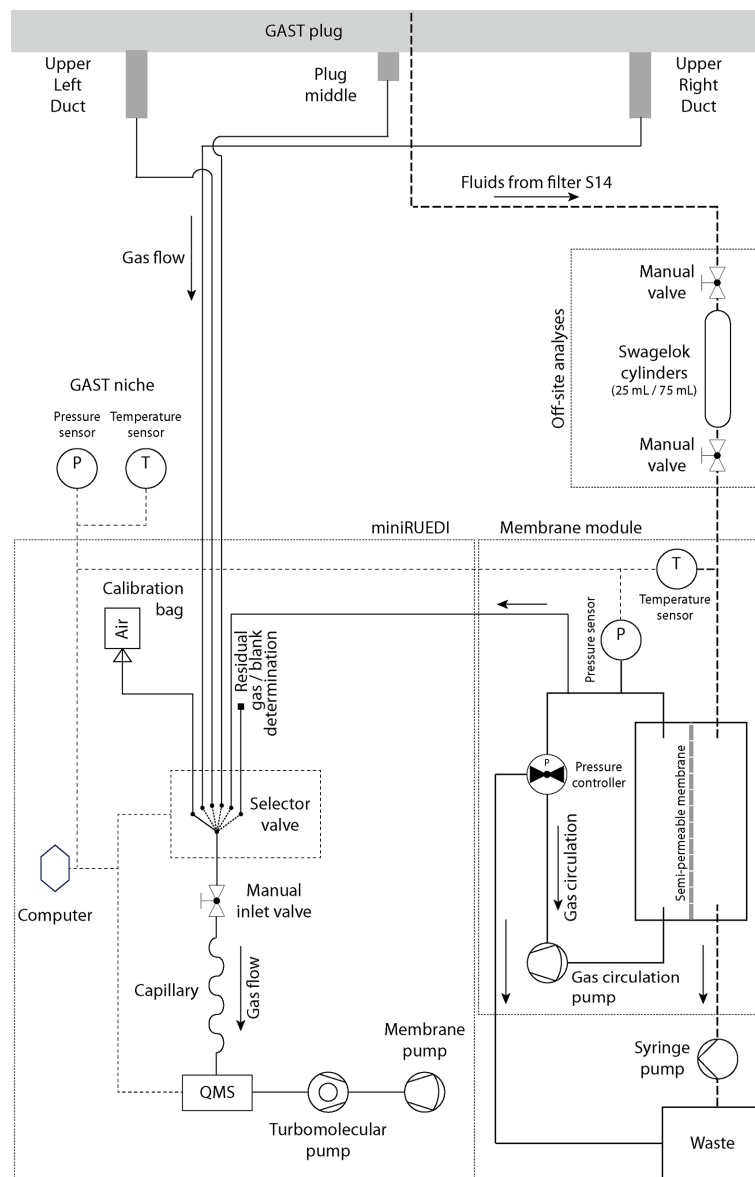


Fig. 3-11: Schematic overview of the GAST gas monitoring system

The sampler was always collected in a bypass from the main extraction line with the membrane module (bypass not represented in this plot for the sake of clarity), and hence never affected by any potential effects of the membrane on gas separations.

3.5.1.4 Analysis of Gas Mix #2

The first gas mix injection at the GAST used He-spiked N₂. While the nominal He concentration in Gas Mix #1 of 2% lies close to the upper limit of detection for He on the electron multiplier detector of the miniRUEDI, the He concentration in Gas Mix #2 was set to about 10%, that of Ar to 15%, and that of Xe to 0.1%. Except for Ar, this gas mix composition cannot be analysed using the standard miniRUEDI protocols. Therefore, an updated appropriate match of gas species, detectors, and calibration gas was required to achieve quantitative measurements.

To investigate the composition and the behaviour of Gas Mix #2, an aliquot of this gas mix was transferred into a miniRUEDI calibration bag. The bag was connected to an inlet of a miniRUEDI at Entracers GmbH to perform (1) scans throughout the spectrum of mass/charge ratios (m/z) measurable with the instrument (i.e., from $m/z = 1$ up to $m/z = 200$), and (2) test the use of the GAST Gas Mix #2 to achieve calibrated gas measurements. The laboratory trials were conducted between 20 January 2023 and 23 January 2023.

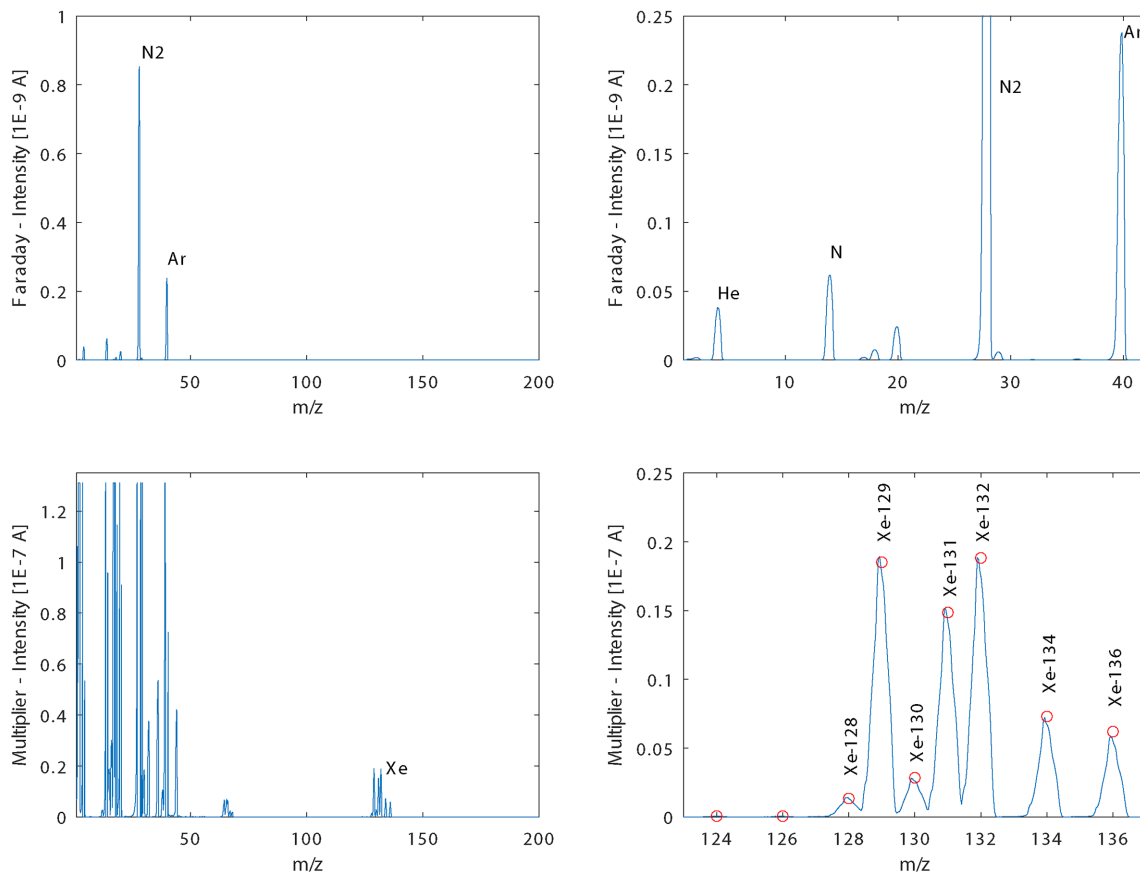


Fig. 3-12: Scans from $m/z = 1$ up to $m/z = 200$ both on the Faraday cup and the electron multiplier detectors

Red open circles indicate the composition expected for atmospheric air.

Two scans were performed: one using the Faraday cup detector and the other using the electron multiplier detector (Fig. 3-12). The scan using the Faraday cup (Fig. 3-12, upper panels) clearly shows the peaks of the major gases present in Gas Mix #2: He ($m/z = 4$, 9.93%), N₂ ($m/z = 28$, 75.00%), and Ar ($m/z = 40$, 14.97%). Slight Xe peaks ($m/z = 124$ up to $m/z = 136$, 997.1 mg/L) were also detected (not shown in Fig. 3-12). However, as the Xe peak intensities are rather close to the background values, a measurement with the electron multiplier detector is more appropriate.

The scan using the electron multiplier detector (Fig. 3-12, lower panels) shows that for major gas species below $m/z = 50$, the measured intensities are close or reach the overload threshold of the detector (about $1.3\text{E-}7$ A). The Xe peaks are clearly visible and well within the detection range of the detector (note the double-charged Xe atoms resulting in peaks around $m/z \sim 65$). The Xe isotope composition is atmospheric (Fig. 3-12, lower panel on the right-hand side), as the measured peaks match the values expected for atmospheric air (Fig. 3-12, red dots in the lower panel on the right-hand side).

From the scan results, it seems reasonable to attempt to use the GAST Gas Mix #2 to calibrate the measurement of He, N₂, and Ar on the Faraday cup detector and Xe (targeting $m/z = 129$, i.e. ¹²⁹Xe which represents about 26.44% of the total Xe; Ozima and Podosek 2002) on the electron multiplier detector.

The GAST Gas Mix #2 was used to calibrate miniRUEDI measurements of He, N₂, Ar, and Xe in ambient air, in a certified gas mixture (Entracers mix) containing He (0.5%) and N₂ (96.5%), and in the GAST Gas Mix #2 itself. Tab. 3-12 lists the deviations of the measurements with respect to the expected values for each gas sample.

Almost all deviations lie close to the typical uncertainty range known for the miniRUEDI measurements (1 – 3%; Brennwald et al. 2016). Only the concentration of He determined in ambient air is significantly higher compared to the concentration expected for atmospheric air (measured volume fraction: $7.35\text{E-}6$; volume fraction expected for atmospheric air: $5.24\text{E-}6$). This is reasonable, as concentrations in the mg/L range can be barely quantified with the Faraday cup detector (i.e., usually such low concentrations are measured on the electron multiplier detector) and the measured concentration is more likely to be related to fluctuations of the He signal baseline.

The results show that Gas Mix #2 can, in principle, be used to calibrate the analyses to detect the breakthrough of fluids with a similar gas composition, especially at the membrane module by Solexperts AG connected to filter S14. It should be noted that the measurement of He on the Faraday cup detector implies that the monitoring system will be about three orders of magnitude less sensitive. Therefore, the detection of Gas Mix #2 emissions using the capillaries installed in the vicinity of the GAST plug based on He only could become more challenging.

Tab. 3-12: Relative deviations of measurements calibrated against Gas Mix #2 with respect to the expected concentrations

Sample	He [%]	N ₂ [%]	Ar [%]	Xe [%]
Ambient air	40.18	0.04	-3.20	-2.76
Entracers mix	0.002	2.70	-	-
GFT Gas Mix #2	-1.26	0.12	1.74	-2.51

3.5.2 miniRUEDI testing and monitoring implementation

Sniffing tests were conducted between 14 March 2022 and 16 March 2022. One side of a PEEK capillary was connected to the outlet of the Gas Mix #1 reservoir containing N₂ quality 5.0 spiked with 2% He quality 4.6 (for the certificate by Westfalen Gas Schweiz GmbH, see Enclosure B.5). The other (open) side of the capillary was set at different positions within the GAST niche, and Gas Mix #1 was released for a limited period at a defined flow rate from the capillary outlet. The gas composition was determined using the miniRUEDI collecting gases mainly from the three pre-defined spots: the URD, the ULD, and the plug middle (Fig. 3-13). From the outcome of the sniffing tests (all details in Enclosure L), the following sniffing strategy was suggested:

- Initial sniffing capillary positions: ULD, URD, and plug middle (the capillary of the last position was fixed at the plug surface (Fig. 3-13)).
- Leaks at the URD and at the ULD are expected to be clearly assessable.
- At further positions around the plug, the ventilation at the GAST niche could cause tracer dilution and lower sensitivity of the monitoring setup. Therefore, shielding of the GAST niche ventilation with a panel (Fig. 3-14) was adopted to allow more sensitive sniffing (periodically, and after any suspicion of a gas leak).

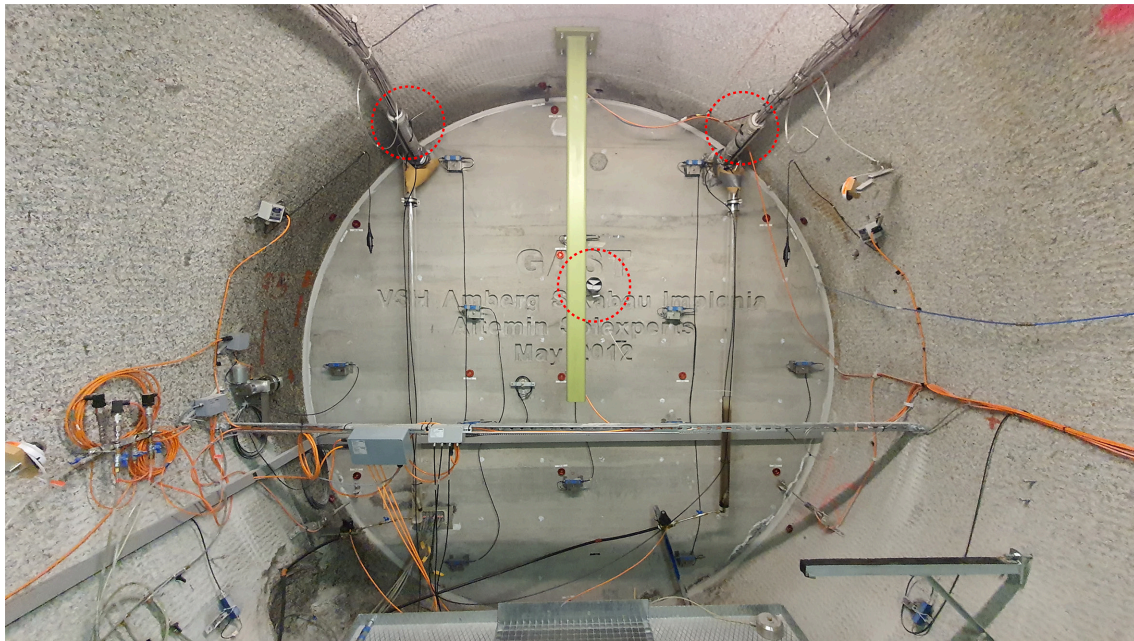


Fig. 3-13: Sniffing capillary setup prior to the GAST GFT

Red-dashed circles mark the position of the open ends of the sniffing capillaries.

The membrane module provided by Solexperts AG was tested to assess the gas dynamics prevailing in it under field conditions (i.e., connected to a water flow). Two trials were conducted by connecting the membrane module directly to different water sources: the first test (21 March – 28 March 2022) involved the injection of BOADUS water (i.e., water from the Grimsel massif) into the water phase side of the membrane module; the second test (28 March – 31 March 2022) used BOADUS water stripped for about 45' with the Gas Mix #1 and kept at 14 bar with the Gas Mix #1 in a tank for about one week to equilibrate.

For both tests, the water was injected into the membrane module at a flow rate of about 1.7 ml/min and a total pressure of 14 bar. Such conditions reflected the most realistic operational flow and pressure known from modelling and calculations as of March 2022. The miniRUEDI determined the evolution of the gas composition in the gas phase side of the membrane module throughout the test periods.

Based on the tests carried out on the membrane module (all details in Enclosure L), it was possible to assess that, under the chosen experimental conditions:

- The setup (miniRUEDI measuring the gas phase of the membrane module) is sensitive to a change in gas composition, and allows a fast detection of gas tracers present.
- The setup allows a qualitative determination of the gas composition trends in the fluid flowing through the membrane module, but with some days to be taken in account for the gas measurements to stabilise.

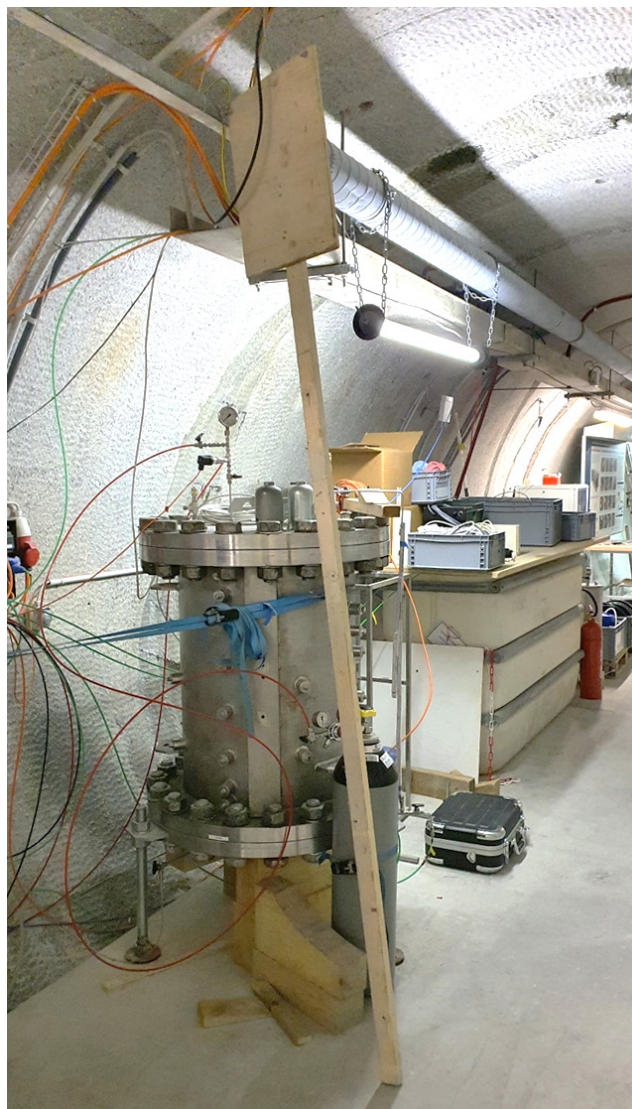


Fig. 3-14: Screening set at the outlet of the ventilation in the GAST niche

4 Gas Flow Test: field work and data

4.1 Hydraulic baseline and preparation for the gas flow test

4.1.1 Phase 1 aims

This chapter describes the field work and results obtained during the preparation phase and GFT Phase 1. The preparation phase included several hydraulic tests and sampling campaigns to determine the baseline conditions:

- Filter saturation by water injections and extractions
- Dipole and injection testing in the S/B using PPE ports
- Fluid sampling
- Index testing

GFT Phase 1 started on 15 March 2022 with the first of a series of pulse injection tests to obtain data for filter compressibility estimation. Hydrochemical sampling and index testing were repeated.

4.1.2 Filter saturation

After the Gas Property Test (GPT1) performed in 2018, the system was resaturated with the aim of equilibrating pore pressures (Lanyon et al. 2022). This equilibration phase continued until 03 May 2022. Target pressures for filter saturation were 20 bar (S02) and 18 bar (S14) by 15 December 2021, when preparations for the GFT began. During the preparation phase, the target filter pressures were reduced to 18 bar (S02) and to 16 bar (S14).

The setup for filter saturation allowed for constant rate injections (RI) into S02 and constant head injections (HI) in S14 (Fig. 4-1). Formation water from BOADUS 96.001-i1 was used for the injections in the filter sections. Tab. 4-1 and Tab. 4-2 summarise the injection protocols for both filters, S02 and S14, respectively. On 19 January 2022, the target pressure at S14 was further reduced from 16 to 14 bar, aiming at establishing a monotonic pore pressure gradient within the S/B body.

This was first realised by reducing the injection flow rate (19 January 2022), and later by temporary fluid extractions (04 February 2022; Tab. 4-2). Water was extracted from PL_S14_L1 to implement the pressure decrease.

Between 14 February and 09 March 2022, the pressure was further decreased by extraction from PL_S14_L1 at a target pressure of 14 bar. The extraction flow rate was measured with a temporarily installed flow controller and data acquisition.

The beginning of the GFT and start of Phase 1 were set to the first short-term pulse injection test to obtain data for an initial compressibility assessment (PI in Tab. 4-1 and Tab. 4-2). Similar PI tests were repeated in later phases to keep track of compressibility changes and to derive filter gas saturations.

On 18 March 2022, the S14 injection at constant head with a target pressure of 14 bar was started again.

Filter flow rates and pressure responses for this GFT preparation period and GFT Phase 1 are displayed in Fig. 4-2 and Fig. 4-3 for filters S02 and S14, respectively.

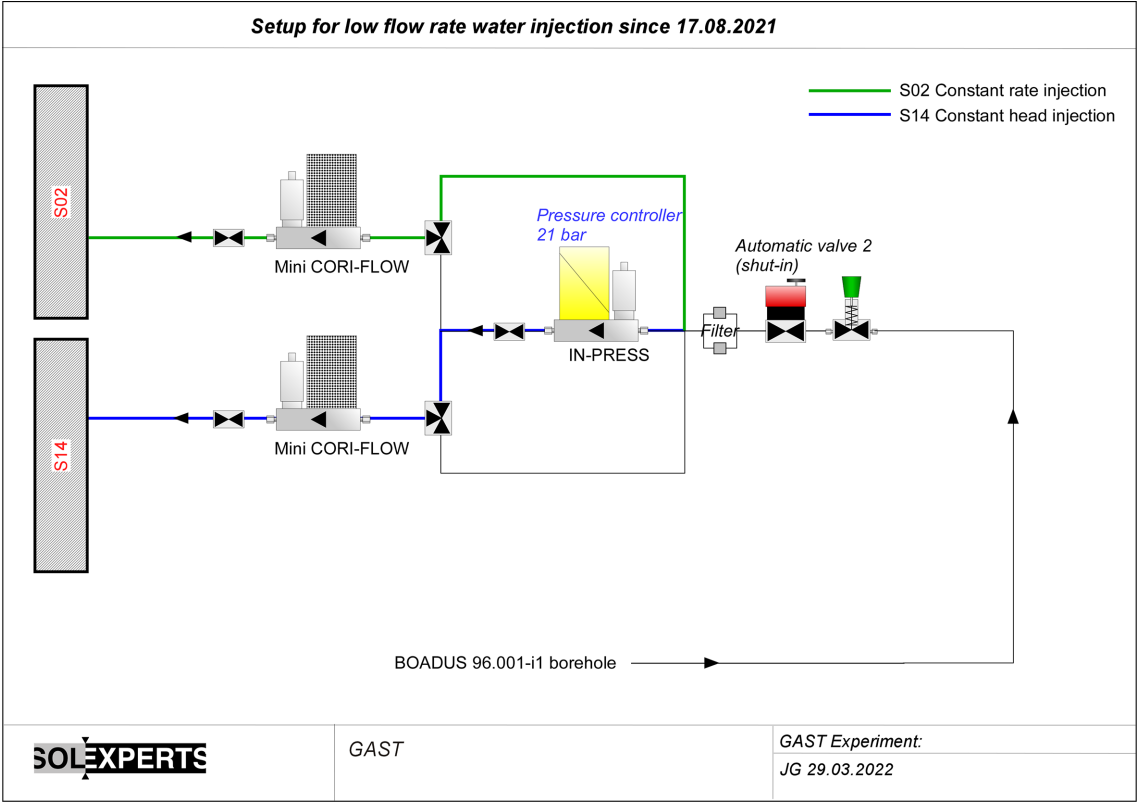


Fig. 4-1: Surface setup for saturation of S02 and S14 between 17 August 2021 and 03 May 2023

Tab. 4-1: Overview of saturation steps for filter Section S02

Start date/time	End date/time	Injection type	Average flow rate [ml/min]	Final pressure PPE_S02_L1 [kPa]	Comment
28.12.21 22:59	04.01.22 08:42	RI	0.06	1,799	
04.01.22 08:42	25.01.22 07:59	RI	0.07	1,789	
25.01.22 07:59	27.01.22 05:22	RI	0.8 → 0.08	1,802	Adjustment to keep P constant
27.01.22 05:22	15.02.22 10:51	RI	0.09	1,789	
15.02.22 10:51	26.02.22 06:58	RI	0.12	1,810	
26.02.22 06:58	08.04.22 13:32	RI	0.11	1,754	
15.03.22 13:39					Start GFT Phase 1
18.03.22 11:00	18.03.22 13:42	PI	dV = 2.44819 l	dP = 373 kPa	PL_S02_L1
08.04.22 13:32	13.04.22 22:51	RI step test	0.11 → 0.17 → 0.24 → 0.11 → 0.22 → 0.11	1,795	
13.04.22 22:51	27.04.22 07:32	RI	0.11	1,792	

Tab. 4-2: Overview of saturation and pressure equilibration steps for filter Section S14

Start date/time	End date/time	Injection type	Average flow rate [ml/min]	Final pressure PPE_S14_L1 [kPa]	Comment
31.12.21 23:37	19.01.22 09:37	HI	0.04 → 0.1	1,599	
19.01.22 09:37	04.02.22 07:45	HI to 14 bar	0.02	1,508	Slow decrease
04.02.22 07:52	04.02.22 11:04	Extraction for pressure reduction	- 4.0	1,405	dV = 712 ml P decrease
04.02.22 11:04	14.02.22 09:31	HI to 14 bar	0.02	1,460	P increase
14.02.22 09:31	09.03.22 15:07	Extraction	Decreasing 0.26 → 0	1,399	P constant
15.03.22 15:15		PI	dV = 3.5519 l	dP = 600 kPa	PL_S14_L1 Start of GFT Phase 1
18.03.22 13:51		PI	dV = 3.42557 l	dP = 600 kPa	PL_S14_L1
18.03.22 14:18	03.05.22 07:22	HI	0.02 → 0.7	1,402	

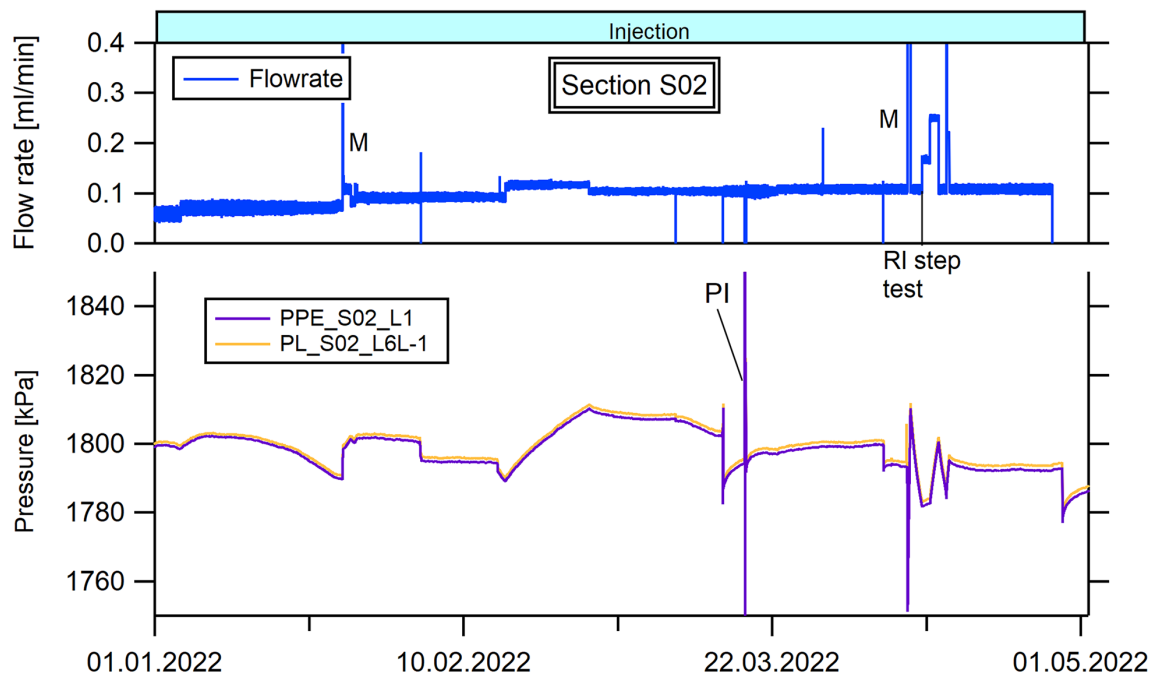


Fig. 4-2: Pressure and flow rate during saturation of filter S02 until 01 May 2022

M: Manipulation, e.g. higher flow rates to stabilise pressure

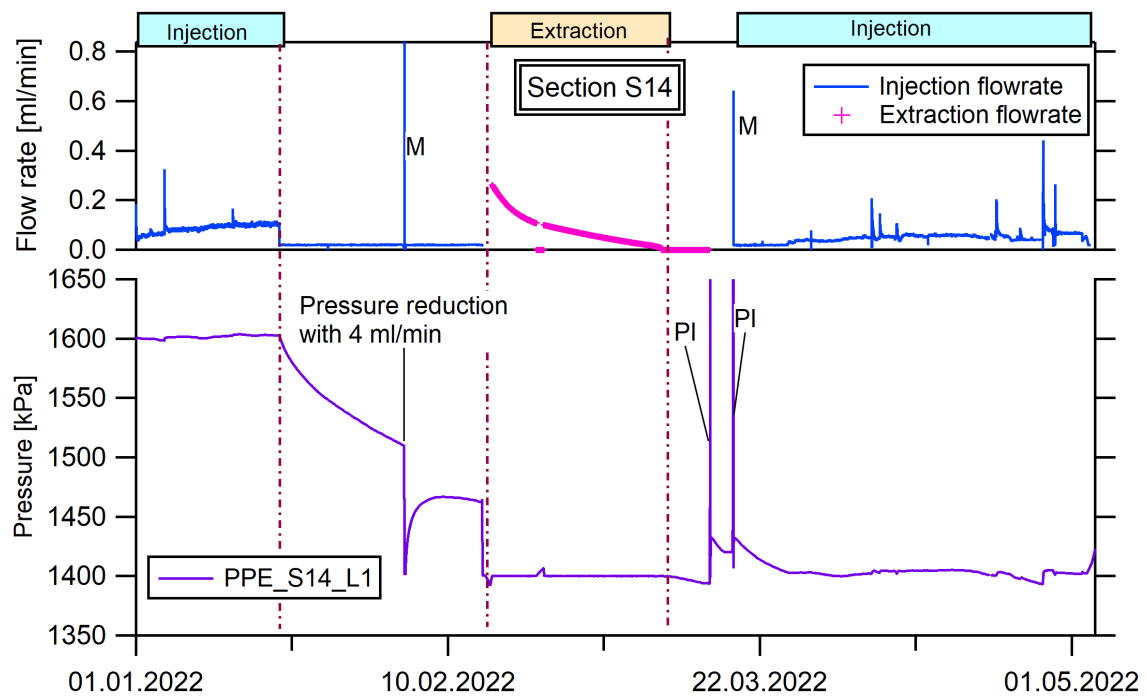


Fig. 4-3: Pressure and flow rate during saturation of filter S14 until 03 May 2022

M: Manipulation, e.g. higher flow rates (not to scale) to stabilise pressure

The filter compressibilities estimated from $\Delta V/\Delta P$ for the three PI tests are 5.6 ml/kPa (S02) and 4.9 ml/kPa (both S14 tests). This is slightly higher than the 3.5 ml/kPa measured in the pre-GPT1 pulse test (12 December 2017) in S02 (at lower pressure and smaller ΔP of 25 kPa). The higher compressibility could indicate either the presence of a small gas volume of ~ 3 l in S02 and of ~ 2 l in S14 or it could reflect changes in the filter state and differences in stress conditions over the intervening 5 years. The results of these PI tests have been used as a baseline measurement for the interpretation of the GFT (see discussion in Nagra 2025).

4.1.3 Dipole test

Piezometer dipole and injection tests were performed as part of the GFT preparation phase to obtain baseline hydraulic permeability information prior to the gas injections. Dipole testing also allowed porewater sampling without heavily affecting the pore pressure distribution.

On 20 December 2021, a dipole test was started with the injection in PPE_S06_L2 and the extraction from PPE_S07_L2 with a straight-line distance of 0.98 m between the two screens (see Rüedi et al. 2012 for sensor coordinates). The test layout is shown in Fig. 4-4. Water was injected in PPE_S06_L2 with a 500-ml single-piston syringe pump.

The volume extracted from PPE_S07_L2 was measured with a second single-piston syringe pump. An electrical conductivity (EC) flow-through cell was installed on the extraction side to measure the conductivity. The setup of the surface equipment and its specifications are shown in Fig. 4-4 and Tab. 4-3.

Field activities for the 84 days testing period are summarised in Tab. 4-4. The monitoring data obtained during the dipole test are shown in Fig. 4-5 and Fig. 4-6. The dipole test started with a pressure of 18 bar on the injection side and 16 bar on the extraction side, resulting in extremely low flow rates of 42 ml/week (injection) and 11 ml/week (extraction). To increase the flow rates, the injection pressure was increased to 20 bar and the extraction pressure was step-wise decreased to finally 7 bar on 27 January 2022.

On 13 January 2022, an anionic tracer vial with a nominal concentration of 10 mg/L 1-Naphthalenesulfonic acid (1-NSA) was installed on the injection side (laboratory results confirmed a concentration of 9,919 $\mu\text{g/L}$) to measure tracer breakthrough time on the extraction side. This installation caused the observed decrease of the injection flow rate from an average of 4.16 $\mu\text{l/min}$ to 1.87 $\mu\text{l/min}$ (Fig. 4-5). Between 04 February and 14 March 2022, four samples were taken on the extraction side during this tracer injection period. None of these samples indicated significant concentrations of 1-NSA tracer at the extraction line. Interestingly, the extraction flow rate increased significantly after 10 March 2022 (Fig. 4-6). Since the instrumentation worked smoothly and pressure data were not affected, the nature of this flow event remained unclear, and the dipole test finished 14 March 2022 because of time constraints. The totally injected and extracted fluid volumes amounted to 306 ml (injection) and 401 ml (extraction). The volume and flow rate calculations are given in Tab. 4-5.

EC monitoring of the extracted fluid indicates variations, the nature of which remains unclear and might be caused by a mix of the S/B porewater with some injected water. Nevertheless, no net decrease of EC towards lower values corresponding to injection water (i.e. 80 – 100 $\mu\text{S/cm}$) was detected at the extraction line. Correspondingly, laboratory results did not indicate any significant concentrations of the injected 1-NSA anionic tracer.

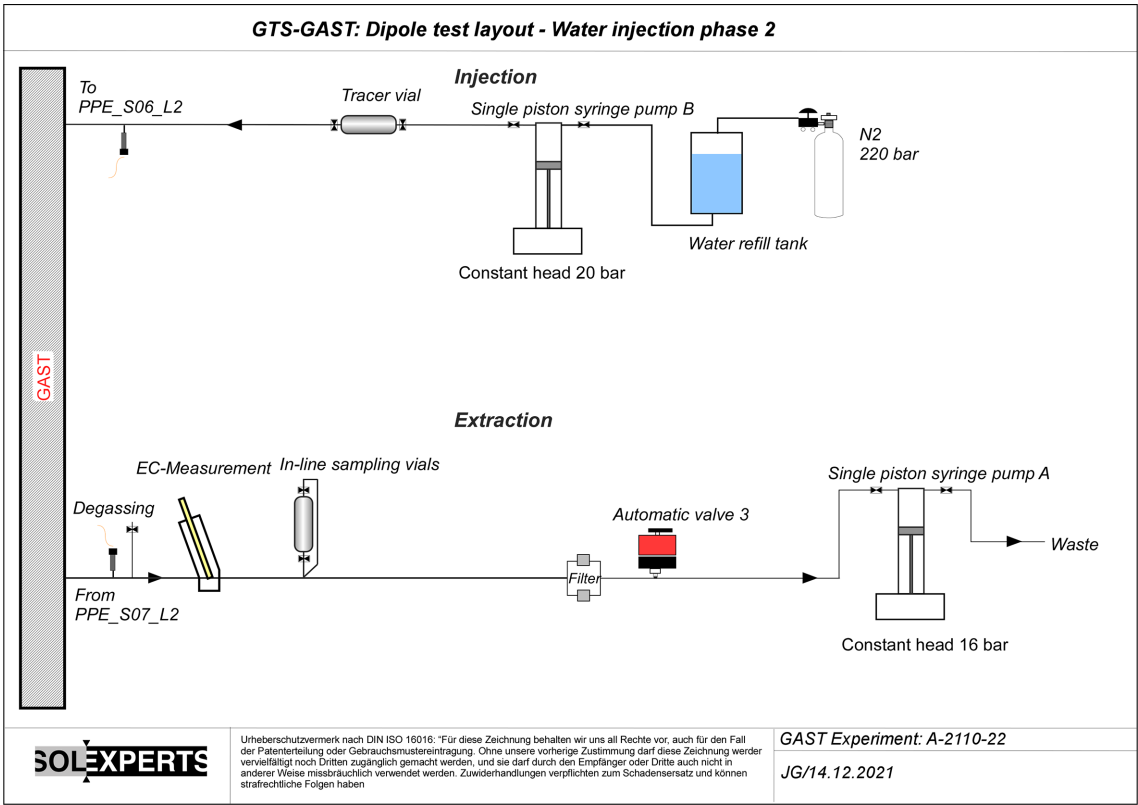


Fig. 4-4: Surface setup for dipole test between PPE_S06_L2 and PPE_S07_L2

Tab. 4-3: Specifications of surface instrumentation for dipole test between PPE_S06_L2 and PPE_S07_L2

Sensor name	DAS ch.	Type	Sensor type	SN	Range	Unit	Used for
DIP_EX_V	901	Volume	Syringe pump		0 – 500	ml	Extraction volume
DIP_EX_Q	902	Flow	Syringe pump		0.001 – 200	ml/min	Extraction flow
DIP_INJ_V	903	Volume	Syringe pump		0 – 500	ml	Injection volume
DIP_EX_EC	904	Conductivity	Conducell	13341	0.1 – 500,000	µS/cm	Extraction monitoring
DIP_EX_ECT	905	Temperature	Conducell	13341	-20 – 135	°C	Extraction

Tab. 4-4: Details of dipole test between PPE_S06_L2 and PPE_S07_L2

Date & time	Sample	Activity
20.12.21 11:50		Start dipole test, injection at PPE_S06_L2 at 18 bar, extraction from PPE_S07_L2 at 16 bar
21.12.21 15:09		Set injection at PPE_S06_L2 to 20 bar and extraction from PPE_S07_L2 to 14 bar
07.01.22 08:17		Reduce extraction pressure to 12.5 bar
11.01.22 08:54		Reduce extraction pressure to 11.0 bar
13.01.22 11:07		Start tracer injection in PPE_S06_L2 (10 ppb 1-NSA in 100 ml vial)
17.01.22 07:45		Reduce extraction pressure to 9.0 bar
27.01.22 14:47		Reduce extraction pressure to 7.0 bar
04.02.22 08:36 – 11:28		Stop dipole extraction and install diffusion module
04.02.22 10:30		Install sampling vial 25 ml
14.02.22 07:45	PPE_01	Remove sampling vial, install new one
23.02.22 14:52	PPE_02	Remove sampling vial, install new one
08.03.22 14:52	PPE_03	Remove sampling vial, install new one
14.03.22 09:01		Stop dipole test
14.03.22 09:07	PPE_04	Remove sampling vial

Tab. 4-5: Volume and flow rate calculation for dipole test between PPE_S06_L2 and PPE_S07_L2

Port	Date [from]	Date [to]	Volume [ml]	Flow rate [ml/week]	Flow rate [ml/min]
Injection PPE_S06_L2	20.12.21 08:40	13.01.22 11:01	144.49	41.97	0.00416
	13.01.22 11:04	14.03.22 09:25	161.63	18.88	0.00187
	20.12.21 08:40	14.03.22 09:25	306.12		
Extraction PPE_S07_L2	20.12.21 08:40	16.01.22 16:53	44.167	11.31	0.00112
	16.01.22 16:53	04.02.22 06:44	74.077	27.91	0.00277
	04.02.22 22:17	07.03.22 18:40	93.116	21.13	0.00210
	10.03.22 10:11	14.03.22 09:33	170.93	301.11	0.02987
	20.12.21 08:40	14.03.22 09:33	401.00		

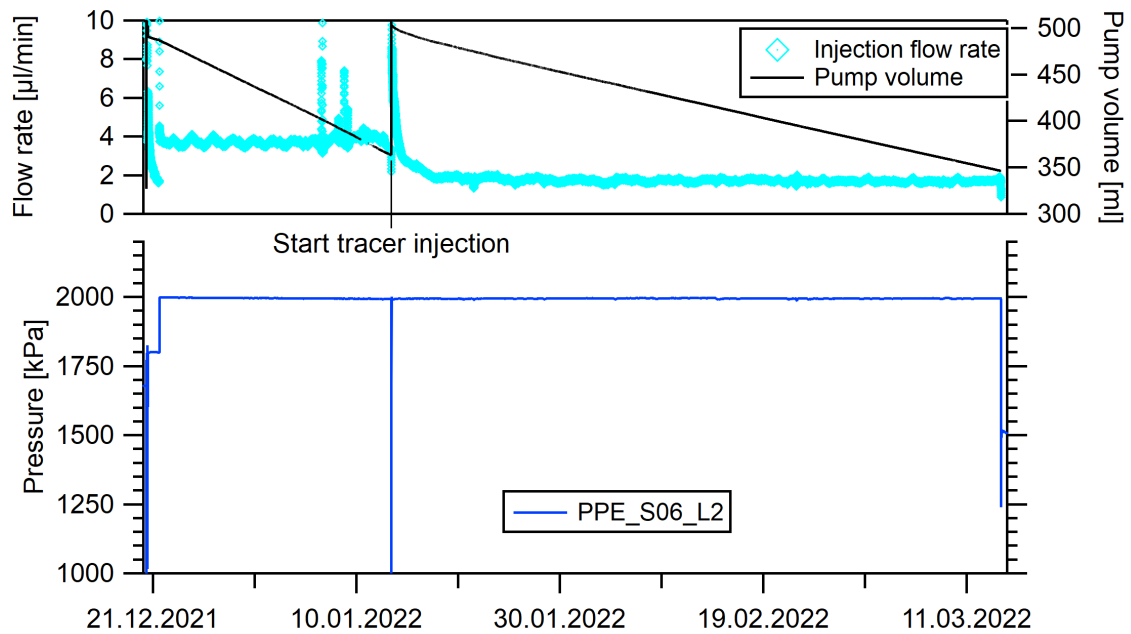


Fig. 4-5: Dipole test: Pump volume, calculated injection flow rate and pressure at PPE_S06_L2

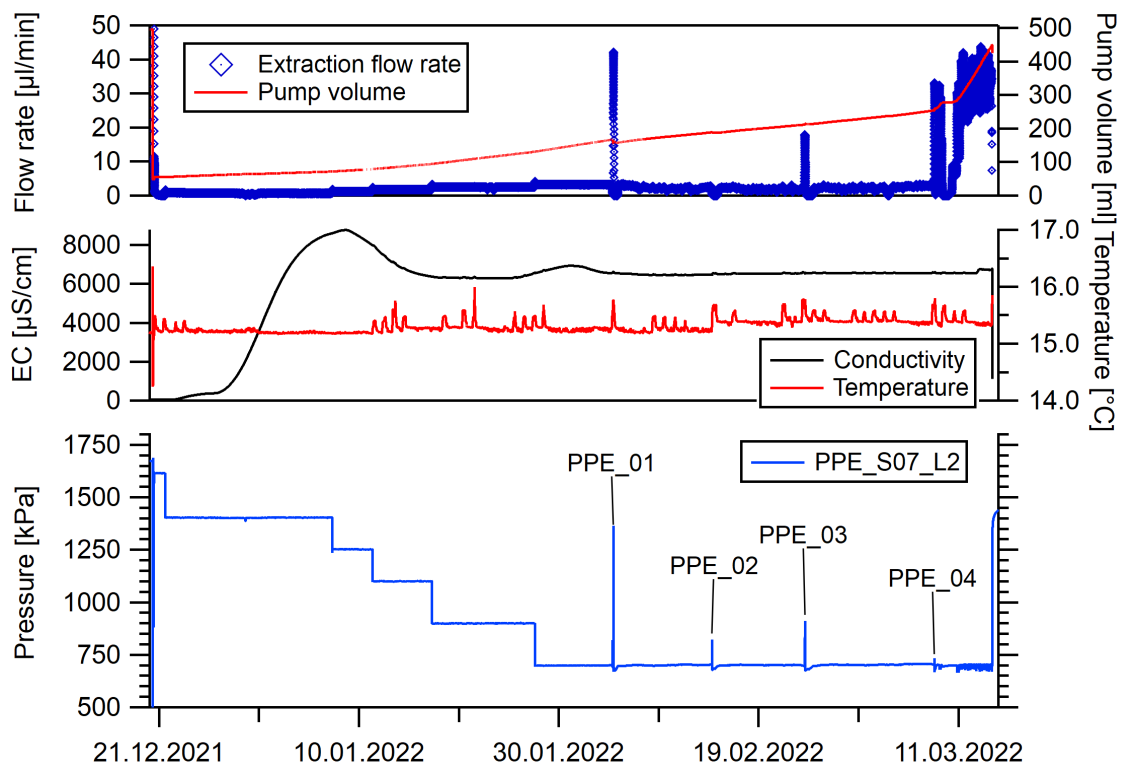


Fig. 4-6: Dipole test: Pump volume, calculated extraction flow rate and pressure at PPE_S07_L2 together with measured EC and temperature

4.1.4 Injection test in PPE_S03_L6H-2

On 14 February 2022, a constant head injection (HI) test was started in PPE_S03_L6H-2 to test hydraulic permeability and the presence of residual gas at this port.

The injection was performed with the setup used for the injection in filter S14 (see Fig. 4-1).

The obtained injection test data for the injection (HI) and recovery (HIS) phases are shown in Fig. 4-7. The straight-line analysis of the HI test gives two straight lines with an initial transmissivity of $5.48\text{E-}11 \text{ m}^2/\text{s}$ and a transmissivity lower by one order of magnitude of $4.32\text{E-}12 \text{ m}^2/\text{s}$ during the late phase of the test (Fig. 4-8). The diagnostic plot of the pressure recovery shows a $\frac{1}{2}$ unit slope of both ΔP and a derivative which refers to linear flow (well model: infinite conductivity fracture) (Fig. 4-9). This suggests channel or pipe-like flow rather than radial flow that might be expected for this sensor location at the S/B – GBM interface. However, the measured flow rates are small given the applied pressure indicating that any flow path is unlikely to be of significance for the GFT. Flow properties for other PPEs were assessed by the simplified index testing approach that is described in Section 4.1.5.

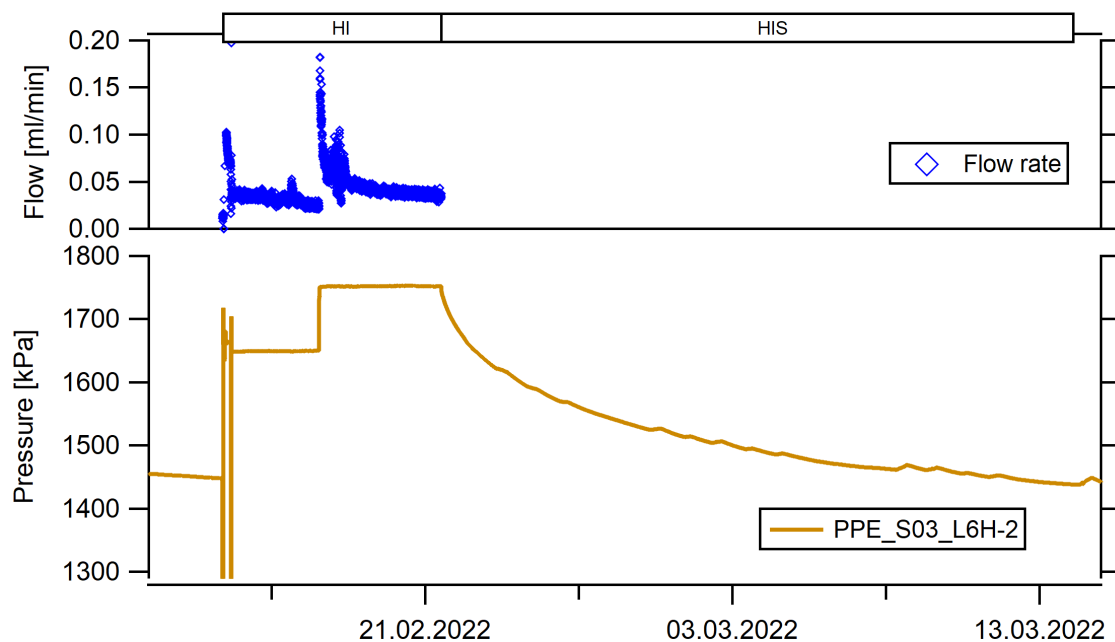


Fig. 4-7: HI injection test and HIS recovery phase in PPE_S03_L6H-2

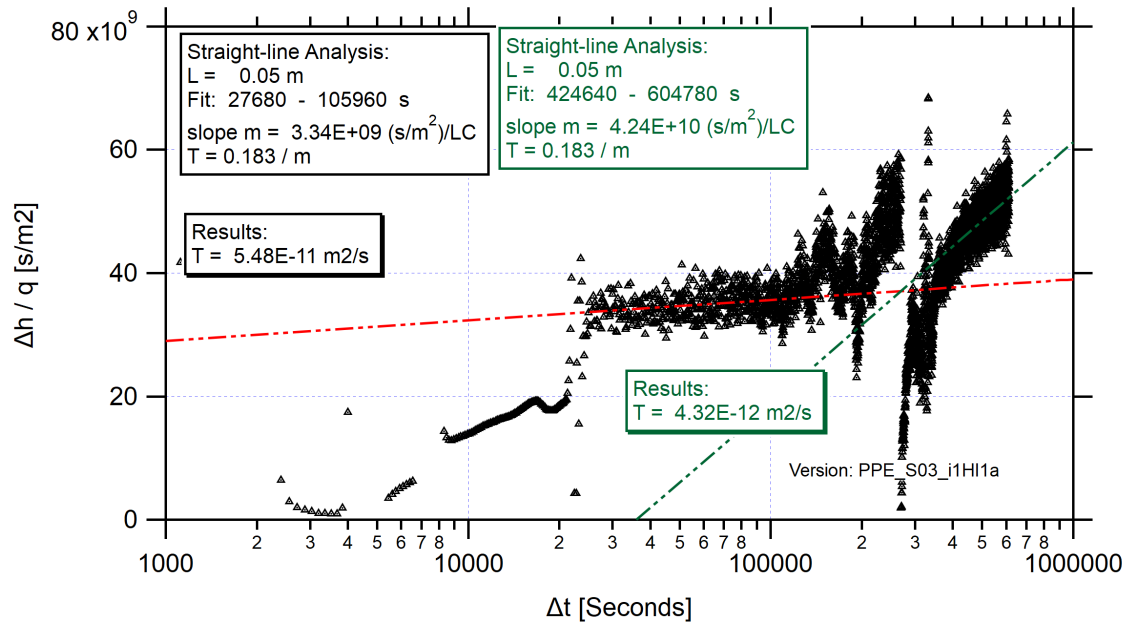


Fig. 4-8: Analysis of HI injection test in PPE_S03_L6H-2
After Jacob & Lohmann (1952)

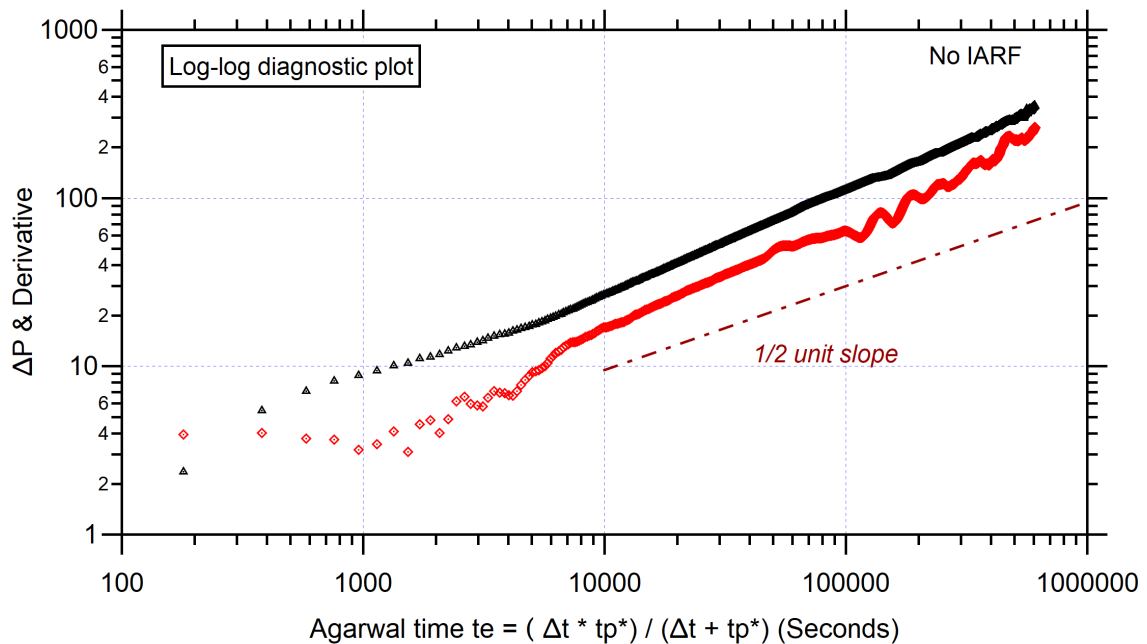


Fig. 4-9: Diagnostic plot of pressure recovery HIS after HI injection test in PPE_S03_L6H-2 with Agarwal time
Agarwal (1980)

4.1.5 Index testing

Between 08 and 31 March 2022, two series of pulse withdrawal (PW) tests were performed in the PPE ports and one in the ventilation side 1 port. The test goal was to find a quick approach to test the material around the PPE sinter filter. The tests later proved useful to assess compressibility as a gas indicator and were repeated multiple times during the GFT.

The applied procedure, called “index testing”, included the following steps:

- Closing the valve between line and pressure transducer and removing the pressure transducer,
- Installing an empty 2 ml volume line between the pressure transducer and the port, and
- Opening the valve to the line and the pressure transducer.

A maximum of 2 ml water/gas at the given pressure were extracted after valve opening.

The measured parameters and the resulting calculated compressibilities are summarised in Tab. 4-6. The plots with the pressures measured during the PW tests are included in Enclosure N.1. The field activity logbook is included in Enclosure F.

An overview of the calculated compressibilities is shown in Fig. 4-10. The results were very consistent, typically falling into the range between $1.24\text{E-}12$ and $2.67\text{E-}12 \text{ m}^3/\text{Pa}$. Higher compressibility was detected for two piezometers (PPE_S06_L6L-1 and PPE_S06_L6H-2).

Since the complete filling of the 2-ml sampling volume could not be controlled during the tests, there may be some uncertainty on the absolute values derived and ΔV in Tab. 4-6 may be overestimated. Quality control was done by pressure monitoring (see comments in Tab. 4-6) and consistency check of the results.

Tab. 4-6: Results of PW tests from PPE lines and ventilation side 1 in March 2022

Date	Time	Sensor	ΔP [kPa]	ΔV ⁽¹⁾ [ml]	C [m ³ /Pa]	Comments
08.03.22	08:45	PPE_S03_L6L-1	1,084.00	2	1.85E-12	Very slow increase
08.03.22	09:00	PPE_S06_L6L-1	314.86	2	6.35E-12	Very slow increase
08.03.22	09:15	PPE_S08_L6L	916.39	2	2.18E-12	Very slow increase
08.03.22	09:30	PPE_S10_L6L-1	750.27	2	2.67E-12	Very slow increase
08.03.22	09:45	PPE_S10_L6H-2	737.86	2	2.71E-12	Very slow increase
08.03.22	10:00	PPE_S06_L6H-2	200.77	2	9.96E-12	Very slow increase
08.03.22	10:15	PPE_S12_L6L-1	902.6	2	2.22E-12	Very slow increase
08.03.22	10:30	PPE_S12_L6H	1,169.52	2	1.71E-12	Very slow increase
14.03.22	09:02	PPE_S03_L4	1,296.44	2	1.54E-12	Fast increase
14.03.22	09:15	PPE_S12_L4	1,318.05	2	1.52E-12	Fast increase
14.03.22	09:31	PPE_S08_L4	1,218.06	2	1.64E-12	Fast increase
14.03.22	09:45	PPE_S06_L4	785.57	2	2.55E-12	Slow increase
14.03.22	10:45	PPE_S07_L4	1,179.73	2	1.70E-12	
14.03.22	12:00	PPE_S09_L4	1,039.84	2	1.92E-12	Slow increase
14.03.22	12:15	PPE_S10_L4	1,296.83	2	1.54E-12	Fast increase
18.03.22	09:22	Ventilation side 1	1,163.53	2	1.72E-12	Very fast increase
18.03.22	09:28	PPE_S12_L2-1	1,329.39	2	1.50E-12	Very slow increase
18.03.22	09:45	PPE_S03_L2-1	1,229.59	2	1.63E-12	Very fast increase
18.03.22	09:55	PPE_S08_L2	1,339.34	2	1.49E-12	Slow increase
18.03.22	11:27	PPE_S12_L2-2	1,348.80	2	1.48E-12	Fast increase
18.03.22	11:47	PPE_S03_L2-2	775.18	2	2.58E-12	
18.03.22	13:10	PPE_S06_L2	1,444.02	2	1.39E-12	
18.03.22	13:50	PPE_S07_L2	1,206.78	2	1.66E-12	
21.03.22	09:10	PPE_S09_L2	837.84	2	2.39E-12	
21.03.22	09:15	PPE_S10_L3	1,240.46	2	1.61E-12	Fast increase
21.03.22	09:31	PPE_S10_L2	1,199.34	2	1.67E-12	Fast increase
21.03.22	10:00	PPE_S11_L3	1,322.40	2	1.51E-12	
21.03.22	14:02	PPE_S12_L3	1,291.09	2	1.55E-12	Fast increase
21.03.22	14:30	PPE_S08_L3	1,350.85	2	1.48E-12	Fast increase
21.03.22	15:14	PPE_S03_L3	1,619.17	2	1.24E-12	Very slow increase
21.03.22	15:25	PPE_S06_L3	1,417.87	2	1.41E-12	Slow increase
21.03.22	15:41	PPE_S04_L3	1,566.26	2	1.28E-12	

⁽¹⁾ Line piece with 2-ml volume connected to PPE port, true extracted volume unknown
Colours: red: compressibility C > 5E-12 m³/Pa, green: very slow increase, blue: very fast increase.

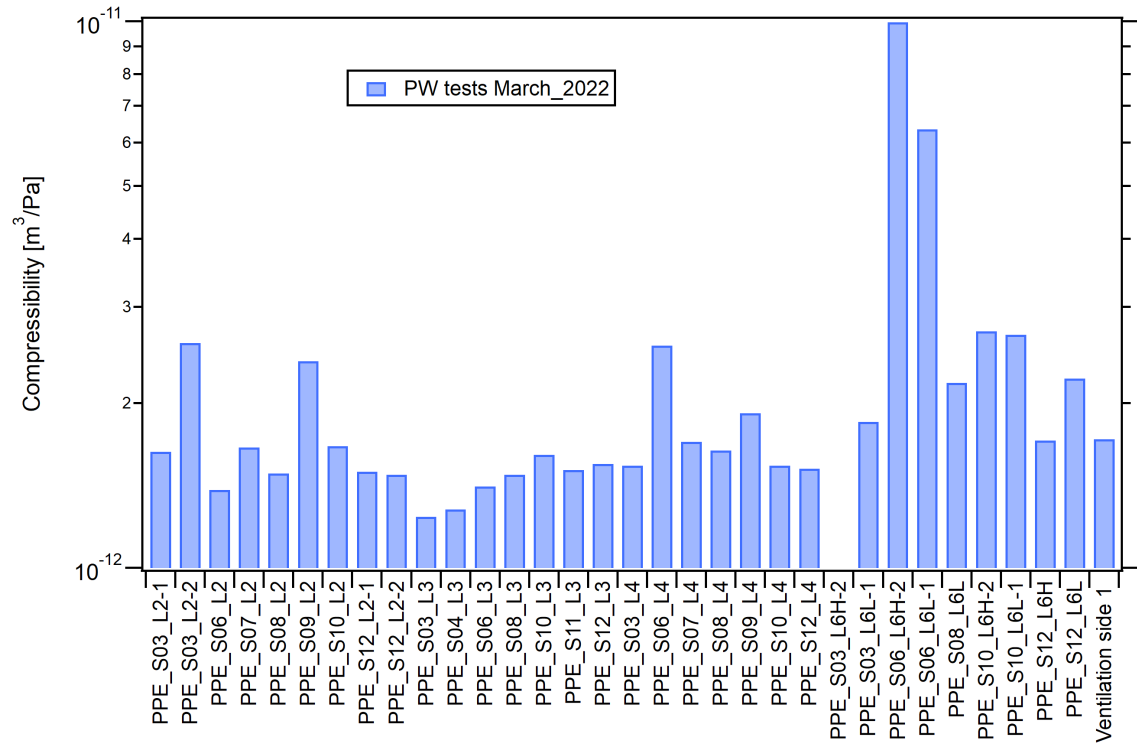


Fig. 4-10: Overview of calculated compressibilities from the PW tests performed in March 2022 (Phase 1)

4.1.6 Sampling

Until 28 March 2022, sampling was performed during the dipole test from the extraction port PPE_S07_L2 and during the diffusion module test (DMT). The samples with the flow rate and the sample weight are noted in Tab. 4-7 (ref. also to Enclosures J and K).

Samples collected during the dipole test were analysed for the gas composition and constitute a baseline reference for conditions inside undisturbed S/B as well as saturated S/B emplaced at L2 prior to the gas tests. The composition of samples collected during the DMT is reported in Tab. 4-8 and Enclosures J and L (miniRUEDI testing).

Tab. 4-7: Sampling performed between 04 February 2022 and 02 May 2022

Phase	Code	Vial	Port	Start date & time	Circulation time [h]	Flow rate [ml/min]	Sample weight [g]
	PPE_001	GAST 01	PPE_S07_L2	04.02.22 10:30	237.25	0.0021	26.86 ⁽¹⁾
	PPE_002	GAST 02	PPE_S07_L2	14.02.22 07:45	223.12	0.0021	26.83 ⁽¹⁾
	PPE_003	GAST 03	PPE_S07_L2	23.02.22 15:45	311.12	0.0021	27.04 ⁽¹⁾
	PPE_004	GAST 04	PPE_S07_L2	08.03.22 15:01	138.10	0.03	26.95 ⁽¹⁾
	GAS_005	GAST 05	Gas Mix #1 ^(*)	15.03.21 13:07	0.03	1.400	Gas ⁽¹⁾
Phase I	DMT_006	GAST 26	DMT #1	21.03.22 13:58	0.00	1.67	25.00 ⁽¹⁾
	DMT_007	GAST 06	DMT #2	28.03.22 07:23	4.32	1.67	27.47 ⁽¹⁾
	DMT_008	GAST 07	DMT #2	28.03.22 07:23	77.05	1.67	27.58 ⁽¹⁾

^(*) Gas Mix #1: 98% N₂ and 2% He, laboratory results presented in Section 4.3.7.1

⁽¹⁾ 25 ml vial

Tab. 4-8: Composition of samples from dipole test (performed at L2 within S/B body)

Tot.: total amount of dissolved gases in cm³_{STP}/kg. The relative composition in [%] was calculated from dissolved species abundance for samples where a direct measurement of a gas phase was not possible (numbers in italics). Empty fields: measurements not performed; “n.d.”: below the detection limit. Full dataset of analytical results available in Enclosure J, full details of sample collection available in Enclosure K.

Sample	Start of collection	Sampling date	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	O ₂	N ₂
			[%]	[cm ³ _{STP} /kg]					[%]			
Dipole PPE_S07_L2	04.02.22 10:30	14.02.22 07:45	100	n.d.	0.02	n.d.	11.4	11.6	<i>n.d.</i>	<i>0.17</i>	<i>n.d.</i>	<i>98.4</i>
Dipole PPE_S07_L2	14.02.22 07:45	23.02.22 14:52	100	n.d.	0.04	n.d.	17.7	18.0	<i>n.d.</i>	<i>0.22</i>	<i>n.d.</i>	<i>98.4</i>
Dipole PPE_S07_L2 (*)	23.02.22 15:45	08.03.22 14:52	100	n.d.	0.05	n.d.	9.7	12.3	<i>n.d.</i>	<i>0.41</i>	<i>n.d.</i>	<i>78.8</i>
Dipole PPE_S07_L2	08.03.22 15:01	14.03.22 09:07	100	n.d.	0.20	n.d.	17.6	18.6	<i>n.d.</i>	<i>1.08</i>	<i>n.d.</i>	<i>94.8</i>

(*) Due to an erratic large relative abundance of about 20% H₂, this sample is suspected to be biased by the gas used for previous analytical elutions in the laboratory (see Enclosure J).

4.2 Water – gas exchange (W-GX) for gas flow test (Phase 2)

4.2.1 Phase 2 aims

Section 4.2 describes the field work and results obtained during GFT Phase 2. This phase aimed at a controlled exchange of pore fluid with gas in the injection filter S02, in short W-GX.

Direct injection of gas without extraction of water would have required very high pressure, so the W-GX balanced gas injection with a volumetric equivalent water extraction without significant pressure changes. The objective was to fill a significant volume of the filter with gas to allow gas to infiltrate the adjacent S/B layers during the subsequent gas injection. No explicit target volume was specified due to uncertainty in the filter pore volume, however, it was hoped to displace water from the filter down to at least Level L4, exposing a significant fraction of the sand/bentonite layers to gas entry.

4.2.2 Field activities

On 02 May 2022 at 08:00, the water-gas exchange (W-GX) was started with the injection of Gas Mix #1 in PL_S02_L6L-2 (1,020 mln/min) and the extraction of fluid from PL_S02_L1 (61 – 85 ml/min). On 06 May 2022, the extracted fluid was mostly gas and the W-GX considered complete. Further activities are summarised in Tab. 4-9, and a detailed logbook is in Enclosure F.

The saturation injection in S14 was continued until 03 May 2022. Afterwards, only sampling was performed until 04 May 2022 21:10, when the extraction from S14 was started with the syringe pump to keep the pressure at 14 bar.

Tab. 4-9: Main field activities for W-GX (Phase 2) between 02 May 2022 and 06 May 2022

	Date & time	Injection PL_S02_L6L-2	Extraction PL_S02_L1	PL_S14_L1	Comments
Phase 2	02.05.22 08:00	18.5 bar, 1,020 mln/min	Manual, 61 – 85 ml/min water	Injection	Fig. 4-11
	02.05.22 19:30 – 19:45	Shut-in	Shut-in		Change EC position, Fig. 4-12
	03.05.22 07:22		Manual	Stop injection	
	03.05.22 13:29		Sampling 100 + 500 ml		
	04.05.22 08:58			Sampling 50 ml	
	04.05.22 09:24			Sampling 125 ml	
	04.05.22 12:20		Sampling 250 ml		
	04.05.22 09:44 – 16:24		3.05 mln/min gas		
	04.05.22 21:04			PW, dV 202.6 ml	
	04.05.22 21:10			Extraction at 14 bar	Using syringe pump
	05.05.22 13:24		Sampling 350 ml		
	05.05.22 13:54			Sampling 100 ml	
	05.05.22 16:02 – 19:55	Shut-in			
	05.05.22 19:55	18.5 bar, 1,300 mln/min	Repeated shut-in due to gas extraction		
	06.05.22 00:08		Sampling 193 ml		
	06.05.22 06:57 – 07:13	Stop injection, injected V_gas: 307.6 l	Saturation with 1.5 l water		WG-X complete
	06.05.22 07:54			EX_SYR_Q (*) at 14 bar (maximum flow 30 ml/min)	Layout Fig. 4-19 Extraction is continuously adjusted.

(*) For sensor names, see Enclosure D.

Tab. 4-10: Volume calculation during W-GX (Phase 2) between 02 May 2022 and 06 May 2022 11:22

Port	Type	Flow rate	Flow volume ⁽¹⁾	Pressure [bar]	Sample volume [l]	Total volume ⁽²⁾ [l]
PL_S02_L6L-1	Injection	1,000 mln/min	5,525.1 ln	18.3		301.6
PL_S02_L1	Extraction	~60 → 0 ml/min	299.603 l	18.2	0.600/ 0.250/ 0.350/ 0.193	300.996
DP-2 Tank	Extraction		212.137 l+ 76.753 l	18.2		288.900
PL_S14_L1 until 06.05.22 06:57	Extraction	Ø 12 ml/min	2.448 l	~14	0.050/ 0.125/ 0.203/ 0.100	2.926

⁽¹⁾ Volume from integrated flow measurements

⁽²⁾ Volume at ambient pressure for volumetric comparison

4.2.3 Flow control

The layout of the surface equipment on 02 May 2022 08:00 is shown in Fig. 4-11. W-GX gas injection was measured with gas flow controller FLOW_HI. Water (FW_EXT) and gas (FG_EXT, FG_EXT_CTL) flow meters and controllers were available on the extraction side. On 02 May 2022 at 19:30 (Fig. 4-12), the EC probe was moved to a position close to the filter unit. This minimised flow lines and positively affected EC monitoring data.

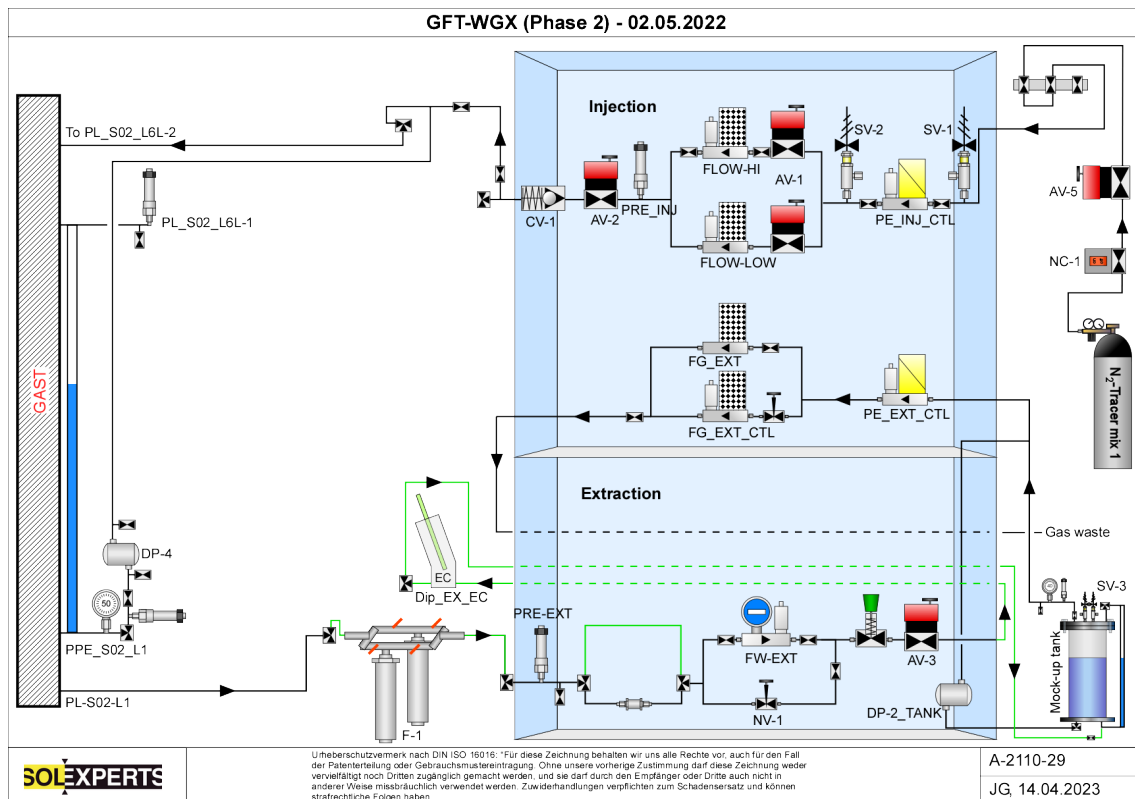


Fig. 4-11: Layout of surface equipment for water-gas exchange in S02 on 02 May 2022

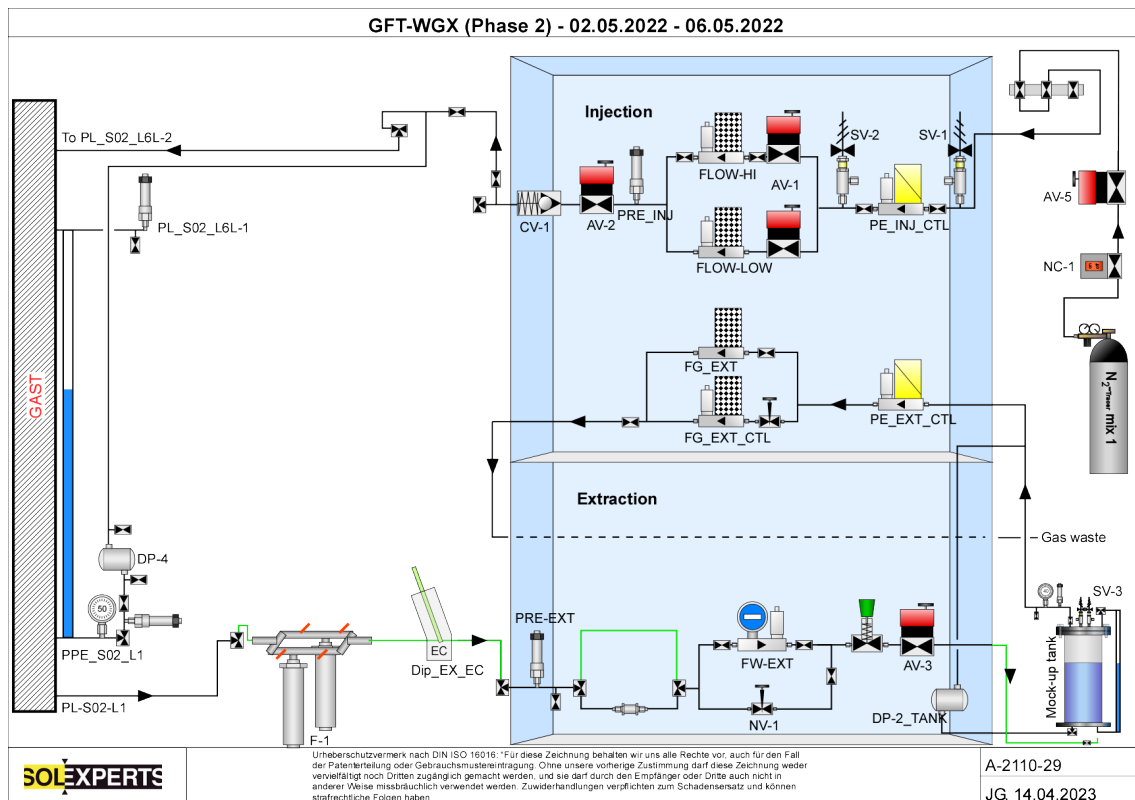


Fig. 4-12: Layout of surface equipment for water-gas exchange in S02 between 02 May 2022 and 06 May 2022

Note: EC position has been moved between the filter unit F-1 and PRE-EXT (see Tab. 4-9).

4.2.4 Monitoring data

Injected gas flow (FLOW-HI) and related pressure recordings during the W-GX are displayed in Fig. 4-13. The extraction side records (FW-EXT for total water volume extracted, FG-EXT for gas released from separator) are displayed in Fig. 4-14. A balance of the injected and extracted volumes for W-GX is given in Tab. 4-10. The estimates for the total injected gas volume (301.6 l) and extracted water volumes (301.0 l) from cumulated flow measurements are in good agreement (Tab. 4-10).

The extracted fluid was collected in the mock-up tank where the rising water level (DP-2_TANK) and released gas (FG_EXT) were measured. The water volume of 288.9 l that accumulated in the separator was found to be slightly lower but fits the cumulated flow reasonably well. Minor gas release was observed from the mock-up separator (FG-EXT in Fig. 4-14), beginning a few hours before DP-4 indicated full drawdown in S02. Further reliable measurements of gas release from the mock-up tank were complicated by manipulations (Enclosure F.2) and problems with the gas flow meter accuracy. Therefore, the extracted gas volume during W-GX was uncertain.

To assess the gas volume in the filter, the differential filter pressure (DP-4 in Fig. 4-12) should record the drawdown of the filter water level. These data, indicating gas saturation on 04 May 2022 at about 12:00 proved not very reliable. Experience from GPT1 showed that it seemed like only 50% of the as-built pore volume (~1,125 L in one filter; Tab. 2-1) was accessible by fluid extraction. The separator tank on the extraction side provided additional data on extracted

volumes, but the estimate of fluid level in S02 remained highly uncertain due to the likely changes in porosity within the filter since emplacement.

The EC measurements after the relocation provided a further indicator for gas arrival in the extraction line. Reliable measurements started on 02 May 2022 at 19:30, measuring highly conductive fluid. On 05 May 2022 at about 16:00, gas started to disturb the readings (Fig. 4-15) and was visually detected (Enclosure F.2).

Pressure in S14 was kept at around 1,400 kPa by repeated extraction pulses (Fig. 4-16).

Most of the point TDRs (TDP sensors) showed no changes during Phase 2, whereas a small number of sensors were somewhat responsive (Enclosure M.4). However, the responses (including scatter possibly resulting from ongoing changes in the sensors themselves) were not straightforward enough to allow directly inferring physical changes in the surrounding sand/bentonite resulting from the W-GX performed in Phase 2. Long TDRs (TDL sensors, except for one that had previously failed) yielded stable signals indicating there were no changes in the S14 filter during Phase 2 (Enclosure M.5).

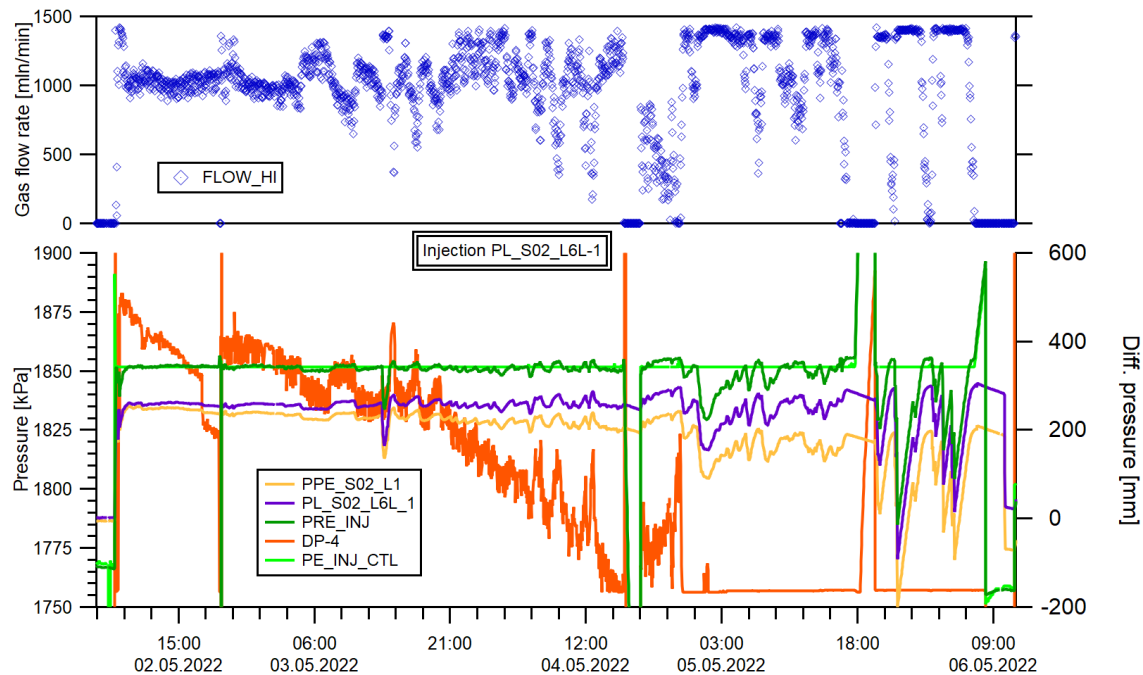


Fig. 4-13: W-GX: Pressures and flow rates on the injection side during Phase 2

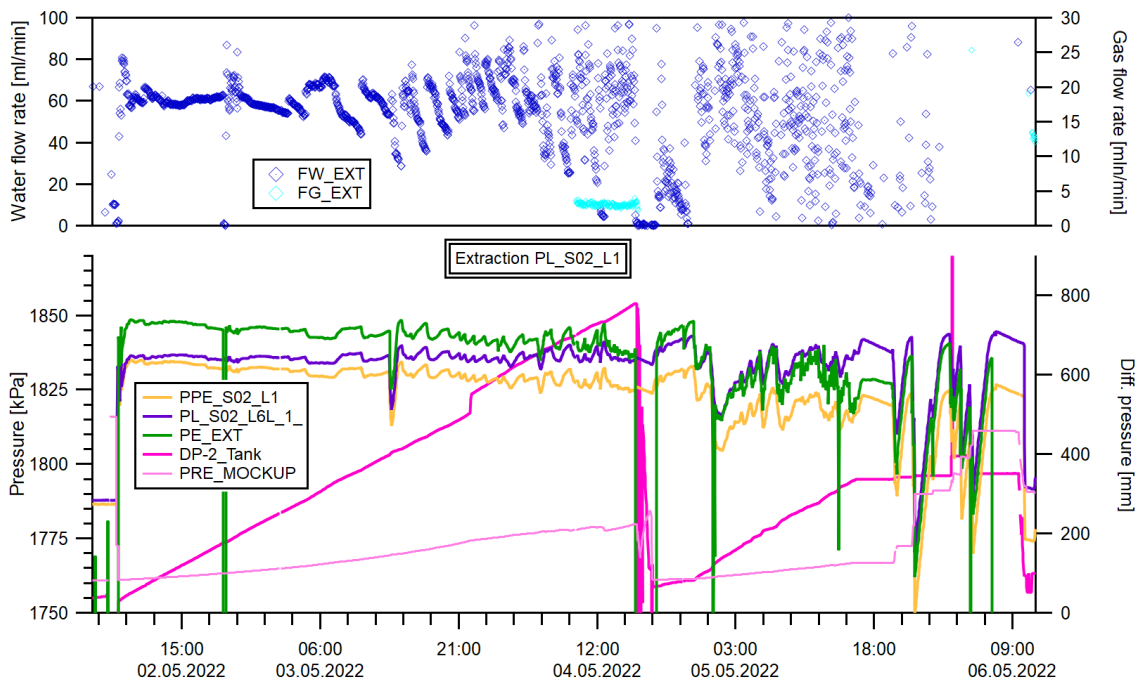


Fig. 4-14: W-GX: Pressures and flow rates on extraction side during Phase 2

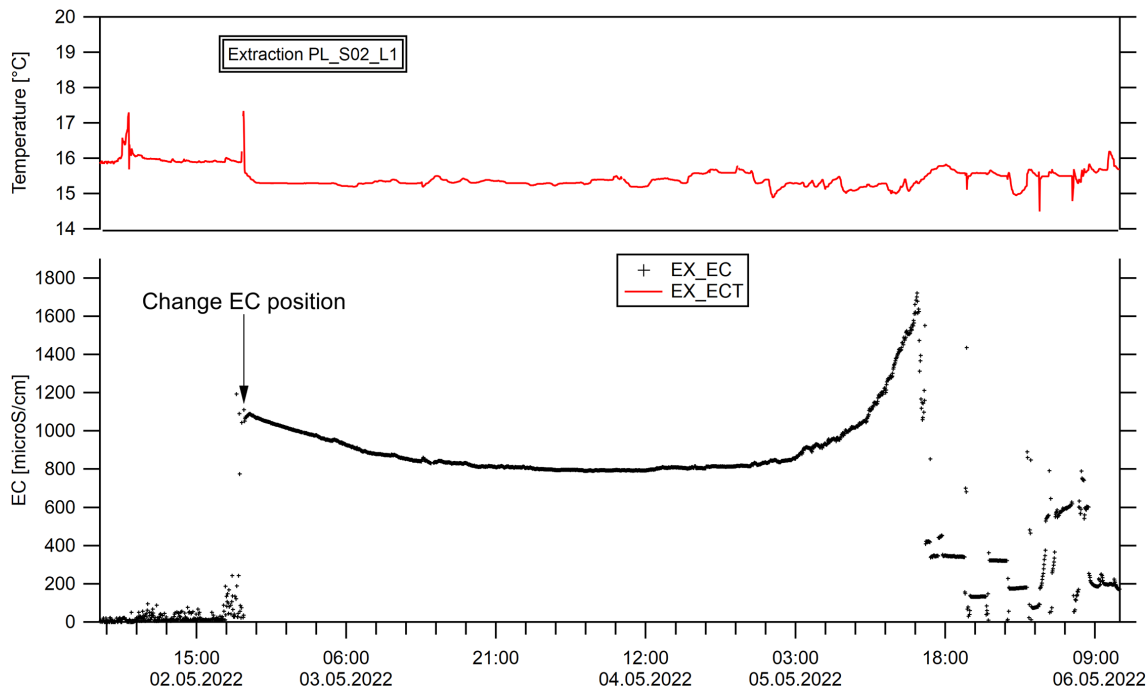


Fig. 4-15: W-GX: EC measurements on extraction side during Phase 2

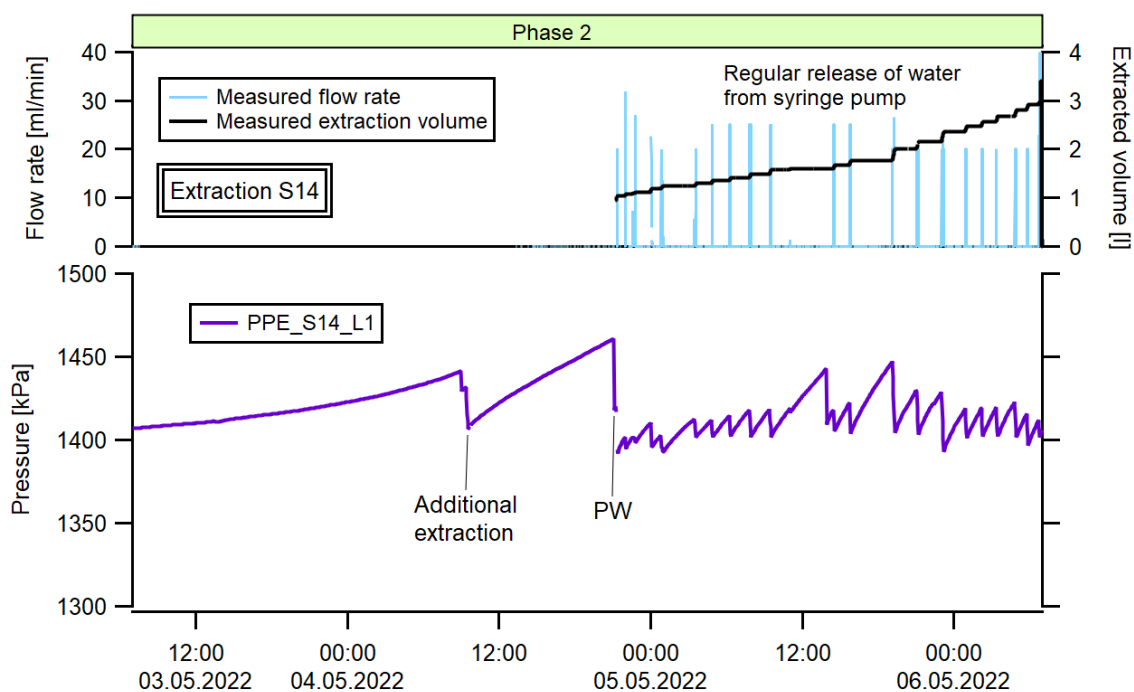


Fig. 4-16: W-GX: Pressure and extraction parameters for S14 during Phase 2

4.2.5 Sampling

Samples for quality control were taken from both filters during the W-GX as shown in Tab. 4-11. Results of off-site laboratory analyses are presented in Section 4.3.7.1 and all information on sampling and analytical results are available in Enclosures J and K.

Tab. 4-11: Sampling performed during GFT W-GX between 02 May 2022 and 06 May 2022

Phase	Code	Vial	Port	Start date & time	Circulation time [h]	Sample weight [g]
Phase 2	S02_009	GAST 08	Mock-up tank	04.05.22 14:00	0.25	- ⁽¹⁾
	S02_010	GAST 09	Mock-up tank	05.05.22 14:40	0.00	- ⁽¹⁾
	S02_011	GAST 10	Mock-up tank	06.05.22 10:15	0.00	- ⁽¹⁾
	S14_012	GAST 25	PL_S14_L1	05.05.22 14:50	0.00	96.01 ⁽²⁾

⁽¹⁾ 25 ml vial

⁽²⁾ 75 ml vial, weight after sampling with nuts

4.2.6 Phase 2 summary

The W-GX was successfully performed at a small overpressure of ~50 kPa, displacing ~300 l of water from the S02 filter. During the W-GX, water displaced from the S/B into the S14 filter resulted in the need to extract a small amount of water to maintain constant pressure.

4.3 Gas Flow Test with Gas Mix #1 (Phases 3 to 5)

4.3.1 Phase 3 – 5 aims

Section 4.3 describes the field work and results obtained during GFT Phases 3 to 5. In Phase 3, the one-sided injection of Gas Mix #1 (98% N₂ and 2% He) started in filter S02, while fluid was extracted at the other filter S14. Gas injection flow was adjusted to increase the injection pressure in S02 from 18 to 19 bar near the end of Phase 3.

Over the first month of Phase 4, it was necessary to adjust the injection and extraction flow rates to maintain the desired pressure gradient. Finally, on 08 June 2022, there was gas breakthrough to the extraction line at the base of L1 and drainage of the S14 filter was largely complete (apart from some trapped water which may have remained). At this point, gas flow from injection (S02) to extraction (S14) had been achieved.

Following the gas breakthrough, a stable gas path was realised, and a campaign of PPE sampling was initiated on 15 June 2022 (Phase 5). Sampling continued until the end of the Gas Mix #1 injection and the start of N₂ flushing in December 2022. During this time, the mean gas injection rates in S02 and extraction rates in S14 were gradually increased to maintain pressures in the two filters.

4.3.2 Field activities

The early phases of the GFT (Phases 3 and 4) were characterised by intense field work as shown in the summary of the most important field activities (Tab. 4-12) and in the complete logbook (Enclosure F). The Gas Mix #1 injection started with the injection in PL_S02_L6L-2 on 06 May 2022 at 11:22 and pulsed extraction at S14, which was activated on the same day a few hours before at 07:54 (see Tab. 4-9 and Fig. 4-29).

The gas injection was divided into three injection methods with generally increasing flow rates into S02 (Tab. 4-13):

- Constant head injection at 18 bar (06 May 2022 11:22 – 12 May 2022)
- Constant head injection at 19 bar (12 May 2022 – 19 May 2022)
- Sinusoidal flow injection at 19 bar (19 May 2022 – 01 December 2022)

Flow parameters for these three injection methods are shown in Tab. 4-13 and are recognisable in the overview flow and pressure displays (Fig. 4-17).

The method of extraction from S14 also changed as follows (see Tab. 4-13 for an overview and Enclosure F for details):

- Pulsed constant head extraction at 14 bar (06 May 2022 07:54 – 07 May 2022 14:06)
- Flow-rate-adjusted extraction at 14 bar (07 May 2022 14:06 – 17 May 2022 11:00)
- Sinusoidal extraction with syringe pump at 14 bar (17 May 2022 11:00 – 15 June 2022 07:15)
- Constant head extraction at 14 bar without flow monitoring³ (15 June 2022 07:15 – 16 August 2022 06:40)
- Constant head extraction with syringe pump at 14 bar (16 August 2022 06:40 – 01 December 2022 07:05)

Flow parameters for fluid extraction from S14 are shown in Tab. 4-13. Flow rates, cumulative extracted volume and S14 filter pressure are visualised in the overview in Fig. 4-18.

Use of sinusoidal injection and extraction rates allowed continuous estimation of the gas volumes within the two filters.

³ The syringe pump was used for sampling and connected to PPE_S10_L4.

Tab. 4-12: Main field activities during GFT Phases 3 to 5 (from 06 May 2022 to 01 December 2022)

Phase	Date & time	Gas Mix #1 injection PL_S02_L6L-2	Extraction PL_S14_L1 total gas + water flow	Comments
Phase 2	06.05.22 07:54		EX_SYR_Q at 14 bar (maximum flow 30 ml/min)	Layout Fig. 4-19 Extraction is continuously adjusted
Phase 3	06.05.22 11:22	FLOW_HI at 18 bar		
	06.05.22 14:17	FLOW_LOW at 18 bar		Increasing injection flow
	07.05.22 14:06		EX_SYR_Q at constant flow (~2 ml/min)	
	09.05.22 07:43 – 08:14		PW, dV = 2.371 l	
	09.05.22 08:51	FLOW_LOW at 18 bar	EX_SYR_Q at 13.5 bar	
	09.05.22 09:17			Maintenance break
	09.05.22 13:41	FLOW_LOW at 18 bar	EX_SYR_Q at 14 bar	
	12.05.22 07:00			PI test in PL_S02_L1, dP: 25 kPa
	12.05.22 07:15	FLOW_HI at 18 bar	EX_SYR_Q at 14 bar	
	12.05.22 07:20 – 12:36	FLOW_HI from 500 to 900 mln/min to 19 bar	EX_SYR_Q at 14 bar	Pressure increase at injection
	12.05.22 08:06 – 08:13		Shut-in	PW test in PL_S14_L1
	12.05.22 08:30 – 08:35		Shut-in	PI test in PL_S14_L1
	12.05.22 10:13		EX_SYR_Q at 14 bar	
Phase 4	12.05.22 12:50	FLOW_HI at 19 bar, Ø 146 mln/min	EX_SYR_Q at 14 bar	
	17.05.22 11:00	FLOW_HI at 19 bar Ø 160 mln/min	10.2 ± 1.5 ml/min period 60 min	Start sinusoidal extraction
	17.05.22 16:00	FLOW_HI at 19 bar Ø 163 mln/min	Mean flow: 11 ml/min, amplitude: 4 ml/min period 120 min	
	18.05.22 10:10	Shut-in		PI test in PL_S02_L1

Tab. 4-12: Cont.

Phase	Date & time	Gas Mix #1 injection PL_S02_L6L-2	Extraction PL_S14_L1 total gas + water flow	Comments
Phase 4	18.05.22 10:18	Shut-in		PW test in PL_S02_L1
	18.05.22 10:22	FLOW_HI at 19 bar Ø 168 mln/min	Mean flow: 11 ml/min	
	19.05.22 10:00	Mean flow: 172 ml/min, amplitude: 80 ml/min period 333 min	Mean flow: 11 ml/min	Start of sinusoidal injection
	19.05.22 13:40	Mean flow: 172 ml/min	Mean flow: 11.2 ml/min	Continuous adjustment of flow rates
	31.05.22 07:00	Mean flow: 210 mln/min	Mean flow: 15.0 ml/min	Instalment of mock-up tank Layout Fig. 4-20
	Until 02.06.22	Mean flow: 225 mln/min	Mean flow: 15 ml/min	Continuous adjustment of flow rates
	06.06.22 06:50	Mean flow: 225 mln/min	No flow	Line clogged
	06.06.22 14:52	Shut-in	No flow	Declogging
	08.06.22 08:01	Shut-in	No flow	Gas breakthrough
	08.06.22 08:17		Constant flow 20 → 15 ml/min	
	08.06.22 09:51	Mean flow: 225 mln/min	Constant flow 15 → 5 → 2 → 3 → 10 → 7 → 10 → 13 → 14 ml/min	Repeated flow adjustment to keep P at 14 bar
	09.06.22 06:56		Shut-in	
	09.06.22 07:53		Constant flow 14 → 16 → 17 → 15 → 14 ml/min	Repeated flow adjustment to keep P at 14 bar
	09.06.22 12:15		Mean flow: 14 ml/min	Start sinusoidal extraction Repeated mean flow adjustment for P=14 bar
	15.06.22 06:12 – 07:56	Shut-in	Flow not measured	Layout Fig. 4-21 Start of extraction without syringe pump

Tab. 4-12: Cont.

Phase	Date & time	Gas Mix #1 injection PL_S02_L6L-2	Extraction PL_S14_L1 total gas + water flow	Comments
Phase 5	15.06.22 08:34			Start of PPE sampling
	15.06.22 13:24 – 16.06.22 07:35	Shut-in, 20:38: injection with 1,300 mln/min 23:06: 280 mln/min		Accidental shut-in
	16.06.22 07:35	Mean flow: 320 mln/min	Flow not measured Volume interpolated	Repeated injection flow adjustment for P = 19 bar
	22.06.22			Layout Fig. 4-22
	28.06.22 13:13 – 29.06.22 12:31	262 mln/min, 10:23: 1,300 mln/min	Shut-in, pressure increase 07:14: release pressure	
	29.06.22 12:31	Mean flow: 310 mln/min		Repeated injection flow increases for P =19 bar
	04.07.22 00:16 – 08:54	Shut-in 06:04: 1,300 mln/min		
	04.07.22 08:54	Mean flow: 350 mln/min		
	29.07.22 20:49		Shut-in	Failure of electro valve
	30.07.22 12:36	Shut-in		Closure of all valves
	03.08.22 07:03		Restart extraction	
	03.08.22 07:33	Restart injection, mean flow: 400 ml/min		Repeated injection flow increases for P =19 bar
	12.08.22 15:45	Mean flow: 500 ml/min		
	16.08.22 07:06		Start extraction with syringe pump, adjust flow rate settings to P = 14 bar	Layout Fig. 4-23 Continuously adjust extraction flow rate
	18.08.22 08:18	Mean flow: 510 ml/min		
	19.08.22 16:11	Mean flow: 520 ml/min		
	22.08.22 19:46	Mean flow: 530 ml/min		

Tab. 4-12: Cont.

Phase	Date & time	Gas Mix #1 injection PL_S02_L6L-2	Extraction PL_S14_L1 total gas + water flow	Comments
Phase 5	29.08.22 08:41	Mean flow: 540 ml/min		
	30.08.22 13:03		Adjust flow rate settings to keep P = 14 bar	
	06.09.22 06:32 – 14:22		Shut-in	Maintenance on syringe pump
	07.09.22 07:12	Mean flow: 560 ml/min		
	14.09.22 10:42	Mean flow: 570 ml/min		
	19.09.22 09:12	Mean flow: 580 ml/min		
	21.09.22 13:56		Adjust flow rate settings to keep P = 14 bar	Empty mock-up tank
	22.09.22 08:13	Mean flow: 590 ml/min		
	26.09.22 14:16	Mean flow: 600 ml/min		
	29.09.22 16:13	Mean flow: 620 ml/min		
	09.10.22 16:28 – 10.10.22 20:41		Shut-in, pressure increase 10.10.22 08:06: release pressure (200 ml/min)	Accidental shut-in
	14.10.22 08:29 – 17.10.22 12:53	17.10.22 05:04: 1,200 mln/min		Failure of sinusoidal injection setup
	17.10.22 12:53	Mean flow: 630 ml/min		
	21.10.22 11:24	Mean flow: 640 ml/min		
	21.10.22 23:01 – 25.10.22 10:24		Repeated extraction flow rate adjustments	
	24.10.22 18:38	Mean flow: 650 ml/min		
	26.10.22 18:38	Mean flow: 660 ml/min		
	31.10.22 07:45	Mean flow: 670 l/min		

Tab. 4-12: Cont.

Phase	Date & time	Gas Mix #1 injection PL_S02_L6L-2	Extraction PL_S14_L1 total gas + water flow	Comments
Phase 5	06.11.22 20:13	Mean flow: 680 ml/min		
	08.11.22 08:52 – 12:50	Constant flow: 635 Restart mean flow: 690 ml/min		Sampling in PL_S02_L1
	09.11.22 00:39 – 17.11.22 10:00		Failure of syringe pump, manually open the valve, pressure decrease	Several attempts to restart syringe pump and to declog valve
	17.11.22 10:00		Restart extraction with syringe pump, P = 14 bar	
	Until 30.11.22	Continuous increase to mean 800 mln/min		No data during DAS replacement
	01.12.22 07:05	Switch from gas mix to N ₂ injection		

Tab. 4-13: Overview of injection and extraction parameters during GFT Gas Mix #1 injection

	P from [bar]	P to [bar]	Flow rate from	Flow rate to	Volume STP [ln]	Volume @ T,P [l]	Comments
GFT Gas Mix #1: 06.05.22 07:54 – 01.12.22 07:05							
Injection S02 Gas Mix #1	18	19	30 mln/min	800 sinusoidal	136,776.10	7,763.06	Mostly sinusoidal
Extraction S14 gas	14	14	0 ml/min	86 ml/min ⁽¹⁾	119,543.89	9,153.66	V partly interpolated
Extraction S14 water						641.14	DP-2 tank

⁽¹⁾ Average flow rate overestimated

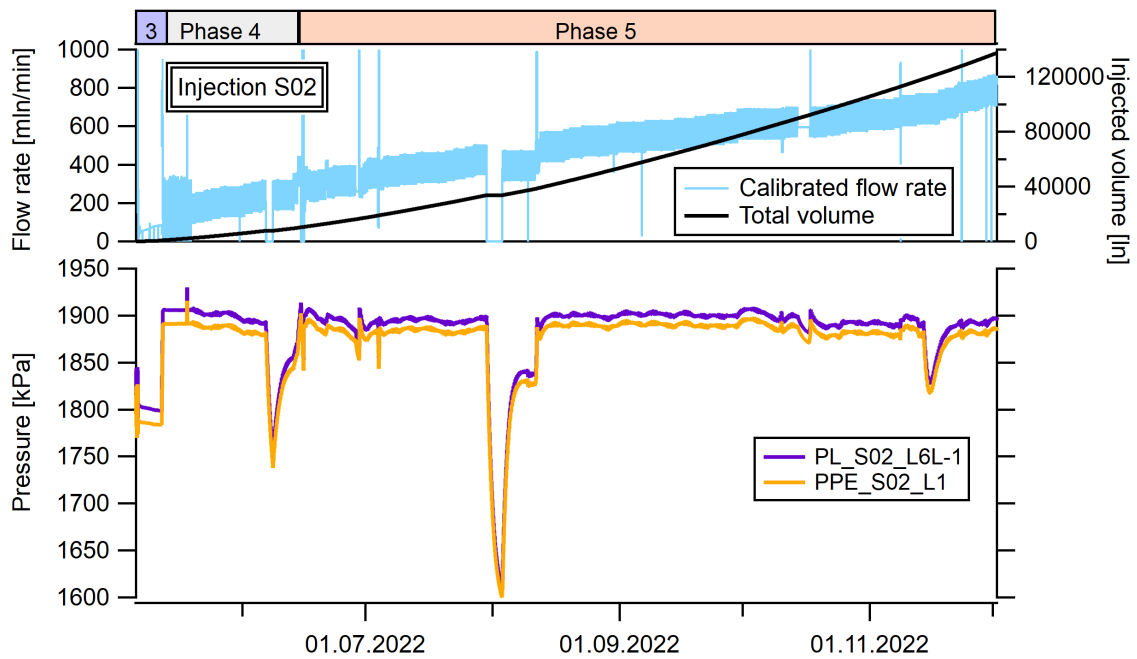


Fig. 4-17: Overview of injection flow rate and cumulative injected gas volume (normalised to STP; top panel) and S02 filter pressure (bottom panel)

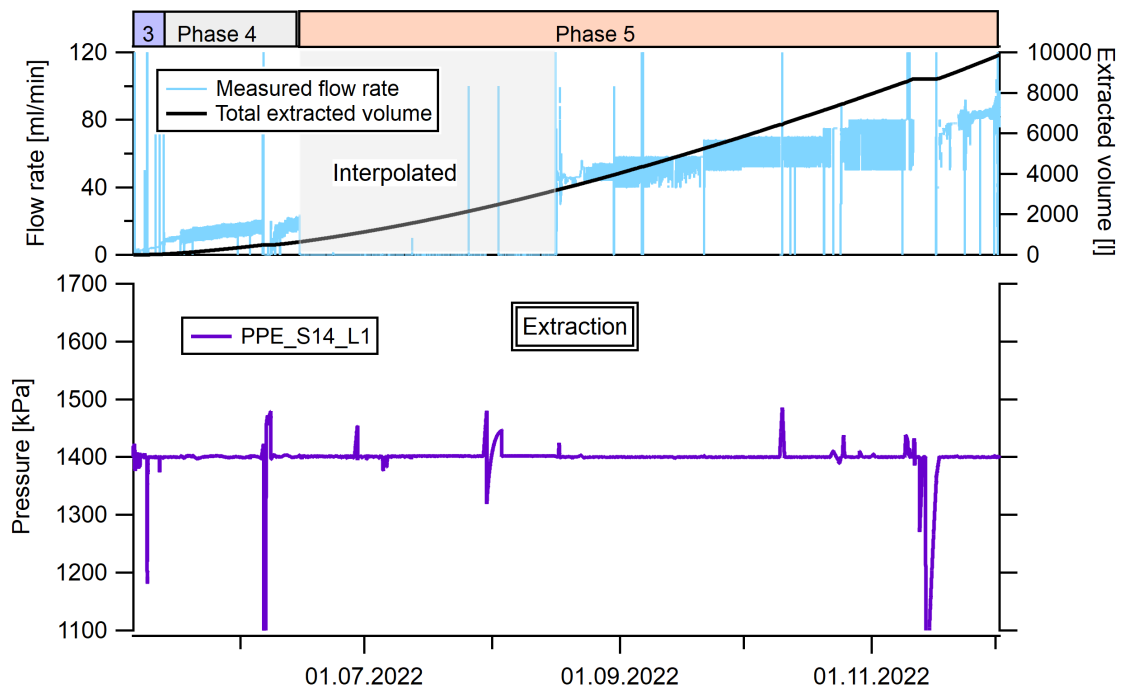


Fig. 4-18: Overview of extraction flow rate and cumulative extracted fluid volume (top panel) and S14 filter pressure (bottom panel)

4.3.3 Flow control

The surface equipment changes performed for the W-GX on the injection side were appropriate and robust also for the long-term gas injection, and were hence not further adjusted. Choosing between two flow controllers, FLOW-LOW and FLOW-HI, precise injection control was possible over a wide range of flow rates. Flow controller switches are noted in Tab. 4-12 and in the logbook (Enclosure F).

The equipment on the extraction side, on the other hand, underwent several changes during the performance of the GFT, with the equipment changes chronologically listed in Tab. 4-12. The initial GFT layout was based on the W-GX layout, with additional syringe pumps for better control of the expected two-phase fluid extraction (Fig. 4-19).

The mock-up was added on 31 May 2022 to act as water/gas separator and volume estimation for both fluid phases (Fig. 4-20). Prior to this, only water had been extracted and it was not until early June that gas was produced from the extraction line at the base of S14 (PL_S14_L1).

The syringe pump in double system configuration was installed in the beginning of the GFT, but it was required for PPE fluid sampling from 15 June 2022 to 16 August 2022. During that period, pressure control was maintained by controlling the pressure at PL_S14_L1 and by closing the automatic valve AV-3 to increase the pressure (see Fig. 4-21 and Fig. 4-22). Flow measurement was only possible via the flowmeter FW-EXT, which delivered highly uncertain values for the two-phase fluid extracted. Extraction volume control improved significantly when a single piston syringe pump could be installed on 16 August 2022 (Fig. 4-23).

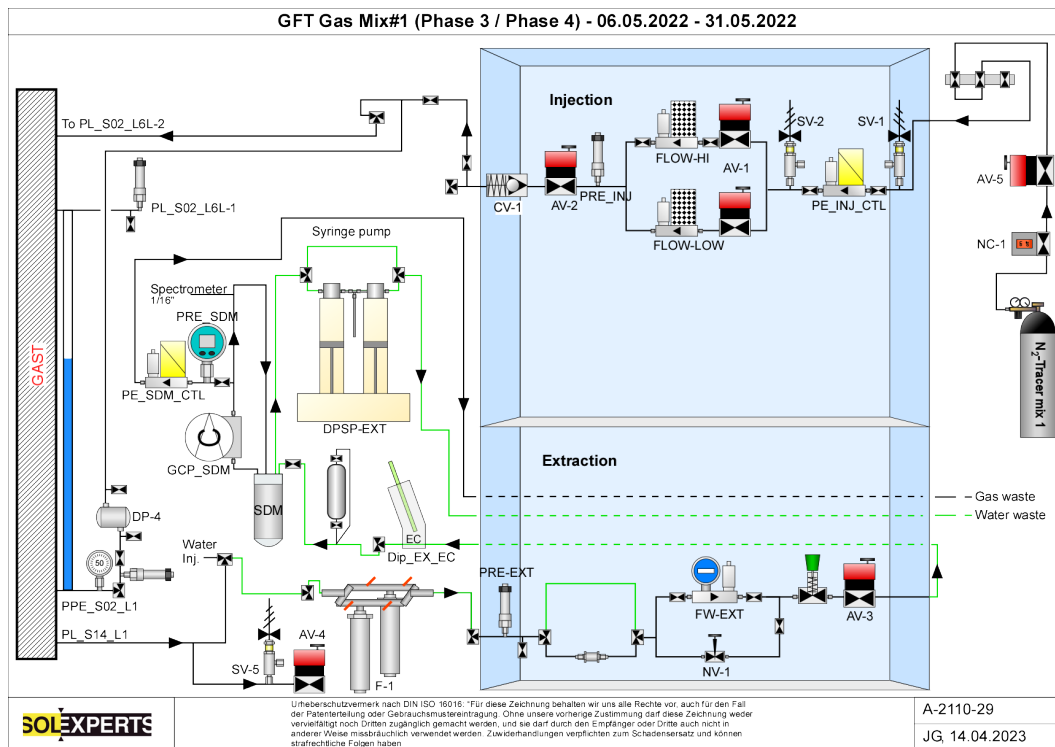


Fig. 4-19: Layout of surface equipment for the GFT between 06 May 2022 and 31 May 2022

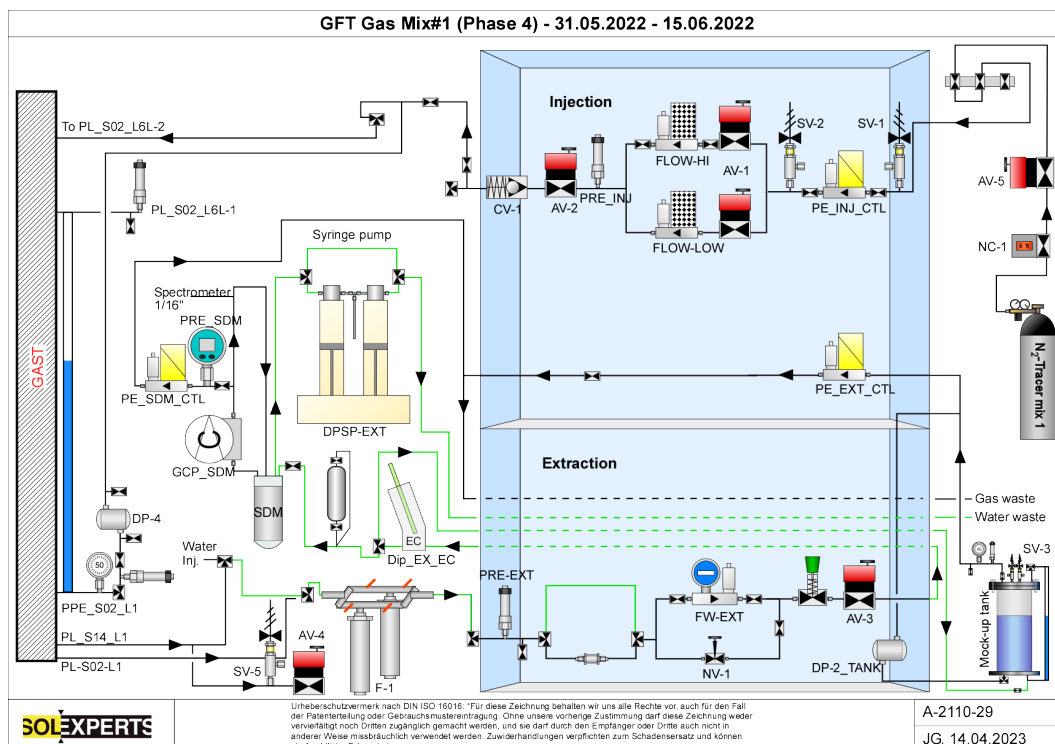


Fig. 4-20: Layout of surface equipment for the GFT between 31 May 2022 and 15 June 2022

Note: Same as Fig. 4-19 with mock-up tank installed as separator

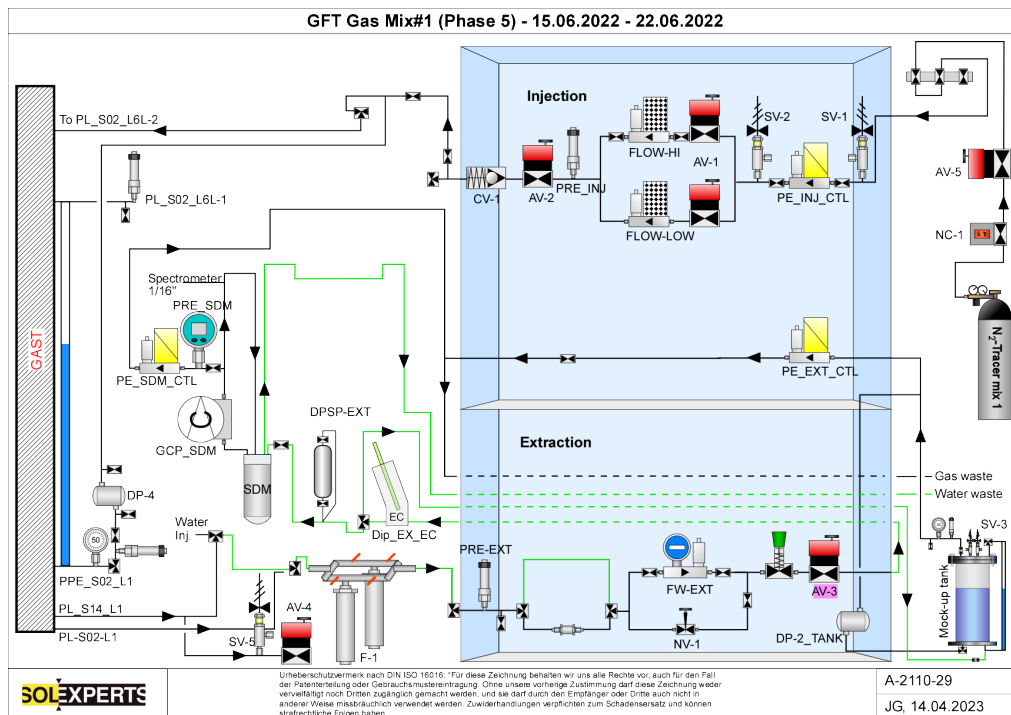


Fig. 4-21: Layout of surface equipment for the GFT between 15 June 2022 and 22 June 2022

Note: Same as Fig. 4-20 with syringe pump removed from extraction line

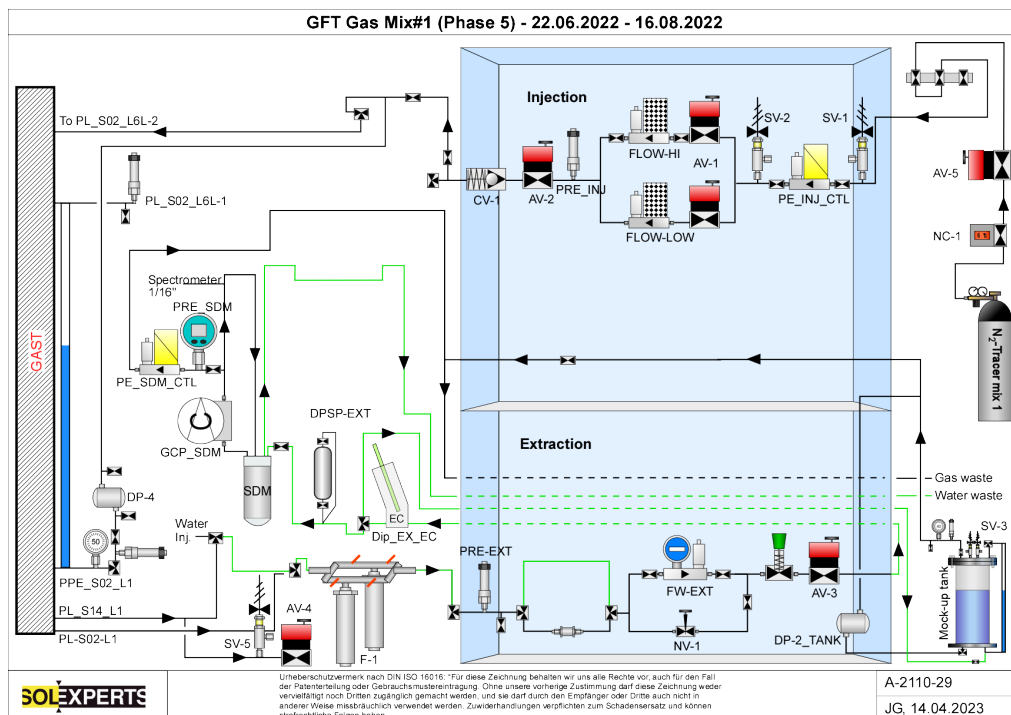


Fig. 4-22: Layout of surface equipment for the GFT between 22 June 2022 and 16 August 2022

Note: Same as Fig. 4-21 with PE_EXT_CTL removed from mock-up gas waste line

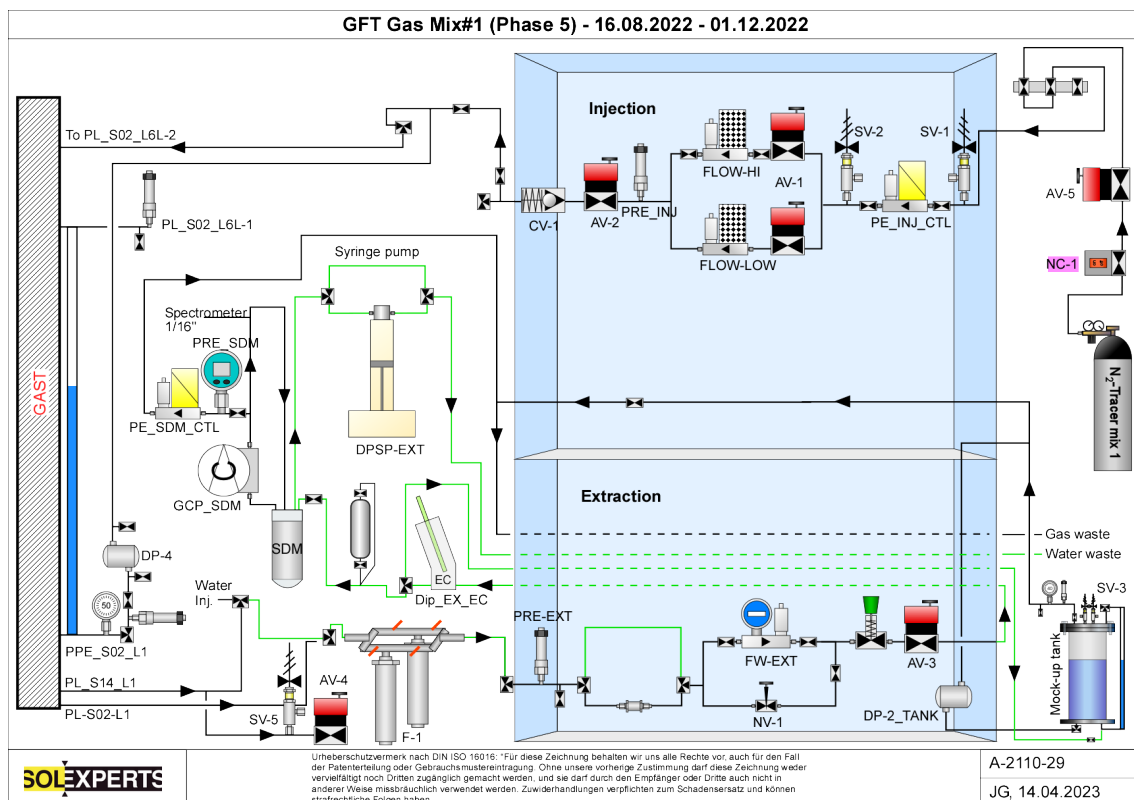


Fig. 4-23: Layout of surface equipment for the GFT between 16 August 2022 and 01 December 2022

Note: Same as Fig. 4-22 with single piston syringe pump installed for extraction flow rate control

4.3.4 Monitoring data

The initial target gas injection pressure was $\sim 1,800$ kPa (Fig. 4-24), which was considered low. Therefore, the target injection pressure was set to $\sim 1,900$ kPa on 12 May 2022 at 12:50, as shown in Fig. 4-24. Except for distinct shut-in events, this new target injection pressure was kept constant throughout Phases 4 and 5 (Fig. 4-17).

Fig. 4-25 illustrates the initially strong flow undulations during the constant head injection regime. Smoother flow rates were achieved after switching to sinusoidal head control, which is beneficial for later data interpretation. A set of detailed plots illustrate the effect of several unplanned shut-in events (Fig. 4-26 to Fig. 4-28).

The extraction-side flow rate and pressure data for Phases 4 to 5 are shown in Fig. 4-29 to Fig. 4-33. In the beginning, a pulsed extraction was tested, leading to a saw-tooth pattern on S14 filter pressures (Fig. 4-29). Switching to constant extraction flow helped to stabilise the pressure at the target pressure of 1,400 kPa (Fig. 4-29). Although frequent flow adjustments were required to keep the pressure steady (Fig. 4-30 and Fig. 4-31), flow noise remained at an acceptable level. To further minimise this random noise signal, sinusoidal extraction flow regime was established on 17 May 2022 at 11:00 (Fig. 4-32). The initial setting of an average flow rate of 10.2 ml/min with a sinus amplitude ± 1.5 ml/min and period 60 min was increased to 11 ± 1.5 ml/min at 16:00. The sinus period was increased to 120 min.

The resulting pressure variations of about ± 1 kPa are displayed in Fig. 4-31. Fig. 4-30 – Fig. 4-33 illustrate the effects of these extraction flow adjustments, hydraulic testing, and of several unplanned shut-in events.

Using the cumulative injection and extraction flow rates, net volumes for injection and extraction were computed for certain time periods and compared (Tab. 4-14). Integration of the injection flow is straightforward, and the local pressure was used to convert from normalised flow to volumetric flow. On the extraction side, net volumes can include water and gas phases. Water level measurements in the mock-up separator, when available, allow an assessment of the water volumes extracted. The extracted gas volumes in Tab. 4-14 are given in litres under extraction pressure (that is PPE_S14_L1 pressure). Cumulative extraction volume between 15 June and 16 August 2022 was not measured, because the syringe pumps were used for sampling. The cumulative volume was obtained by iterative fitting of a polynomial curve to data points before and afterwards. The following parameters were used:

3rd degree polynomial function $y = K0 + K1*x + K2*x^2$; with

$$K0 = 3.3106e+08$$

$$K1 = -0.17748$$

$$K2 = 2.3785e-11$$

According to the calculations for Phases 3 – 5, a total volume of $\sim 136,776$ l_n Gas Mix #1 was injected and $\sim 119,644$ l_n gas was extracted (Tab. 4-13). Note that these volumes relate to normalised conditions (STP) and indicate a net gas injection.

Refer to Nagra (2025) for more details on the flow balance.

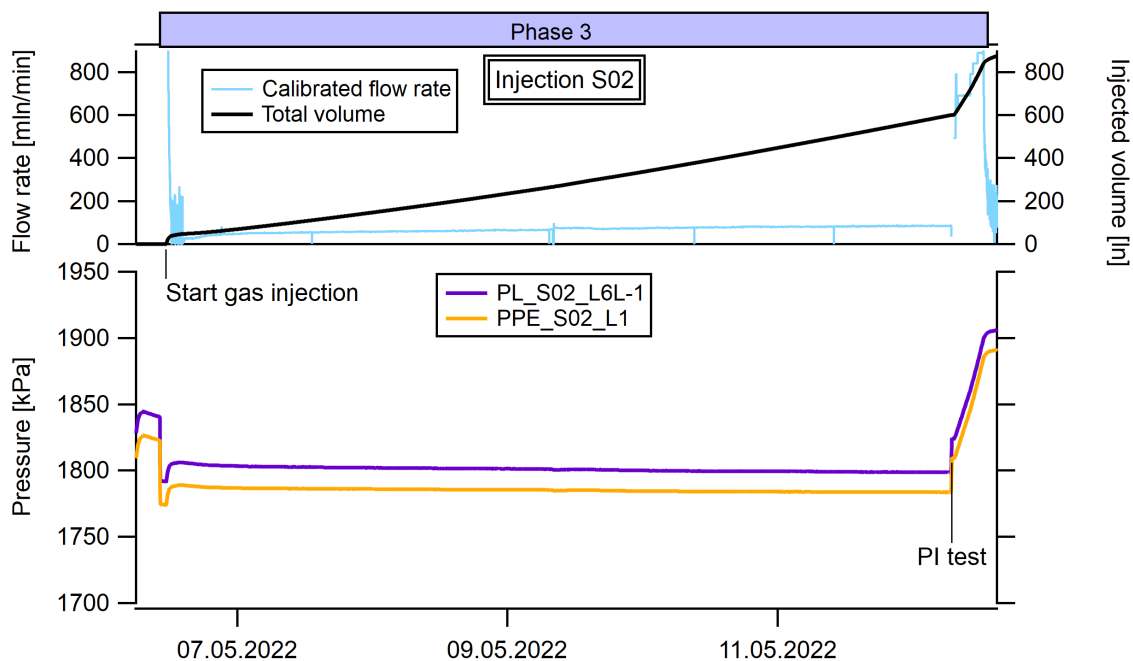


Fig. 4-24: S02: detailed view of injection between 06 May 2022 and 11 May 2022 (Phase 3)

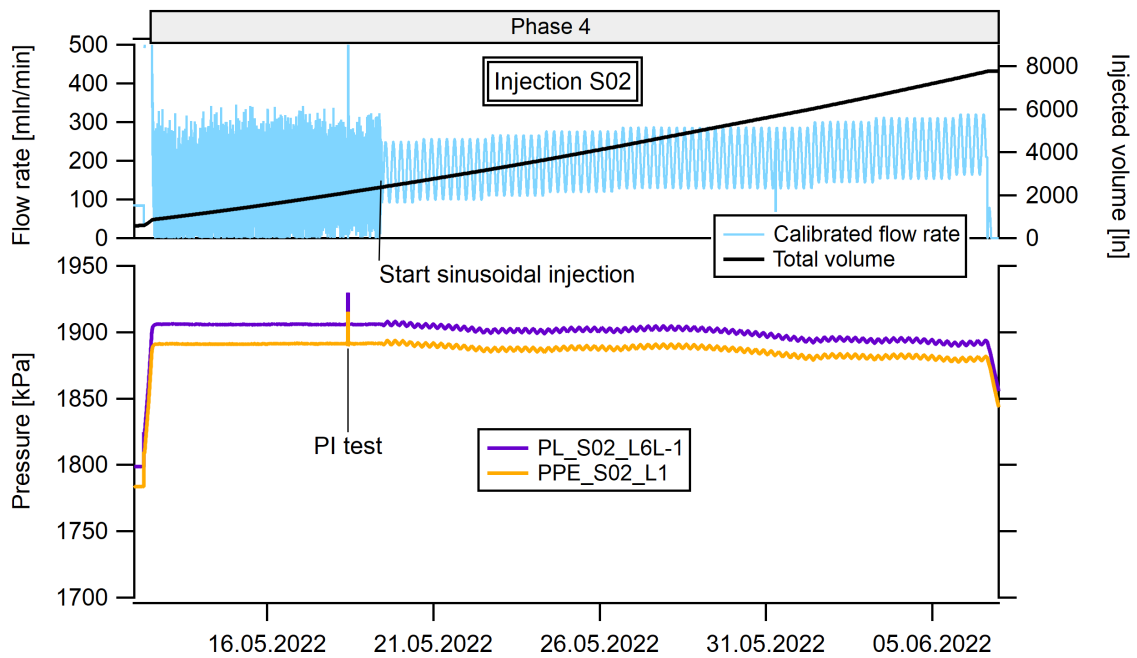


Fig. 4-25: S02: detailed view of injection between 12 May 2022 and 07 June 2022 (Phase 4)

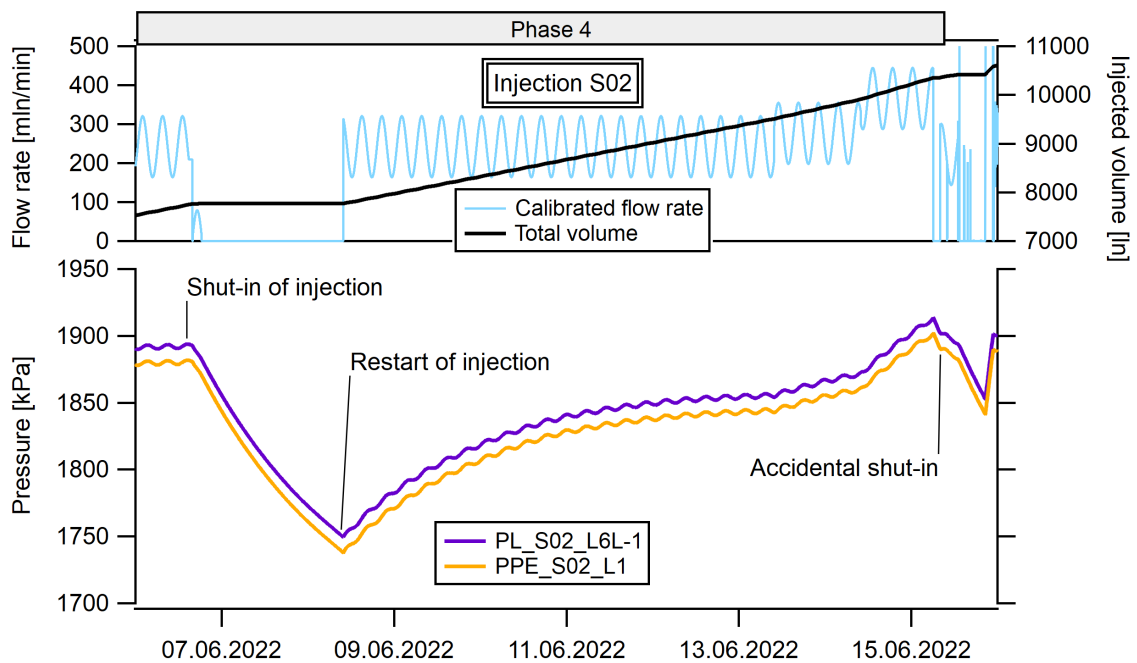


Fig. 4-26: S02: detailed view of injection between 07 June 2022 and 16 June 2022 (Phase 4)

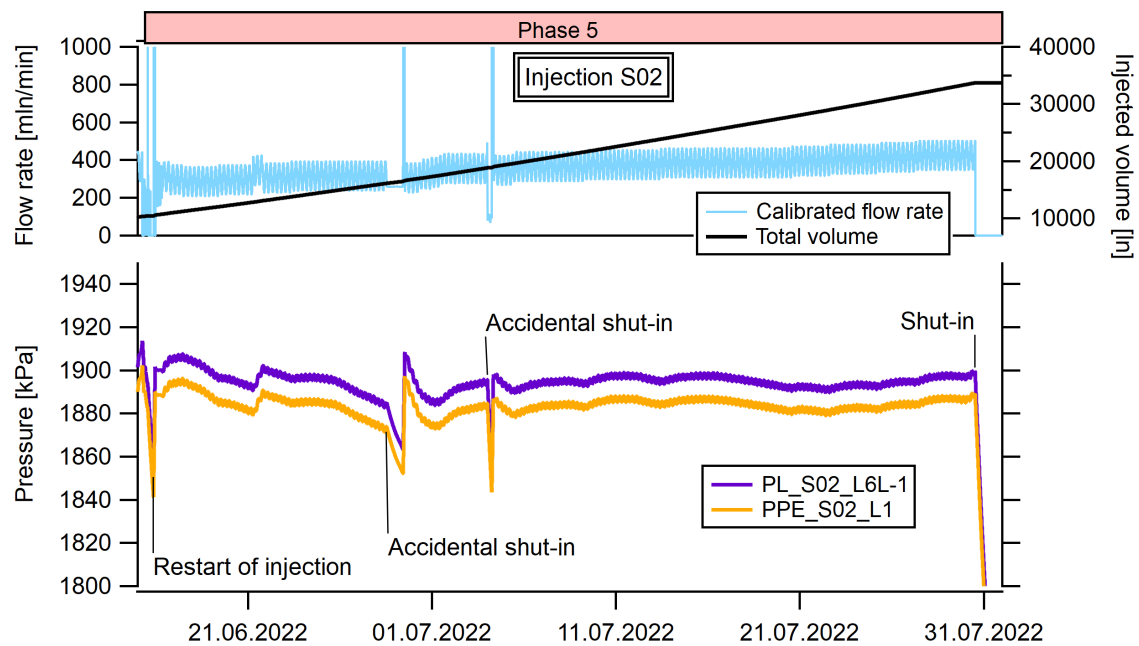


Fig. 4-27: S02: detailed view of injection between 15 June 2022 and 01 August 2022 (Phase 5)

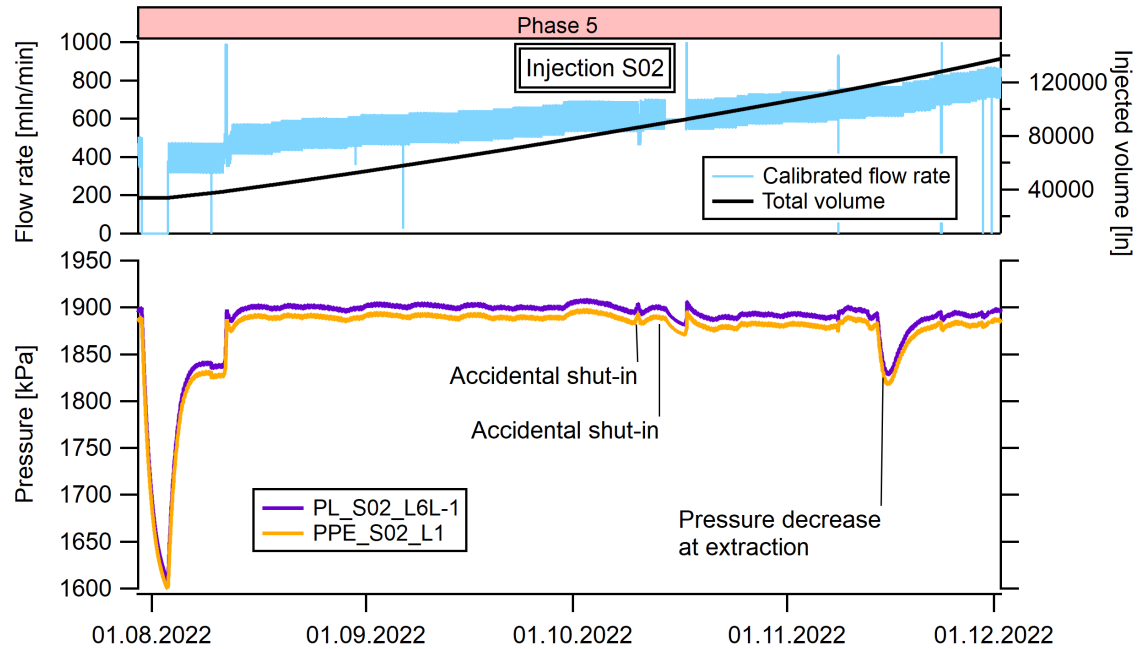


Fig. 4-28: S02: detailed view of injection between 30 July 2022 and 01 December 2022 (Phase 5)

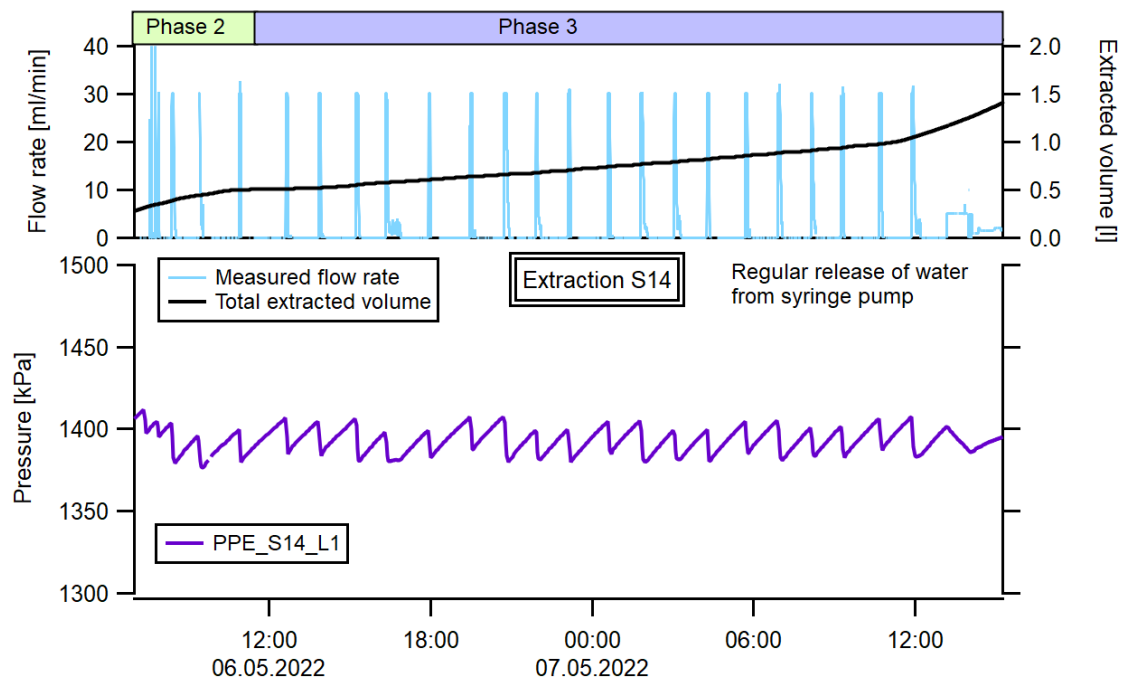


Fig. 4-29: S14: detailed view of extraction between 06 May 2022 and 07 May 2022 (Phases 2 + 3)

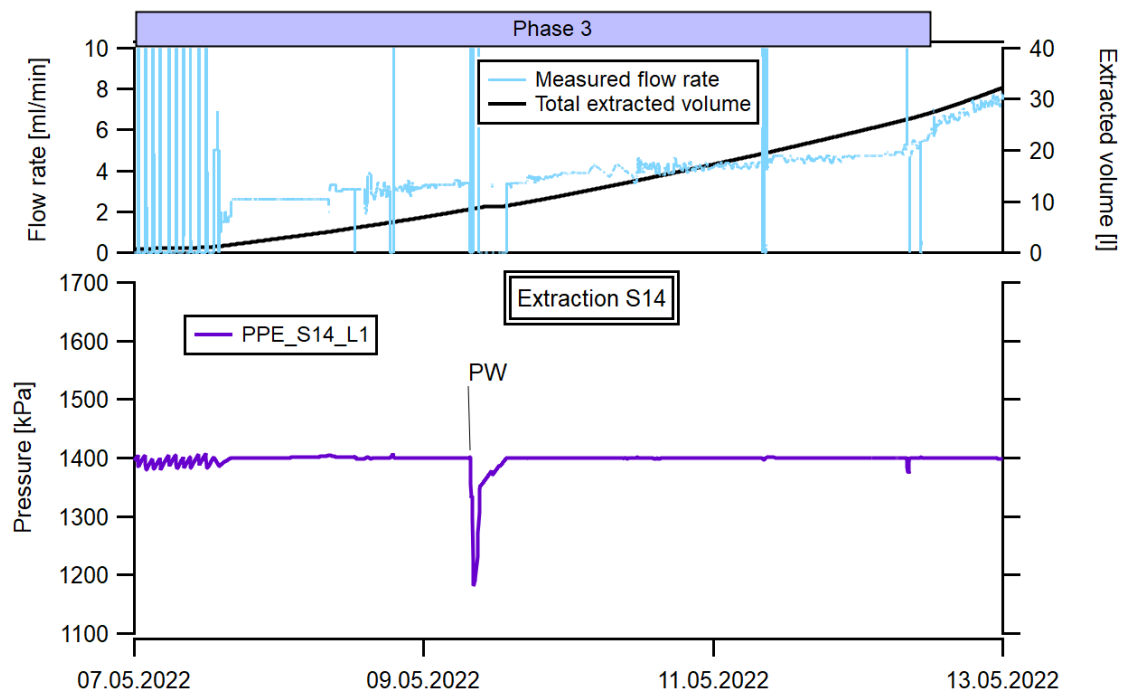


Fig. 4-30: S14: detailed view of extraction between 07 May 2022 and 12 May 2022 (Phase 3)

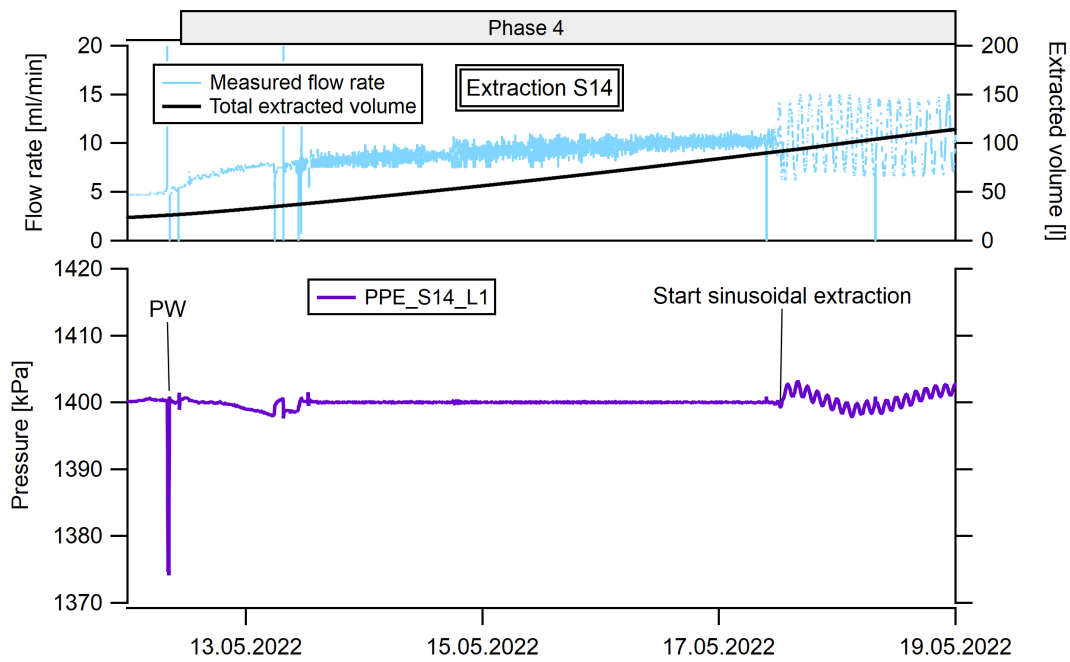


Fig. 4-31: S14: detailed view of extraction between 12 May 2022 and 19 May 2022 (Phase 4)

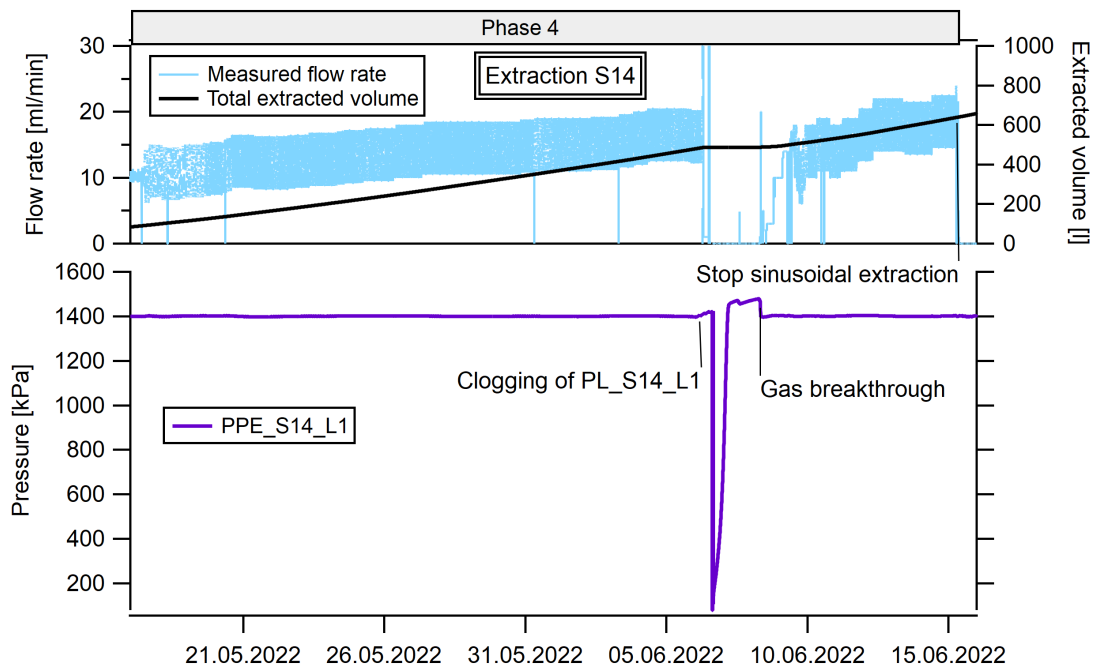


Fig. 4-32: S14: detailed view of extraction between 17 May 2022 and 15 June 2022 (Phase 4)
Sinusoidal pressure variation is not visible due to large y-axis range

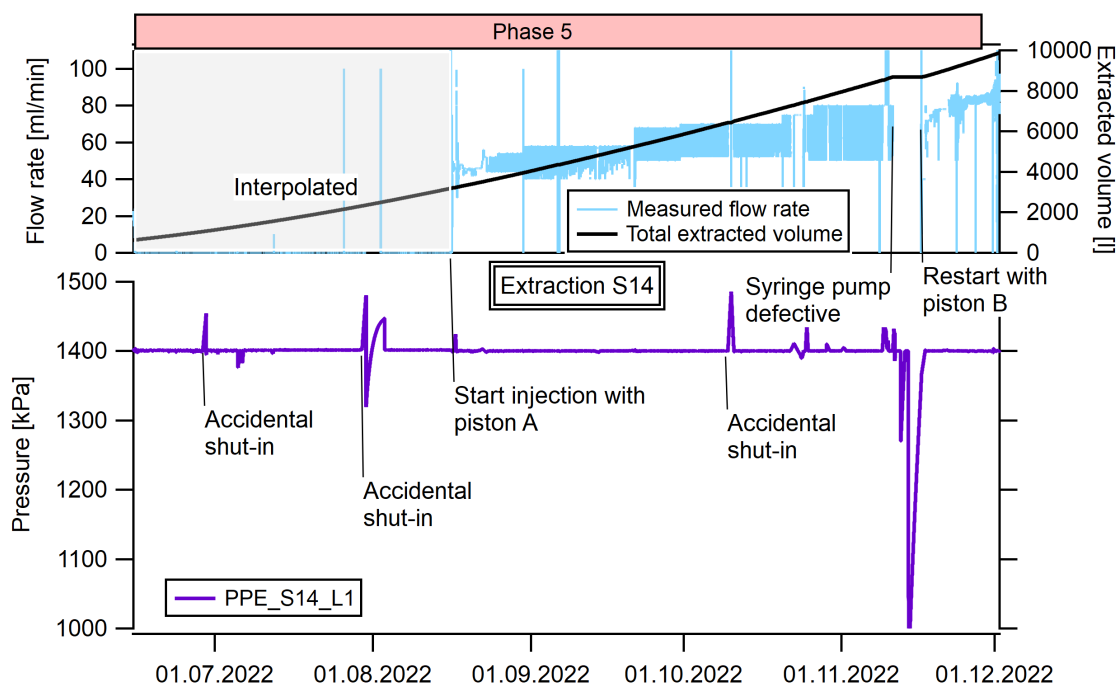


Fig. 4-33: S14: detailed view of extraction between 15 June 2022 and 01 December 2022 (Phase 5)

After 16 August 2022, noise in the flow rate was caused by the use of the single piston syringe pump.

Many of the point TDRs (TDP sensors) showed no changes during Phases 3, 4 and 5 (Enclosure M.3). Several showed some scatter, possibly resulting from changes in the sensors themselves, and others indicated possible wetting-like changes which made the interpretation difficult with respect to identifying the gas phase being injected. Therefore, the responses of TDPs were not straightforward enough to directly infer physical changes resulting from the Gas Mix #1 injection performed in Phases 3, 4 and 5. The operating TDL sensors, on the other hand, yielded a clear sign of gas accumulation in the S14 filter during Phases 3, 4 and 5 (Enclosure M.5). The signals were generally distinct enough so that the timing of the gas accumulation in the S14 filter could be accurately identified. As summarised in Fig. 4-34 below, TDLs in L5 started to respond first (18 May 2022) to the accumulation of gas which propagated down to L3. Although difficult to see on this scale, travel time at the L2 sensors decreased gradually.

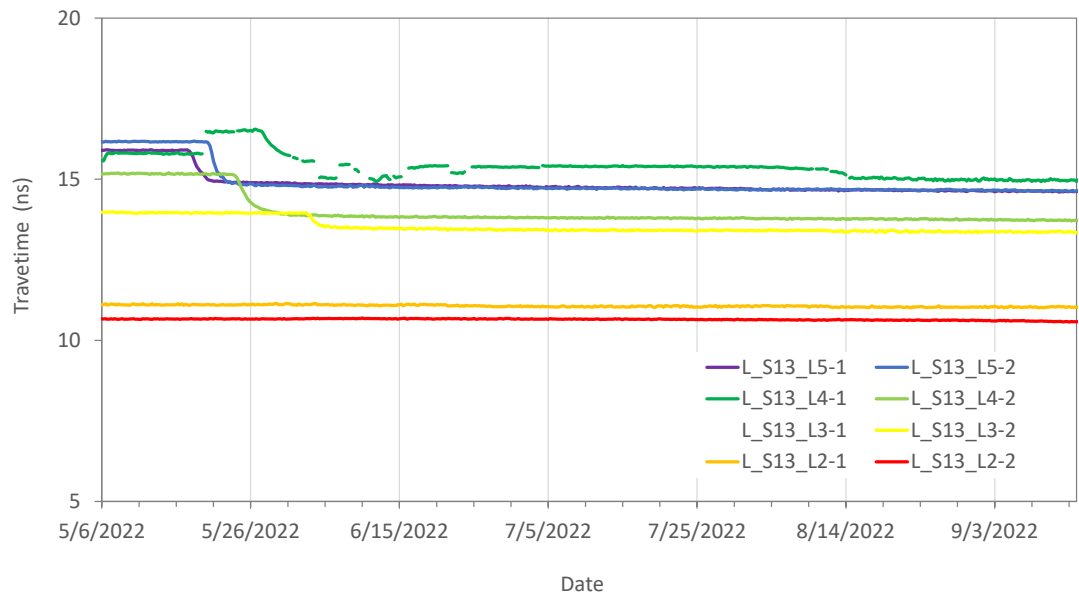


Fig. 4-34: Changes in travel time with TDLs due to gas accumulation in S14 filter during Phases 3, 4 and 5

Tab. 4-14: Details of volume calculation during GFT Gas Mix #1 between 06 May 2022 and 01 December 2022

Port	Start date & time	Flow rate	V gas STP [ln]	V gas @ T, P [l]	V water [l] ⁽¹⁾	P [bar]
Injection						
PL_S02_L6L-1	06.05.22 11:22	HI 87/424 mln/min	846.46	49.94		18 – 19
	12.05.22 12:50	HI/sinusoidal mean 280 → 350 mln/min	6,923.35	390.76		19
	08.06.22 09:51	Sinusoidal mean 280 → 350 mln/min	2,651.55	154.17		19 – 17.5 – 19
	15.06.22 20:38	Sinusoidal mean 280 → 350 mln/min	23,288.74	1,318.72		~19
	03.08.22 07:33	Sinusoidal mean 400 → 800 mln/min	103,066.10	5,849.47		16 – 19
Total	01.12.22 07:05		136,776.10	7,763.06		
Extraction						
PL_S14_L1	06.05.22 06:56	Ø 2.2 ml/min			6.13	~14
	07.05.22 15:14	1.5 → 5.5 ml/min			33.72	~14
	12.05.22 12:50	5.5 → 6.8 ml/min			62.97	~14
	17.05.22 11:00	Sinusoidal	2,295.34	175.38	408.91	~14
	15.06.22 08:34	Not measured ^(*)	33,093.08	2,529.47	67.18	~14
	16.08.22 12:18	40 → 86 ml/min	84,255.47	6,448.80	62.23	~14
Total	01.12.22 07:05		119,643.89	9,153.66	641.14	

⁽¹⁾ Extracted water volume estimation:

Until 31 May 2022: entire extracted volume estimated as water

Since 31 May 2022: water volume calculated from mock-up tank water level

^(*) Extracted volume assumed by extrapolation, no flow data, syringe pump used for sampling

T: Temperature of 16 °C

P: Pressure at the time stamp. Pressure in the S02 filter was measured on the PL_S02_L6L-1 and PPE_S02_L1 lines. Pressure in the S14 filter was measured using the PPE_S14_L1 line

STP: Standard conditions (T = 273.15 K, P = 101.3225 kPa)

4.3.5 Index testing

Three hydraulic index test campaigns were performed during GFT Phases 3 – 5:

- Pulse injection (PI) campaign 31 May – 06 June 2022
- Pulse withdrawal (PW) campaign 15 June 2022
- Pulse withdrawal (PW) campaign 29 – 30 Sept 2022

On 31 May and 06 June, PI tests were conducted in the ports of Levels 4 and 6, using a water column flow meter. The derived data and compressibility results are listed in Tab. 4-15. The graphs of the PI tests are shown in Enclosure N.2. The comparison with the PW tests from March 2022 indicates consistent results for the PW test series in March 2022, which was only partially repeatable with the PI tests. The PI test campaign shows significantly more variation in calculated compressibilities (Fig. 4-35). It is uncertain to which degree the observed differences relate to the test methodology. The PW tests are likely more susceptible to degassing as the drawdowns can be large, which may also affect compressibility estimations. However, due to the relatively simple and repeatable field procedure, the PW index tests were repeated in all phases and provided valuable qualitative information over the complete GFT.

PW index tests were performed in the following test campaigns for an efficient and coherent procedure, providing comparable results (Tab. 4-16 and Tab. 4-17). Compressibilities significantly higher than the baseline measurements in March 2022 are considered as indicative for the possible presence of gas in the S/B (Fig. 4-36).

Tab. 4-15: Results of PI tests in PPE lines on 31 May and 06 June 2022

Date	Time	Sensor	ΔP [kPa]	ΔV ⁽¹⁾ [ml]	C [m ³ /Pa]	Comments
31.05.22	12:06	PPE_S03_L4	183.77	0.08	4.59E-13	
31.05.22	12:30	PPE_S07_L4	174.18	0.07	3.80E-13	
31.05.22	12:45	PPE_S09_L4	296.73	0.48	1.62E-12	
31.05.22	13:00	PPE_S12_L4	238.85	0.05	1.91E-13	
31.05.22	13:15	PPE_S06_L4	323.88	0.22	6.89E-13	
31.05.22	13:30	PPE_S08_L4	97.98	0.07	7.64E-13	
31.05.22	13:45	PPE_S10_L4	45.80	0.06	1.42E-12	
31.05.22	14:00	PPE_S03_L6H-2	73.82	1.11	1.50E-11	Very slow decrease
06.06.22	13:13	PPE_S03_L6L-1	83.87	0.17	2.00E-12	Very slow decrease
06.06.22	13:20	PPE_S06_L6L-1	791.53	2.03	2.57E-12	Very slow decrease
06.06.22	13:34	PPE_S08_L6L	708.05	0.09	1.30E-13	Slow decrease
06.06.22	13:38	PPE_S10_L6L-1	392.00	0.20	5.08E-13	Slow decrease
06.06.22	13:44	PPE_S12_L6L	326.29	0.09	2.82E-13	Very slow decrease
06.06.22	13:49	PPE_S08_L4	1,199.91	2.00 ^(*)	1.67E-12	
06.06.22	13:55	PPE_S06_L6H-2	223.29	1.13	5.08E-12	Very slow decrease
06.06.22	13:58	PPE_S10_L6H-2	586.01	0.28	4.72E-13	Very slow decrease
06.06.22	14:01	PPE_S12_L6H	615.48	0.08	1.30E-13	
06.06.22	14:04	PPE_S10_L4	70.50	2.00*	2.84E-11	

⁽¹⁾ Injected volume calculated from the water column flow meter (WCFM)

^(*) PW test with line piece with about 2 ml volume connected to PPE port, true volume unknown

Colour marks piezometers with slow pressure increase (light green) or compressibility > 6E-12 m³/Pa (light red).

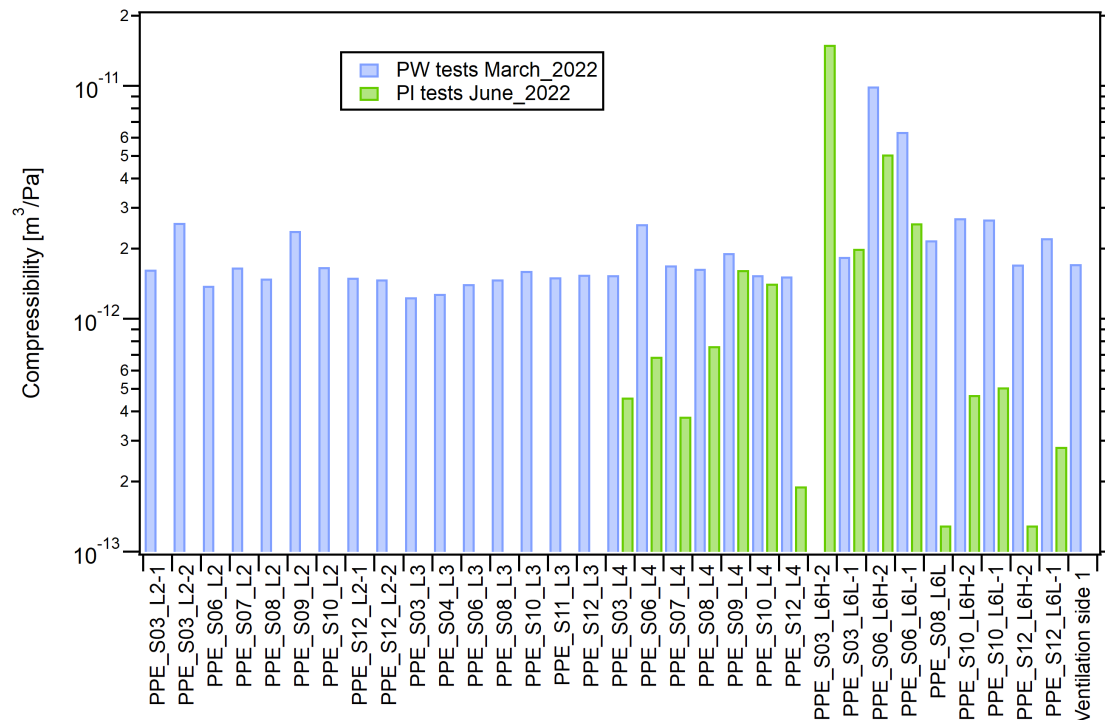


Fig. 4-35: Overview of calculated compressibilities for PI tests from June 2022 (Phase 4) compared to PW tests from March 2022 (Phase 1)

Tab. 4-16: Results of PW tests from PPE lines on 15 June 2022

Date	Time	Sensor	ΔP [kPa]	$\Delta V^{(1)}$ [ml]	C [m^3/Pa]	Comments
15.06.22	08:00	PPE_S03_L2-1	1,332.75	2.00	1.50E-12	Very fast increase
15.06.22	10:23	PPE_S06_L2	1,585.172	2.00	1.26E-12	
15.06.22	13:03	PPE_S08_L2	1,440.64	2.00	1.39E-12	
15.06.22	13:06	PPE_S10_L2	1,400.97	2.00	1.43E-12	
15.06.22	13:07	PPE_S12_L2-1	1,379.822	2.00	1.45E-12	Slow increase
15.06.22	13:11	PPE_S03_L2-2	808.3	2.00	2.47E-12	
15.06.22	13:31	PPE_S09_L2	1,048.83	2.00	1.91E-12	

⁽¹⁾ Line piece with about 2 ml volume connected to PPE port, true volume unknown
 Colour marks piezometers with green: very slow increase, blue: very fast increase.

Tab. 4-17: Results of PW tests from PPE lines in September 2022

Date	Time	Sensor	ΔP [kPa]	$\Delta V^{(1)}$ [ml]	C [m ³ /Pa]	Comments
29.09.22	7:46	PPE_S03_L2-1	1,410.47	2.00	1.42E-12	Fast increase
29.09.22	7:51	PPE_S03_L2-2	788.82	2.00	2.54E-12	
29.09.22	9:47	PPE_S08_L4	476.35	2.00	4.20E-12	Very fast increase
29.09.22	9:50	PPE_S07_L4	1,316.48	2.00	1.52E-12	
29.09.22	9:58	PPE_S03_L6H-2	75.56	2.00	2.65E-11	Very slow increase
29.09.22	10:03	PPE_S06_L6H-2	27.05	2.00	7.39E-11	Slow increase
29.09.22	10:08	PPE_S08_L6L	1,001.00	2.00	2.00E-12	Very slow increase
29.09.22	10:12	PPE_S03_L6L-1	192.96	2.00	1.04E-11	Very slow increase
29.09.22	10:16	PPE_S06_L6L-1	357.70	2.00	5.59E-12	Very slow increase
29.09.22	10:22	PPE_S03_L4	1,464.51	2.00	1.37E-12	Fast increase
29.09.22	10:44	PPE_S04_L3	1,679.10	2.00	1.19E-12	
29.09.22	11:00	PPE_S06_L3	1,528.27	2.00	1.31E-12	Slow increase
29.09.22	13:12	PPE_S06_L2	1,588.08	2.00	1.26E-12	
29.09.22	13:16	PPE_S07_L2	1,398.03	2.00	1.43E-12	Fast increase
29.09.22	13:19	PPE_S08_L3	1,416.90	2.00	1.41E-12	Fast increase
29.09.22	13:37	PPE_S10_L4	48.04	2.00	4.16E-11	Very slow increase
29.09.22	13:42	PPE_S09_L2	1,273.01	2.00	1.57E-12	
29.09.22	13:49	PPE_S10_L6H-2	875.11	2.00	2.29E-12	Very slow increase
29.09.22	13:52	PPE_S08_L2	1,426.92	2.00	1.40E-12	Slow increase
29.09.22	14:28	PPE_S12_L6L-1	956.85	2.00	2.09E-12	Very slow increase

⁽¹⁾ Line piece with 2 ml volume connected to PPE port, true extracted volume unknown
 Colours: red: compressibility $C > 6E-12$ m³/Pa, green: very slow increase, blue: very fast increase.

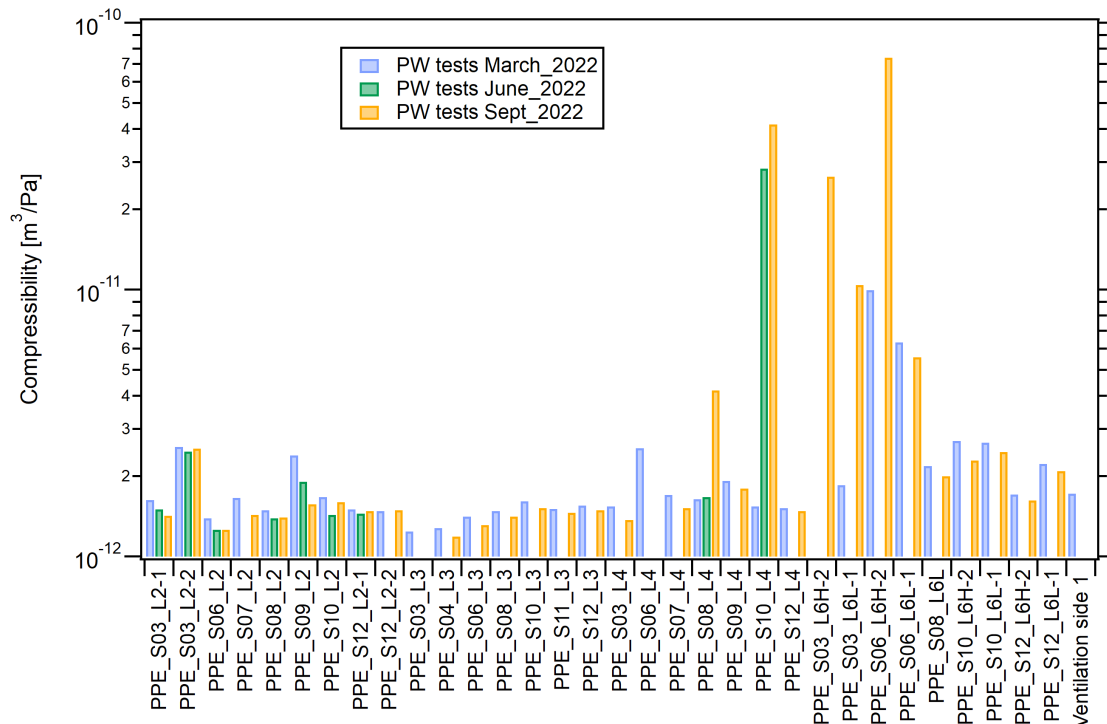


Fig. 4-36: Overview of calculated compressibilities from PW tests in March 2022 (Phase 1), June 2022 (Phase 5) and September 2022 (Phase 5)

4.3.6 Sampling

Monitoring data for the GFT Phases 3 – 5 were backed up with an extensive hydrochemical sampling campaign. In the beginning of the GFT (Phases 3 and 4) samples were taken primarily from the extraction port PL_S14_L1. After confirmation of the gas breakthrough in PL_S14_L1, more and more PPE piezometers were tested to attempt the collection of fluid samples. Tab. 4-18 lists all sampling activities in Phases 3 – 5. Fig. 4-37 and Fig. 4-38 illustrate the very low flow rates and drawdown curves realised for two exemplary sampling tests. Piezometer pore pressures typically recovered within several days after completion or shut-in of a particular sample port.

Fig. 4-39, Fig. 4-40, Fig. 4-41 and Fig. 4-42 show examples of pressure readings at PPEs during sampling.

The samples were normally collected with the single piston syringe pump. Three samples were taken by applying vacuum to the sampler and further connecting the sampler to the port, due to the very low flow rates yielded and the already large pressure decrease (Tab. 4-18). These samples are marked by a sudden decrease of pressure due to the vacuum and a slow subsequent pressure recovery.

Tab. 4-18: Sampling performed during GFT Gas Mix #1 between 06 May 2022 and 01 December 2022

Phase	Code	Vial	Port	Start date & time	Flow rate [ml/min] or [mln/min]	Pressure [bar]	Sample weight [g]
Phase 3	S14_013	GAST 11	PL_S14_L1	06.05.22 14:00	4.4	14	72.85 ⁽²⁾
	S14_014	GAST 12	PL_S14_L1	11.05.22 09:12	4.8	14	72.82 ⁽²⁾
	S14_015	GAST 13	PL_S14_L1	12.05.22 10:30	7.0	14	74.5 ⁽²⁾
Phase 4	S14_016	GAST 14	PL_S14_L1	13.05.22 12:32	10	14	72.5 ⁽²⁾
	S14_017	GAST 15	PL_S14_L1	17.05.22 09:34	10	14	72.9 ⁽²⁾
	S14_018	GAST 16	PL_S14_L1	18.05.22 08:40	11.5	14	74.4 ⁽²⁾
	S14_019	GAST 17	PL_S14_L1	20.05.22 08:44	14	14	73.5 ⁽²⁾
	S14_020	GAST 18	PL_S14_L1	31.05.22 08:38	15.2	14	73.6 ⁽²⁾
	S14_021	GAST 19	PL_S14_L1	03.06.22 07:29	Down to 2	14	71.8 ⁽²⁾
	S14_022	GAST 20	PL_S14_L1	09.06.22 09:09	16	14	0.8 ⁽²⁾
	S14_023	GAST 21	PL_S14_L1	09.06.22 10:35	15	14	70.7 ⁽²⁾
	S14_024	GAST 22	PL_S14_L1	10.06.22 11:44	15	14	71.8 ⁽²⁾
	S14_025	GAST 23	PL_S14_L1	15.06.22 07:58	20	14	2.6 ⁽²⁾
Phase 5	S14_026	GAST 24	PL_S14_L1	28.06.22 12:42	20	14	30.8 ⁽²⁾
	PPE_027	GAST 01	PPE_S10_L4	15.06.22 08:34	0.006	12.3 ⁽³⁾	1 ⁽¹⁾
	GAS_028	GAST 02	Gas Mix #1*	15.06.22 10:00	225 mln/min	20	0.5 ⁽¹⁾
	PPE_029	GAST 03	PPE_S10_L4	28.06.22 07:23	0.006	14.0 ⁽³⁾	3.7 ⁽¹⁾
	PPE_030	GAST 04	PPE_S08_L4	03.08.22 11:26	0.01	14.3 ⁽³⁾	27.5 ⁽¹⁾
	PPE_031	GAST 05	PPE_S08_L4	09.08.22 14:02	0.01	12.6 ⁽³⁾	27.6 ⁽¹⁾
	PPE_032	GAST 06	PPE_S03_L3	16.08.22 14:09	- ⁽⁴⁾	18.6 ⁽³⁾	27.4 ⁽¹⁾
	PPE_033	GAST 07	PPE_S06_L6H-2	06.09.22 14:20	0.025	15.0 ⁽³⁾	0.4 ⁽¹⁾
	PPE_034	GAST 08	PPE_S06_L4	21.09.22 10:15	0.01	15.7 ⁽³⁾	27 ⁽¹⁾
	PPE_035	GAST 09	PPE_S03_L6L-1	20.10.22 10:41	0.01 – 0.03 → - ⁽⁴⁾	10.0 ⁽³⁾	- ⁽¹⁾
	PPE_036	GAST 10	PPE_S07_L2	20.10.22 10:40	- ⁽⁴⁾	15.4 ⁽³⁾	27.4 ⁽¹⁾
	S14_037	GAST 25	PL_S14_L1	12.07.22 13:33	39	14	49.7 ⁽²⁾
	S14_038	GAST 11	PL_S14_L1	26.07.22 11:09	39	14	45.1 ⁽²⁾
	S14_039	GAST 12	PL_S14_L1	30.08.22 11:55	50	14	- ⁽²⁾
	S14_040	GAST 13	PL_S14_L1	21.09.22 09:00	60	14	39.8 ⁽²⁾
	S14_041	GAST 14	PL_S14_L1	20.10.22 09:40	75	14	1.8 ⁽²⁾
	PPE_042	GAST 01	PPE_S08_L4	08.11.22 13:48	0.1	14	26.1 ⁽¹⁾
	S02_043	GAST 15	PL_S02_L1	08.11.22 10:03	25	19	72.2 ⁽²⁾
	S02_044	GAST 16	PL_S02_L1	08.11.22 10:19	25	19	73.3 ⁽²⁾
	S14_045	GAST 17	PL_S14_L1	08.11.22 10:40	80	14	38 ⁽²⁾
	GAS_046	GAST 18	Gas Mix #1*	08.11.22 11:19	940	20	1.4 ⁽²⁾

(*) Gas Mix #1: 98% N₂ and 2% He

(1) 25 ml vial

(2) 75 ml vial

(3) Pressure at closure time of valve to sampler

(4) Vacuum applied

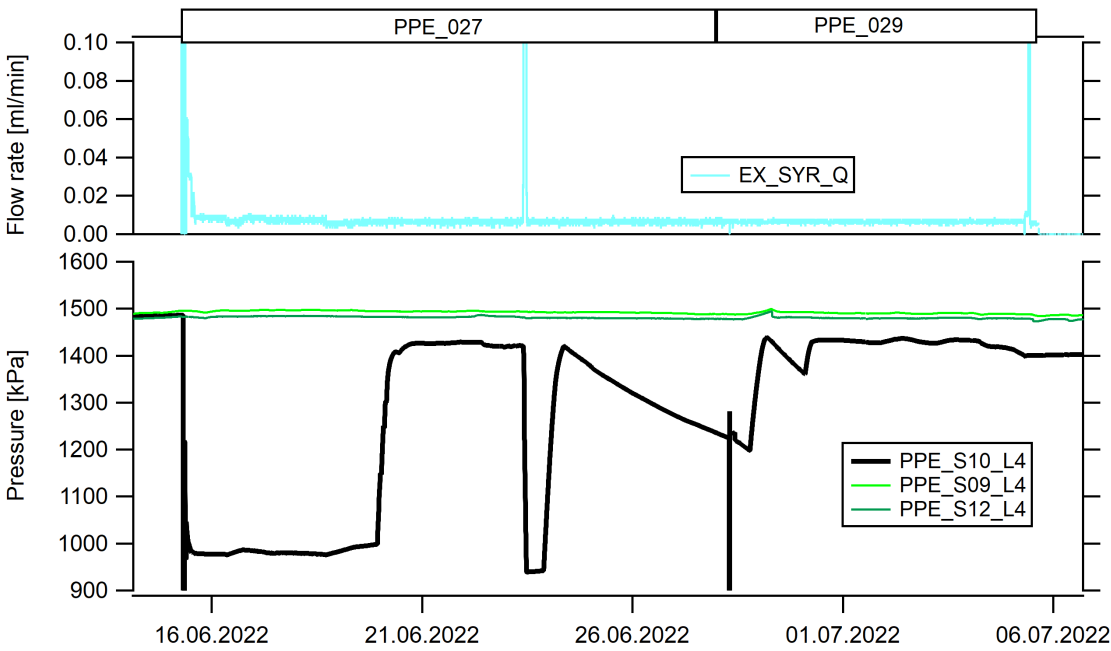


Fig. 4-37: Sampling from PPE_S10_L4 for sample PPE_027/PPE_029

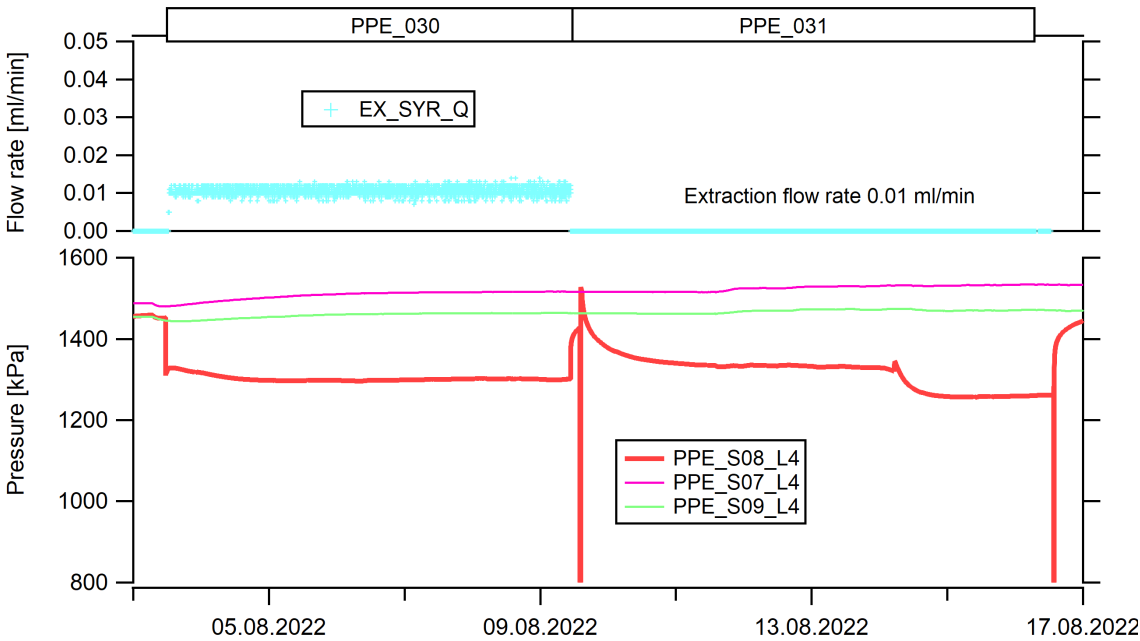


Fig. 4-38: Sampling from PPE_S08_L4 for sample PPE_030/PPE_031

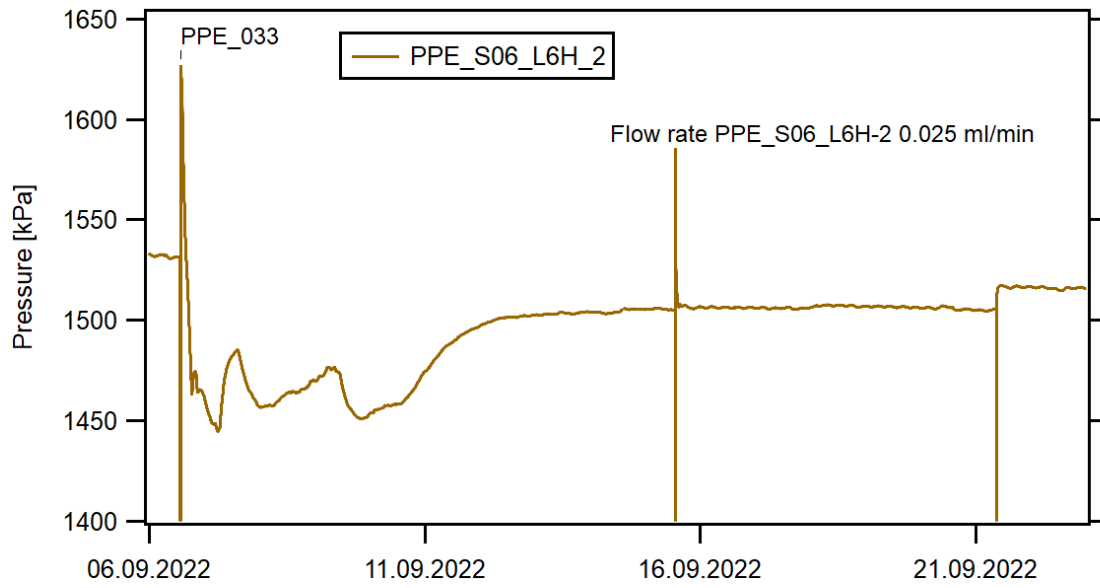


Fig. 4-39: Sampling from PPE_S06_L6H-2 for sample PPE_033

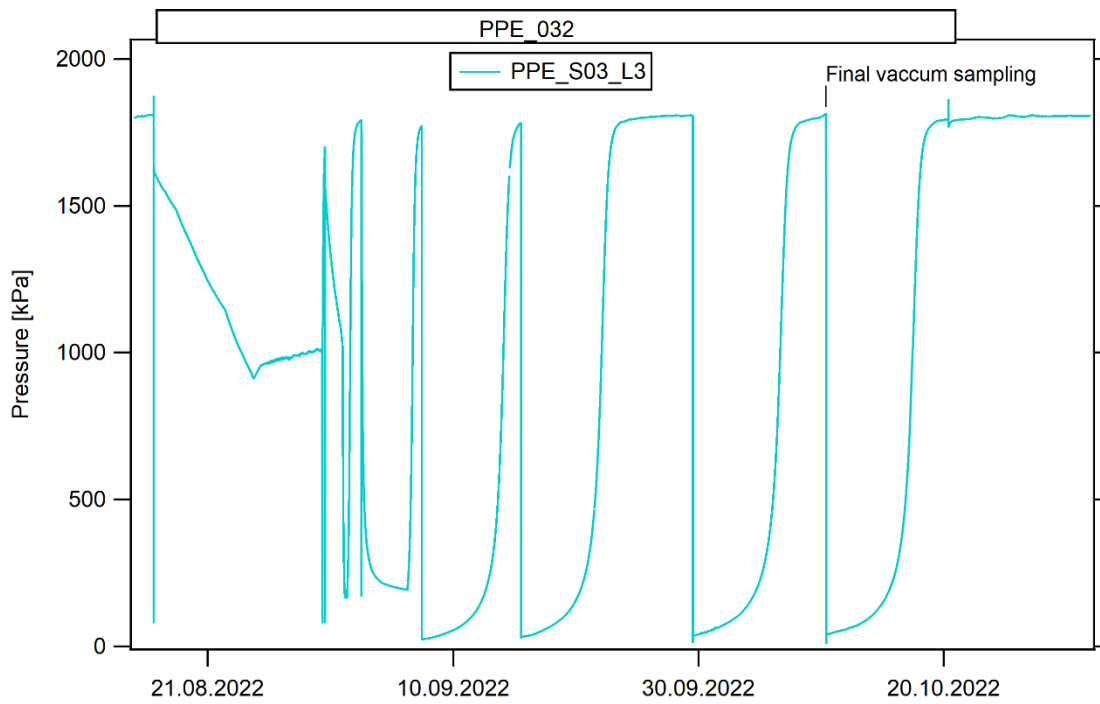


Fig. 4-40: Sampling from PPE_S03_L3 for sample PPE_032

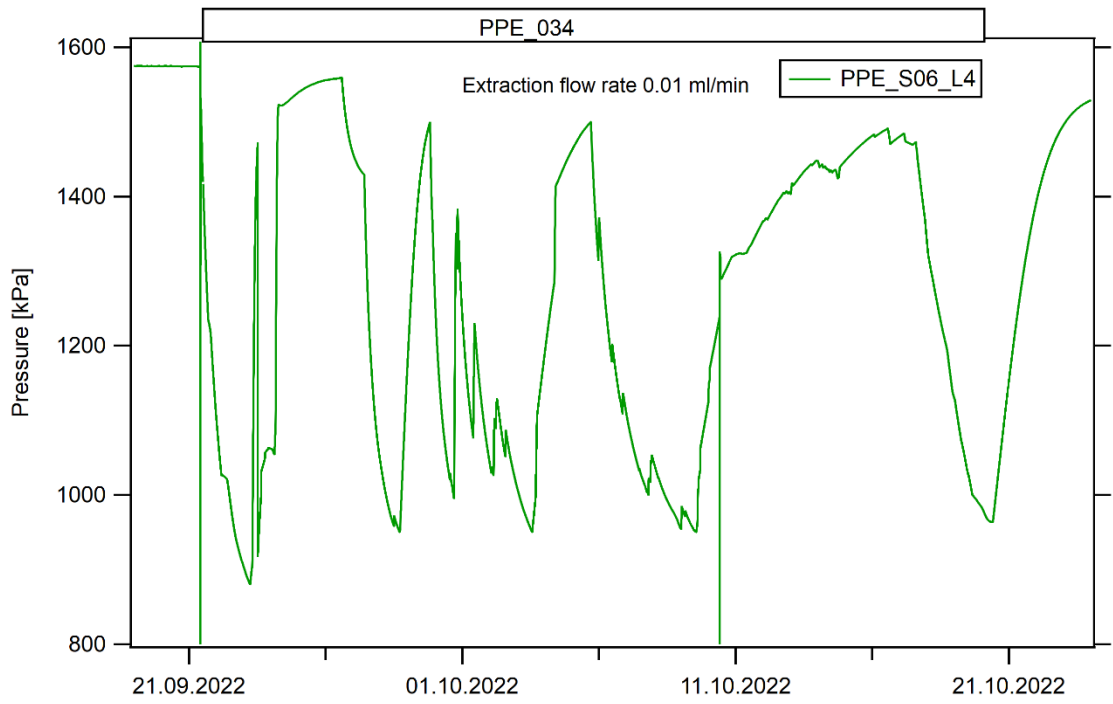


Fig. 4-41: Sampling from PPE_S06_L4 for sample PPE_034

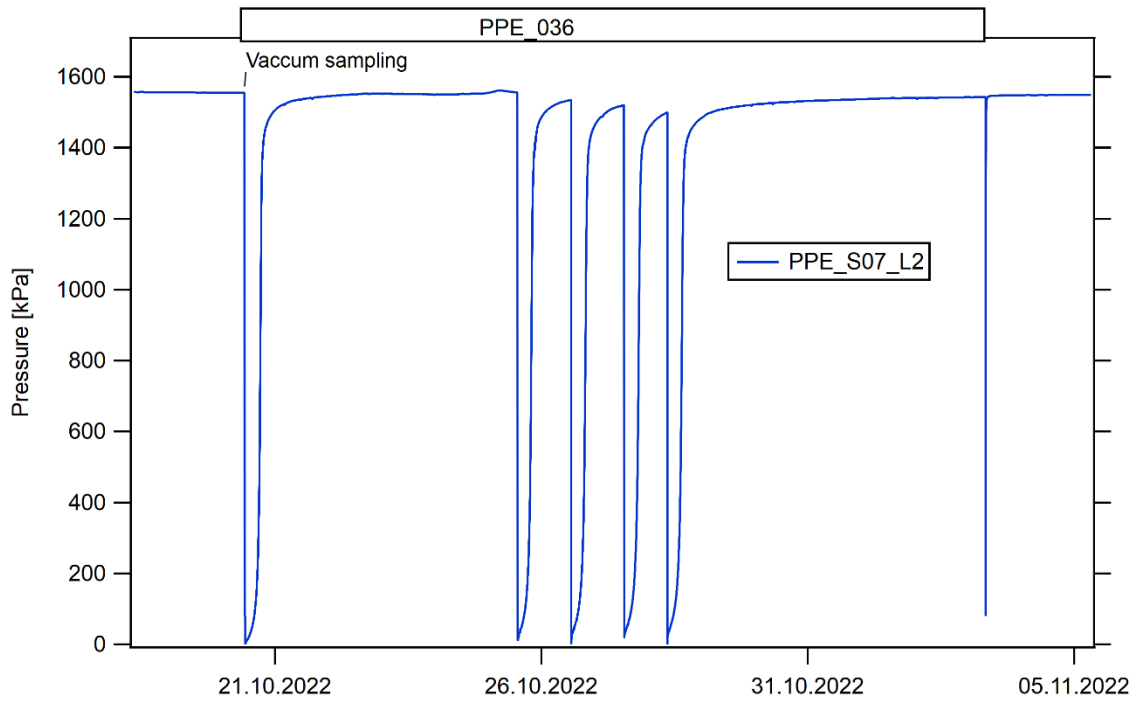


Fig. 4-42: Pressure and flow rate measured during the acquisition of sample PPE_036 from PPE_S07_L2

4.3.7 Gas monitoring results

In the present section, we describe the outcome of the measurements based on the miniRUEDI portable mass spectrometer system installed at the GAST (Section 3.5.1) as well as the laboratory-based analyses achieved to monitor the breakthrough of gas during the first injection of Gas Mix #1 (N₂ spiked with 2% He) performed between May 2022 and November 2022.

The gas flow test was conducted to assess the gas migration inside the S/B pore space using He as a conservative gas tracer. The He concentration of 2% of the injected gas mixture was chosen as a compromise between the capability to determine the concentrations of such gas species close to the upper detection limit of the miniRUEDI standard protocols and the possibility to detect potential gas leakages at the plug.

The monitoring of the gas composition at PL_S14_L1, both using the qualitative on-site continuous measurements by the miniRUEDI and quantitative off-site discrete sample laboratory analyses, allowed detailed observation of the gas flow through the GAST seal. He traces were identifiable at PL_S14_L1 just a few days after the completion of gas-water exchange operation at S02 and the start of the Gas Mix #1 injection. After about one month, on 08 June 2022, Gas Mix #1 reached PL_S14_L1 as a macroscopic gas phase with He concentrations from laboratory measurements in agreement with the nominal 2%. For the whole successive part of the gas test, both on-site and off-site measurements delivered a consistent overview of the gas tracer evolution at PL_S14_L1 until the end of Gas Mix #1 injection on 30 November 2022. It should be noted that, since the first detection of a macroscopic gas phase at filter S14, the amount of extracted water in the samples for off-site analyses strongly varied. These observations prove that gas can flow through the seal.

PPE samples of appreciable quality, such as those from PPE_S06_L6 and PPE_S10_L4, clearly point to the presence of a macroscopic free gas phase characterised by the signature of the injected Gas Mix #1 migrating through the S/B domain.

Gas sniffing at the plug and at the well head did not reveal measurable leaks from the experiment.

4.3.7.1 On-site monitoring and off-site laboratory gas concentrations

The results of the on-site gas monitoring achieved with the miniRUEDI as well as the off-site laboratory-based analyses for PL_S14_L1 are plotted in Fig. 4-43 (scaled to maximum values) and Fig. 4-44 (magnification of the most relevant concentration ranges, see also Enclosures I and J). For comparison, the measurements of samples from PL_S02_L1 and of samples of the injected gas are also depicted in the same figures. As the miniRUEDI gas partial pressures measured in the membrane module cannot be quantitatively converted into dissolved-gas concentrations (see Section 3.5.1 and Enclosure I), the relative gas composition (i.e., percentages of the total gas pressure) is used in the further discussion. The dissolved gas concentrations (in cm³_{STP}/kg, see Enclosure J) from the off-site laboratory analyses are also converted into their shares with respect to the sum of all determined concentrations.

The Gas Mix #1 injection started on 02 May 2022 and ended on 30 November 2022. The following time windows/events should be considered in the further discussions of gas results (further details in Enclosures H, J and K):

- 02 May 2022 – 05 May 2022 (Phase 2): Water-gas exchange inside filter S02 only, where the Gas Mix #1 was injected into PL_S02_L6-2 and extracted from PL_S02_L1. S02 samples for off-site analyses were collected from the headspace of the mock-up tank installed after S02_L1 to check the presence of He to assess the completion of the gas-water exchange operations. An S14 sample was collected on 05 May 2022 to check any interaction with the ongoing operations.
- 06 May 2022 – 12 May 2022 (Phase 3): Acquisition of the first PL_S14_L1 sample during operations and adjustments to stabilise the gas flow.
- 13 May 2022 – 10 June 2022 (Phase 4): PL_S14_L1 samples were collected over several days and, at least according to their weight, they contained mainly water. After PL_S14_L1 clogging, cleaning, and reactivation occurred between 08 June 2022 and 10 June 2022, the outbreak of a gas phase was observed.
- Since then (Phases 4 and 5), PL_S14_L1 samples showed a mix consisting of a liquid phase and a free gas phase.
- 08 November 2022: S02 samples were taken directly from the PL_S02_L1 line (i.e., not from the mock-up tank headspace as the previous ones). The samples contained mainly water (no significant free gas phase anymore) which could be ascribed to the different sampling setup and to the possibility that, after the water-gas exchange operations, water might have well reoccupied the lower level of filter S02.

The membrane module connected to the miniRUEDI was fed by fluids from PL_S14_L1 starting on 09 May 2022 at 14:30. Before this date, the gas composition in the membrane module monitored by the miniRUEDI fluctuated strongly. This is due to adjustments of the system feeding fluids to the membrane module. It should be noted that the total pressure in the headspace of the membrane module before 09 May 2022 was equal to the atmospheric pressure in the GTS, and the composition of N₂, O₂ and Ar pointed to the presence of an air-like gas phase.

The injected gas tracer He, migrating from S02 towards S14, was detected by the miniRUEDI measurements immediately after connection of the membrane module to PL_S14_L1. A transition towards the composition of the gas mix characterised by sharp changes in the percentages of all gases is observed over the following two days (Fig. 4-43, Fig. 4-44). N₂ reaches almost 99%, O₂ is close to 0%, Ar goes below 0.2%, and He is slightly above 1%. After this rather dynamic phase, the shares of O₂ and Ar remain close to 0% while He tends to slowly reach 2% around the end of October 2022. During November 2022, the He share reaches values of about 2.5%. Such a value exceeds the composition of the injected Gas Mix #1 and seems to be related to the gas partitioning processes within the membrane module and the pressure release valve connected to the module headspace (i.e., an experimental artifact).

Quantitative off-site laboratory measurements of samples collected at PL_S14_L1 agree well with the on-site measurements by the miniRUEDI. Nevertheless, the concentrations delivered by the on-site monitoring for PL_S14_L1 could be affected by biases due to the experimental setup (membrane module, pressure release valve), while the laboratory analyses quantitatively demonstrate the arrival of He from Gas Mix #1.

From an initial dissolved share of 0.6%, the He composition increased rapidly and stabilised around the nominal concentration of 2% right after the gas phase breakthrough at PL_S14_L1 and until the end of the first injection experiment.

The first sample with detectable amounts of dissolved He (0.5%, in an overall dissolved gas content of $12 \text{ cm}^3_{\text{STP}}/\text{kg}$) was collected on 05 May 2022, indicating the presence of gas tracers at PL_S14_L1 already at the end of the water-gas exchange operations at S02. The arrival of a free gas phase (“breakthrough”) was observed between 08 June and 10 June 2022, as confirmed by a significantly lower sampler weight after sample collection (see Enclosures J and K). Therefore, it appears that the migration of the He detected before the gas breakthrough was fostered by preferential pathways characterised by an interplay of advection, diffusion, and gas dissolution (i.e., no free gas phase was present at filter S14 on 05 May 2022).

N₂ concentrations remained stable throughout the Gas Mix #1 injection at values above ~95%. The laboratory analytical uncertainty of 4% does not allow for a more detailed interpretation of minor concentration changes of this gas species. For most samples, O₂ was below the detection limit and, if measurable, the respective share never exceeded 0.01%. Low O₂ concentrations are supportive for the good quality of the samples (i.e., no or very minor air contamination). The first sample collected from PL_S14_L1 exhibits an atmospheric-like Ar share of about 0.7%. The respective absolute Ar concentration of $0.09 \text{ cm}^3_{\text{STP}}/\text{kg}$ agrees with the Ar concentration range determined in BOADUS water and in samples from the dipole test ($0.02 - 0.20 \text{ cm}^3_{\text{STP}}/\text{kg}$, see Enclosure J), the latter of which can be considered as an “experimental baseline”. Over time, the Ar share decreased until 21 September 2022, when Ar concentration went below the detection limit. The observed Ar decrease is in line with the injection of an Ar-free gas mix (i.e., behaving in the opposite way compared to He). Four samples taken at the beginning of June 2022 showed higher Ar percentages and lower He percentages compared to the preceding/following samples. The collection of the samples coincided with the clogging of PL_S14_L1 and the subsequent actions (i.e., cleaning with BOADUS water) undertaken to reactivate the extraction line. Thus, field operations could have resulted in the admixture of a BOADUS-like signature.

In terms of sample collection quality, from May 2022 until November 2022, the time required to collect each sample decreased due to the increase in sustainable extraction flow rates (i.e., the samplers were flushed faster with fluids from PL_S14_L1, especially after the breakthrough of a macroscopic free gas phase).

The water content of the samples for off-site analysis is depicted in Fig. 4-45. The water content (W in %) was calculated using the weight difference between full and empty samplers (Δm in g), the sampler average inner volumes as determined by laboratory measurements (V_{avg} in ml; i.e., 26.5 ml for samplers with a nominal volume of 25 ml and 71.9 ml for samplers with a nominal volume of 75 ml, data in Enclosure K), and assuming a water density $\rho_{\text{H}_2\text{O}} = 1 \text{ g/ml}$ as $W = (\Delta m / \rho_{\text{H}_2\text{O}}) / V_{\text{avg}} \times 100$. Before 10 June 2022, the samplers were filled with water. After this date (i.e., after the gas breakthrough to S14 extraction), the water content drops considerably from 100%, indicating the presence of variable shares of a free gas phase and liquid. Consequently, the interpretation of dissolved-gas concentrations can be problematic. According to the relatively low solubility of gases in water, in a closed system (such as the mentioned samplers) gases tend to partition preferentially (if available) into a free gas phase until they attain solubility equilibrium. This is likely to be the case for the samples collected at GAST that were analysed weeks after their collection. In turn, the amount of dissolved gas is about two or three orders of magnitude lower compared to the free gas counterpart. Very roughly exemplified, a bubble of less than 1 ml in a 75 ml Swagelok cylinder could carry the same amount of gas as the remaining 74 ml of water. Therefore, whenever a gas phase was measured by means of off-site laboratory analyses (i.e., between a few and several ml of gas were available), the gas phase values were taken to generate the plots in this and the following sections.

A total of 5 samples were collected from PL_S02_L1. The first 3 samples were acquired (after pre-evacuation) daily at the headspace of the mock-up tank during the water-gas exchange operations at filter S02. Only one sample arrived intact at the laboratory (06 May 2022) and showed an He percentage of about 1.5%, confirming the successful completion of water-gas

exchange procedures. The samples collected directly from PL_S02_L1 in November 2022 are affected by air contamination, as indicated by the presence of O₂ and Ar shares (see Fig. 4-43). It should be noted that the evolution of the water content for the samples collected at PL_S02_L1 from about 0% in May 2022 up to nearly 100% in November 2022 (Fig. 4-45) clearly indicates reingression of water into the lower part of the filter S02. While the N₂ shares in the measured samples do not vary significantly over time, the He shares tend to decrease and the Ar shares tend to increase. Such a trend indicates the admixture of water present in the experiment before gas injection (e.g. results from samples collected within the framework of the dipole test, see Section 4.1.6).

On 15 March 2022, 15 June 2022, and 11 November 2022, gas samples were acquired directly from the cylinders containing the injected Gas Mix #1. The measured He concentrations of 2.0 – 2.1% match the expected nominal value of 2% of Gas Mix #1 (Enclosure B.5). The remaining gas share is N₂ with values ranging from 96.3% to 98.1%.

Tab. 4-19: Results of the off-site laboratory analyses conducted on Gas Mix #1, PL_S02_L1 and PL_S14_L1 samples collected during the gas flow test with Gas Mix #1

Water content: approximate percentage of the sampler volume filled with water. Tot.: total amount of dissolved gases in cm³_{STP}/kg. The relative composition in [%] was calculated from dissolved species abundance for samples where a direct measurement of a gas phase was not possible (numbers in italics). Empty fields: measurements not performed; “n.d.”: below the detection limit. Full dataset of analytical results available in Enclosure J, full details of sample collection available in Enclosure K.

Sample	Start of collection	Sampling date	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	O ₂	N ₂
			[%]	[cm ³ _{STP} /kg]					[%]			
GAS MIX #1	15.03.22 13:07	15.03.22 13:09							2.1	n.d.	n.d.	98.1
GAS MIX #1	15.06.22 10:00	15.06.22 10:05	2						2.1	n.d.	n.d.	96.3
GAS MIX #1	08.11.22 11:19	08.11.22 11:25	2						2.0	n.d.	n.d.	98.0
PL_S02_L1	06.05.22 10:15	06.05.22 10:15	1						1.5	0.03	0.3	98.0
PL_S02_L1	08.11.22 10:03	08.11.22 10:08	100	3.5	0.8	0.94	322	327	<i>1.1</i>	<i>0.3</i>	<i>0.3</i>	<i>98.3</i>
PL_S02_L1	08.11.22 10:19	08.11.22 10:25	102	3.3	0.9	0.65	350	355	<i>0.9</i>	<i>0.3</i>	<i>0.2</i>	<i>98.6</i>
PL_S14_L1	05.05.22 14:50	05.05.22 14:50	134	0.06	0.09	n.d.	12.0	12.2	<i>0.5</i>	<i>0.7</i>	<i>n.d.</i>	<i>98.7</i>
PL_S14_L1	06.05.22 14:00	11.05.22 09:05	101	0.5	0.3	n.d.	86	87	<i>0.6</i>	<i>0.3</i>	<i>n.d.</i>	<i>99.1</i>
PL_S14_L1	11.05.22 09:12	12.05.22 10:22	101	1.2	0.6	n.d.	169	171	<i>0.7</i>	<i>0.4</i>	<i>n.d.</i>	<i>98.9</i>

Tab. 4-19: Cont.

Sample	Start of collection	Sampling date	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	O ₂	N ₂
			[%]	[cm ³ _{STP} /kg]					[%]			
PL_S14_L1	12.05.22 10:30	13.05.22 12:34	104	1.1	0.5	n.d.	151	153	0.7	0.3	n.d.	98.8
PL_S14_L1	13.05.22 12:32	17.05.22 09:34	101	1.0	0.3	n.d.	99	100	1.0	0.3	n.d.	98.7
PL_S14_L1	17.05.22 09:34	18.05.22 08:40	101	0.9	0.1	n.d.	89	93	0.9	0.1	n.d.	96.3
PL_S14_L1	18.05.22 08:40	20.05.22 08:42	103	1.2	0.2	n.d.	100	102	1.2	0.2	n.d.	98.4
PL_S14_L1	20.05.22 08:44	31.05.22 08:34	102	1.1	0.2	n.d.	91	93	1.2	0.2	n.d.	98.6
PL_S14_L1	31.05.22 08:38	03.06.22 07:24	102	1.6	1.2	n.d.	141	143	1.1	0.9	n.d.	98.1
PL_S14_L1	03.06.22 07:29	08.06.22 12:43	100	3.0	4.0	n.d.	220	228	1.3	1.7	n.d.	96.7
PL_S14_L1	09.06.22 09:09	09.06.22 10:33	1						0.8	0.04	n.d.	98.0
PL_S14_L1	09.06.22 10:35	10.06.22 11:39	98	3.1	4.0	n.d.	281	289	1.1	1.4	n.d.	97.2
PL_S14_L1	10.06.22 11:44	10.06.22 14:10	100	11.8	6.8	n.d.	639	658	1.8	1.0	n.d.	97.2
PL_S14_L1	15.06.22 07:58	15.06.22 08:08	4						2.0	n.d.	n.d.	96.1

Tab. 4-19: Cont.

Sample	Start of collection	Sampling date	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	O ₂	N ₂
			[%]	[cm ³ _{STP} /kg]					[%]			
PL_S14_L1	28.06.22 12:42	29.06.22 07:48	43						2.1	n.d.	n.d.	94.5
PL_S14_L1	12.07.22 13:33	12.07.22 14:47	69	120	0.3	0.28	5,255	5,375	2.2	0.01	0.005	96.1
PL_S14_L1	26.07.22 11:09	26.07.22 13:45	63	152	0.3	0.29	6,800	6,953	2.2	0.004	0.004	95.4
PL_S14_L1	30.08.22 11:55	30.08.22 11:55	95	11.7	0.01	0.01	557	569	2.1	0.002	0.002	95.0
PL_S14_L1	21.09.22 09:00	21.09.22 09:50	55	212	n.d.	n.d.	9,922	10,134	2.1	n.d.	n.d.	97.5
PL_S14_L1	20.10.22 09:40	20.10.22 10:55	3						2.1	n.d.	n.d.	98.0
PL_S14_L1	08.11.22 10:40	08.11.22 11:10	53						2.1	n.d.	n.d.	98.0

The following events are related to field operations as well as to experimental issues (Enclosures F and H), resulting in significant short-term deviations of the measured gas composition from the overall trend:

- On 06 June 2022, issues with the electrical conductivity, flow rates and pressure measurements suggested the clogging of the extraction line PL_S14_L1. Several operations took place until 08 June 2022, including flow reversal and the injection of BOADUS water into S14 to unclog the line, and filter cartridges cleaning. Such field operations resulted in gas trend offsets for both the miniRUEDI and the laboratory-based measurements. On 06 June 2022, the miniRUEDI measurements showed a strong drop in the total gas pressure related to the impossibility to extract water from the experiment. Such a pressure drop correlates with a decrease in the N₂ concentration, an He concentration increase to about 2%, and a very slight Ar concentration increase (Fig. 4-44).
- Between 28 June 2022 and 05 July 2022, Solexperts AG performed operations related to the line connecting the mock-up tank, which was maintaining the pressure at S14. Connection and disconnection of the tank resulted in two clear drops of the pressure in the headspace of the membrane module. The gas composition shifted towards a pattern similar to the event of 06 June 2022.
- A shut-in of the PL_S14_L1 extraction line occurred on 30 July 2022. Total gas pressure as well as the gas composition reproduced a similar pattern as the one observed on 06 June 2022. After the mentioned decrease, the total gas pressure recovered and exceeded the controlled pressure threshold (1,400 mbar measured instead of about 930 mbar). It turned out that the valve connecting the membrane module headspace and pressure controller was closed. The valve was reopened on 11 August 2022, and pressure stabilised back to approximately 930 mbar.
- On 21 August 2022, an He concentration decrease was observed in the membrane module. This seemed to be related to the operation of the syringe pump or to changes in the flow rates.
- On 21 August 2022, 25 September 2022, and 27 September 2022, a large scattering of the measurements was likely related to temporary electrical issues.
- On 11 November 2022, significant consecutive pressure drops were registered in the gas phase of the membrane module. Such pressure drops were related to issues in controlling the pressure of filter S14.

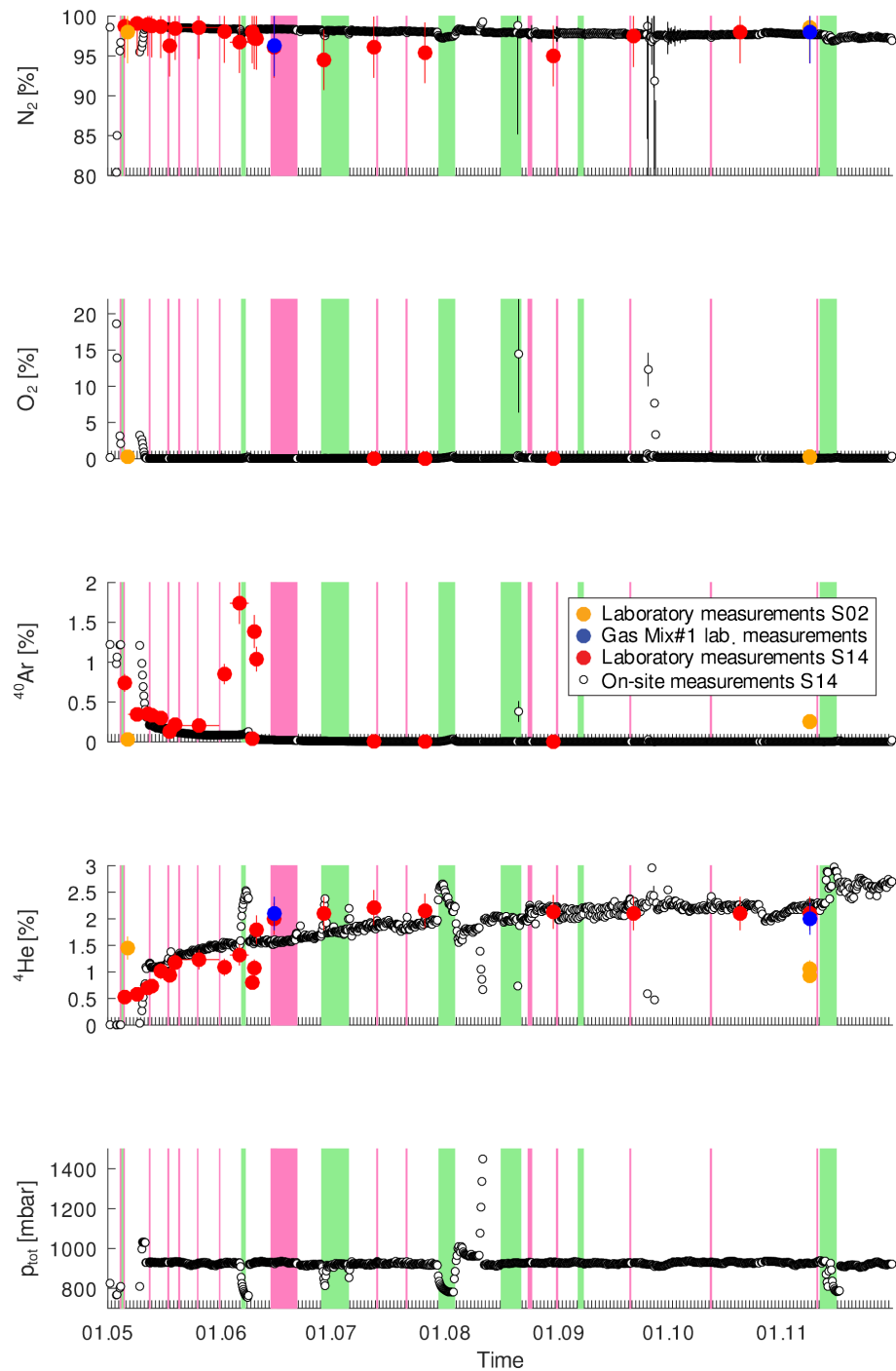


Fig. 4-43: Evolution of the gas composition with on-site and off-site measurements between 01 May 2022 and 30 November 2022 (Phases 2 to 5)

Empty circles: qualitative on-site measurements with miniRUEDI; red dots: quantitative off-site laboratory measurements of samples from PL_S14_L1; orange dots: off-site laboratory measurements on samples from PL_S02_L1; blue dots: off-site laboratory measurements of Gas Mix #1 samples. Vertical error bars indicate the respective analytical uncertainties. Horizontal error bars indicate the sampling time span. Results from off-site laboratory analyses are plotted only if above the respective detection limits. Magenta- and green-shaded areas mark the timing of ventilation shielding and relevant field operations, respectively.

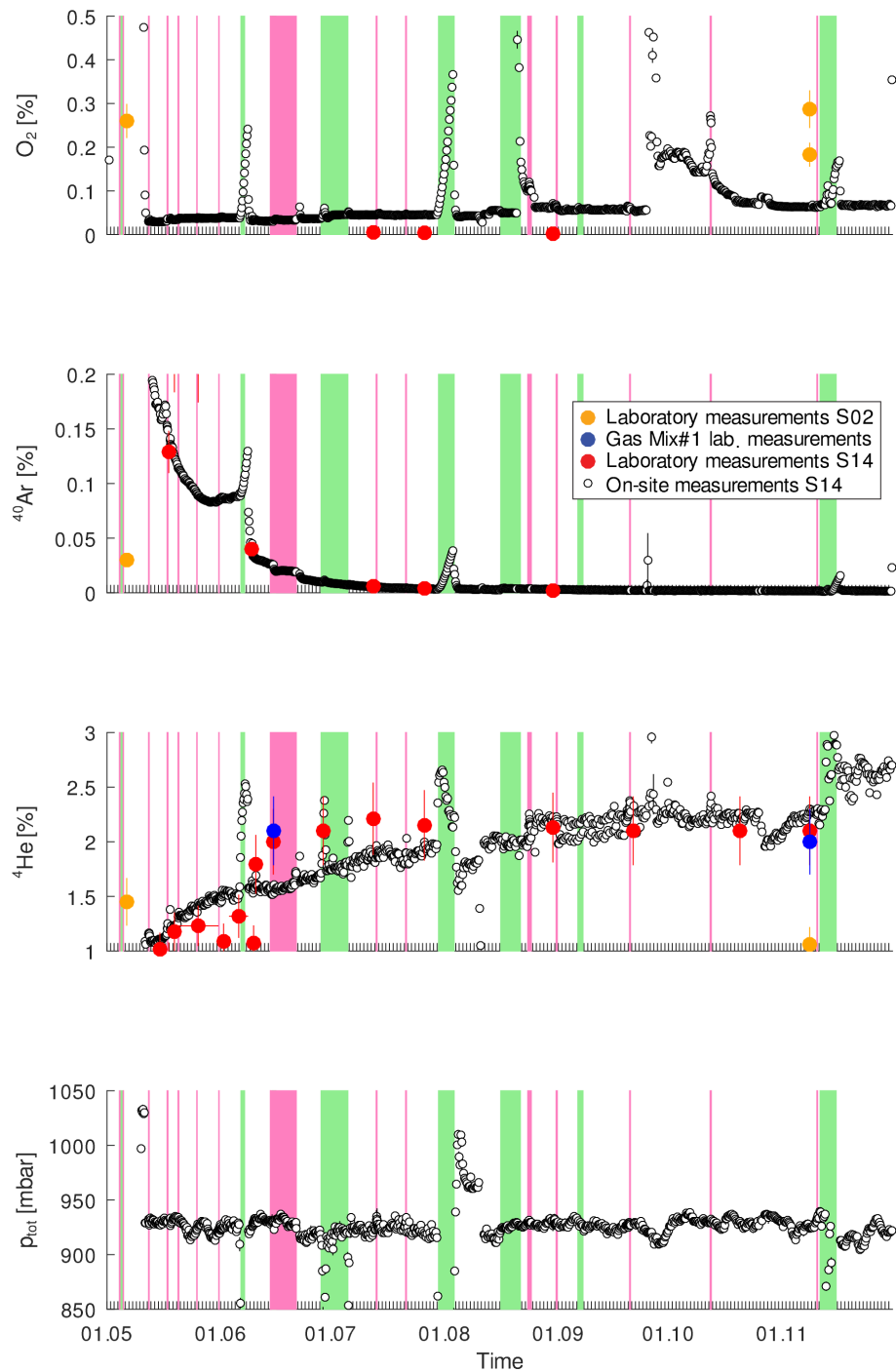
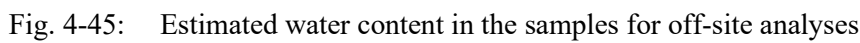


Fig. 4-44: Evolution of the gas composition with on-site and off-site measurements between 01 May 2022 and 30 November 2022 (Phases 2 to 5). Magnification to highlight concentration fluctuations closer to steady-state conditions

Empty circles: qualitative on-site measurements with miniRUEDI; red dots: quantitative off-site laboratory measurements of samples from PL_S14_L1; orange dots: off-site laboratory measurements on samples from PL_S02_L1; blue dots: off-site laboratory measurements of Gas Mix #1 samples. Vertical error bars indicate the respective analytical uncertainties. Results from off-site laboratory analyses are plotted only if above the respective detection limits. Magenta- and green-shaded areas mark the timing of ventilation shielding and relevant field operations, respectively.



The water content was calculated using the difference between the full and empty weights of the samplers normalised by the average volume of the used Swagelok cylinders. Magenta- and green-shaded areas mark the timing of ventilation shielding and relevant field operations, respectively.

The collection of PPE samples in 25 ml Swagelok cylinders for off-site analyses was conducted to better understand the gas dynamics within the experiment and to identify the migration of Gas Mix #1 (i.e., He) inside the S/B seal system. The PPEs to be sampled were selected according to the likelihood of the presence of a free gas phase in their proximity. The total pressure behaviour and compressibility tests were used as criteria to estimate such a likelihood.

It should be noted that the sampling of the PPEs was rather challenging. In general, the flow rates were low due to the necessity to keep the system pressurised above 9 bar using a syringe pump (i.e., to avoid excessive degassing). Whenever the pressure drop approached the 9-bar threshold, the extraction from the respective PPE was stopped until the total pressure recovered. Thus, the changing flow rates directly affected the time required to purge the line volume, then to flush the sampling cylinders for at least $1 \times$ volume, then to fill them. Furthermore, the variable shares of liquid and gas phases made the estimation of the volumes being extracted from the PPEs rather approximate. Some samples had to be collected by forcibly extracting the fluids from the PPE, applying a vacuum to the sampler (i.e., the 9-bar threshold could not be guaranteed), and hence these samples should be considered only for the qualitative evaluation of the He tracer presence/absence only. Further details are presented in Enclosure K.

The results of the off-site laboratory analyses conducted on PPE samples are summarised in Tab. 4-20. Most of the PPE samples contained mainly water, apart from samples PPE_S06_L6H-2 and PPE_S10_L4. Indeed, the injected Gas Mix #1 was detected at PPE_S06_L6H-2 (He ~2%) and PPE_S10_L4 (He ~0.7 – 1.3%). The sample from PPE_S10_L4 collected on 05 July 2022 showed Ar and O₂ concentrations above the detection limits and a slightly lower He concentration compared to the sample collected on 28 June 2022. This result suggests a potential air contamination with some loss of He that, however, does not affect the assessment of the arrival of the injected Gas Mix #1 at the respective PPE.

Particularly relevant is the clear presence of the gas tracer He in PPE_S10_L4 in the gas phase, indicating active pathways for gas flow inside the emplaced S/B.

All other PPE samples were characterised by Ar concentrations ranging between 0.4% and 1.1%, and O₂ concentrations ranging between 0.7% and 4.1%. Especially the presence of significant shares of O₂ indicates potential sampling issues (e.g., air intrusion through slightly leaky fittings during prolonged sampling periods, handling issues during the connection of the samplers to the extraction line, or due to incomplete/partial evacuation of the sampling cylinders) and the respective results should not be over-interpreted. During the dipole test run conducted in February/March 2022 on layer L02 inside the S/B (see Section 4.1.6), Ar concentrations were between 0.2% and 1.1%. This agrees with the shares at the PPEs where Ar was measured (see Enclosure J). However, O₂ during the dipole test was always below the detection limit, suggesting that the O₂ observed in the PPE samples has a more recent origin.

It should be noted that the overall amounts of dissolved gases determined for the PPEs are significantly higher (from 50 cm³_{STP}/kg up to 250 cm³_{STP}/kg, for samples mostly filled with water) than those observed during the dipole test (12 – 19 cm³_{STP}/kg, Section 4.1.6). This suggests that the pressurisation of the system and the gas flow test resulted in a forced dissolution of gases in the experiment.

Tab. 4-20: Gas composition in PPE samples collected during the first gas mix injection (Phases 2 to 5)

Water content: approximate percentage of the sampler volume filled with water. Tot.: total amount of dissolved gases in cm³_{STP}/kg. (*): vacuum sampling, results for qualitative information only, i.e. tracer presence/absence. (**): Sampling date needs to be calculated back into S/B to account for PPE line length and extraction volumes, under piston flow model assumption and for samples not collected under vacuum, see notes below.

PPE	Start of collection (**)	Sampling date (**)	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	O ₂	N ₂
			[%]	[cm ³ _{STP} /kg]					[%]			
S03_L3 (*)	16.08.22 14:09	20.10.22 09:34	103	n.d.	1.3	1.87	126	130	<i>n.d.</i>	<i>1.0</i>	<i>1.44</i>	<i>97.1</i>
S06_L4	21.09.22 10:15	20.10.22 09:46	102	n.d.	1.5	1.63	248	251	<i>n.d.</i>	<i>0.6</i>	<i>0.65</i>	<i>98.7</i>
S06_L6H-2	06.09.22 14:20	21.09.22 08:30	2						2.00	n.d.	n.d.	96.8
S07_L2 (*)	20.10.22 10:40	03.11.22 08:05	103	n.d.	0.9	1.67	77	79	<i>n.d.</i>	<i>1.1</i>	<i>2.11</i>	<i>96.8</i>
S08_L4	03.08.22 11:26	09.08.22 14:02	104	n.d.	0.3	2.00	47	50	<i>n.d.</i>	<i>0.5</i>	<i>3.97</i>	<i>92.9</i>
S08_L4	09.08.22 14:02	16.08.22 13:33	104	n.d.	0.3	3.30	77	80	<i>n.d.</i>	<i>0.4</i>	<i>4.11</i>	<i>95.3</i>
S08_L4	08.11.22 13:48	15.11.22 --:--	98	n.d.	0.8	1.85	88	90	<i>n.d.</i>	<i>0.9</i>	<i>2.05</i>	<i>97.1</i>
S10_L4	15.06.22 08:34	28.06.22 07:12	1						1.30	n.d.	n.d.	95.9
S10_L4	28.06.22 07:23	05.07.22 07:23	14	400.0	28.7	40.20	55,170	55,640	0.70	0.1	0.07	96.4

Tab. 4-20: Notes

The relative composition in [%] was calculated from dissolved species abundance for samples where a direct measurement of a gas phase was not possible (numbers in italics). Sampling of line PPE_S03_L6L-1 was attempted but the sampler arrived at the laboratory open, and hence data are not reported. Full dataset of analytical results available in Enclosure J, full details of sample collection available in Enclosure K.

PPE_S10_L4: line length 19.53 m, diameter 2.4 mm, approx. volume 88.4 cm³. Using the extraction rate of 0.006 ml/min, samples date back 10 days before in S/B compared to sampling. The sample collected on 28 June 2022 was a trial without prior line purging, while the sample collected successively until 05 July 2023 was on a purged line and the sampler volume was purged at least twice.

PPE_S06_L6H-2: line length 22.84 m, diameter 2.4 mm, approx. volume 103.3 cm³. Using the extraction rate 0.025 ml/min, samples date back about 3 days before in S/B compared to sampling date. The line was fully cleaned between 06 September 2022 and 15 September 2022, and the sample was collected between 15 September 2022 and 21 September 2022, ensuring also full sampler volume purging >3 times.

PPE_S08_L4: line length 21.88 m, diameter 2.4 mm, approx. volume 98.9 cm³. Using the extraction rate of 0.01 ml/min, samples date back about 7 days before in S/B compared to sampling date. Line cleaning started on 30 July 2022, and was almost complete on 03 August 2022 when the collection of the first sample started. For both samples collected on 09 August 2022 and on 16 August 2022, the full sampler volume purging >3 times was ensured. For the sample collected on 15 November 2022, no prior line purging was performed, and the sampler was collected after 34 ml had been extracted due to operational issues. Therefore, the sampler volume was exchanged only once.

PPE_S06_L4: line length 22.99 m, diameter 2.4 mm, approx. volume 103.9 cm³. Using the extraction rate of 0.01 ml/min, samples date back about 7 days before in S/B compared to sampling date. Line cleaning was operated at different flow rates between 21 September 2022 and 10 October 2022, and the sample was collected between 10 October 2022 and 22 October 2022, ensuring a full sampler volume purging >3 times.

4.3.7.3 Gas sniffing results

The gas sniffing in the GAST niche was performed to identify any potential gas mix leakage from the experiment (Fig. 4-46, see also Section 3.5.1.2). After any suspect of potential gas leak (notified by an automatic warning system when the measured He intensities exceeded by 10% the He intensity for the gas from the calibration bag containing atmospheric air), the miniRUEDI data were evaluated to confirm or reject the hypothesis of the emission of Gas Mix #1. In addition, in most cases a ventilation shielding was done to enhance the sensitivity of the sniffing (i.e., reduced admixture with the air from the ventilation system, Fig. 4-46 thick magenta lines) and the measurement frequency was increased to better characterise the any potential leaks dynamics.

The gas sniffing at the GAST plug during the first gas mix injection (Phases 2 to 5) did not reveal measurable leakages of gas from the plug. Erratic fluctuations in gas concentrations in Fig. 4-46 related to equipment manipulations and associated releases of Gas Mix #1 into the GAST niche.

It should be noted that on 31 May 2022 the capillary initially installed at the plug middle was moved close to the URD at the plug/granite interface, due to suspicion of leaks at that position based on acoustic emission patterns. Similarly, the same sniffing capillary was moved again on 06 June 2022 in the proximity of the well head.

The following events are known and relate to field operations as well as to experimental issues resulting in temporary fluctuations of gas concentrations in the GAST niche (see also Enclosures F and H):

- Field operations resulted in a few experimental artifacts. On 05 May – 06 May 2022, Solexperts AG performed on-site works that resulted in gas mix release.
- On 08 June 2022, an He release was detected at the URD and later at further sniffing points. The He accumulation was found to be the result of Solexperts AG purging the filter S14.
- On 15 June 2022, Solexperts AG was working on the extraction hardware and caused the release of some He into the GAST niche.
- Between 28 June 2022 and 05 July 2022, Solexperts AG performed operations related to the connection to mock-up tank resulting in detectable gas release into the GAST niche. The “waste” gas line was shortened. However, after detection of He at the plug, the line was extended again until the tunnel branch.
- On 30 July 2022, a manual gas release was done in the GAST niche in relation to a shut-in. A large volume of gas was released at the gas storage located at the tunnel branch. On 02 August 2022 and 03 August 2022 Solexperts AG intervened to troubleshoot the shut-in of the S14 extraction line. These works could have released a small amount of gas.
- On 21 August 2022, 25 September 2022, and 27 September 2022 a large scattering of the measurements was likely related to temporary electrical issues.

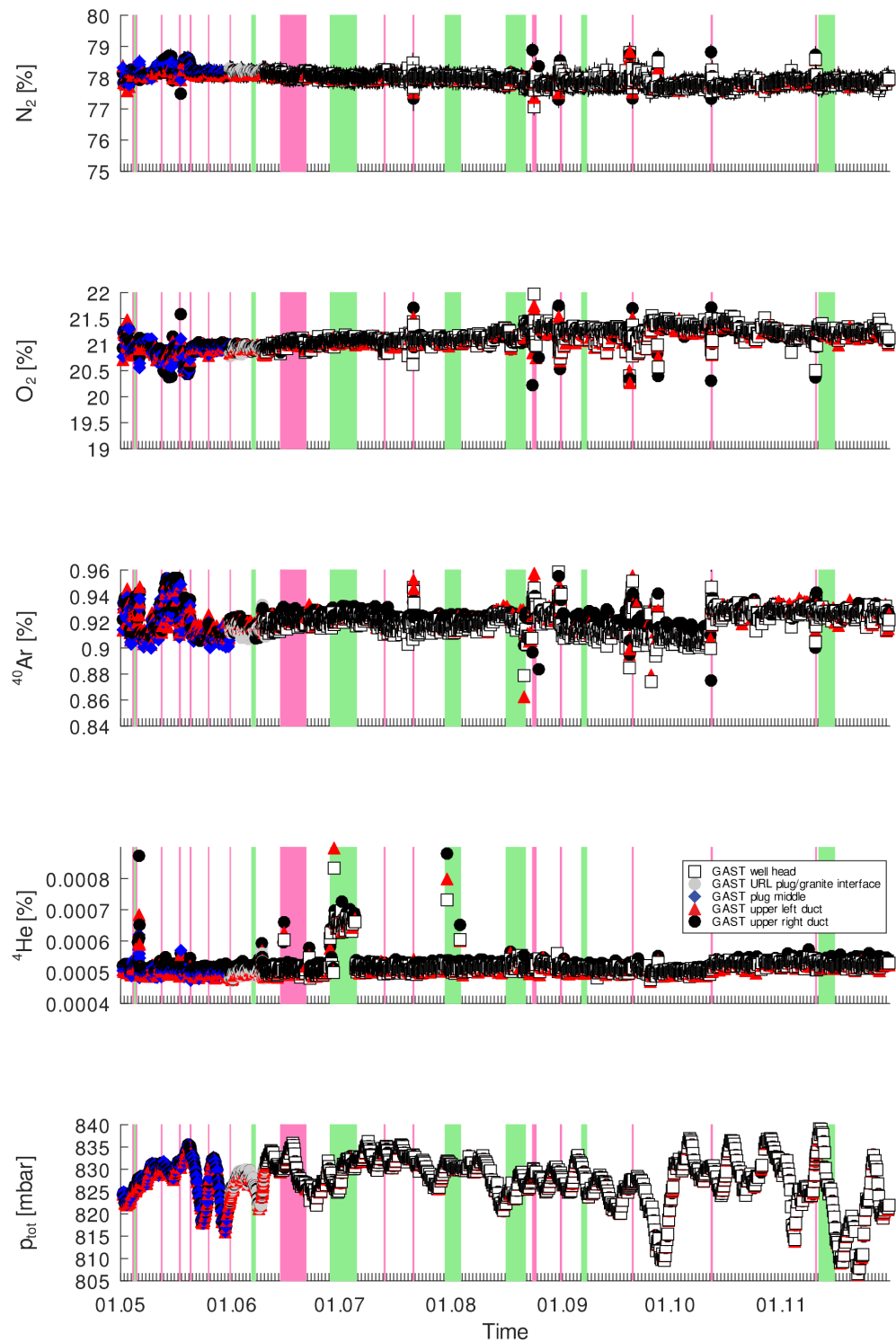


Fig. 4-46: Gas composition in proximity of the GAST plug between 01 May 2022 and 30 November 2022 (Phases 2 to 5)

Magenta and green shaded areas mark the timing of ventilation shielding and relevant field operations, respectively. Empty squares: well head; grey circles: URL plug/granite interface; blue rhomboids: plug middle; red triangles: ULD; black dots: URD. The capillary initially installed at the plug middle position was moved close to the URD at the plug/granite interface, and again in the proximity of the well head, where potential leaks were suspected.

4.3.8 Phases 3, 4 and 5 summary

During Phases 3, 4 and 5 the continued gas injection into S02 formed a gas path through the seal-section to the S14 filter. In order to maintain a constant 1,400 kPa pressure in the S14 filter it was necessary to maintain continuous extraction from the base of filter (PL_S14_L1). Initially only water was extracted, resulting in drainage of the S14 filter until the extraction line clogged on 06 June 2022 which resulted in a significant pressure rise in the S14 filter and the decision to shut-in the S02 gas injection. After the S14 extraction line was successfully unclogged on 08 June 2022, the outflow was dominantly gas, and the S02-to-S14 gas flow was established once gas injection to S02 was resumed.

The gas volumes in the S02 and S14 filters can be estimated by the measurement of the displaced water and were subsequently monitored by sinusoidal injection and extraction to characterise the filter compressibility. Pulse tests were also performed in the two filters to confirm the gas volumes.

Gas flow was maintained throughout the two phases and the injection and extraction rates were increased over time to maintain the specified pressure in S02 (Phase 3 1,800 kPa, and then 1,900 kPa during Phases 4 – 5) and S14 (1,400 kPa).

Samples of the fluid extracted at the filter S14 and from selected piezometers showed the presence of the injected gas tracer (He), and hence confirmed longitudinal flow from the injection to the extraction filter as well as gas invasion into the S/B.

Pore pressure monitoring showed the response to gas path development (displacement of water) and the pressure increase within the S02 filter. Total pressure measurements demonstrated that, overall, compressive stress was maintained within the seal section during gas path creation and development.

Hydraulic index tests (PI, PW) performed in the PPEs within the seal section were used to assess compressibility changes around the piezometers in the seal section and also supported the selection of PPEs for targeted gas sampling.

No leakage of Gas Mix #1 into the WT tunnel was detected during the period.

4.4 Gas Flow Test with pure N₂ nitrogen (Phases 6 – 7)

4.4.1 Phase 6 – 7 aims

Section 4.4 describes the field work and results obtained during Phases 6 – 7, when pure N₂ was injected in GAST.

4.4.2 Field activities

The injection gas was changed from Gas Mix #1 to pure N₂ nitrogen on 01 December 2022 at 07:05. The events on the injection and extraction sides are summarised in Tab. 4-21. The layouts of the surface equipment are given in Section 4.4.3. Changes in the layout are indicated in Tab. 4-21 and referenced to the corresponding graph.

FLOW-HI was used for gas injection until 26 January 2023, when it was removed for calibration at the manufacturer and replaced with the Alicat flowmeter. FLOW-HI was reinstalled after calibration on 30 March 2023.

The target pressure was 19 bar until 22 February 2023 when a pressure decrease was started to about 17 bar (Phase 7). The corresponding overview graph for injection pressure, flow rate and total volume is given in Fig. 4-51. The events that took place during injection are marked in the detail graphs Fig. 4-53 to Fig. 4-54.

The switch to rate control of the gas injection into S02 from 22 February 2023 and consequent pressure reduction was motivated by the increasing injection rates over the previous phases. There was a requirement to limit the maximum injection rate (flowmeter/controller range) and control the use of the Gas Mix #2 during the later Phase 8 (only a limited supply of the Gas Mix #2 could be produced). Rate control also simplified day-to-day management of the test and improved the quality of the pressure data. This was possible because of the high stability of the gas path and predictability of the recovery from S14.

The injection and extraction regime with flow parameters for Phases 6 and 7 is given in Tab. 4-22. Tab. 4-23 summarises the inflow/outflow volume calculations.

The extraction side was held at a constant pressure of 14 bar during the December 2022 injection period. Extraction rates were affected by three shut-ins (Tab. 4-21) and adjustments of the injection rate from January to March 2023, as shown in the corresponding overview graph (Fig. 4-52) and in detail graphs (Fig. 4-55 and Fig. 4-56).

Tab. 4-21: Main field activities during GFT N₂ (Phases 6 and 7) between 01 December 2022 and 18 April 2023

More details available in Enclosure F.

Phase	Date & time	Gas injection PL_S02_L6L-2	Extraction PL_S14_L1 Total gas + water flow	Comments
Phase 6	01.12.22 07:05	Switch from Gas Mix #1 to N ₂ injection		Layout Fig. 4-47 Start N ₂ injection
	Until 30.12.22	Continuous increase to mean 860 mln/min		
	30.12.22 09:39	Shut-in	Shut-in	
	10.01.23 08:49 – 11.01.23 20:50		Continuous increase of flow rate to 110 ml/min	
	10.01.23 12:13	Start with 1,000 mln/min		
	11.01.23 18:44	Keep P = 19 bar		
	13.01.23 11:07	Start sinusoidal flow rate with mean 950 mln/min		
	17.01.23 13:17 – 18.01.23 07:45		Attempt to extract with two independent pistons (2 nd flow rate not recorded)	V _{extr} gives total extraction volume, failure of piston B
	17.01.23 13:36	Shut-in		
	18.01.23 07:18	Start constant head (HI) with 960 mln/min and 19 bar		
	18.01.23 07:45		Repeated adjustments of flow rate from 35 to 140 ml/min to P = 14 bar	

Tab. 4-21: Cont.

Phase	Date & time	Gas injection PL_S02_L6L-2	Extraction PL_S14_L1 Total gas + water flow	Comments
Phase 6	20.01.23 07:25	1,100 mln/min		
	20.01.23 09:14	1,400 mln/min and 19 bar		Decrease of flow rate at 19 bar
	20.01.23 18:41		160 ml/min	
	23.01.23 07:06		180 ml/min with adjustments for P = 14 bar	
	26.01.23 13:47	Mass flow rate 90 g/h increasing to 96 g/h (19 bar)		Layout Fig. 4-48 Injection with Alicat flow meter
Phase 7	22.02.23 13:21	Mass flow rate 80 g/h P decrease		
	22.02.23 13:57		135.7 ml/min	
	23.02.23 10:39	Mass flow rate 60 g/h		
	23.02.23 11:16		87 ml/min	
	09.03.23 14:44		60 → 58 ml/min Double piston pump	Layout Fig. 4-49
	30.03.23 07:35	FLOW_HI 845 mln/min – mass flow rate 60 g/h		Installation of calibrated FLOW_HI Injection P decrease to 17.3 bar Layout Fig. 4-50
	09.04.23 18:17	P = 17.3 bar	Accidental shut-in	
	10.04.23 05:59	Shut-in		
	11.04.23 12:01	Restart with 200 mln/min	Restart with 20 ml/min	
	11.04.23 14:00	500 mln/min	40 ml/min	
	12.04.23 08:37	1,000 mln/min, P increase to 17.9 bar	90 ml/min at 14.4 bar	
	13.04.23 07:22	1,000 mln/min	70 ml/min	
	18.04.23 07:20	Switch from N ₂ to Gas Mix #2 injection P = 17.5 bar	P = 14 bar	Start Gas Mix #2 injection

Tab. 4-22: Overview of injection and extraction parameters during GFT N₂ (Phases 6 and 7)

	P from [bar]	P to [bar]	Flow rate from	Flow rate to	Volume STP [ln]	Volume @ T, P [l]	Comments
GFT N ₂ : 01.12.22 07:05 – 18.04.23 07:20							
Injection S02 N ₂	19	17.5	800 mln/min sinusoidal	1,000 mln/min	167,040.91	9,727.82	Sinusoidal, since 17.01.23 RI
Extraction S14 gas	14	14	86 ml/min ⁽¹⁾	70 ml/min	158,047.15	11,999.00	RW
Extraction S14 water						29.55	DP-2 Tank

⁽¹⁾ Average flow rates partly overestimated

T: Temperature of 16 °C

P: Pressure at the time stamp

STP: Standard conditions (T = 273.15 K, P = 101.3225 kPa)

Tab. 4-23: Details of volume calculation during GFT N₂ (Phases 6 and 7)

Port	Start date & time	Flow rate	V gas STP [ln]	V gas @ T, P [l]	V water [l] ⁽¹⁾	P [bar]
PL_S02_L6L-1 Injection	01.12.22 07:05	Sinusoidal mean 280 → 350 mln/min	34,297.56	1,937.34		19 → 16
	10.01.23 12:13		9,385.38	537.29		19
	18.01.23 07:13	960 → 1,440 mln/min	61,323.26	3,469.71		19 → 17 → 19
	22.02.23 13:21	1,440 → 900 mln/min	53,596.54	3,265.93		19 → 17 → 16
	11.04.22 12:01	200 → 1,000 mln/min	8,438.17	517.56		17.5
Total	18.04.23 07:20		167,040.91	9,727.82		
PL_S14_L1 Extraction	01.12.22 07:05	100 ml/min	32,436.16	2,484.35	7.51	14
	10.01.23 08:50	100 → 200 ml/min	14,047.32	1,037.48	2.97	15 → 14
	22.02.23 13:21	87 → 70 ml/min	111,563.67	8,477.17	19.06	14
Total	18.04.23 07:20		158,047.15	11,999.00	29.55	

⁽¹⁾ Extracted water volume calculated from mock-up tank water level

T: Temperature of 16 °C

P: Pressure at the time stamp

STP: Standard conditions (T = 273.15 K, P = 101.3225 kPa)

4.4.3 Flow control

For Phase 6, no changes were made at the surface equipment (Fig. 4-47), except for the exchange of the pressure vessel to N_2 . Between 26 January 2023 and 30 March 2023, FLOW-HI was temporarily removed for calibration purposes and a mass flow controller was installed to calculate injection flow rates (Fig. 4-48). In addition, the second piston of the syringe pump, so far used for sampling, was installed in the extraction flow circuit to ensure continuous flow rates (Fig. 4-49). The calibrated flow meter FLOW_HI was reinstalled on 30 March 2023 (Fig. 4-50).

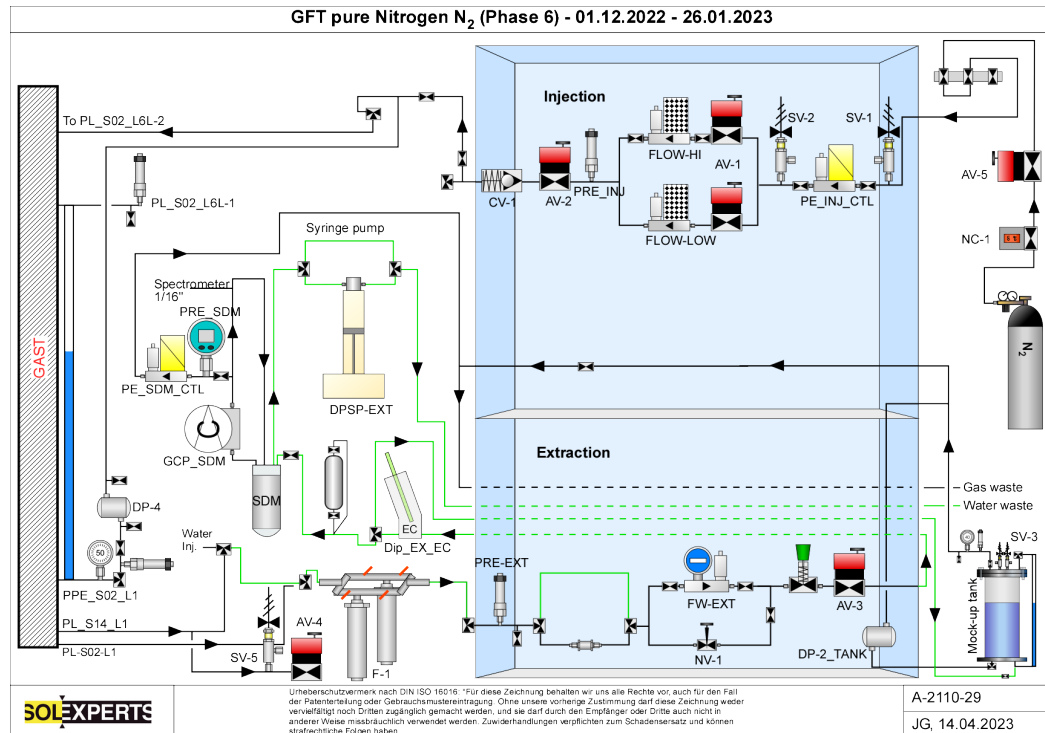


Fig. 4-47: Layout of surface equipment for the GFT between 01 December 2022 and 26 January 2023

Note: same as Fig. 4-23 except for exchange of pressure vessel with N_2 gas vessel

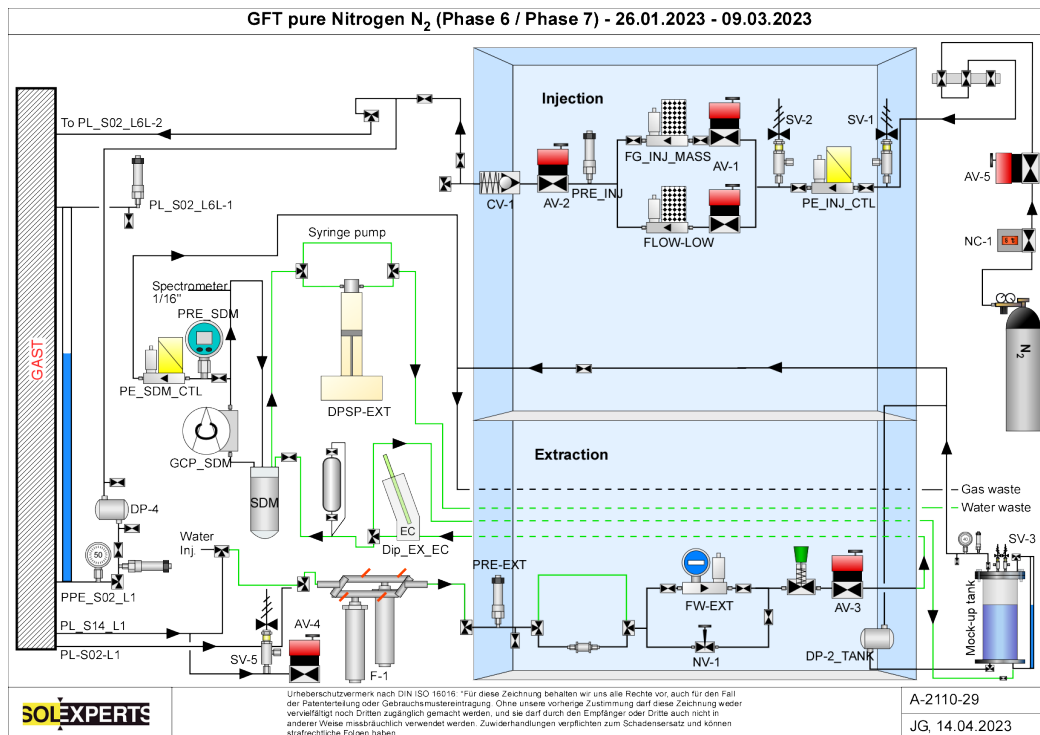


Fig. 4-48: Layout of surface equipment for the GFT between 26 January 2023 and 09 March 2023

Note: same as Fig. 4-47 with flow meter FLOW-HI replaced by CODA Alicat type mass flow controller (FG_INJ_MASS)

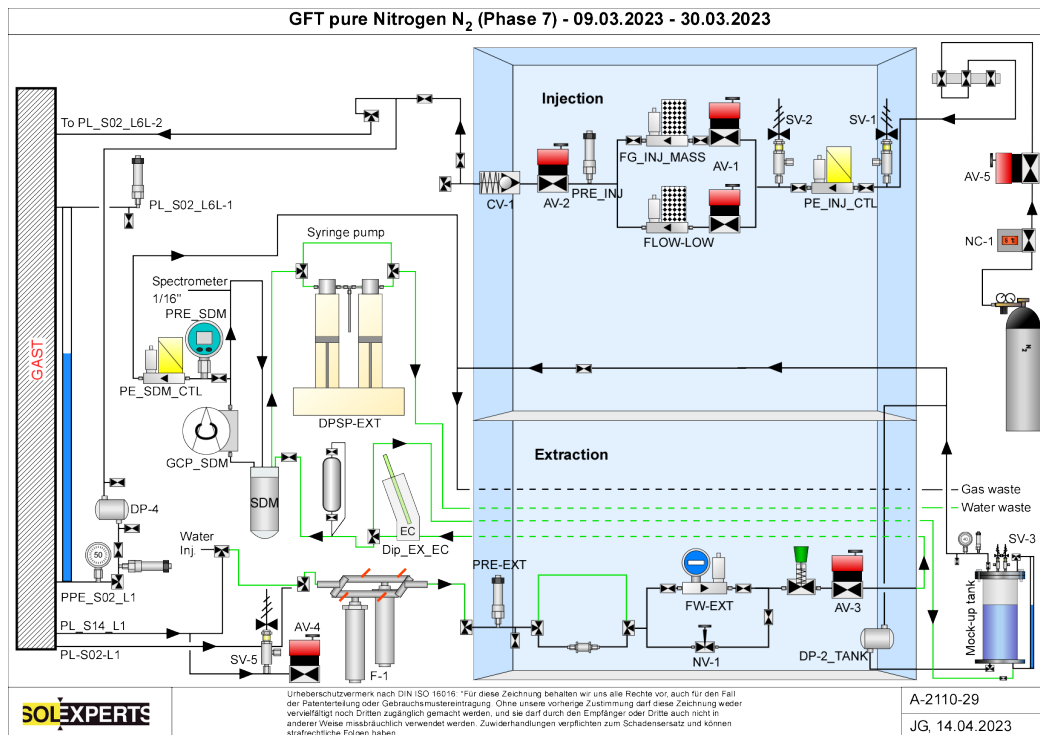


Fig. 4-49: Layout of surface equipment for the GFT between 09 March 2023 and 30 March 2023

Note: additional piston for syringe pump installed (DPSP)

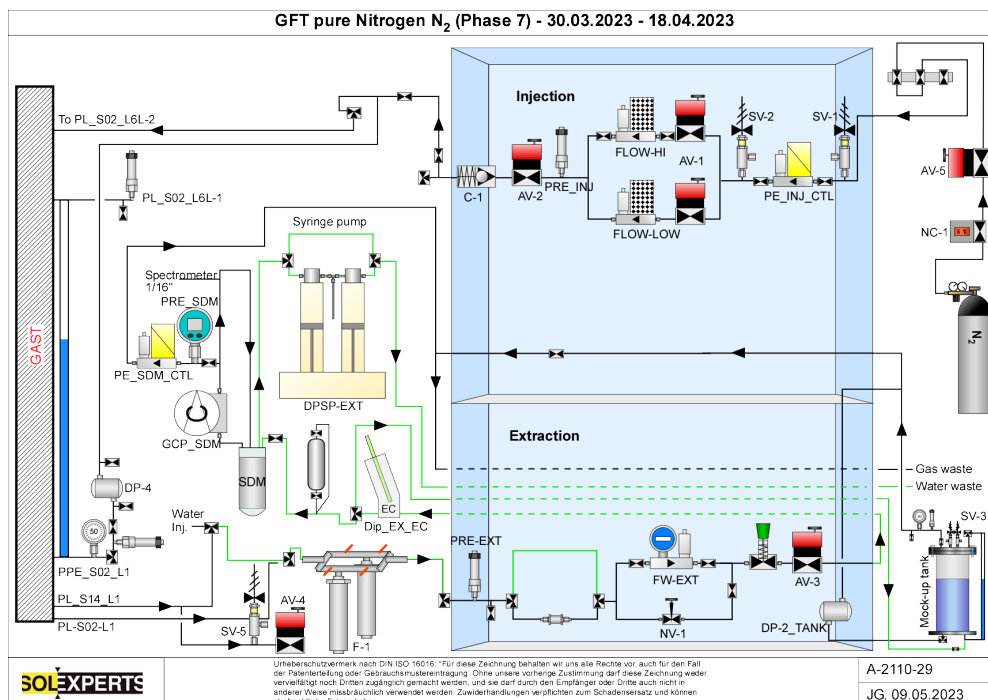


Fig. 4-50: Layout of surface equipment for the GFT between 30 March 2023 and 18 April 2023

Note: installation of calibrated FLOW_HI, removal of CODA ALICAT type mass flow controller

4.4.4 Monitoring data

The monitoring data for Phases 6 and 7 are shown in Fig. 4-51 (injection side) and Fig. 4-52 (extraction side). The dominant pressure fluctuations in Phase 6 resulted from two temporary shut-in periods (30 December 2022 – 10 January 2023 and on 17 January 2023, see Tab. 4-21 for details). Flow rates were reduced in Phase 7, and a flow-controlled regime was established (Fig. 4-52) to maintain the extraction flow rate within the specifications for the syringe pump. Consequently, injection pressure in S02 decreased to about 1,750 kPa (Fig. 4-51).

Many of the point TDRs (TDP sensors) showed no changes during Phases 6 – 7. As in the previous phases, the responses of some TDPs were not straightforward enough to directly infer physical changes resulting from the nitrogen injection performed in Phases 6 – 7. The TDL sensors showed a stable gas accumulation within the S14 filter during Phases 6 – 7 without major dynamic changes. an overview of TDP and TDL data plots is shown in Enclosure M.

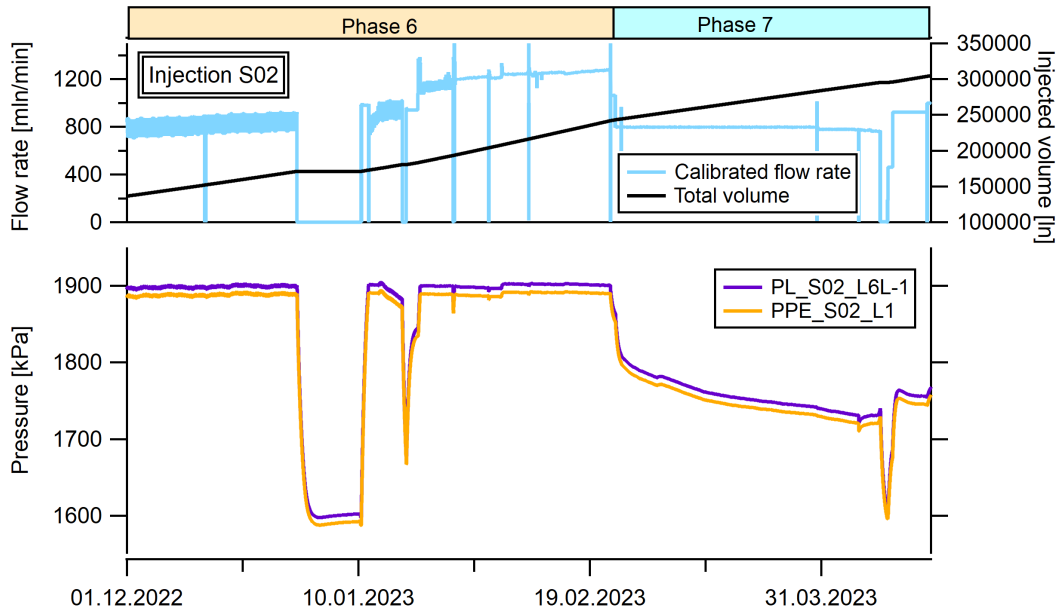


Fig. 4-51: Injection pressures, flow rate and total volume for GFT N₂ (Phases 6 and 7)

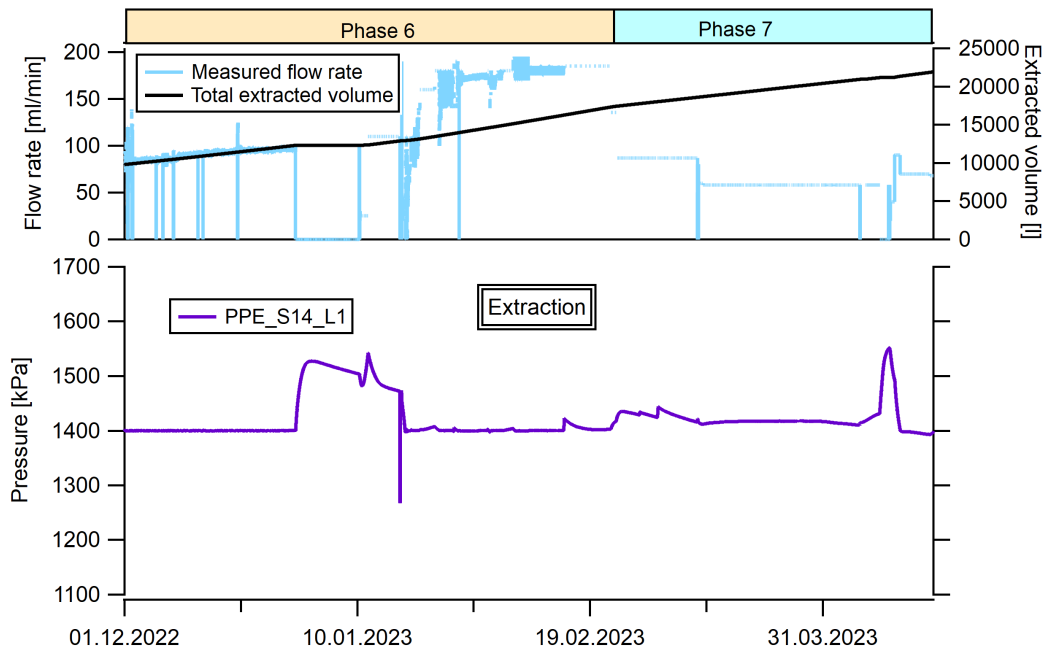


Fig. 4-52: Extraction pressure, flow rate and total volume for GFT N₂ (Phases 6 and 7)

4.4.4.1 Detailed view

Fig. 4-53 to Fig. 4-56 illustrate the flow and pressure variations during Phases 6 and 7 in more detail, first for the injection side (Fig. 4-53 and Fig. 4-54), then for the extraction side (Fig. 4-55 and Fig. 4-56).

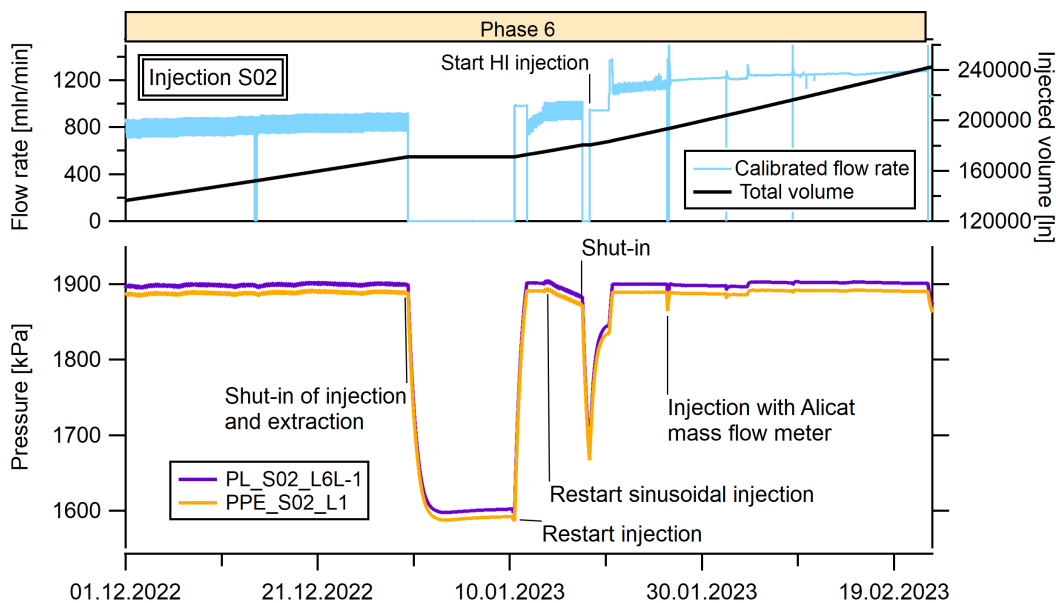


Fig. 4-53: S02: detailed view of injection between 01 December 2022 and 22 February 2023 (Phase 6)

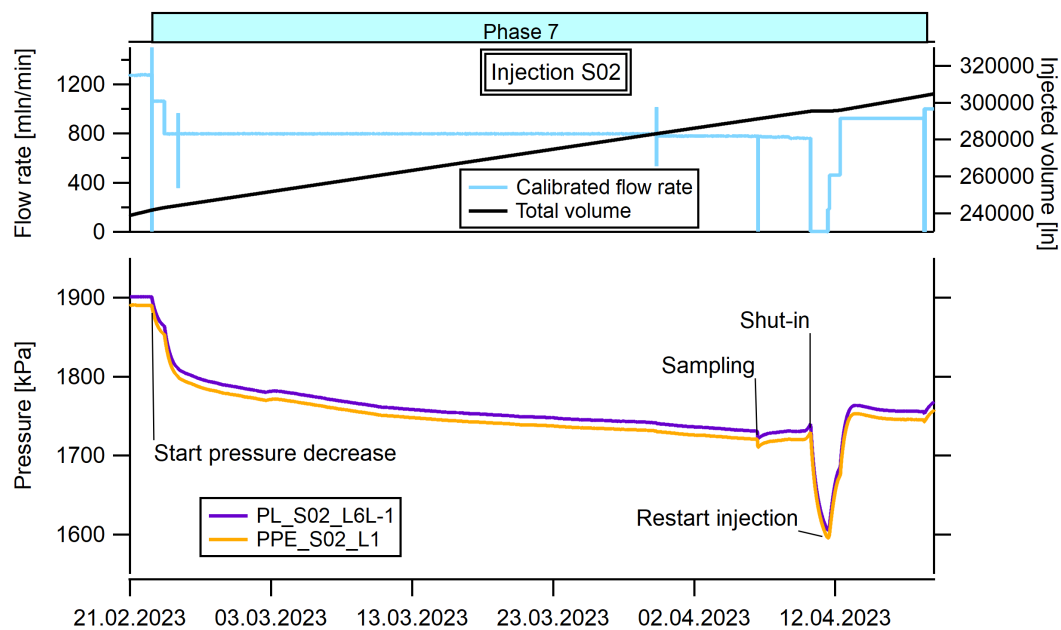


Fig. 4-54: S02: detailed view of injection between 21 February 2023 and 18 April 2023 (Phase 7)

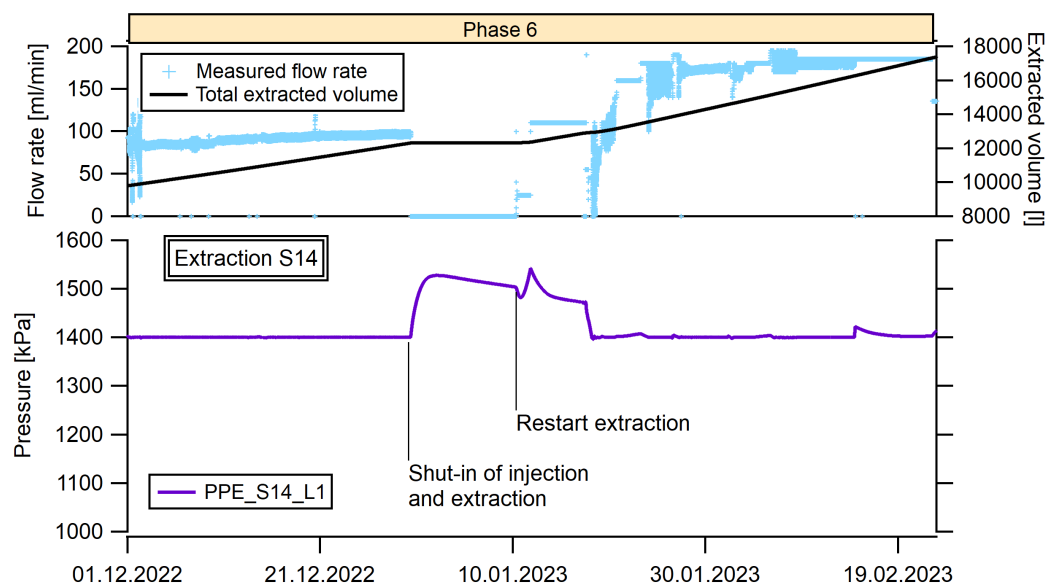


Fig. 4-55: S14: detailed view of extraction between 01 December 2022 and 22 February 2023 (Phase 6)

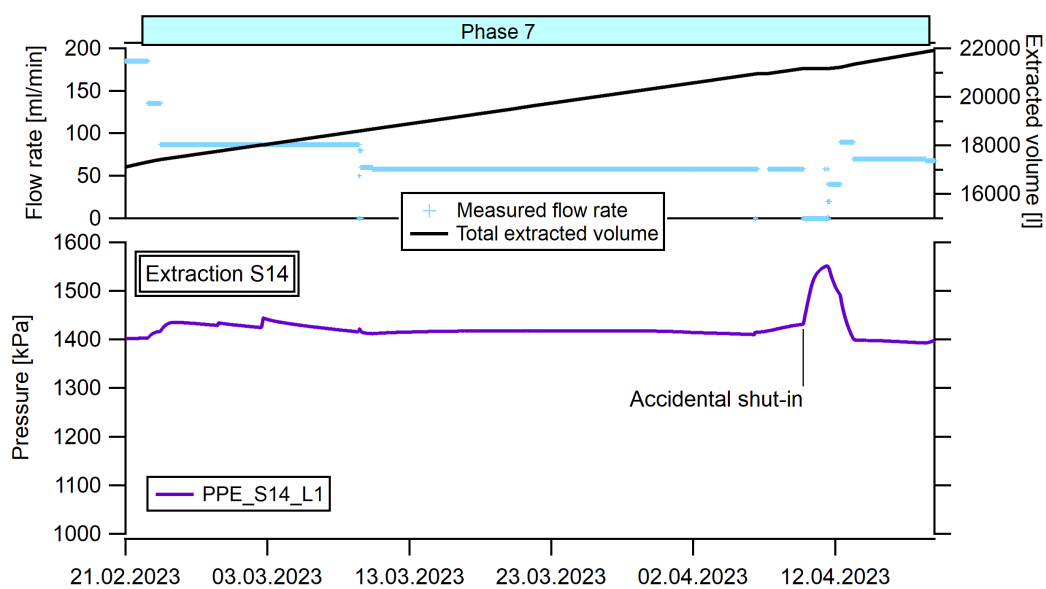


Fig. 4-56: S14: detailed view of extraction between 21 February 2023 and 18 April 2023 (Phase 7)

4.4.5 Sampling

The details of the samples taken during GFT N₂ are given in Tab. 4-24. Sampling flow rates and resulting pressure fluctuations are shown Fig. 4-57 for sampling PPE_S10_L4/ PPE_S06_L6H-2. Fig. 4-58 shows the same parameter for sampling of PPE_S03_L6L-1.

Tab. 4-24: Sampling performed during GFT N₂ (Phases 6 and 7) between 01 December 2022 and 18 April 2023

Phase	Code	Vial	Port	Start date & time	Flow rate [ml/min] or [mln/min]	Pressure [bar]	Sample weight [g]
Phase 6	S14_047	GAST 19	PL_S14_L1	01.12.22 13:18	85 – 90	14	6 ⁽²⁾
	S14_048	GAST 20	PL_S14_L1	02.12.22 07:18	85 – 90	14	15.4 ⁽²⁾
	S14_049	GAST 21	PL_S14_L1	06.12.22 10:14	85 – 90	14	1.8 ⁽²⁾
	S14_050	GAST 22	PL_S14_L1	07.12.22 14:33	85 – 90	14	8.4 ⁽²⁾
	S14_051	GAST 23	PL_S14_L1	09.12.22 09:54	85 – 90	14	14.1 ⁽²⁾
	S14_052	GAST 24	PL_S14_L1	13.12.22 14:39	85 – 90	14	10.4 ⁽²⁾
	GAS_053	GAST 30	Gas N ₂ *	14.12.22 14:49	830	20	1.2 ⁽²⁾
	S14_054	GAST 25	PL_S14_L1	20.12.22 10:27	100	14	38.9 ⁽²⁾
	S14_055	GAST 11	PL_S14_L1	30.12.22 09:15	100	14	21.5 ⁽²⁾
	S02_056	GAST 12	PL_S02_L1	10.01.23 08:21	100	15.8	72.4 ⁽²⁾
	S14_057	GAST 13	PL_S14_L1	01.02.23 13:02	110	14	7.5 ⁽²⁾
	S14_058	GAST 14	PL_S14_L1	15.02.23 11:07	110	14	9.1 ⁽²⁾
	S14_059	GAST 15	PL_S14_L1	06.04.23 10:09	58	14.15	5.4 ⁽²⁾
	S02_060	GAST 16	PL_S02_L1	06.04.23 11:28	50	17.2	73.8 ⁽²⁾
	GAS_061	GAST-31-Sol	Gas N ₂ (*)	06.04.23 12:36	840	20	2 ⁽²⁾
	PPE_062	GAST 01	PPE_S06_L6 H-2	01.02.23 13:44	0.05	15.1 ⁽³⁾	0.4 ⁽¹⁾
Phase 7	PPE_063	GAST 02	PPE_S10_L4	08.02.23 10:54	0.01 → 0.015	13.8 ⁽³⁾	1.5 ⁽¹⁾
	PPE_064	GAST 04	PPE_S06_L6 H-2	16.03.23 08:33	0.05	14.8 ⁽³⁾	0.4 ⁽¹⁾
	PPE_065	GAST 05	PPE_S10_L4	17.03.23 08:50	0.01 → 0.015	13.9 ⁽³⁾	1.2 ⁽¹⁾
	PPE_066	GAST 06	PPE_S03_L6 L-1	30.03.23 13:03	0.01	15.4 ⁽³⁾	0.9 ⁽¹⁾

(*) Gas N₂: 100% N₂

(1) 25 ml vial

(2) 75 ml vial

(3) Pressure at closure time of valve to sampler

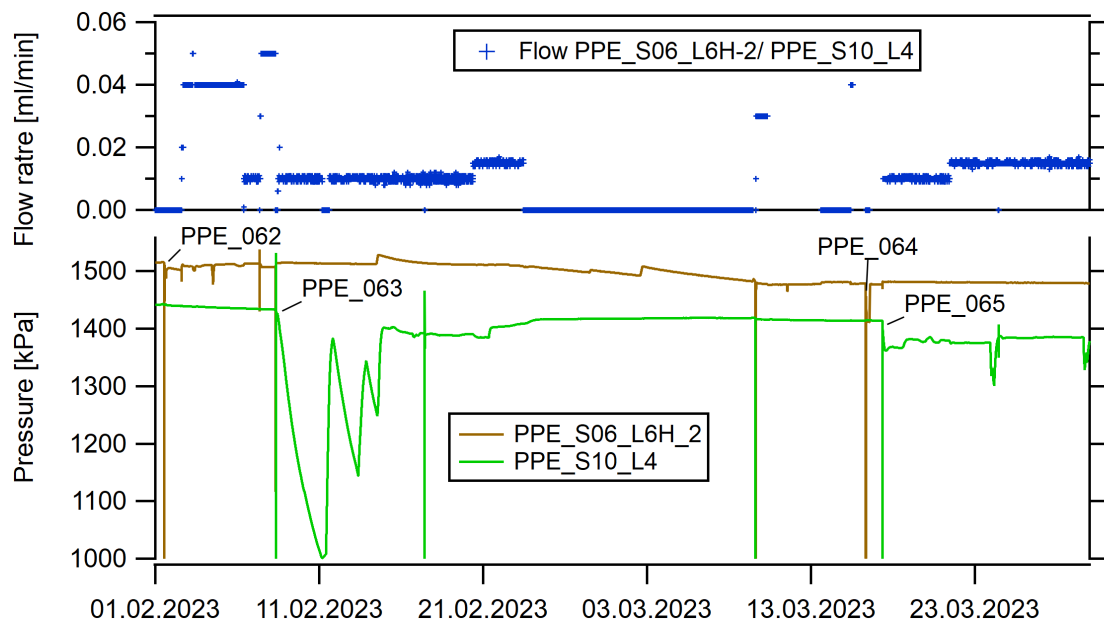


Fig. 4-57: Pressure and flow rate measured during the acquisition of samples PPE_062 to PPE_065 from PPE_S06_L6H-2 and PPE_S10_L4

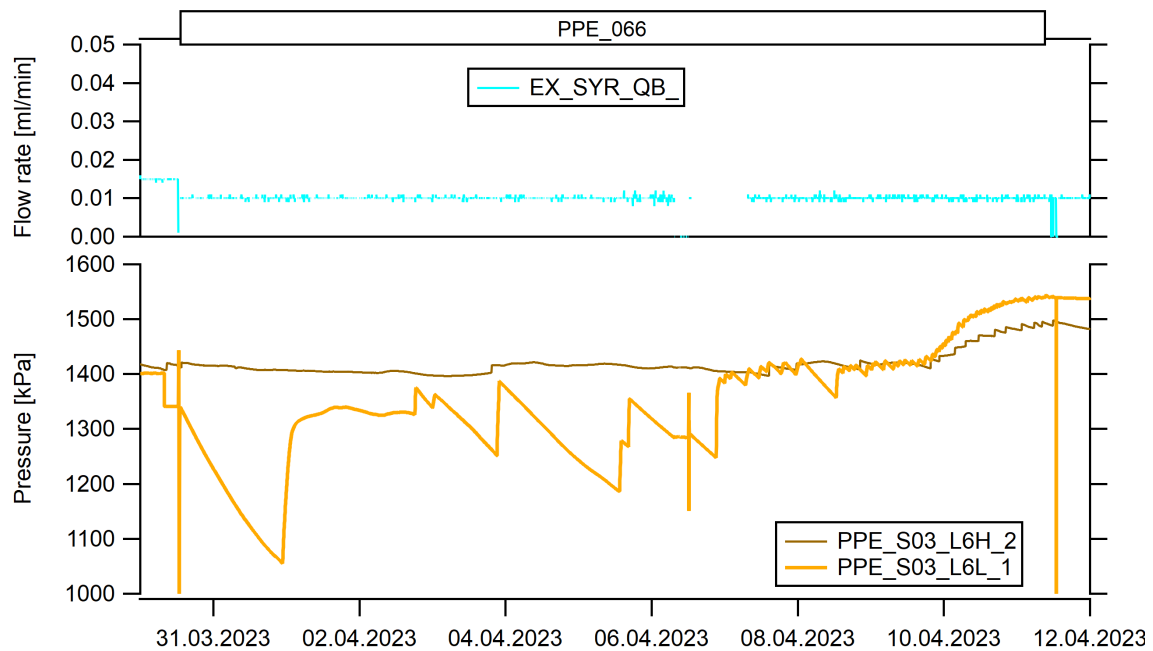


Fig. 4-58: Pressure and flow rate measured during the acquisition of sample PPE_066 from PPE_S03_L6L-1

4.4.6 Index testing

During GFT N₂ (Phases 6 and 7), two pulse test campaigns were performed, one in January 2023 and one in March 2023. The pulse injection tests were conducted in most PPE ports. The test goal was a quick approach to assess the behaviour of the ports. The applied procedure is described in Section 4.1.5.

The test parameters are summarised in Tab. 4-25 and Tab. 4-26. The graphs of the PW tests are shown in Enclosure N.3. The comparisons of the calculated compressibilities with the compressibilities measured in previous tests are shown in Fig. 4-59 and Fig. 4-60.

The index testing results vary over one magnitude or more, and several ports were found with higher compressibilities in January 2023 (Fig. 4-59). Although the accuracy of the method is limited, it is assumed that the higher compressibilities indicate the presence of a gas phase.

A comparison of the pressure behaviour during the successive tests in several example ports is given in Section 6.5.

Tab. 4-25: Results of PW tests from PPE lines in January 2023

Date	Time	Sensor	ΔP [kPa]	$\Delta V^{(1)}$ [ml]	C [m ³ /Pa]	
18.01.23	10:14	PPE_S12_L4	244.84	2.00	8.17E-12	
18.01.23	10:23	PPE_S10_L6H-2	516.83	2.00	3.87E-12	Slow to fast increase
18.01.23	10:25	PPE_S08_L2	1,415.51	2.00	1.41E-12	
18.01.23	10:32	PPE_S12_L6L-1	1,240.82	2.00	1.61E-12	Fast increase
18.01.23	10:38	PPE_S10_L2	1,226.71	2.00	1.63E-12	Very fast increase
18.01.23	10:40	PPE_S09_L2	1,394.35	2.00	1.43E-12	
18.01.23	11:08	PPE_S08_L6L	915.69	2.00	2.18E-12	Very slow increase
18.01.23	11:10	PPE_S11_L3	1,381.12	2.00	1.45E-12	
18.01.23	13:20	PPE_S12_L6H-2	694.04	2.00	2.88E-12	
18.01.23	13:22	PPE_S09_L4	1,068.16	2.00	1.87E-12	Very fast increase
18.01.23	13:26	PPE_S10_L6L-1	412.87	2.00	4.84E-12	
18.01.23	13:43	PPE_S12_L3	1,354.84	2.00	1.48E-12	
18.01.23	13:47	PPE_S10_L3	1,336.86	2.00	1.50E-12	
18.01.23	14:05	PPE_S08_L3	1,408.56	2.00	1.42E-12	
26.01.23	10:23	PPE_S12_L2-1	1,353.00	2.00	1.48E-12	Slow increase
26.01.23	10:34	PPE_S10_L4	58.52	2.00	3.42E-11	
26.01.23	10:45	PPE_S06_L6L-1	261.94	2.00	7.64E-12	Very slow increase
26.01.23	10:55	PPE_S03_L6H-2	98.84	2.00	2.02E-11	Very slow increase
26.01.23	11:04	PPE_S12_L2-2	1,344.88	2.00	1.49E-12	
26.01.23	11:24	PPE_S08_L4	71.40	2.00	2.80E-11	
26.01.23	11:38	PPE_S03_L2-1	1,450.20	2.00	1.38E-12	Very fast increase
26.01.23	11:47	PPE_S07_L2	1,418.80	2.00	1.41E-12	
26.01.23	11:57	PPE_S04_L3	1,660.64	2.00	1.20E-12	
26.01.23	13:18	PPE_S06_L2	1,544.93	2.00	1.29E-12	
26.01.23	13:35	PPE_S07_L4	1,032.60	2.00	1.94E-12	
26.01.23	13:46	PPE_S03_L2-2	835.97	2.00	2.39E-12	
26.01.23	14:07	PPE_S06_L3	1,536.20	2.00	1.30E-12	Slow increase
26.01.23	14:23	PPE_S03_L3	1,420.06	2.00	1.41E-12	Very slow increase
26.01.23	14:33	PPE_S06_L4	173.05	2.00	1.16E-11	Very slow increase
26.01.23	14:51	PPE_S03_L6L-1	62.90	2.00	3.18E-11	Very slow increase
26.01.23	15:10	PPE_S06_L6H-2	25.02	2.00	7.99E-11	

⁽¹⁾ Line piece with about 2-ml volume connected to PPE port, true volume unknown

Colours: red: higher compressibility $C > 6E-12$ m³/Pa, green: very slow increase, blue: very fast increase

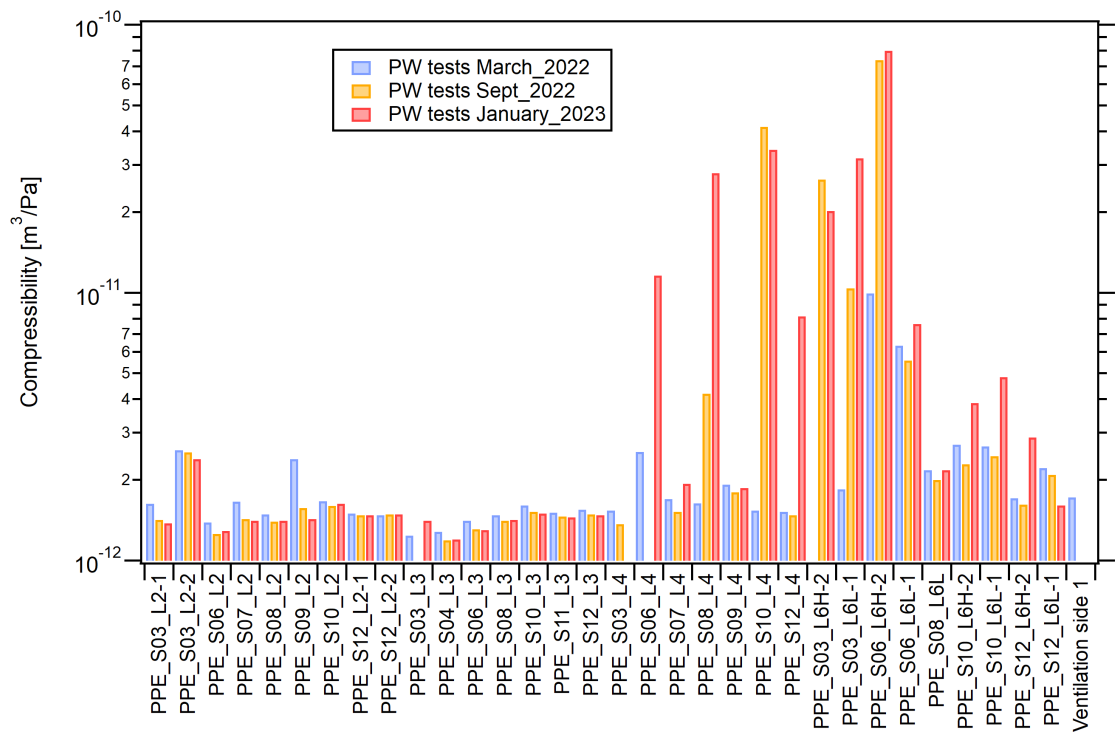


Fig. 4-59: Overview of calculated compressibilities from PW tests in March 2022 (Phase 1) and September 2022 (Phase 5) and January 2023 (Phase 6)

Tab. 4-26: Results of PW tests from PPE lines in March 2023

Date	Time	Sensor	ΔP [kPa]	$\Delta V^{(1)}$ [ml]	C [m ³ /Pa]	
30.03.23	7:52	PPE_S06_L6L-1	226.48	2.00	8.83E-12	Very slow increase
30.03.23	7:55	PPE_S03_L6L-1	60.10	2.00	3.33E-11	Very slow increase
30.03.23	9:43	PPE_S08_L4	59.23	2.00	3.38E-11	Slow increase
30.03.23	9:50	PPE_S09_L4	598.57	2.00	3.34E-12	Fast increase
30.03.23	9:52	PPE_S03_L4	1,320.81	2.00	1.51E-12	Fast increase
30.03.23	10:00	PPE_S04_L3	1,587.41	2.00	1.26E-12	
30.03.23	10:03	PPE_S06_L4	157.59	2.00	1.27E-11	Very slow increase
30.03.23	10:06	PPE_S07_L2	1,369.33	2.00	1.46E-12	
30.03.23	10:10	PPE_S12_L2-1	1,344.98	2.00	1.49E-12	Slow increase
30.03.23	10:13	PPE_S10_L6L-1	262.37	2.00	7.62E-12	Fast increase
30.03.23	10:16	PPE_S03_L2-1	1,454.45	2.00	1.38E-12	Very fast increase
30.03.23	10:19	PPE_S06_L3	1,468.37	2.00	1.36E-12	Slow increase
30.03.23	10:30	PPE_S07_L4	1,015.02	2.00	1.97E-12	Fast increase
30.03.23	10:33	PPE_S12_L2-2	1,351.26	2.00	1.48E-12	
30.03.23	10:40	PPE_S03_L3	1,325.75	2.00	1.51E-12	
30.03.23	10:42	PPE_S06_L2	1,514.07	2.00	1.32E-12	
30.03.23	13:07	PPE_S06_L6H-2	24.93	2.00	8.02E-11	Fast increase
30.03.23	13:38	PPE_S08_L2	1,394.16	2.00	1.43E-12	
30.03.23	13:41	PPE_S08_L6L	754.81	2.00	2.65E-12	
30.03.23	13:42	PPE_S09_L2	1,378.79	2.00	1.45E-12	
30.03.23	13:46	PPE_S10_L4	29.47	2.00	6.79E-11	Slow increase
30.03.23	13:50	PPE_S11_L3	1,357.06	2.00	1.47E-12	
30.03.23	13:53	PPE_S10_L3	1,299.28	2.00	1.54E-12	
30.03.23	13:56	PPE_S12_L3	1,320.63	2.00	1.51E-12	
30.03.23	14:02	PPE_S12_L4	768.63	2.00	2.60E-12	
30.03.23	14:08	PPE_S10_L6H-2	360.40	2.00	5.55E-12	
30.03.23	14:12	PPE_S10_L2	1,240.44	2.00	1.61E-12	
30.03.23	14:17	PPE_S12_L6L	75.17	2.00	2.66E-11	Slow increase
30.03.23	14:23	PPE_S12_L6H	477.99	2.00	4.18E-12	

⁽¹⁾ Line piece with about 2 ml volume connected to PPE port, true volume unknown

Colours: red: higher compressibility $C > 6E-12$ m³/Pa, green: very slow increase, blue: very fast increase

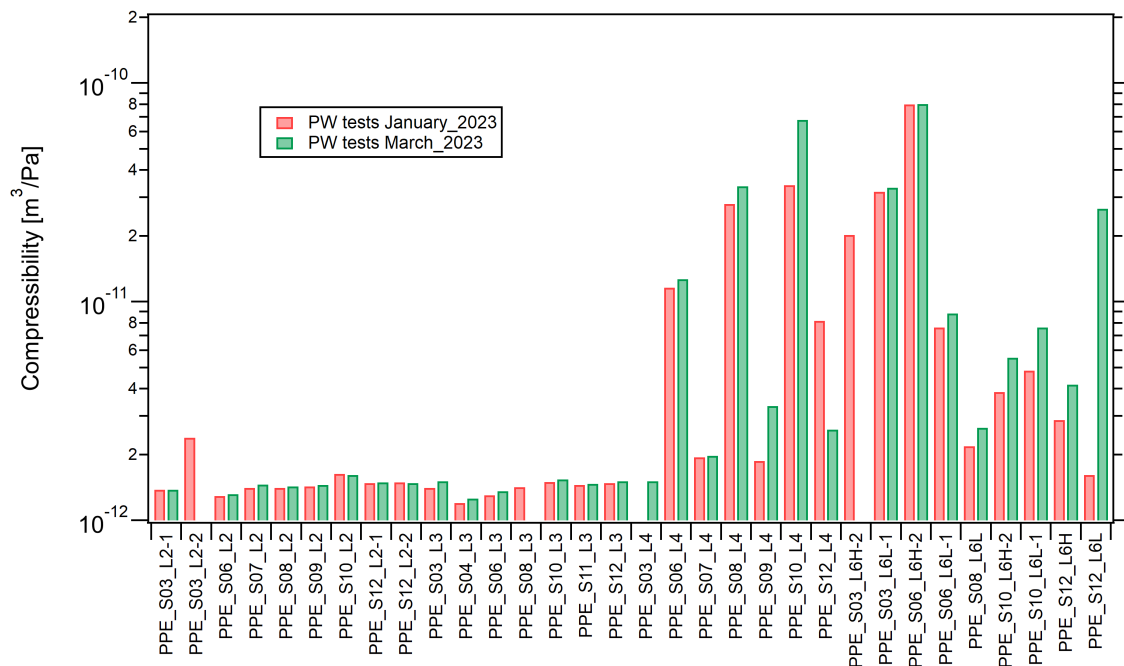


Fig. 4-60: Overview of calculated compressibilities from PW tests in January 2023 (Phase 6) and March 2023 (Phase 7)

4.4.7 Gas monitoring results

In the present section, we describe the outcome of the measurements based on a miniRUEDI portable mass spectrometer system and on the laboratory-based analyses achieved to monitor the first cleaning/flushing with pure N_2 performed between December 2022 and April 2023.

The cleaning with pure N_2 was done to remove as much tracer as possible from the experiment (i.e., He from the injected Gas Mix #1; see Section 4.3.7) in preparation of the second gas flow test using Gas Mix #2 (see Section 4.5.6) and to obtain information on the tracer removal dynamics (i.e., He “tailing”).

The on-site monitoring with the miniRUEDI allowed the qualitative estimation of the injected gas arriving at filter line PL_S14_L1 from the beginning of the N_2 flushing. The first arrival of the injected pure N_2 was detected on 03 December 2022 (i.e., about 3 days after injection start). The off-site laboratory analyses allowed the quantitative assessment of the changes in the gas composition at filter S14 and confirmed that cleaning with N_2 progressively removed the He used as tracer during the previous injection. From an initial share of about 95%, the N_2 values rose to 99.8%. The He shares followed an opposite trend, with a decrease from 2.1% to values below the detection limit (last detectable He concentration on 30 December 2022: 0.2%).

These observations, and especially the quantitative off-site analyses, indicate that the removal of the tracer gas He was successful, and the experiment was ready for the next test phase(s).

Samples collected at the PPEs between February and March 2023 show responsiveness to cleaning with N₂. The He concentration at PPE_S06_L6L-H2 decreased from 2.0% (measured during the first gas mix injection) to values below the detection limit of the off-site analyses. The He concentration at PPE_S10_L4 decreased from 0.7% (last measurement during the first gas mix injection) to 0.1 – 0.2%. The different behaviour of these two PPEs is likely to relate to their degree of connection to the preferential pathways where the migration of the injected gases occurs.

No measurable gas leaks could be identified in the GAST niche. Although a few N₂ concentration increases in the range of 1% were detected between 19 December 2022 and 29 December 2022, the absence of a corresponding signal in He suggests an experimental artifact.

4.4.7.1 On-site monitoring and off-site laboratory gas concentrations

The results of the on-site gas monitoring achieved with the miniRUEDI as well as the off-site laboratory-based analyses for PL_S14_L1 are plotted in Fig. 4-61 (overview) and Fig. 4-62 (magnification of the most relevant concentration ranges, Enclosures I.2 and J). For comparison, the measurements of samples from PL_S02_L1 and of samples of the injected gas are also depicted in the same figures. The conversion of the miniRUEDI and off-site laboratory measurements into a relative gas composition is described in Section 4.3.7.1. It should be noted that the miniRUEDI measurements during the cleaning with N₂ were performed until 30 March 2023. After this date, gas monitoring was stopped to perform instrument maintenance and set the new analytical protocols for the second Gas Mix #2 injection (see Section 4.5). The sampling for off-site analyses on PL_S14_L1, PL_S02_L1, and PPEs continued until 06 April 2023.

The flushing with pure N₂ started on 01 December 2022 at 07:05 and ended on 18 April 2023 at 08:00. Until about 03 December 2022, the gas composition in the membrane module exceeded the nominal 2% He of Gas Mix #1, with the He share reaching almost 3%. This He excess seems to relate to the gas dynamics within the membrane module connected to PL_S14_L1 and to preparatory field operations performed at the end of November 2022, which resulted in an experimental bias that persisted over the initial phase of the N₂ injection. In addition, at the beginning of the N₂ flushing, potential electronic issues of the miniRUEDI resulted in a notable measurement scattering.

From 03 December 2022, the N₂ and Ar shares started to increase. The He share started to decrease and reached values below 0.004% at the end of N₂ flushing. O₂ remained close to 0% for the whole N₂ injection time. At the end of the first N₂ flushing phase, the gas composition was dominated by N₂ at almost 100%. A minor share of Ar of about 0.1% was measured, indicating little presence of this tracer in the injected N₂ and potentially also little egression of Ar dissolved in porewater in the experiment.

Quantitative off-site laboratory measurements for PL_S14_L1 samples (Enclosure J) present trends in the gas composition similar to those measured by the miniRUEDI at the headspace of the membrane module. The He concentrations determined by the off-site analyses on 01 December and 02 December 2022 are 2% (nominal concentration of Gas Mix #1 injected first), again making the case that the higher He shares measured by the miniRUEDI are likely an experimental artifact of the membrane module setup. In line with the initial trials conducted on the membrane module (see Section 3.5.1.3 and Enclosure L), the temporal discrepancy for on-site measurements to reach He concentrations similar to those of the off-site measurements was about 4 – 6 days.

After 02 December 2022, the He concentrations decreased almost exponentially until 01 February 2023, when they went below the detection limit of the laboratory-based analyses (i.e., lower than about 0.05%, see Enclosure J). After this date, the off-site measurements of He were always below the detection limit (the last sample of Phase 7 was taken on 06 April 2023).

At the start of the N₂ injection, the Ar concentrations were below the detection limit, but from 13 December 2022 until the end of the pure N₂ injection, the Ar shares increased from 0.05% to 0.06 – 0.09%. It should be noted that in the “pure” N₂ used for the flushing, a small but clearly detectable amount of Ar was found by the miniRUEDI measurements (see above) and was quantitatively confirmed by off-site analyses (see below) to be 0.07% in gas samples collected directly from the gas cylinders containing N₂. O₂ concentrations were almost always below the detection limit, with a few exceptions observed on 30 December 2022 (0.06%) and 23 April 2023 (0.01%), which were most likely due to the sampling operations (resulting in minor leaks).

The shares of He and Ar were found to be lower than the concentrations determined by the on-site analyses, suggesting again potential biases in relation to the experimental setup of the membrane module. The quality of the samples for off-site laboratory analyses is generally good and no major contamination/issues could be identified.

Two samples were collected from the filter line PL_S02_L1 during the N₂ flushing. A first sample was acquired on 10 January 2023 (i.e., more than one month after starting the N₂ injection) and still showed an He share of about 1%, which is significantly higher compared to the values determined for PL_S14_L1 (see Fig. 4-62). A second sample collected on 06 April 2023 was characterised by an He share of 0.3%, which was still higher compared to the values determined during the same period at PL_S14_L1. As noted for the test with Gas Mix #1 (see Section 4.3.7), porewater occupied the lower levels of filter S02, likely “trapping” part of the previously injected gas mix and preventing direct connection with the “pure” N₂ injected at PL_S02_L6.

The water content of the samples collected from S14 and S02 during the cleaning with N₂ is plotted in Fig. 4-63. Almost all samples contained large free-gas phase shares (the water content ranged from 3% to 54%). The content of water in samples collected on PL_S14_L1 might not be fully consistent with the injection and extraction calculations due to the presence of filter devices upstream of the sampler. These might collect some water egressing the experiment over time, and the water collection might be enhanced by the application of the vacuum to the samplers. The only samples (almost) completely filled with water were the ones from filter S02 (see Section 4.3.7.1).

On 14 December 2022 and 06 April 2023, gas samples were acquired directly from the cylinders containing the injected N₂. The major gas share was N₂ with values ranging from 98.0% to 99.7%. In line with the miniRUEDI measurements and the laboratory-based analyses of the fluids from PL_S14_L1, a small but significant Ar share of about 0.07% was observed.

Tab. 4-27: Results of the off-site laboratory analyses conducted on the injected N₂, PL_S02_L1 and PL_S14_L1 samples collected during the first cleaning with pure N₂

Water content: approximate percentage of the sampler volume filled with water. Tot.: total amount of dissolved gases in cm³_{STP}/kg. The relative composition in [%] was calculated from dissolved species abundance for samples where a direct measurement of a gas phase was not possible (numbers in italics). Empty fields: measurements not performed; “n.d.”: below the detection limit. Full dataset of analytical results available in Enclosure J, full details of sample collection available in Enclosure K.

Sample	Start of collection	Sampling date	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	O ₂	N ₂
			[%]	[cm ³ _{STP} /kg]					[%]			
GAS N ₂	14.12.22 14:49	14.12.22 15:10	2						n.d.	0.07	n.d.	98.0
GAS N ₂	06.04.23 12:36	06.04.23 12:55	3						n.d.	0.07	n.d.	99.7
PL_S02_L1	10.01.23 08:21	10.01.23 08:36	101	1.53	0.3	n.d.	161	163	1.0	0.2	n.d.	98.8
PL_S02_L1	06.04.23 11:28	06.04.23 12:23	103	0.3	0.1	0.26	45	47	<i>0.6</i>	<i>0.2</i>	<i>0.6</i>	<i>95.3</i>
PL_S14_L1	01.23.22 13:18	01.22.22 13:38	8						2.1	n.d.	n.d.	95.8
PL_S14_L1	02.12.22 07:18	02.12.22 07:38	21						2.0	n.d.	n.d.	95.0
PL_S14_L1	06.12.22 10:14	06.12.22 10:35	3						1.5	n.d.	n.d.	96.9
PL_S14_L1	07.12.22 14:33	07.12.22 14:52	12						1.3	n.d.	n.d.	95.8
PL_S14_L1	09.12.22 09:54	09.12.22 10:13	20						1.1	n.d.	n.d.	96.7

Tab. 3-27: Cont.

Sample	Start of collection	Sampling date	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	O ₂	N ₂
			[%]	[cm ³ _{STP} /kg]					[%]			
PL_S14_L1	13.12.22 14:39	13.12.22 15:00	14						0.7	0.05	n.d.	96.7
PL_S14_L1	20.12.22 10:27	20.12.22 10:29	54						0.4	0.06	n.d.	97.6
PL_S14_L1	30.12.22 09:15	30.12.22 09:35	30						0.2	0.07	0.06	97.1
PL_S14_L1	01.02.23 13:02	01.02.23 13:44	10						n.d.	0.08	n.d.	99.0
PL_S14_L1	15.02.23 11:07	15.02.23 11:37	13						n.d.	0.06	n.d.	99.0
PL_S14_L1	06.04.23 10:09	06.04.23 10:40	8						n.d.	0.09	0.01	99.8

The following events are known to relate to field operations as well as to experimental issues (Enclosures F and H), resulting in significant short-term deviations of the measured gas concentrations from the general trends induced by the first N₂ flushing:

- On 06 December 2022, the miniRUEDI suffered instability issues, possibly of electronic origin. Such instability is reflected in the uncertainties of the measurements (e.g., N₂ in Fig. 4-62).
- The slight increase in the O₂ concentrations observed around 06 December 2022 seems to be related to the field operations by Solexperts AG (i.e., sampling for off-site analysis) conducted on 06 December 2022 and 07 December 2022.
- The experiment underwent a shut-in from 29 December 2022 until 13 January 2023. During this period, no measurements were conducted in the membrane module. The slight O₂ increase after the shut-in has to be attributed to the field operations to resume the extraction of fluids from filter S14.

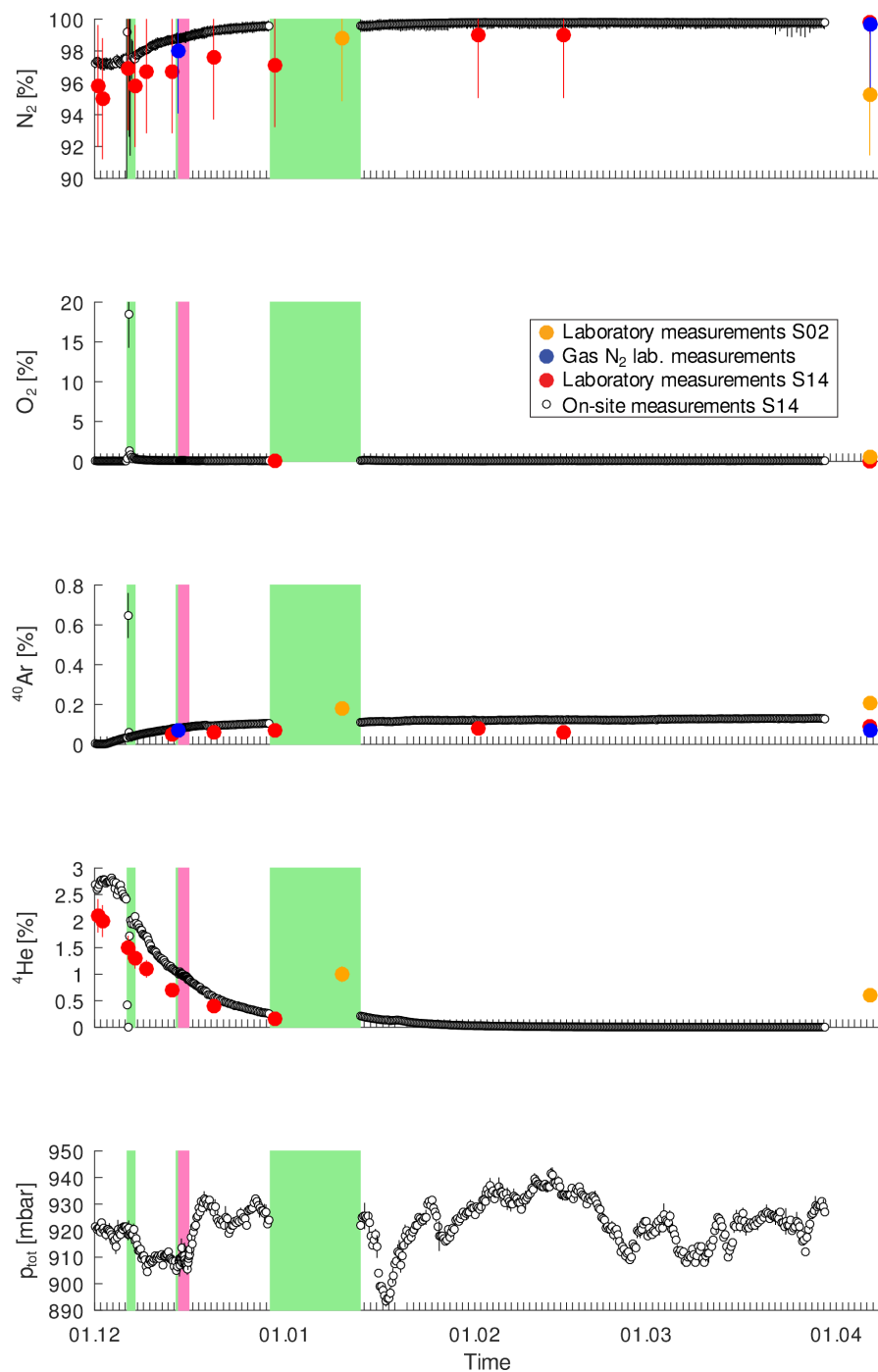


Fig. 4-61: Evolution of the gas composition with on-site and off-site measurements between 01 December 2022 and 06 April 2023 (Phases 6 and 7)

Empty circles: qualitative on-site measurements with miniRUEDI; red dots: quantitative off-site laboratory measurements of samples from PL_S14_L1; orange dots: off-site laboratory measurements on samples from PL_S02_L1; blue dots: off-site laboratory measurements of gas N_2 samples. Vertical error bars indicate the respective analytical uncertainties. Horizontal error bars indicate the sampling time span. Results from off-site laboratory analyses are plotted only if above the respective detection limits. Magenta- and green-shaded areas mark the timing of ventilation shielding and relevant field operations, respectively.

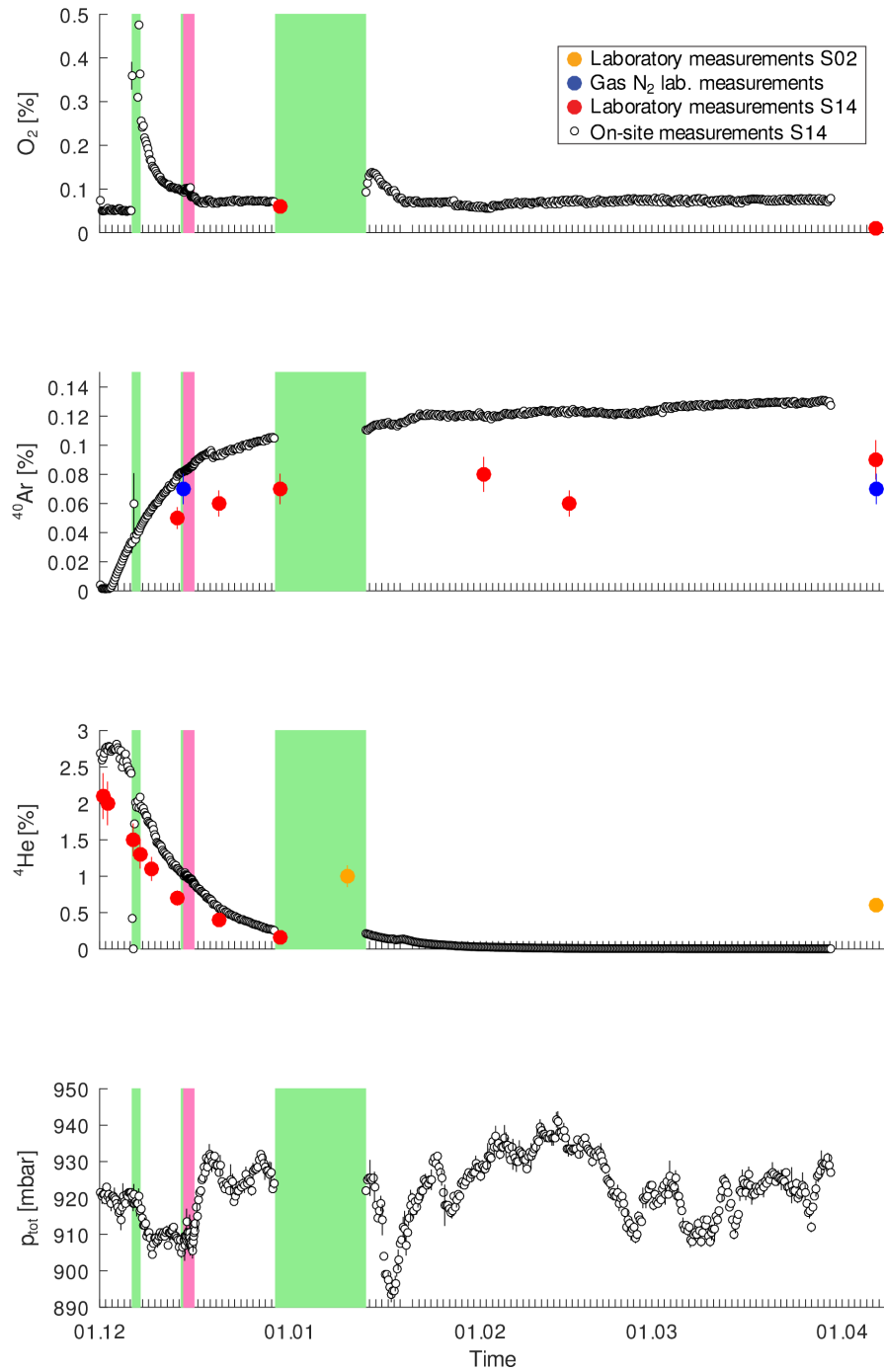


Fig. 4-62: Evolution of the gas composition with on-site and off-site measurements between 01 December 2022 and 06 April 2023 (Phases 6 and 7). Magnification to highlight concentration fluctuations closer to steady-state conditions.

Empty circles: qualitative on-site measurements with miniRUEDI; red dots: quantitative off-site laboratory measurements of samples from PL_S14_L1; orange dots: off-site laboratory measurements on samples from PL_S02_L1; blue dots: off-site laboratory measurements of gas N_2 samples. Vertical error bars indicate the respective analytical uncertainties. Horizontal error bars indicate the sampling time span. Results from off-site laboratory analyses are plotted only if above the respective detection limits. Magenta- and green-shaded areas mark the timing of ventilation shielding and relevant field operations, respectively.

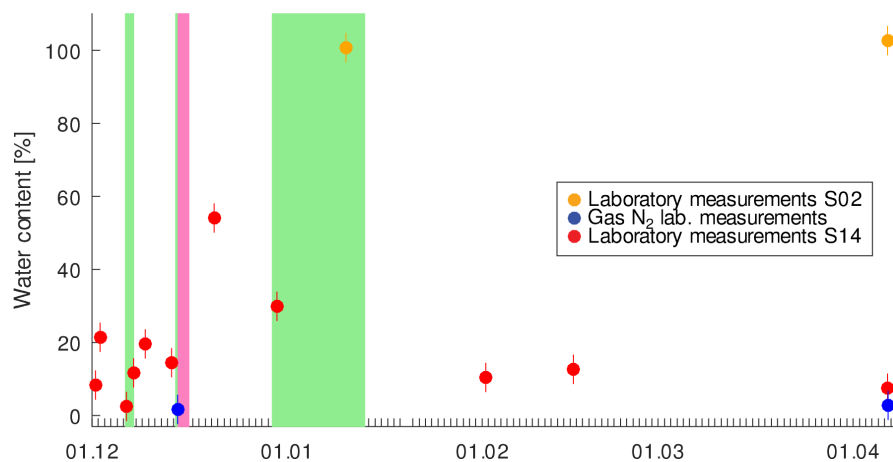


Fig. 4-63: Estimated water content in the samples for off-site analyses

The water content was calculated using the difference between the full and empty weight of the samplers normalised by the average volume of the used Swagelok cylinders. Magenta- and green-shaded areas mark the timing of ventilation shielding and relevant field operations, respectively.

4.4.7.2 Gas concentrations of PPE samples

Samples for off-site laboratory analyses were collected from the PPEs during the cleaning with pure N₂ (Phases 6 and 7) to assess the efficiency of the cleaning strategy (i.e., quantify the removal of the gas tracer He used in the preceding first gas mix injection), acquire a dataset describing the baseline concentrations of all relevant gas species before the start of the second gas mix injection (see Section 4.5.6), and to continue observation of the gas dynamics within the experiment inside the S/B.

The sampling of the PPEs still proved to be quite challenging. Flow rates were still variable (i.e., approximately 0.01 – 0.05 ml/min), despite the presence of a larger free gas phase inside the experiment. The syringe pump was set to stop when attaining a pressure decrease to below 10 bar, and to resume extraction after recovery to pressure in the range of 13 bar, in order to keep the pressure above 9 bar and hence minimise the risk of potential degassing. The changing flow rates resulted in different time spans required to purge the line volume, to flush the sampling cylinders for at least one volume, and to fill them (details in Enclosure K).

Off-site laboratory analyses conducted on PPE samples are summarised in Tab. 4-28 (further details are available in Enclosure J). All samples consisted mainly of a free gas phase with a water content ranging between approximately 2% and 6%.

The gas composition at PPE_S06_L6H-2 reflects that of the injected gas N₂, and He from the preceding Gas Mix #1 injection could not be detected anymore. Some He from the Gas Mix #1 injection was still detected at PPE_S10_L4 (He ~0.1 – 0.2%). The last PPE sample taken during Phase 7 at S03_L6L-1 on 11 April 2023 showed the highest He share of 0.7%, suggesting that this PPE is likely less directly connected to the main gas flow pathways. It should be noted that a large amount of CH₄ of about 16% was detected in the PPE_S03_L6L-1 sample (see Enclosure J), resulting in lower shares of other gas species (especially N₂). Such a different gas composition seems to be related to reactions occurring in the extraction line, as little or no significant amounts of CH₄ were detected elsewhere inside the experiment (e.g., 0.05% to 2.6% in S06_L4, and 0.2% to 2.6% in PPE_S08_L4 during the Gas Mix #1 injection).

For PPE_S03_L6L-1 and PPE_S10_L4, the presence of traces of O₂ indicates a slight air contamination that could imply a bias towards measured He concentrations being lower than in reality. However, such an issue appears to be negligible (up to 0.3% of air contamination) with respect to the analytical uncertainties, and the quality of the samples is considered to be good with respect to the experiment aims.

Tab. 4-28: Gas composition in PPE samples collected during the first flushing with pure N₂ (Phases 6 and 7)

Water content: approximate percentage of the sampler volume filled with water. Tot.: total amount of dissolved gases in cm³_{STP}/kg. The relative composition in [%] was calculated from dissolved species abundance for samples where a direct measurement of a gas phase was not possible (numbers in italics). Full dataset of analytical results available in Enclosure J, full details of sample collection available in Enclosure K.

PPE	Start of collection (*)	Sampling date (*)	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	O ₂	N ₂
			[%]	[cm ³ _{STP} /kg]					[%]			
S03_L6L-1	30.03.23 13:03	11.04.23 12:53	3						0.72	0.1	0.03	83.5
S06_L6H-2	01.02.23 13:44	08.02.23 07:45	2						n.d.	0.1	n.d.	99.0
S06_L6H-2	16.03.23 08:33	17.03.23 08:28	2						n.d.	0.1	n.d.	99.6
S10_L4	08.02.23 10:54	21.02.23 08:35	6						0.18	0.2	0.06	97.2
S10_L4	17.03.23 08:50	30.03.23 12:30	5						0.12	0.2	0.02	99.8

(*) Sampling date needs to be calculated back into S/B to account for PPE line length and extraction volumes, under piston flow model assumption and for samples not collected under vacuum:

PPE_S10_L4: line length 19.53 m, diameter 2.4 mm, approx. volume 88.4 cm³. Using an average extraction rate of 0.01 ml/min, the samples date back about 6 days before in S/B compared to sampling date. Assuming a rate of 0.015 ml/min the samples date back about 4 days before in S/B. Sample collected on 21 February 2023: line was purged from 08 February 2023 to 17 February 2023 with 112 ml extracted, sampler was reinstalled and about 63 additional ml were flushed until sample collection was complete; most of the time, the extraction rate was 0.01 ml/min. Sample collected on 30 March 2023: line purged from 17 March 2023 to 24 March 2023 with about 122 ml extracted, sampler was reinstalled and about 130 additional ml were purged until final sampling; most of the time, the extraction rate was 0.015 ml/min

PPE_S06_L6H-2: line length 22.84 m, diameter 2.4 mm, approx. volume 103.3 cm³. Using an extraction rate of 0.05 ml/min, samples date back about 1.5 – 2 days before in S/B compared to sampling date. Sample collected on 08 February 2023: line purged between 01 February 2023 and 07 February 2023 with about 210 ml extracted, sampler was reinstalled and about 72 additional ml were extracted until sample collection was complete. Sample collected on 17 March 2023: after about 320 ml extracted since start, a leak was noticed in the sampler, and hence a new sampler was installed on 16 March 2023 for sample collection until 17 March 2023 with 54 ml extracted.

PPE_S03_L6L-1: line length 25.32 m, diameter 2.4 mm, approx. volume 114.5 cm³. Using an extraction rate of 0.01 ml/min, samples date back about 8 days before in S/B compared to sampling date. Sampler was cleaned and reinserted on 06 April 2023, after which 93 ml were extracted from the line. Further extraction of 73 ml until sample collection was complete.

4.4.7.3 Gas sniffing results

Some N₂ (+1% compared to atmospheric background) at the GAST plug was detected on 19 December 2022 and lasted until the shut-in of the experiment on 29 December 2022, but no He above background level was detected for the same time window (Fig. 4-64).

The following events are known and relate to field operations as well as to experimental issues resulting in temporary fluctuations of gas concentrations in the GAST niche (from Enclosures F and H):

- On 14 December 2022, an N₂ bottle was found empty in a cabinet installed in the GAST niche. The N₂ increase observed at the URD at this time is more likely to originate from the leakage from the bottle in the cabinet rather than from a release from the experiment.
- Successive ventilation shielding from 14 December 2022 until 16 December 2022 did not reveal any N₂ increase, confirming the likely release of N₂ from a gas cylinder lasting until 14 December 2022.
- On 16 December 2022, the miniRUEDEI protocols were set back to normal mode after a period of high-frequency analyses with the shielding of the niche ventilation. From 29 December 2022 until 13 January 2023, the gas monitoring was set in shut-in mode whereby only gas sniffing at the GAST plug was performed.

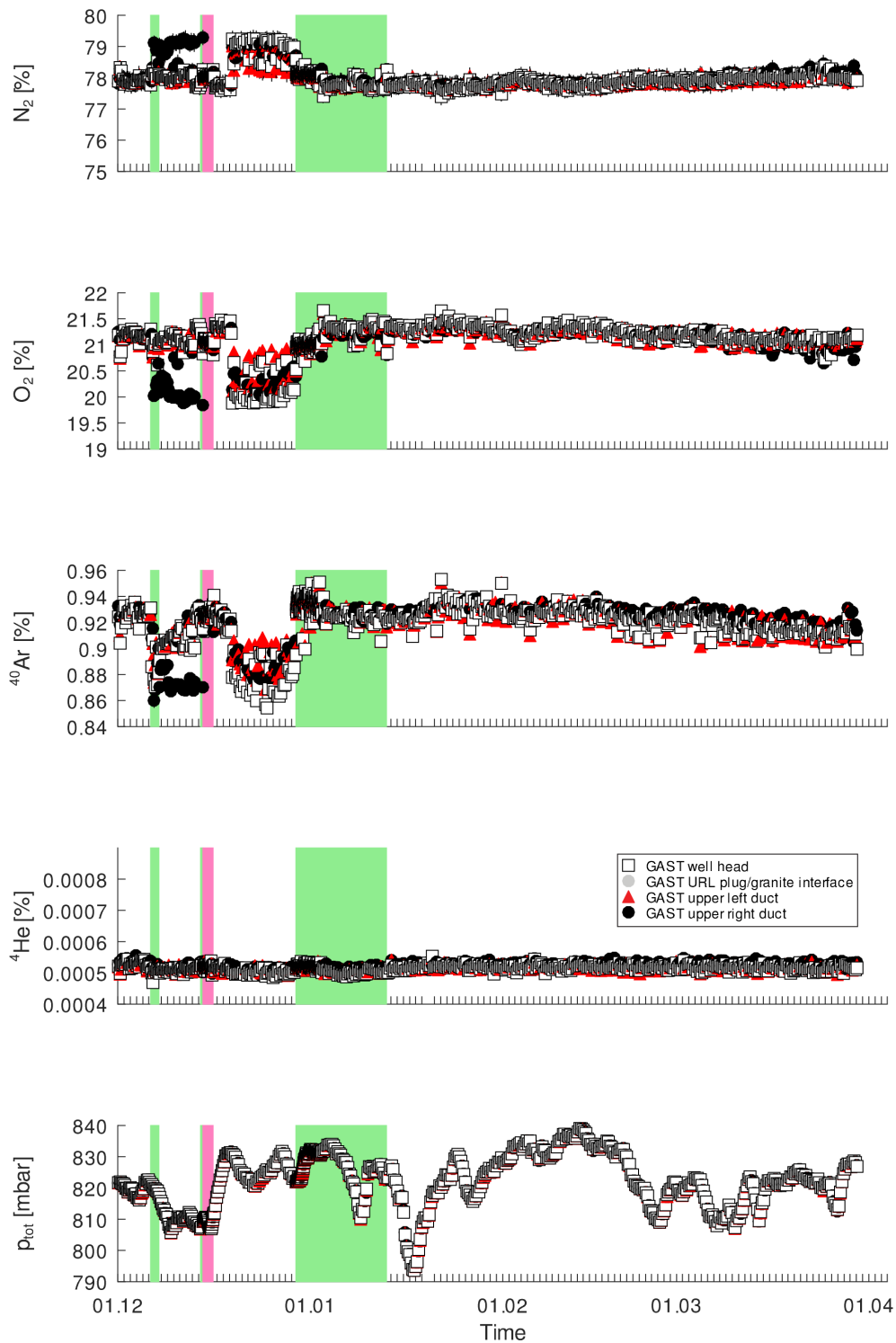


Fig. 4-64: Gas composition at the GAST plug between 01 December 2022 and 30 March 2023 (Phases 6 and 7)

Magenta- and green-shaded areas mark the timing of ventilation shielding and relevant field operations, respectively. Empty squares: well head; grey circles: URL plug/granite interface; red triangles: ULD; black dots: URD.

4.4.8 Phases 6 – 7 summary

During Phases 6 – 7, continued gas injection into S02 and extraction from S14 resulted in the development of the gas path. The continued increase in flow rates at constant pressure during Phase 6 resulted in the decision to switch to rate-controlled injection at a lower pressure gradient to limit the flow rate and total mass of gas injected.

The stable gas path allowed continued sampling from the S14 extraction and from selected piezometers. These samples clearly showed the tailing of the Gas Mix #1 tracer (He) providing further information on gas mixing with the S02 and S14 filters and transport along the gas path.

Pore pressure monitoring showed the ongoing response to gas path development with dissipation of the induced pressure rise caused by displacement of water, and the response to the change in pressure gradient across the seal section at the start of Phase 7.

The shut-in period performed during Phase 6 showed an initial pressure equalisation between the two filters and a subsequent closure of the gas path (snap-off) resulting in a pressure offset between the two filters. The resumption of gas injection resulted in a fast reopening of the gas path and the need to resume extraction from S14.

Hydraulic index tests (PW) performed in the PPEs within the seal section were used to monitor compressibility changes around the piezometers in the seal section and supported the selection of PPEs for targeted gas sampling.

Total pressure measurements demonstrated that overall compressive stress was maintained within the seal section during the phases.

No relevant leakage of gas into the WT tunnel was detected during the period.

4.5 Gas Flow Test with Gas Mix #2 (Phase 8)

4.5.1 Phase 8 aims

Section 4.5 describes the field work and results obtained during GFT Phase 8.

Phase 8 focused on the injection of Gas Mix #2. Steady injection and extraction conditions were maintained during the phase to facilitate the monitoring of the tracer concentration response, by sampling of the S14 extraction and of the PPEs. In particular, continuous sampling was possible in two PPEs providing a time history of the tracer concentrations at two points in the seal section. In addition, the long-term evolution of the gas path was characterised by the decreasing pressure gradient needed to maintain the constant mass-rate gas injection and the measured pressures in the seal section. To minimise disruption during the tracer injection, no PW index tests were performed within this phase.

4.5.2 Field activities

The injection gas was changed from N₂ to Gas Mix #2 on 18 April 2023 at 07:20. The events on the injection and extraction sides are summarised in Tab. 4-29. The layouts of the surface equipment are given in Section 4.5.3. Changes in the layout are indicated in Tab. 4-29 and referenced to the corresponding graph.

The target pressure on the injection side was 17.9 bar. The corresponding overview graph with the marked events is given in Fig. 4-67.

Rate control of gas injection at 1,000 mln/min (as measured by FLOW_HI calibrated to Gas Mix #2) continued, but the change in gas mixture resulted in an effective increase in gas volumetric flow rate due to the differences in density and thermal conductivity. This increase in

rate also caused a transient increase of pressure in both S02 and S14, followed by a stabilisation phase and slow pressure decrease (due to an ongoing trend towards decreasing flow resistance across the seal section).

The extraction side slightly increased to a pressure of 14.4 bar. This pressure increase was sufficient to allow the specified volumetric gas flow rate to match the injected mass rate.

The corresponding overview graph is given in Fig. 4-68. The overview of the injection and extraction parameters and the corresponding volumes is given in Tab. 4-30.

Tab. 4-29: Main field activities during GFT Gas Mix #2 injection (Phase 8) between 18 April 2023 and 29 June 2023

Date & time	Gas Mix #2 injection PL_S02_L6L-2	Extraction PL_S14_L1 Total gas + water flow	Comments
18.04.23 07:20	Switch from N ₂ to Gas Mix #2 injection 1,000 mln/min P increase to 17.9 bar	70 ml/min P increase to 14.4 bar	Layout Fig. 4-65 Start Gas Mix#2 injection
18.04.23 09:13	1,000 mln/min	68 ml/min	Minor adjustments were made to the extraction rates to maintain roughly constant pressure in S14
21.04.23 09:13	1,000 mln/min	70 ml/min	
24.04.23 09:13	1,000 mln/min	72 ml/min	
25.04.23 06:38			Layout Fig. 4-66 New position sampling vial
28.06.23 07:33	Start HI at 17.81 bar		Switch to HI to cover initial period of change in gas mix
29.06.23 09:14			Sampling in PL_S02_L1
29.06.23 12:16	Switch from Gas Mix #2 to N ₂ injection HI at 17.81 bar		

Tab. 4-30: Overview of injection and extraction parameters during GFT Gas Mix #2

	P from [bar]	P to [bar]	Flow rate from	Flow rate to	Volume STP [ln]	Volume @ T, P [l]	Comments
GFT mix 2: 18.04.23 07:20 – 29.06.23 12:16*							
Injection S02 Gas Mix #2	17.5	17.8	1,000 mln/min		104,417.85	6,273.09	RI
Extraction S14 gas	14.0	14.5	70 ml/min	72 ml/min	100,305.47	7,448.69	RW*
Extraction S14 water						10.47	

* Between 09 May 2023 05:58 and 11 May 2023 06:00, the extracted volume was linearly extrapolated due to failure of the syringe pump

T: Temperature of 16 °C

P: Pressure at the time stamp

STP: Standard conditions (T = 273.15 K, P = 101.3225 kPa)

4.5.3 Flow control

Except for the change of the injection gas, no changes were made to the surface equipment at the beginning of Phase 8. On 25 April 2023, the position of the sampling vial was changed.

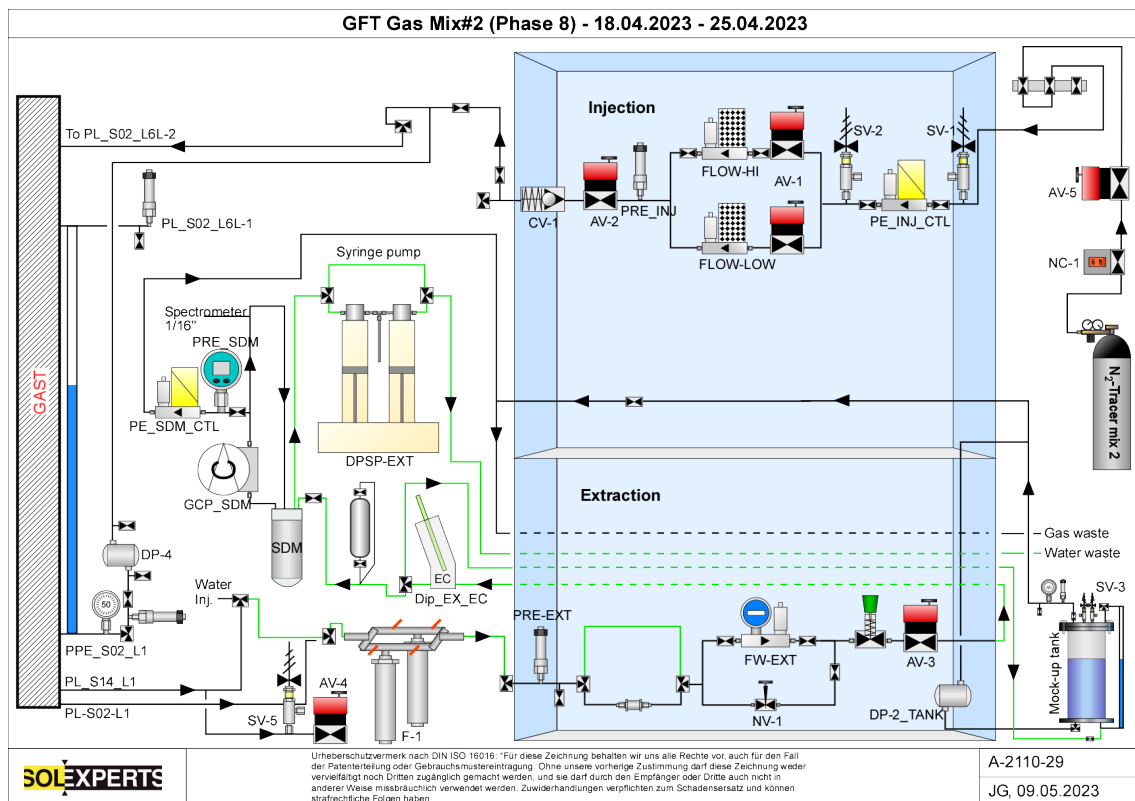


Fig. 4-65: Layout of surface equipment for the GFT between 18 April 2023 and 25 April 2023

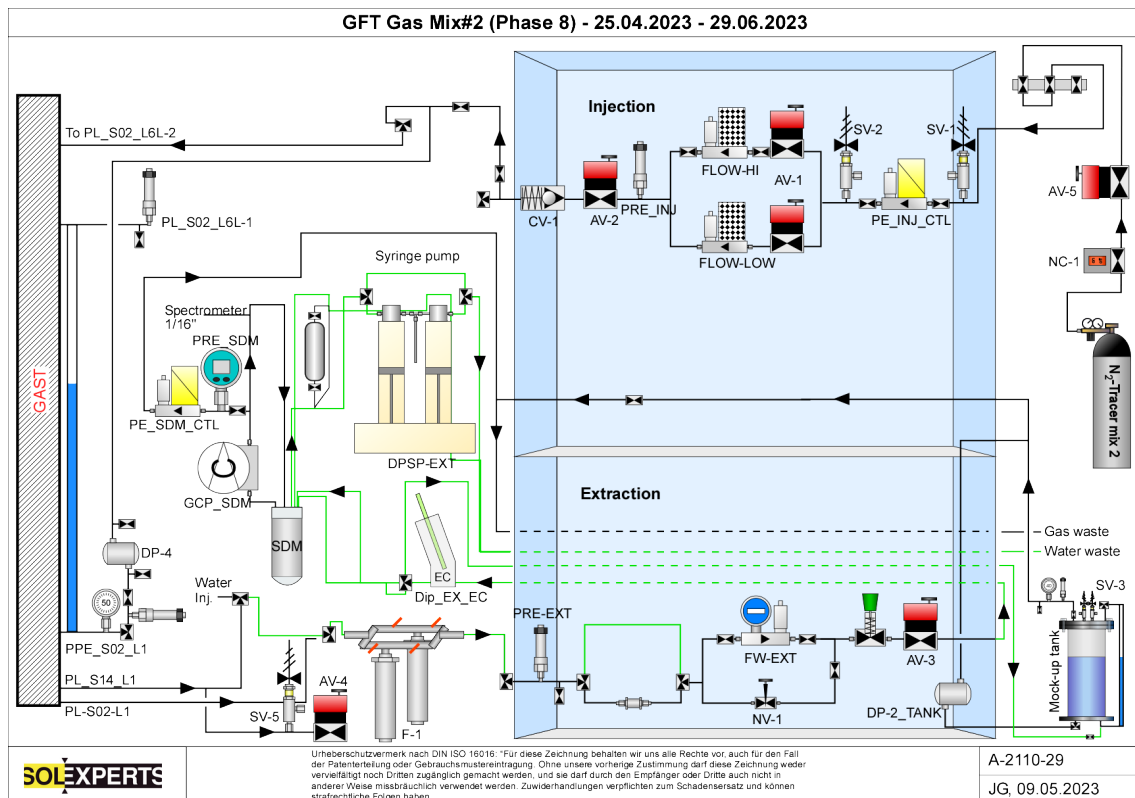


Fig. 4-66: Layout of surface equipment for the GFT between 25 April 2023 and 29 June 2023

Note: position of the sampling vial has been changed.

4.5.4 Monitoring data

The monitoring data for Phase 8 are shown in Fig. 4-67 (injection side) and Fig. 4-68 (extraction side). Flow rates (mln/min) were held constant during this phase, and pressure transients were limited to an initial response to the change in gas composition.

Many of the point TDRs (TDP sensors) showed no changes during Phase 8. As in the previous phases, the responses of some TDPs were not straightforward enough to directly infer physical changes resulting from the Gas Mix #2 injection performed in Phase 8. The TDL sensors showed a stable gas accumulation in the S14 filter during Phase 8 without major dynamic changes (Enclosure M).

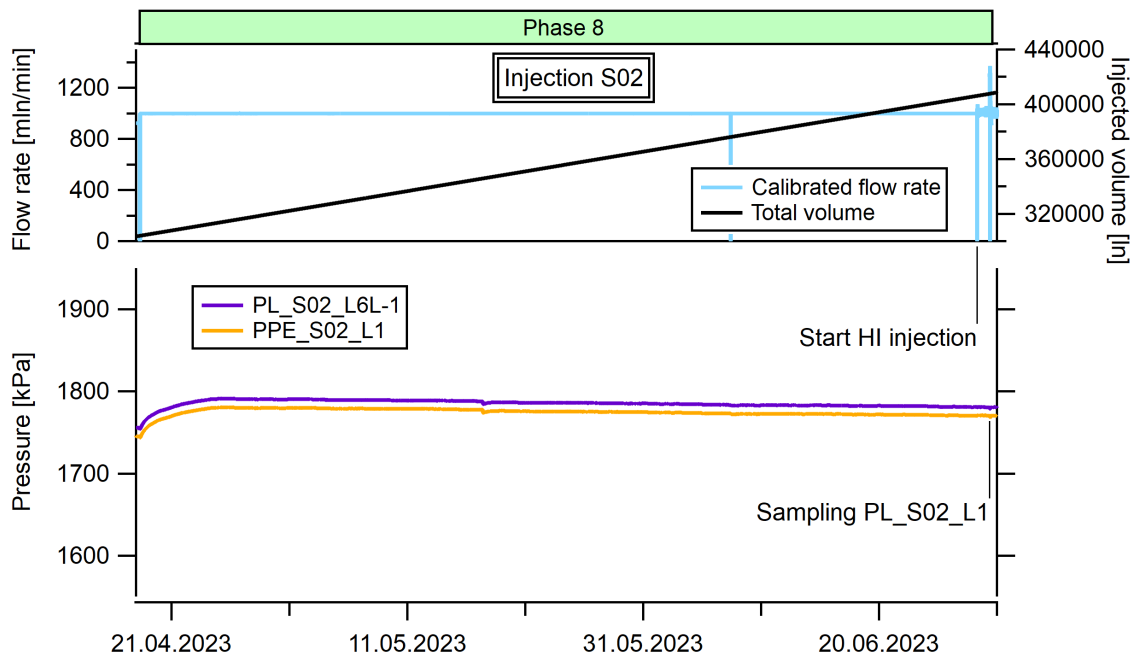


Fig. 4-67: Injection pressures, flow rate and total volume for GFT Gas Mix #2

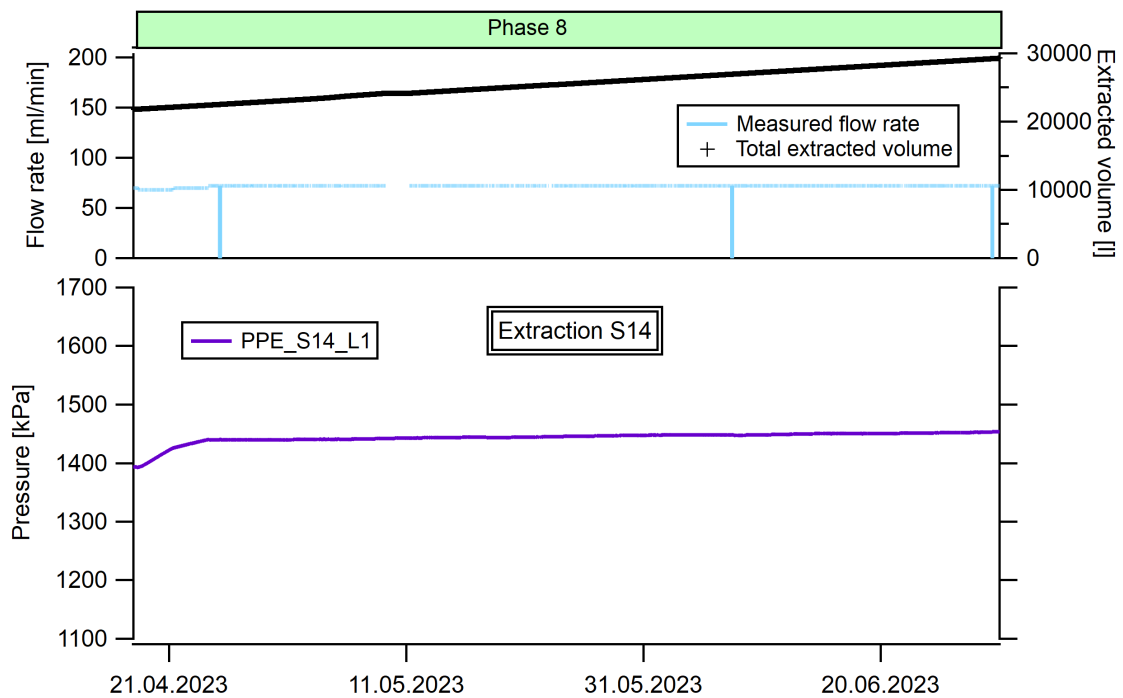


Fig. 4-68: Extraction pressures, flow rate and total volume for GFT Gas Mix #2

4.5.5 Sampling

The details of the samples taken during the GFT Gas Mix #2 injection are given in Tab. 4-31. Fig. 4-69 shows an example of the sampling parameters pressures and flow rates for PPE_S06_L6H-2 and PPE_S10_L4.

Tab. 4-31: Sampling performed during GFT Gas Mix #2 between 18 April 2023 and 29 June 2023

Phase	Code	Vial	Port	Start date & time	Flow rate [ml/min] or [mln/min]	Pressure [bar]	Sample weight [g]
Phase 8	GAS_067	GAST 17	Gas Mix #2 (*)	18.04.23 07:20	1,000	ca. 20	1.5 ⁽²⁾
	S14_068	GAST 18	PL_S14_L1	18.04.23 13:58	68	14	44.9 ⁽²⁾
	S14_069	GAST 19	PL_S14_L1	19.04.23 07:13	70	14	34 ⁽²⁾
	S14_070	GAST 20	PL_S14_L1	20.04.23 07:09	70	14.1	40.5 ⁽²⁾
	S14_071	GAST 21	PL_S14_L1	21.04.23 07:07	70	14.2	35.8 ⁽²⁾
	S14_072	GAST 22	PL_S14_L1	25.04.23 07:07	70	14.4	32.4 ⁽²⁾
	S14_073	GAST 30-SOL	PL_S14_L1	25.04.23 07:39	72	14.4	16.7 ⁽²⁾
	S14_074	GAST 23	PL_S14_L1	29.04.23 07:42	72	14.4	27.4 ⁽²⁾
	S14_075	GAST 32-SOL	PL_S14_L1	29.04.23 08:16	72	14.4	27 ⁽²⁾
	S14_076	GAST 24	PL_S14_L1	02.05.23 09:01	72	14.4	26.2 ⁽²⁾
	S14_077	GAST 25	PL_S14_L1	05.05.23 12:09	72	14.4	24.9 ⁽²⁾
	S14_078	GAST 11	PL_S14_L1	09.05.23 09:28	72	14.4	26.8 ⁽²⁾
	S02_079	GAST 12	PL_S02_L1	17.05.23 09:49	25	17.7	6.6 ⁽²⁾
	S14_080	GAST 13	PL_S14_L1	23.05.23 10:13	72	14.4	26.8 ⁽²⁾
	S14_081	GAST 14	PL_S14_L1	07.06.23 09:14	72	14.5	27.3 ⁽²⁾
	S14_082	GAST 15	PL_S14_L1	20.06.23 09:30	72	14.5	24.6 ⁽²⁾
	S14_083	GAST 17	PL_S14_L1	29.06.23 10:04	72	14.5	23.8 ⁽²⁾
	S02_084	GAST 16	PL_S02_L1	29.06.23 09:14	25	17.7	73.1 ⁽²⁾
	GAS_085	GAST 18	Gas Mix #2*	29.06.23 09:59	1,000	20	1.8 ⁽²⁾
	PPE_086	GAST 07	PPE_S10_L4	11.04.23 13:36	0.01	14.8 ⁽³⁾	2.1 ⁽¹⁾
	PPE_087	GAST 08	PPE_S06_L6H-2	11.04.23 13:36	0.012	15.1 ⁽³⁾	0.5 ⁽¹⁾
	PPE_088	GAST 09	PPE_S10_L4	29.04.23 08:34	0.01	14.4 ⁽³⁾	6.4 ⁽¹⁾
	PPE_089	GAST 10	PPE_S06_L6H-2	29.04.23 08:34	0.012	15.1 ⁽³⁾	0.5 ⁽¹⁾
	PPE_090	GAST 01	PPE_S10_L4	09.05.23 12:55	0.01	14.4 ⁽³⁾	1.0 ⁽¹⁾
	PPE_091	GAST 02	PPE_S06_L6H-2	09.05.23 12:55	0.012	15.1 ⁽³⁾	0.4 ⁽¹⁾
	PPE_092	GAST 34-Sol	PPE_S10_L4	17.05.23 10:45	0.01	14.3 ⁽³⁾	2.7 ⁽²⁾

Tab. 4-31: Cont.

Phase	Code	Vial	Port	Start date & time	Flow rate [ml/min] or [mln/min]	Pressure [bar]	Sample weight [g]
Phase 8	PPE_093	GAST 33-Sol	PPE_S06_L6H-2	17.05.23 10:45	0.012	15.1 ⁽³⁾	0.0 ⁽²⁾
	PPE_094	GAST 04	PPE_S10_L4	02.06.23 14:48	0.01	14.4 ⁽³⁾	0.0 ⁽¹⁾
	PPE_095	GAST 06	PPE_S06_L6H-2	02.06.23 14:48	0.012	15.1 ⁽³⁾	0.5 ⁽¹⁾
	PPE_096	GAST 05	PPE_S08_L4	07.06.23 11:00	0.01 → 0.015	14.9 ⁽³⁾	1.3 ⁽¹⁾
	PPE_097	GAST 07	PPE_S03_L6L-1	07.06.23 11:00	0.01 → 0.015	14.7 ⁽³⁾	0.6 ⁽¹⁾
	PPE_098	GAST 08	PPE_S10_L4	20.06.23 12:58	0.01 → 0.02	14.1 ⁽³⁾	2.3 ⁽¹⁾
	PPE_099	GAST 09	PPE_S06_L6H-2	20.06.23 12:58	0.012 → 0.024	15.1 ⁽³⁾	0.2 ⁽¹⁾

(*) Gas Mix #2: 10% He, 15% Ar, 0.1% Xe and 74.9% N₂

(1) 25 ml vial

(2) 75 ml vial

(3) Pressure at closure time of valve to sampler

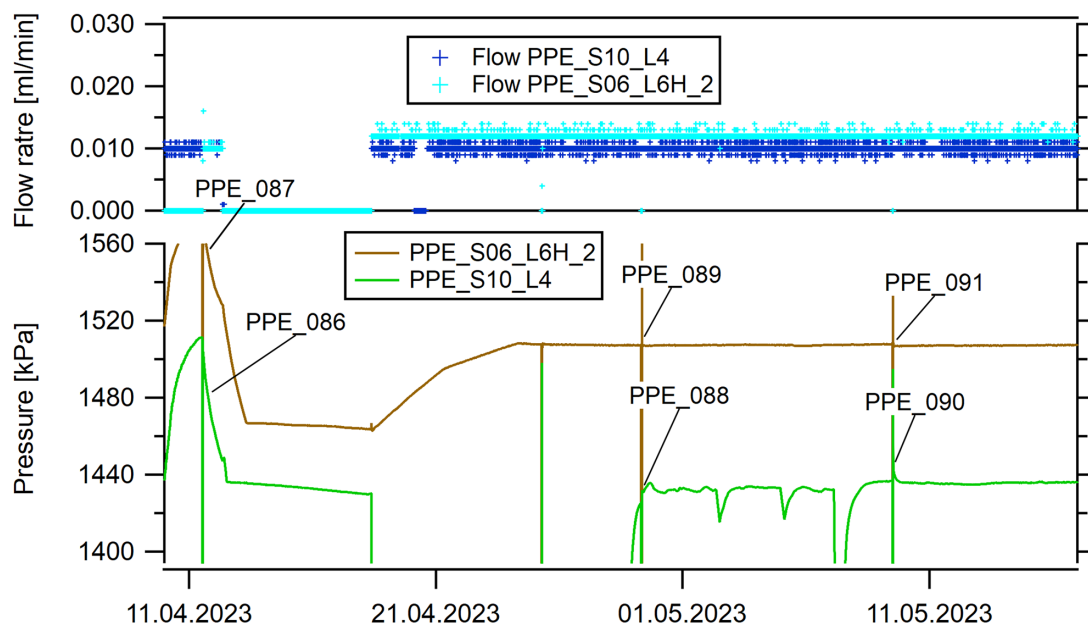


Fig. 4-69: Pressure and flow rate measured during the acquisition of sample PPE_087 to PPE_090 from PPE_S06_L6H-2 and PPE_S10_L4

4.5.6 Gas monitoring results

In the present section, we describe the outcome of the measurements based on a miniRUEDI portable mass spectrometer system as well as the laboratory-based analyses achieved to monitor the breakthrough of gases during the injection of Gas Mix #2 (N₂ spiked with 10% He, 15% Ar, and 0.1% Xe; for the corresponding certificates by PanGas AG, see Enclosure B.6) performed between April 2023 and June 2023.

The second gas mix injection adopted a set of inert gas tracers (i.e., He, Ar, and Xe) with distinct physical properties to characterise the gas flow pathways and explore the extent and relevance of different transport (e.g., advection and diffusion) and gas exchange processes (e.g., gas partitioning between liquid and gas phases).

Both on-site and off-site measurements describe the increase of the injected tracer concentrations over time. The He, Ar, and Xe concentrations determined by the miniRUEDI increased almost synchronously on 20 April 2023. The quantitative laboratory-based measurements confirmed this observation with two samples collected on 20 April 2023 at 07:27 and on 21 April 2023 at 07:21. According to these measurements, the values expected for the injected Gas Mix #2 (He ~10.0%, Ar ~16.2%, Xe ~0.07%) were attained around 07 June 2023 (measured values: He ~9.8%, Ar ~16.0%, Xe ~0.07%).

Between the first quantitative detection of tracer gases on 21 April 2023 and the attainment of steady-state-like conditions in the gas composition on 07 June 2023, the concentrations of the injected tracers increased over time, with some slightly different behaviour. A steep concentration change was observed between 21 April 2023 and 25 April 2023 when the shares of He, Ar, and Xe increased from a few % (or values below the detection limit) to about 50% of the nominal values of the injected Gas Mix #2. More specifically, on 25 April 2023, the He was about 45% of its nominal concentration, Ar was about 61% of its nominal concentration, and Xe was about 57% of its nominal concentration. While Ar and Xe presented similar increase rates towards the injected gas concentrations, He presented somewhat lower increase rates.

The quantitative off-site analyses on PPE samples clearly indicate the presence of the injected Gas Mix #2 at PPE_S06_L6H-2, PPE_S10_L4, and PPE_S08_L4, confirming the existence of gas flow paths inside the S/B. Furthermore, for the first time, five samples were collected in parallel for PPE_S06_L6H-2 and PPE_S10_L4, showing a slightly different temporal evolution of their gas composition, and hence a likely different connection/proximity to the major gas flow paths developed inside the S/B.

The gas sniffing in the GAST niche did not reveal any measurable gas leaks from the experiment and, when a leakage was suspected, high-frequency measurements performed with the shielding of the ventilation did not indicate significant gas emissions.

4.5.6.1 On-site monitoring and off-site laboratory gas concentrations

The Gas Mix #2 injection started on 18 April 2023 at 07:02 and ended on 29 June 2023 (Phase 8). The results of the on-site gas monitoring achieved with the miniRUEDI as well as the off-site laboratory-based analyses for PL_S14_L1 are plotted in Fig. 4-70. For comparison, the measurements of samples from PL_S02_L1 and of samples of the injected Gas Mix #2 are also depicted in the same figures. The conversion of the miniRUEDI and off-site laboratory measurements into a relative gas composition is described in Section 4.3.7.1.

The on-site monitoring with the miniRUEDI allowed the qualitative appreciation of the Gas Mix #2 arrival at PL_S14_L1 (Enclosure I.3). Overall, the quality of the miniRUEDI measurements was good. Measurement scattering was observed before the start of Gas Mix #2 injection only, and hence did not affect the relevant experimental time span.

Until about 20 April 2023, the gas composition in the membrane module was similar to that of the N₂ used to flush the experiment in the preceding months. The Gas Mix #2 signature was first detected on 20 April 2023 at 12:38 (about 3 days after start of gas injection, with He increasing from values of around 0.001% to 0.04%, Ar increasing from values of around 0.14% to 0.22%, and increasing Xe from about 3E-6% to 2E-4%). Afterwards, the concentrations of He, Ar, and Xe started to increase gradually and that of N₂ to decrease, indicating the arrival of Gas Mix #2 at PL_S14_L1. It is to be noted that N₂ progressively decreased and stabilised to relative abundances as low as 63%, well below the range known for Gas Mix #2 (about 75%). Similarly, at almost 9%, the He share remained slightly lower compared to the He share in Gas Mix #2 (~10%), while the Ar and Xe shares (almost 29% and 0.14%, respectively) exceeded the nominal Gas Mix #2 composition (15% and 0.1%, respectively).

These differences in gas composition with respect to the expected composition of the injected Gas Mix #2 suggest a mass-dependent gas fractionation at the membrane module. Lighter gases such as He and N₂ seem to be able to escape preferentially from the headspace of the membrane module (e.g., through the valve regulating the total pressure in the membrane module and/or different separation of gases via the membrane). This could lead to an increase of the Ar and Xe shares. Fractionation processes within the membrane module are confirmed with the results from the samples for off-site analyses, where the gas compositions matched those of injected Gas Mix #2 (see below).

The quality of the samples from PL_S14_L1 for off-site laboratory analyses was good, and no air contamination was detected (Enclosure J). The quantitative off-site laboratory measurements for PL_S14_L1 present similar trends in the gas composition as measured by the miniRUEDI (i.e., tracer gas concentration increases over time, starting from 20 April – 21 April 2023). In the sample collected on 20 April, the He and Xe concentrations were below the detection limit and the Ar share was about 0.1%. The sample collected on 21 April showed clear He and Ar enrichments of 0.5% and 1.5%, respectively (Xe remained below the detection limit). Xe was first identified by the off-site analyses in the successive PL_S14_L1 sample collected on 25 April 2023.

According to the off-site analyses, between 21 April 2023 and 07 June 2023, the concentrations of the injected tracers increased over time until they reached steady-state-like values. The largest concentration change was observed between 21 April 2023 and 25 April 2023, when all tracer gas shares reached about 50% of the nominal values of the injected Gas Mix #2. In detail, on 25 April 2023, the He (~4.5%), Ar (~9.8%), and Xe (~0.04%) shares corresponded to about 45%, 61%, and 57% of the respective values determined in the injected Gas Mix #2. While the Ar and Xe rate increases were similar (Ar from 13% to 15 – 16%, and Xe from 0.06% to 0.07%), the increase in He concentrations was somewhat lower (from 7% to 9.8%) until about 07 June 2023. From 07 June 2023 onwards, the concentrations of all tracer gases reached the values of injected Gas Mix #2 and remained comparatively constant despite some minor fluctuations.

Both the He and Ar concentrations determined by the off-site analyses reached the nominal values of Gas Mix #2 (i.e., 10% and 15 – 17%, respectively). Xe showed slightly lower values (i.e., ~0.07% instead of 0.1%) which are, however, consistent with the concentrations directly determined in a sample of the gas mixture (i.e., 0.07%, see below). The N₂ share at the end of the Gas Mix #2 injection also reached the expected value of about 75%. These observations underline again that the gas dynamics in the setup of the membrane module are responsible for experimental artifacts that limit quantitative assessments via the on-site monitoring system.

Two samples were collected from filter line PL_S02_L1 during the Gas Mix #2 injection. The first sample was acquired on 17 May 2023 (i.e., about one month after starting the injection) and consisted mostly of a gas phase (see Fig. 4-70 and Fig. 4-71), which is different from the PL_S02_L1 samples collected before and after. He and Ar were characterised by shares of 0.02% and 0.1%, respectively, while almost 100% of the gas consisted of N₂. According to the field logs

by Solexperts (Enclosure F), on 17 May 2023 at 09:22, a flushing with N₂ was done before starting the sampling at PL_S02_L1. Thus, it is likely that this first sample was affected by a sampling artifact (i.e., flushing with N₂). The second sample from PL_S02_L1 collected on 29 June 2023 showed somewhat higher amounts of He (0.2%) and Ar (0.8%). A remarkable share of O₂ of more than 15%, however, indicated significant air contamination.

The water content of the samples collected from PL_S14_L1 and PL_S02_L1 during the second gas flow test is plotted in Fig. 4-71. Most samples contained relatively large free-gas shares (the water content was equal to or lower than 62%). At PL_S14_L1, the water content decreased slowly from 62% (18 April 2023) to about 40% (from 29 April 2023 onwards). The content of water in samples collected on PL_S14_L1 might not be fully consistent with the injection and extraction calculations due to the presence of filter devices upstream of the sampler. These might collect some water egressing the experiment over time, and the water collection was enhanced by the application of the vacuum to the samplers. The only sample filled with water was collected from PL_S02_L1 at the end of Phase 8.

On 18 April 2023 and 29 June 2023, two samples were acquired directly from the cylinders containing Gas Mix #2 for off-site analyses. The first sample (He ~10.2%, Ar ~17.1%, Xe ~0.11%, N₂ ~73.1%) was similar to the expected nominal gas mix composition, apart from some larger Ar concentration (He ~9.93%, Ar ~15.0%, Xe ~0.998%, N₂ ~74.09%). The second sample showed similar He, Ar, and N₂ shares (10.0%, 16.2%, and 74.0%, respectively) but slightly lower Xe concentrations (0.07%). It should be noted that similar Xe concentrations were measured at PL_S14_L1 at the end of the second gas flow test. Such a difference could be due to:

- An analytical error larger than 15% for Xe concentrations being close to the detection limit.
- Preferential partitioning of gases in a supercritical state inside Gas Mix #2 cylinders. This could explain both the lower Xe and the larger Ar concentrations on the Gas Mix #2 measured in the laboratory as compared to the analyses on the Gas Mix #2 from the producer.

The following events are known and relate to field operations as well as to experimental issues (Enclosure H):

- On 16 April 2023, fluctuations in the gas partial pressures at the membrane module correlate with temporary electronic issues of the miniRUEDI.

Tab. 4-32: Results of the off-site laboratory analyses conducted on Gas Mix #2, PL_S02_L1 and PL_S14_L1 samples collected during the second gas mix injection.

Water content: approximate percentage of the sampler volume filled with water. Tot.: total amount of dissolved gases in cm³_{STP}/kg. The relative composition in [%] was calculated from dissolved species abundance for samples where a direct measurement of a gas phase was not possible (numbers in italics). Empty fields: measurements not performed; “n.d.”: below the detection limit. Full dataset of analytical results available in Enclosure J, full details of sample collection available in Enclosure K.

Sample	Start of collection	Sampling date	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	Xe	O ₂	N ₂
			[%]	[cm ³ _{STP} /kg]					[%]				
GAS MIX #2	18.04.23 07:20	18.04.23 08:46	2						10.2	17.1	0.11	n.d.	73.1
GAS MIX #2	29.06.23 09:59	29.06.23 10:18	3						10.0	16.2	0.07	n.d.	74.0
PL_S02_L1	17.05.23 09:49	17.05.23 10:18	9						0.02	0.1	n.d.	n.d.	99.8
PL_S02_L1	29.06.23 09:14	29.06.23 09:49	102	0.9	3.0	59.9	324	388	<i>0.2</i>	<i>0.8</i>	<i>n.d.</i>	<i>15.4</i>	<i>83.5</i>
PL_S14_L1	18.04.23 13:58	18.04.23 14:11	62						n.d.	0.2	n.d.	n.d.	99.7
PL_S14_L1	19.04.23 07:13	19.04.23 07:38	47						n.d.	0.07	n.d.	n.d.	99.9
PL_S14_L1	20.04.23 07:09	20.04.23 07:25	56						n.d.	0.1	n.d.	n.d.	99.5
PL_S14_L1	21.04.23 07:07	21.04.23 07:27	50						0.5	1.5	n.d.	n.d.	97.2
PL_S14_L1	25.04.23 07:07	25.04.23 07:21	45						4.5	9.8	0.04	n.d.	86.2

Tab. 4-32: Cont.

Sample	Start of collection	Sampling date	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	Xe	O ₂	N ₂
			[%]	[cm ³ _{STP} /kg]					[%]				
PL_S14_L1	29.04.23 07:42	29.04.23 08:07	38						6.7	12.7	0.06	n.d.	80.6
PL_S14_L1	02.05.23 09:01	02.05.23 09:18	36						7.7	13.5	0.06	n.d.	78.6
PL_S14_L1	05.05.23 12:09	05.05.23 12:25	35						7.9	13.8	0.06	n.d.	77.3
PL_S14_L1	09.05.23 09:28	09.05.23 09:47	37						8.7	14.8	0.06	n.d.	76.5
PL_S14_L1	23.05.23 10:13	23.05.23 10:48	37						8.8	15.5	0.06	n.d.	75.1
PL_S14_L1	07.06.23 09:14	07.06.23 09:48	38						9.8	16.0	0.07	n.d.	73.7
PL_S14_L1	20.06.23 09:30	20.06.23 10:00	34						10.3	16.3	0.07	n.d.	74.3
PL_S14_L1	29.06.23 10:04	29.06.23 10:29	33						10.0	15.4	0.07	n.d.	72.0

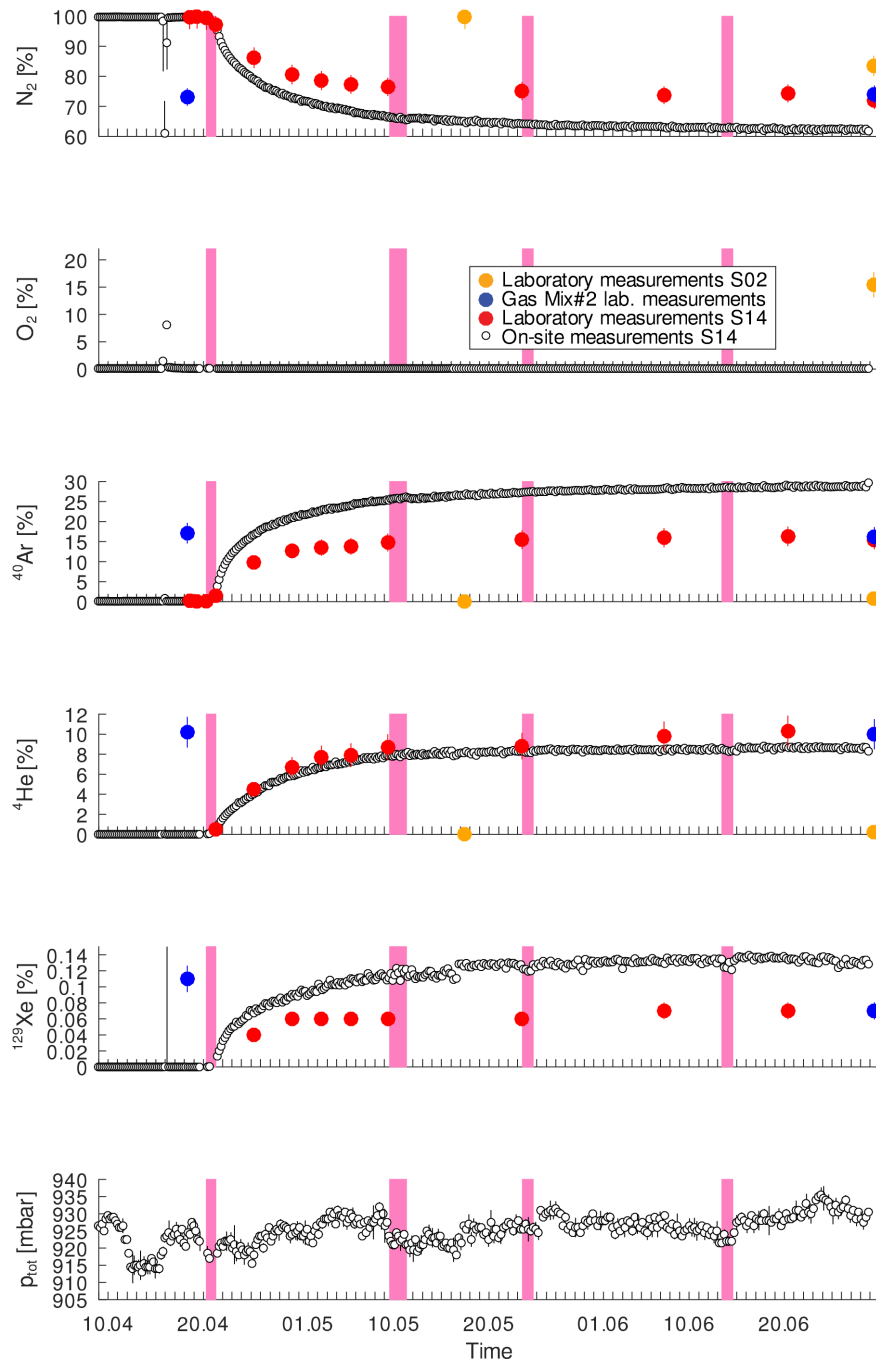


Fig. 4-70: Evolution of the gas composition with on-site and off-site measurements between 05 April 2023 and 29 June 2023 (Phase 8)

Empty circles: qualitative on-site measurements with miniRUEDI; red dots: quantitative off-site laboratory measurements of samples from PL_S14_L1; orange dots: off-site laboratory measurements on samples from PL_S02_L1; blue dots: off-site laboratory measurements of Gas Mix #2 samples. Vertical error bars indicate the respective analytical uncertainties. Horizontal error bars indicate the sampling time span. Results from off-site laboratory analyses are plotted only if above the respective detection limits. Magenta-shaded areas mark the timing of ventilation shielding.

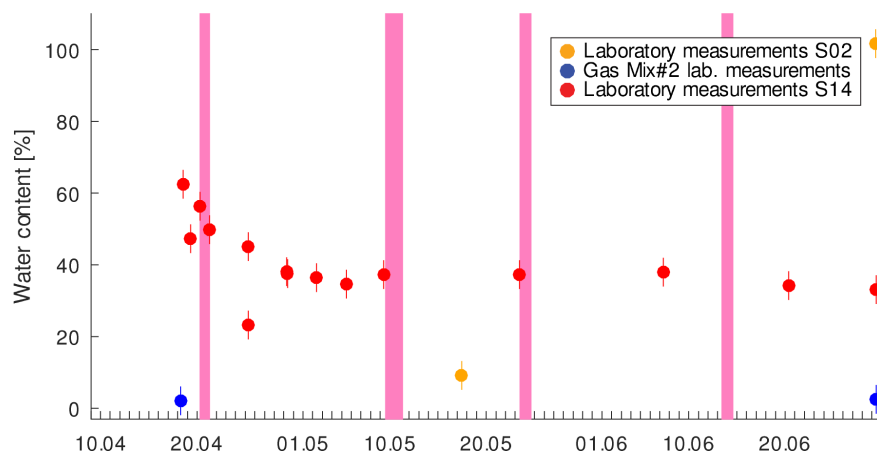


Fig. 4-71: Estimated water content in the samples for off-site analyses

The water content was calculated using the difference between the full and empty weights of the samplers normalised by the average volume of the used Swagelok cylinders.

4.5.6.2 Gas concentrations of PPE samples

Sampling of PPEs was also performed during Phase 8 to investigate the progress/distribution of the three adopted gas tracers (i.e., He, Ar, and Xe) inside the S/B seal system of the experiment. It is worth noting that, during the Gas Mix #2 injection, a parallel sampling was conducted at PPE_S06_L6H-2 and PPE_S10_L4: five samples were collected at both PPEs during the injection time span to better investigate the spatiotemporal evolution of the tracers at the PPEs.

The sampling of the PPEs required constant attention to the pressure development at the extraction lines, with the aim to keep the system pressurised above 9 bar to limit degassing as much as possible. Due to larger gas presence in proximity of the PPEs, near constant flow rate conditions could be ensured compared to the PPE sampling in previous phases. Especially for PPE_S06_L6H-2 and PPE_S10_L4, the more stable flow rates allowed the coordination of the time spans required to purge the line volume and to flush and fill the sampling cylinders and, thus, to collect samples in parallel from these PPEs.

The shares of liquid and gas phases (water content from 0% to 24%; see Tab. 4-33) were less variable compared to the first gas flow test. No trend in the water content could be identified for the PPE samples. It should be noted that for the first time, a sample from PPE_S08_L4 also consisted mostly of a free gas phase. Further details on PPE sampling are available in Enclosure K.

Off-site laboratory analyses conducted on PPE samples are summarised in Tab. 4-33. The gas composition of the sample collected at PPE_S06_L6H-2 on 29 April 2023 is clearly atmospheric and the respective results should be not considered for further interpretations due to sample contamination with atmospheric air.

The gas composition at all sampled PPEs, with the exception of PPE_S03_L6L-1, is affected by the arrival of Gas Mix #2, as shown by the respective He, Ar, and Xe concentrations.

As mentioned above, PPE_S06_L6H-2 and PPE_S10_L4 were sampled in parallel and their gas dynamics (i.e., the gas tracer concentration increases) were found to behave in a slightly different manner. At PPE_S06_L6H-2, Ar and Xe reached the value range measured in the injected Gas Mix #2 and stabilised from 09 May onwards around these values, while the He shares fluctuated around 7% during the whole sampling period. The tracer concentration changes at PPE_S10_L4

were more gradual, lasting from 11 April 2023 until 29 June. At the end of Phase 8, the shares of He (~6%), Ar (~13%), and Xe (~0.03%) at PPE_S10_L4 were still below the nominal values for the injected Gas Mix #2.

The sample from PPE_S08_L4 collected on 20 June 2023 shows similar gas tracer concentrations as those assessed for PPE_S06_L6H-2. This is the first observation of both an injected tracer and of a free gas phase at this PPE. The measured tracer gas concentrations suggest the development of a flow path network for preferential gas transport also reaching this PPE inside S/B over time.

As for the previous PPE sampling campaign (Section 4.4.7.2), some He excess was again observed at PPE_S03_L6L-1, but no Ar or Xe enrichments in response to the Gas Mix #2 injection. A significant share of CH₄ (20%) and detectable amounts of ethane and propane were present in this sample (see Enclosure J). The CH₄ isotopy ($\delta^{13}\text{C} = -71.9 \text{ ‰}_{\text{VPDB}}$, $\delta^2\text{H} = -326 \text{ ‰}_{\text{VSMOW}}$) indicates methanogenic conditions. The limited/absent response to the injected gases and the high CH₄ concentration are consistent with the previous observations at the same PPE. These results suggest the likely isolation of PPE_S03_L6L-1 from the main gas flow pathways, and that artifacts, e.g. related to the sampling line and the use of bentogel (employed in the sealing of instrumentation risers, main duct and well head), should be considered.

Tab. 4-33: Gas composition in PPE samples collected during Gas Mix #2 injection (Phase 8)

Water content: approximate percentage of the sampler volume filled with water. Tot.: total amount of dissolved gases in cm³_{STP}/kg. The relative composition in [%] was calculated from dissolved species abundance for samples where a direct measurement of a gas phase was not possible (numbers in italics). Full dataset of analytical results available in Enclosure J, full details of sample collection available in Enclosure K.

PPE	Start of collection ^(*)	Sampling date ^(*)	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	Xe	O ₂	N ₂
			[%]	[cm ³ STP/kg]					[%]				
S03_L6L-1	07.06.23 11:00	20.06.23 09:00	2						0.56	0.1	n.d.	0.05	79.6
S06_L6H-2	11.04.23 13:36	29.04.23 07:44	2						n.d.	0.9	n.d.	19.50	78.8
S06_L6H-2	29.04.23 08:34	09.05.23 12:19	2						6.80	17.2	0.06	n.d.	75.9
S06_L6H-2	09.05.23 12:55	17.05.23 07:39	2						8.70	17.2	0.07	n.d.	74.0
S06_L6H-2	02.06.23 14:48	07.06.23 08:45	2						7.10	16.5	0.07	n.d.	76.9
S06_L6H-2	20.06.23 12:58	29.06.23 06:47	1						6.60	14.1	0.06	n.d.	79.3
S08_L4	07.06.23 11:00	20.06.23 09:00	5						7.30	16.5	0.07	n.d.	76.0
S10_L4	11.04.23 13:36	29.04.23 07:44	8						0.78	1.4	0.02	n.d.	96.9
S10_L4	29.04.23 08:34	09.05.23 12:19	24						4.40	7.8	n.d.	n.d.	87.6
S10_L4	09.05.23 12:55	17.05.23 07:39	4						4.20	10.4	0.01	n.d.	85.3

Tab. 3-33: Cont.

PPE	Start of collection	Sampling date	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	Xe	O ₂	N ₂
			[%]	[cm ³ STP/kg]					[%]				
S10_L4	02.06.23 14:48	07.06.23 08:45	0						4.90	12.6	0.02	n.d.	82.8
S10_L4	20.06.23 12:58	29.06.23 06:47	9						6.60	12.5	0.03	n.d.	80.3

(*) Sampling date needs to be calculated back into S/B to account for PPE line length and extraction volumes, under piston flow model assumption and for samples not collected under vacuum:

PPE_S10_L4: line length 19.53 m, diameter 2.4 mm, approx. volume 88.4 cm³. Using an average extraction rate of 0.01 ml/min, the samples date back about 6 days before in S/B compared to sampling date. Assuming a rate of 0.02 ml/min, the sample would date back about 3 days before in S/B. Sample collected on 29 April 2023: line was purged from 11 April 2023 to 25 April 2023 at 0.01 ml/min, then sampler was reinstalled and about 58 additional ml were flushed until sample collection was complete. Successive samples were collected in sequence and line was not purged, with extraction rates kept at 0.01 ml/min. Sample collected on 29 June 2023: line purged from 20 June 2023 to 29 June 2023 at 0.02 ml/min, after 151 ml extracted, then on 27 June 2023, sampler was cleaned and reinstalled and about 48 additional ml were flushed until sample collection was complete.

PPE_S06_L6H-2: line length 22.84 m, diameter 2.4 mm, approx. volume 103.3 cm³. Using an average extraction rate of 0.012 ml/min, the samples date back about 6 days before in S/B compared to sampling date. Assuming a rate of 0.024 ml/min the sample date back about 3 days prior to sampling. Sample collected on 29 April 2023: line was purged from 11 April 2023 to 25 April 2023 at 0.012 ml/min, then sampler was reinstalled and about 69 additional ml were flushed until sample collection was complete. Successive samples were collected in sequence and line was not purged, with extraction rates kept at 0.012 ml/min. Sample collected on 29 June 2023: line purged from 20 June 2023 to 29 June 2023 at 0.024 l/min, after 182 ml extracted, then on 27 June 2023, sampler was cleaned and reinstalled and about 58 additional ml were flushed until sample collection.

PPE_S03_L6L-1: line length 25.32 m, diameter 2.4 mm, approx. volume 114.5 cm³. Using extraction rate of 0.015 ml/min, samples date back about 5 days before in S/B compared to sampling date. Line cleaning was operated from 07 June 2023 to 15 June 2023, with 133 ml extracted. Sampler was inserted on 15 June 2023 and an additional 104 ml were extracted until sampling was concluded.

PPE_S08_L4: line length 21.88 m, diameter 2.4 mm, approx. volume 98.9 cm³. Using extraction rate of 0.015 ml/min, samples date back about 4 – 5 days before in S/B compared to sampling date. Line cleaning was operated from 07 June 2023 to 15 June 2023, with 133 ml extracted. Sampler was cleaned and reinserted on 15 June and an additional 104 ml were extracted until sampling was concluded.

4.5.6.3 Gas sniffing results

The He sniffing at the plug presented much lower sensitivity as compared to the first gas mix injection phase (i.e., by about three orders of magnitude) due to the respective measurements being conducted on the Faraday cup detector instead of the electron multiplier detector (see Section 3.5.1.4 for details).

Some increase of the N₂ share from about 20 April 2023 until about 29 May 2023 was recorded in the vicinity of the URD, but none of the injected tracers showed the same behaviour (Fig. 4-72). No event resulting in experimental artifacts for the gas sniffing of the GAST plug is known for the Gas Mix #2 injection, not even during repeated ventilation shielding at the tunnel branch to improve the sensitivity of any potential leak detections (Enclosure H). Just one period characterised by higher Xe concentrations stretching from 05 April 2023 to 17 April 2023 (i.e. preceding the injection in the experiment) suggests that some of Gas Mix #2 could have been released in the GAST drift during preparatory work.

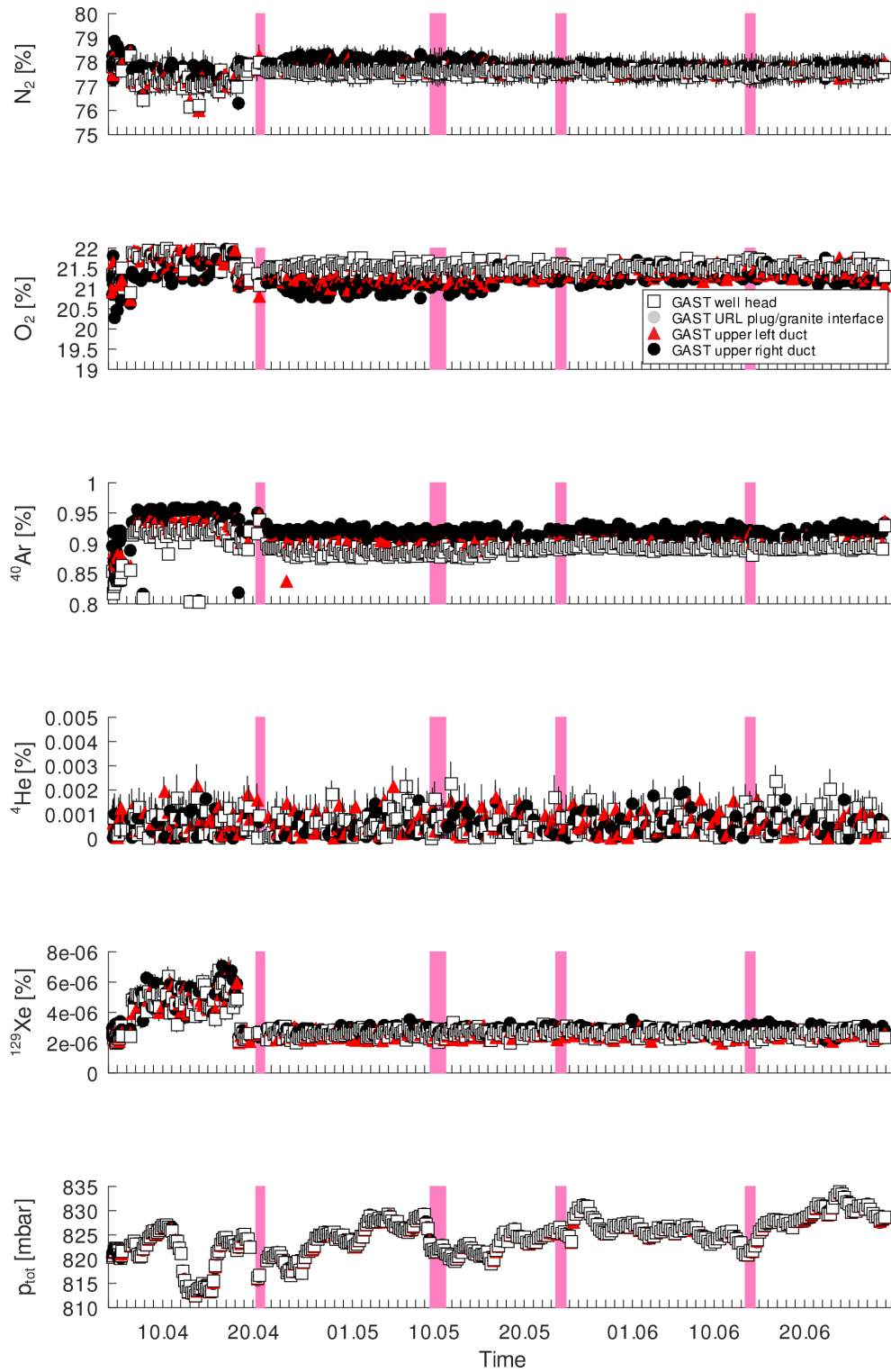


Fig. 4-72: Gas composition at the GAST plug between 05 April 2023 and 29 June 2023 (Phase 8)

Magenta-shaded areas mark the timing of ventilation shielding and relevant field operations, respectively. Empty squares: well head; grey circles: URL plug/granite interface; red triangles: ULD; black dots: URD.

4.5.7 Phase 8 summary

During Phase 8, the continued rate-controlled gas injection into S02 and extraction from S14 resulted in the further development of the gas path, with a reduction in the pressure gradient across the seal section with a constant rate injection (1,000 mln/min).

The stable gas path allowed continued sampling from the S14 extraction and from selected piezometers. These samples clearly showed the arrival of Gas Mix #2 tracers (He, Ar, and Xe) at PL_S14_L1 and their stabilisation at concentrations close to those of the injected mixture. Continuous extraction and regular sampling from two piezometers confirmed the presence of the injected gas inside the S/B and showed potential differences in gas tracer transport within the seal.

Total pressure measurements demonstrated that overall compressive stress was maintained within the seal section during this phase.

No leakage of Gas Mix #2 into the WT tunnel was detected during the period.

4.6 Gas Flow Test using pure nitrogen N₂ (Phase 9)

4.6.1 Phase 9 aims

Section 4.6 describes the field work and results obtained during GFT Phase 9.

Phase 9 focused on the flushing of the gas tracers from the filters and the gas path via the injection of pure N₂. Steady injection and extraction conditions were maintained during the phase to facilitate monitoring of the tailing response by sampling of the S14 extraction and directly from PPEs. Continuous sampling from two PPEs provided a time history of the decrease in tracer concentrations at two points in the seal section. Monitoring of the long-term evolution of the gas path continued during the phase and included a campaign of PW index testing.

4.6.2 Field activities

The injection gas was changed from Gas Mix #2 to pure nitrogen N₂ on 29 June 2023 at 12:16. The events on the injection and extraction sides are summarised in Tab. 4-34. The layout of the surface equipment is given in Fig. 4-73. The surface equipment was not changed during Phase 9.

During this phase, the N₂ gas injection rate was maintained at 1,080 mln/min (as measured by FLOW_HI calibrated to Gas Mix #2). This was an equivalent injection rate to 1,000 mln/min of Gas Mix #2 accounting for differences in density and thermal conductivity. To manage the transition between the two gases, an initial period (~1 day) of constant pressure injection was used, after which the injection was rate controlled. The target pressure on the injection side was about 17.8 bar. The corresponding overview graph with the marked events is given in Fig. 4-74.

The volumetric extraction from S14 was maintained at 72 ml/min, approximately equivalent to the S02 gas mass injection rate accounting for the pressure and temperature at the S14 extraction.

The extraction side pressure was about 14.6 bar. The corresponding overview graph is given in Fig. 4-75. The overview of the injection and extraction parameters and the corresponding volumes is given in Tab. 4-35.

Tab. 4-34: Main field activities during GFT N₂ (Phase 9) between 29 June 2023 and 01 September 2023

Date & time	Gas injection PL_S02_L6L-2	Extraction PL_S14_L1 Total gas + water flow	Comments
29.06.23 12:16	Switch from Gas Mix #2 to N ₂ injection HI at 17.81 bar	72 ml/min P 14.5 bar	Start N ₂ injection
30.06.23 10:50	Switch from HI to RI, 1,080 mln/min	72 ml/min P 14.6 bar	Switch to rate control after HI period covering initial transient due to switch from Gas Mix #2
04.07.23 11:00	1,000 mln/min	70 ml/min	Minor rate adjustment to maintain steady pressure in S14 filter
01.09.23 11:00	Shut-in N ₂ injection	Shut-in extraction	Final shut-in

Tab. 4-35: Overview of injection and extraction parameters during GFT N₂ (Phase 9)

	P from [bar]	P to [bar]	Flow rate from	Flow rate to	Volume STP [ln]	Volume @ T, P [l]	Comments
GFT pure nitrogen N ₂ : 29.06.23 12:16 – 01.09.23 11:00							
Injection S02 N ₂	17.5	17.8	1,000 mln/min		92,195.25	5,589.28	RI
Extraction S14 gas	14.0	14.5	72 ml/min	70 ml/min	90,101.53	6,622.77	RW
Extraction S14 water						6.89	

T: Temperature of 16 °C

P: Pressure at the time stamp

STP: Standard conditions (T = 273.15 K, P = 101.325 kPa)

4.6.3 Flow control

The surface equipment was not changed for the injection of N₂ during Phase 9.

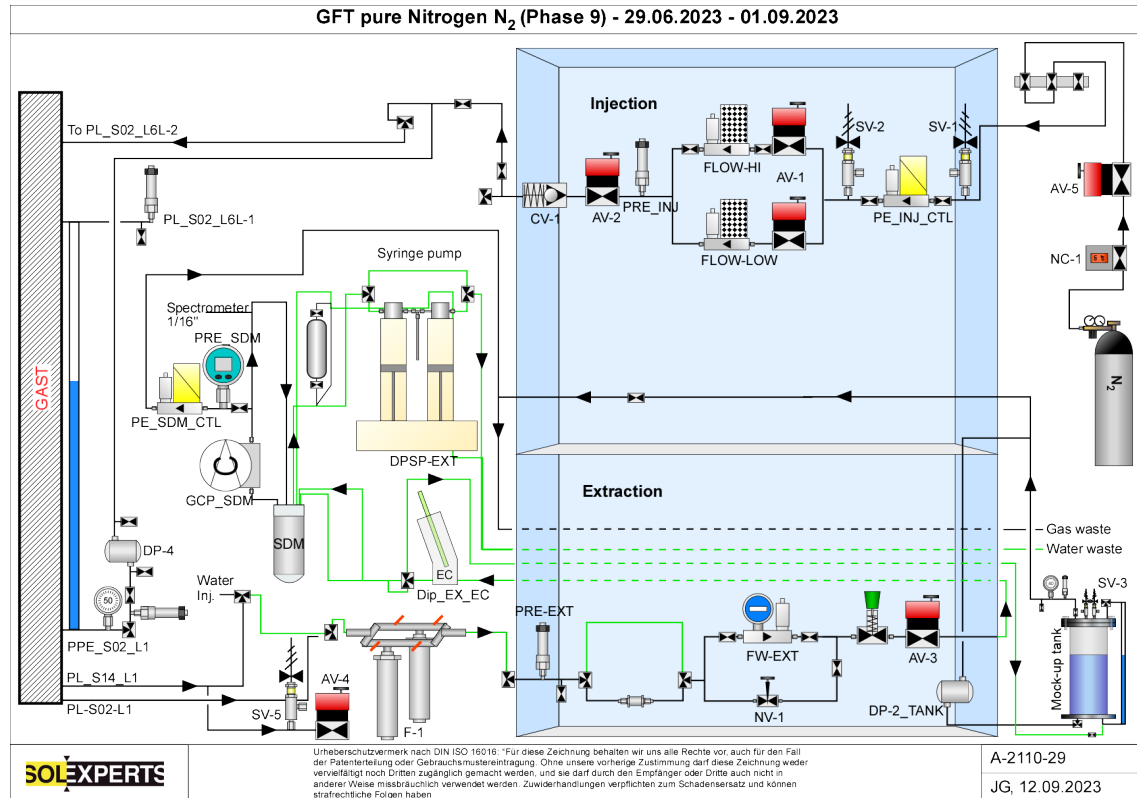


Fig. 4-73: Layout of surface equipment for GFT between 29 June 2023 and 01 September 2023

4.6.4 Monitoring data

The monitoring data for Phase 9 are shown in Fig. 4-74 (injection side) and Fig. 4-75 (extraction side). Gas injection flow rates in S02 (mln/min) were held constant during the phase, as were the volumetric extraction rate (ml/min) from S14. Pressures showed only a very slow decreasing trend in S02 and a slight initial increase in S14.

Many of the point TDRs (TDP sensors) showed no changes during Phase 9. As in the previous phases, the responses of some TDPs were not straightforward enough to directly infer physical changes resulting from the Nitrogen injection performed in Phase 9. The TDL sensors showed a stable gas accumulation in the S14 filter during Phase 9 without major dynamic changes (Enclosure M).

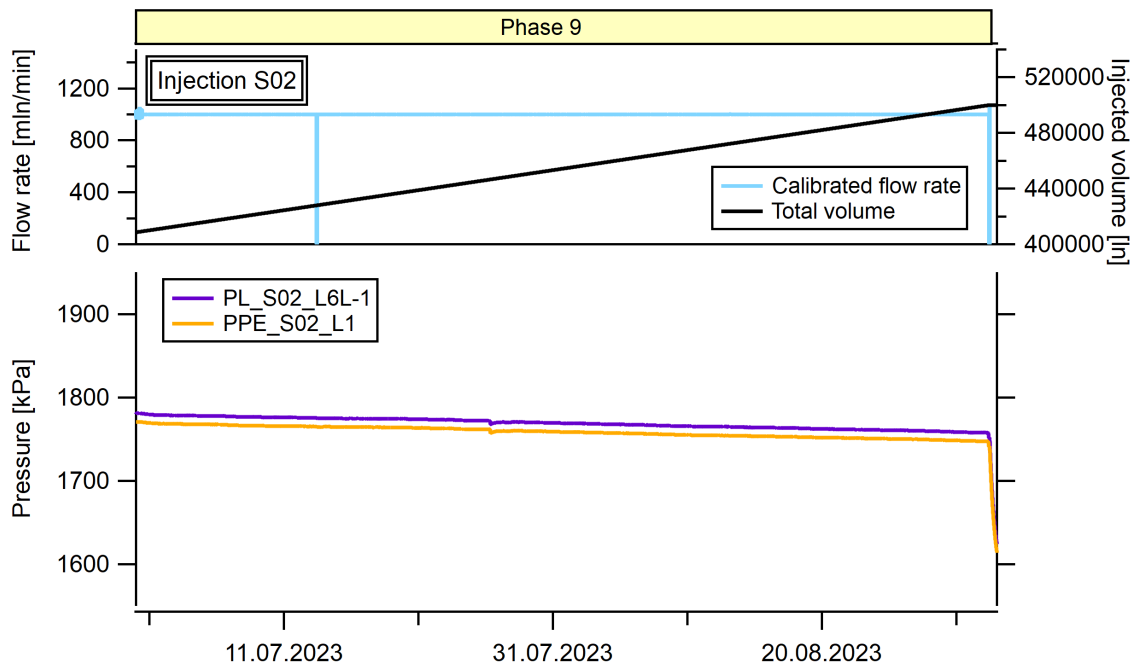


Fig. 4-74: Injection pressures, flow rate and total volume for GFT N₂ (Phase 9)

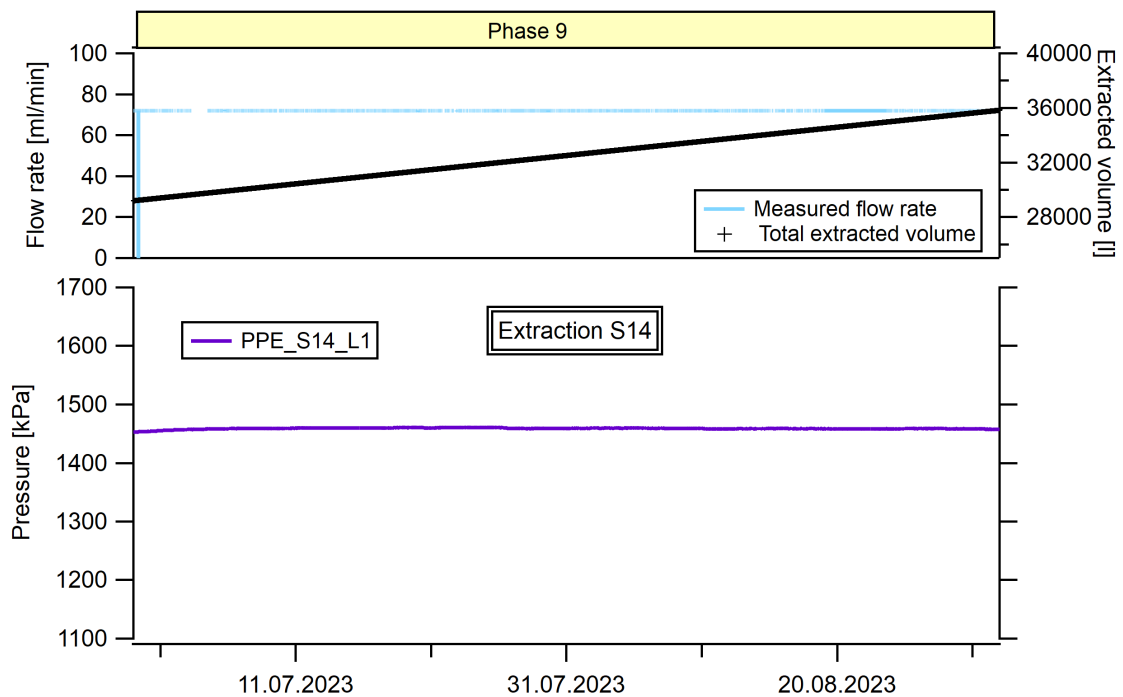


Fig. 4-75: Extraction pressures, flow rate and total volume for GFT N₂ (Phase 9)

4.6.5 Sampling

The details of the samples taken during GFT Phase 9 (N₂ injection) are given in Tab. 4-36. Fig. 4-76 and Fig. 4-77 show examples of the sampling parameters pressure and flow rate for PPE_S08_L4, PPE_S06_L6H-2 and PPE_S10_L4.

Tab. 4-36: Sampling performed during GFT N₂ (Phase 9) between 29 June 2023 and 01 September 2023

Phase	Code	Vial	Port	Start date & time	Flow rate [ml/min] or [mln/min]	Pressure [bar]	Sample weight [g]
Phase 9	S14_100	GAST 19	PL_S14_L1	30.06.23 12:18	72	14.5	25.7 ⁽²⁾
	S14_101	GAST 20	PL_S14_L1	03.07.23 06:17	72	14.6	27.6 ⁽²⁾
	S14_102	GAST 21	PL_S14_L1	06.07.23 12:13	72	14.6	24.5 ⁽²⁾
	S14_103	GAST 22	PL_S14_L1	13.07.23 07:17	72	14.6	25.9 ⁽²⁾
	GAS_104	GAST 30-SOL	GAS N ₂ (*)	13.07.23 10:14	1,080	20	2 ⁽²⁾
	S14_105	GAST 23	PL_S14_L1	20.07.23 10:23	72	14.6	25.8 ⁽²⁾
	S14_106	GAST 24	PL_S14_L1	26.07.23 07:56	72	14.6	26.6 v ⁽²⁾
	S02_107	GAST 25	PL_S02_L1	26.07.23 07:44	25	17.6	73.6 ⁽²⁾
	S14_108	GAST 11	PL_S14_L1	02.08.23 09:53	72	14.6	28 ⁽²⁾
	S14_109	GAST 12	PL_S14_L1	16.08.23 08:52	72	14.6	28.3 ⁽²⁾
	S14_110	GAST 13	PL_S14_L1	01.09.23 08:25	72	14.6	3.2 ⁽²⁾
	S02_111	GAST 14	PL_S02_L1	01.09.23 08:46	25	17.6	72 ⁽²⁾
	GAS_112	GAST 15	GAS N ₂ (*)	01.09.23 09:50	1,080	20	0 ⁽²⁾
	PPE_113	GAST 01	PPE_S10_L4	29.06.23 12:30	0.01	14.4 v ⁽³⁾	0.6 ⁽¹⁾
	PPE_114	GAST 02	PPE_S06_L6H-2	29.06.23 12:30	0.012	15.1 ⁽³⁾	0.5 ⁽¹⁾
	PPE_115	GAST 10	PPE_S10_L4	26.07.23 12:40	0.01	14.5 ⁽³⁾	1 ⁽¹⁾
	PPE_116	GAST 04	PPE_S06_L6H-2	26.07.23 12:40	0.012	15.2 ⁽³⁾	0 ⁽¹⁾
	PPE_117	GAST 05	PPE_S10_L4	16.08.23 13:30	0.01	14.4 ⁽³⁾	1.2 v ⁽¹⁾
	PPE_118	GAST 06	PPE_S06_L6H-2	16.08.23 13:30	0.012	15.1 ⁽³⁾	0 ⁽¹⁾
	PPE_119	GAST 08	PPE_S08_L4	24.08.23 10:16	0.02	14.5 ⁽³⁾	0.3 ⁽¹⁾
	PPE_120	GAST 09	PPE_S03_L6L-1	24.08.23 10:16	0.02	14.8 ⁽³⁾	0.2 v ⁽¹⁾

(*) Gas N₂: 100% N₂

(1) 25 ml vial

(2) 75 ml vial

(3) Pressure at closure time of valve to sampler

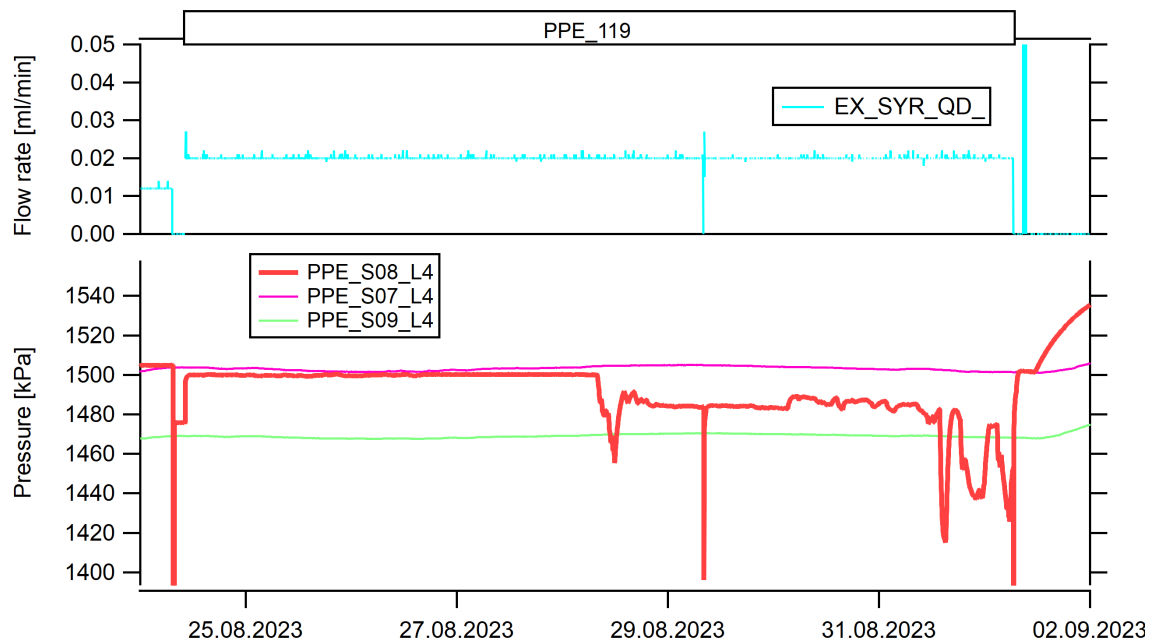


Fig. 4-76: Pressure and flow rate measured during the acquisition of sample PPE_119 from PPE_S08_L4

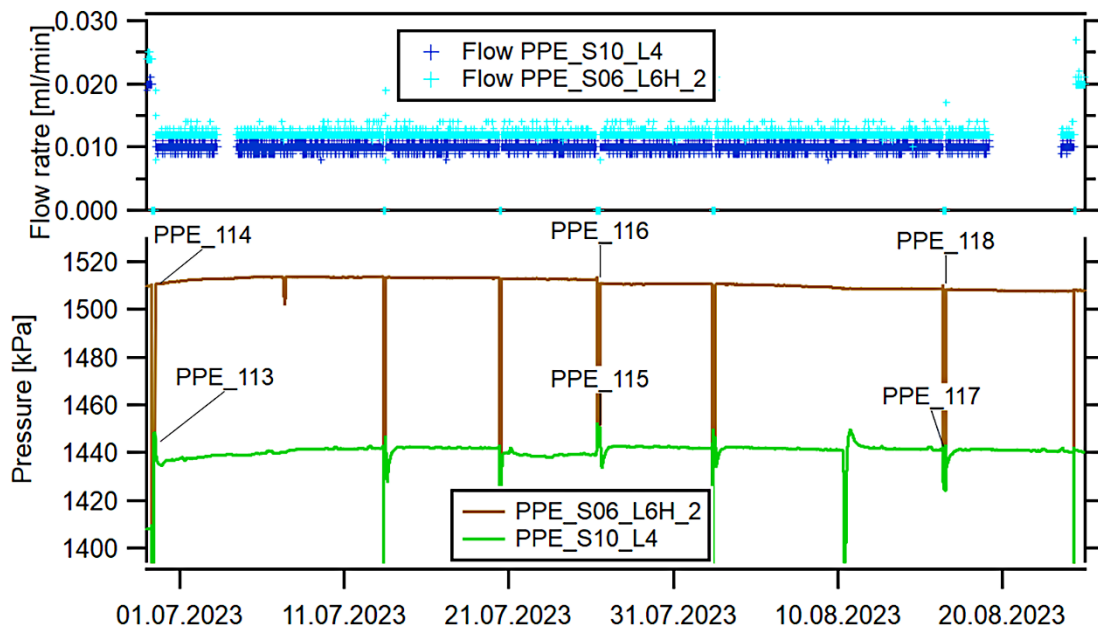


Fig. 4-77: Pressure and flow rate measured during the acquisition of samples PPE_114 to PPE_118 from PPE_S08_L4

4.6.6 Index testing

During GFT N₂ (Phase 9), one PW test campaign was performed in July 2023. In addition, a further PW test campaign was conducted after the end of GFT N₂ on 21 September 2023 which is included in this chapter for clarity. The goal was to extend the time series of compressibility measurements across the seal section using an efficient approach to monitoring the conditions at ~30+ PPEs during gas injection. The applied procedure is described in Section 4.1.5.

The test parameters are summarised in Tab. 4-37 and Tab. 4-42. The graphs of the PW tests are shown in Enclosure M.4. An overview of the calculated compressibilities between March and September 2023 is shown in Fig. 4-78.

Please note that the filling volume of the 2 ml volume line piece could not be controlled during the tests. Therefore, the ΔV in Tab. 4-37 and Tab. 4-42 might overestimate the true extracted volume.

A comparison of the pressure behaviour during the successive tests in several example ports is given in Section 6.5.

Tab. 4-37: Results of PW tests from PPE lines in July 2023

Date	Time	Sensor	ΔP [kPa]	$\Delta V^{(1)}$ [ml]	C [m ³ /Pa]	
06.07.23	07:00	PPE_S06_L6L-1	208.71	2.00	9.58E-12	Very slow increase
06.07.23	07:33	PPE_S03_L6L-1	9.85	2.00	2.03E-10	Very fast increase
06.07.23	07:36	PPE_S08_L4	30.34	2.00	6.59E-11	Very slow increase
06.07.23	07:52	PPE_S09_L4	450.65	2.00	4.44E-12	
06.07.23	09:44	PPE_S03_L4	1,429.72	2.00	1.40E-12	Fast increase
06.07.23	09:57	PPE_S04_L3	1,604.50	2.00	1.25E-12	
06.07.23	10:15	PPE_S06_L4	195.08	2.00	1.03E-11	Very slow increase
06.07.23	10:20	PPE_S07_L2	1,414.45	2.00	1.41E-12	
06.07.23	10:33	PPE_S12_L2-1	1,381.12	2.00	1.45E-12	Slow increase
06.07.23	10:42	PPE_S10_L6L-1	234.21	2.00	8.54E-12	Very fast increase
06.07.23	10:47	PPE_S03_L2-1	1,527.31	2.00	1.31E-12	Fast increase
06.07.23	10:52	PPE_S06_L3	1,490.59	2.00	1.34E-12	Slow increase
06.07.23	12:17	PPE_S07_L4	711.82	2.00	2.81E-12	Fast increase
06.07.23	12:20	PPE_S12_L2-2	1,387.49	2.00	1.44E-12	
06.07.23	12:33	PPE_S03_L3	1,386.53	2.00	1.44E-12	Slow increase
06.07.23	12:39	PPE_S06_L2	1,530.30	2.00	1.31E-12	
06.07.23	12:52	PPE_S08_L2	1,425.85	2.00	1.40E-12	
06.07.23	12:57	PPE_S08_L6L	759.16	2.00	2.63E-12	Very slow increase
06.07.23	13:02	PPE_S09_L2	1,409.14	2.00	1.42E-12	
06.07.23	13:12	PPE_S11_L3	1,391.36	2.00	1.44E-12	
06.07.23	13:21	PPE_S10_L3	1,364.30	2.00	1.47E-12	
06.07.23	13:26	PPE_S12_L3	1,373.48	2.00	1.46E-12	Fast increase
06.07.23	13:32	PPE_S12_L4	586.30	2.00	3.41E-12	Fast increase
06.07.23	13:37	PPE_S10_L6H-2	294.31	2.00	6.80E-12	
06.07.23	13:43	PPE_S10_L2	1,275.70	2.00	1.57E-12	
06.07.23	13:48	PPE_S03_L6H-2	102.61	2.00	1.95E-11	Very slow increase with jumps
06.07.23	13:54	PPE_S12_L6H-2	325.13	2.00	6.15E-12	Fast increase
06.07.23	14:01	PPE_S03_L2-2	958.69	2.00	2.09E-12	
06.07.23	14:12	PPE_S08_L3	1,417.06	2.00	1.41E-12	
06.07.23	14:18	PPE_S12_L6L-1	65.99	2.00	3.03E-11	

⁽¹⁾ Line piece with about 2 ml volume connected to PPE port, true volume unknown

Colours: red: higher compressibility $C > 5E-12$ m³/Pa, green: very slow increase, blue: very fast increase

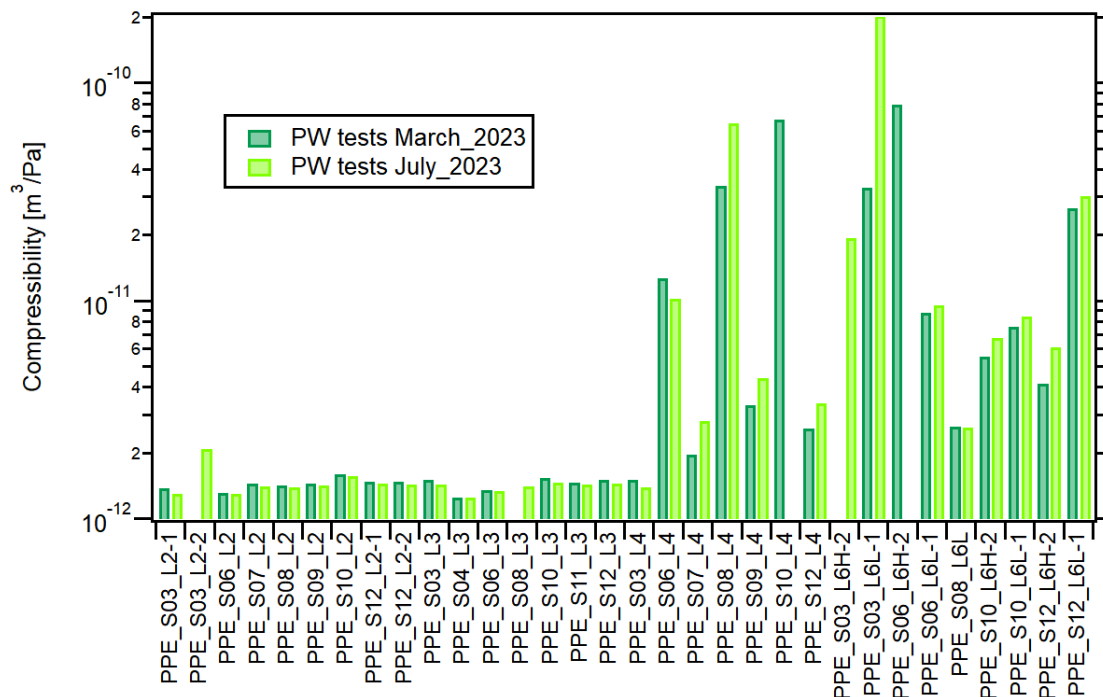


Fig. 4-78: Overview of calculated compressibilities from PW tests in March 2023 (Phase 7) and July 2023 (Phase 9)

4.6.7 Gas monitoring results

In the present section, we describe the outcome of the measurements based on a miniRUEDI portable mass spectrometer system as well as the laboratory-based analyses achieved to monitor the second flushing with pure N₂ performed between June 2023 and September 2023. After the N₂ flushing, the miniRUEDI was set in stand-by mode on 04 September 2023 and subsequently removed from the GAST niche on 14 September 2023.

The second flushing/cleaning with pure N₂ was conducted to remove as many gas tracers as possible from the experiment (i.e., He, Ar, and Xe injected during the second gas flow test) and investigate the respective gas dynamics (i.e., tailing injected gas tracers). As for the preceding Phase 8, a parallel sampling was conducted for selected PPEs (see below).

The on-site monitoring with the miniRUEDI of the membrane module headspace and the off-site quantitative laboratory analyses allowed the assessment of the gas dynamics related to the N₂ flushing. The arrival of the injected N₂ was detected between the end of June and the beginning of July, with the tracer (He, Ar, and Xe) concentrations from the Gas Mix #2 injection continuously decreasing over time and N₂ concentrations increasing towards 100% until the end of the N₂ injection. While the residual He and Xe concentrations remained higher than the natural background (e.g., higher than those in BOADUS water and in the atmosphere), the attained values would, in principle, allow the usage of the experiment for future trials with tracers (e.g., possibly in the same concentration ranges as those used for both Gas Mix #1 and Gas Mix #2 flow tests presented in this report).

PPEs S06_L6H-2 and S10_L4 were sampled in parallel to observe the temporal evolution of tracers inside the S/B (three samples were collected at each PPE). Both PPEs showed the effect of the cleaning with pure N₂, with the gas tracer concentrations decreasing over time, but with

some differences, indicating a different level of connection of the PPEs with the main gas flow paths. The decrease in gas tracer concentrations was further observed in PPE S08_L4, also located inside the S/B.

No evident anomaly was detected by the gas sniffing at the plug. During the second cleaning phase, neither excesses of the previously injected gas tracers nor fluctuations related to the injection of pure N₂ were measured. Thus, no measurable leakage was observed during Phase 9.

4.6.7.1 On-site and off-site laboratory gas concentrations

The results of the on-site gas monitoring achieved with the miniRUEDI as well as the off-site laboratory-based analyses for PL_S14_L1 are plotted in Fig. 4-79 (Enclosures I.4 and J). For comparison, the measurements of samples from PL_S02_L1 and from the injected gas N₂ are also depicted in the same figures. The conversion of the miniRUEDI and off-site laboratory measurements into a relative gas composition is described in Section 4.3.7.1.

The flushing with pure N₂ started on 29 June 2023 at 12:30 and ended on 01 September 2023. Based on miniRUEDI measurements of the headspace of the membrane module along line PL_S14_L1, by 30 June 2023, the shares of He, Ar, and Xe already started to decrease while the N₂ share started to increase, indicating the admixture of the injected N₂. More precisely, from the beginning until the end of the cleaning with N₂, the He shares dropped from about 9% to values below 0.02%, the Ar shares from about 29% to values below 0.2%, and the Xe shares from about 0.13% to values below 0.002%. In parallel, the N₂ shares increased from about 62% to 99.6%, while O₂ remained constant at about 0.1% throughout the second N₂ flushing phase. While both He and Xe concentrations remained above those of atmospheric air, on 09 August 2023, the Ar concentration in the headspace of the membrane module was lower than the atmospheric concentration and decreased further. Overall, the quality of the miniRUEDI measurements is considered to be good. No issues were observed in relation to the operation of the instrument. A couple of slight fluctuations in the measured time series pointed to what was most likely believed to be operational changes (i.e. not related to the experimental setup).

Quantitative off-site laboratory measurements of samples collected at PL_S14_L01 from 30 June 2023 until 01 September 2023 presented the same trends as the gas composition measured by the miniRUEDI. The He shares decreased from 9.7% to 0.02% and the Ar shares from 16.3% to 0.2% (Tab. 4-38). The shares determined for Xe evolved from 0.09% (30 June 2023) to 0.06% (06 July 2023). After 06 July 2023, the Xe concentrations went below the detection limit of the off-site analyses, but the miniRUEDI analyses suggested final Xe concentrations below 0.002%. The off-site laboratory analyses clearly depict a parallel decrease of the Gas Mix #2 tracer concentrations over time, with similar removal rates of He, Ar, and Xe (also considering the analytical uncertainties of about 15%). None of the samples for off-site measurements presented indications of significant air contamination.

As observed for the Gas Mix #2 injection, the setup of miniRUEDI coupled with the membrane module resulted in some biases of the gas measurements as compared to the quantitative off-site analyses. While the He values were similar between on-site and off-site measurements, the laboratory measurements provided lower Ar and Xe, and higher N₂ concentrations compared to those delivered by the miniRUEDI. This discrepancy was particularly evident for the initial period of the cleaning with N₂ and smoothed out as the N₂ injection progressed.

Two samples were collected from PL_S02_L1 during the second N₂ flushing on 26 July 2023 and 01 September 2023. Both samples showed relatively high He concentrations of 1.2 – 1.3%. The Ar concentrations were relatively low (about 0.3%) and the Xe concentrations were below the detection limit. The gas composition of neither sample seems to indicate traces of the second gas mix injection, but rather of the first gas mix injection. This observation consolidates the idea that water re-infiltrating into the lower S02 level hampered the transport of gases injected in Phases 8

and 9. It should be noted, however, that the analyses of the samples from PL_S02_L01 were conducted on a relatively small volume of free gas present in the Swagelok cylinders (total gas pressures determined in the off-site laboratory: 0.73 bar and 1.1 bar) and the analytical sensitivity might not have been sufficient to detect Xe.

The water content of the samples collected from PL_S14_L1 and PL_S02_L1 during the second cleaning with the N₂ test is plotted in Fig. 4-80. Similarly to the preceding Phase 8, most samples at PL_S14_L1 contained relatively large free-gas shares with the respective water content being slightly lower than 40% (i.e., following the values reached at the end of the preceding gas flow test). No remarkable trends were observed in the water content at PL_S14_L1, which is somehow reflected in the stable total gas pressures registered by the laboratory analyses ranging between about 11.7 bar and 13.3 bar. Only the last sample taken on 01 September 2023 consisted mostly of a free gas phase. The content of water in samples collected on PL_S14_L1 might not be fully consistent with the injection and extraction calculations due to the presence of filter devices upstream of the sampler, which could collect some water egressing the experiment over time, and due to the water collection enhanced by the application of vacuum to the samplers. In line with observations at the end of Phase 8, both samples collected from filter PL_S02_L1 during Phase 9 were filled with water.

On 13 July 2023 and 01 September 2023, gas samples were acquired directly from the cylinders containing the injected N₂. The vast majority of gas was N₂ with values ranging from 98.8% to 99.2%. Consistently with the previous analyses of the gas in the N₂ cylinders, an Ar share of about 0.07 – 0.1% was quantified. It should be noted that a small He share of 0.02% (at the border of the detection limit of the laboratory measurements) in the sample of 13 July 2023 might indicate some cross-contamination with the previously injected Gas Mix #2, either in the field or in the analytical laboratory pipeline, or be already present in the N₂ gas as a minor impurity.

The following events are known and relate to field operations as well as to experimental issues (Enclosure H), resulting in significant short-term deviations of the measured gas concentrations from the general trends:

- The He, Ar, and Xe concentration drop observed in on-site measurements between 07 July and 08 July 2023 seems to be related to the sampling for off-site analyses and handling operations conducted on 06 July 2023.
- Slightly positive fluctuations were observed for He, Ar, and Xe on 13 July 2023 and 17 July 2023. On 13 July 2023, a sample was acquired from PL_S14_L1 but no field activities were conducted on 17 July 2023. Thus, the origin of such fluctuations may be due to processes occurring within the experiment, or to the automatic operation of the devices installed to control the gas injection/extraction.

Tab. 4-38: Results of the off-site laboratory analyses conducted on pure N₂, PL_S02_L1 and PL_S14_L1 samples collected during the second N₂ cleaning phase

Water content: approximate percentage of the sampler volume filled with water. Tot.: total amount of dissolved gases in cm³_{STP}/kg. The relative composition in [%] was calculated from dissolved species abundance for samples where a direct measurement of a gas phase was not possible (numbers in italics). Empty fields: measurements not performed; “n.d.”: below the detection limit. Full dataset of analytical results available in Enclosure J, full details of sample collection available in Enclosure K.

Sample	Start of collection	Sampling date	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	Xe	O ₂	N ₂
			[%]	[cm ³ _{STP} /kg]					[%]				
GAS N ₂	13.07.23 10:14	13.07.23 11:54	3						0.02	0.1	n.d.	n.d.	98.8
GAS N ₂	01.09.23 09:50	01.09.23 10:00	0						n.d.	0.07	n.d.	0.06	99.2
PL_S02_L1	26.07.23 07:44	26.07.23 08:19	102						1.2	0.3	n.d.	0.06	96.1
PL_S02_L1	01.09.23 08:46	01.09.23 09:30	100						1.3	0.3	n.d.	n.d.	97.8
PL_S14_L1	30.06.23 12:18	30.06.23 12:37	36						9.7	16.3	0.09	n.d.	74.4
PL_S14_L1	03.07.23 06:17	03.07.23 06:39	38						8.3	14.4	0.07	n.d.	77.0
PL_S14_L1	06.07.23 12:13	06.07.23 12:34	34						6.1	11.4	0.06	n.d.	82.7
PL_S14_L1	13.07.23 07:17	13.07.23 07:56	36						2.5	4.2	n.d.	n.d.	90.5
PL_S14_L1	20.07.23 10:23	20.07.23 10:53	36						1.3	2.1	n.d.	n.d.	95.4

Tab. 4-38: Cont.

Sample	Start of collection	Sampling date	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	Xe	O ₂	N ₂
			[%]	[cm ³ STP/kg]					[%]				
PL_S14_L1	26.07.23 07:56	26.07.23 08:25	37						0.8	1.8	n.d.	n.d.	97.8
PL_S14_L1	02.08.23 09:53	02.08.23 10:26	39						0.3	0.8	n.d.	n.d.	98.3
PL_S14_L1	16.08.23 08:52	16.08.23 09:21	39						0.1	0.3	n.d.	n.d.	98.9
PL_S14_L1	01.09.23 08:25	01.09.23 08:50	4						0.02	0.2	n.d.	0.2	99.2

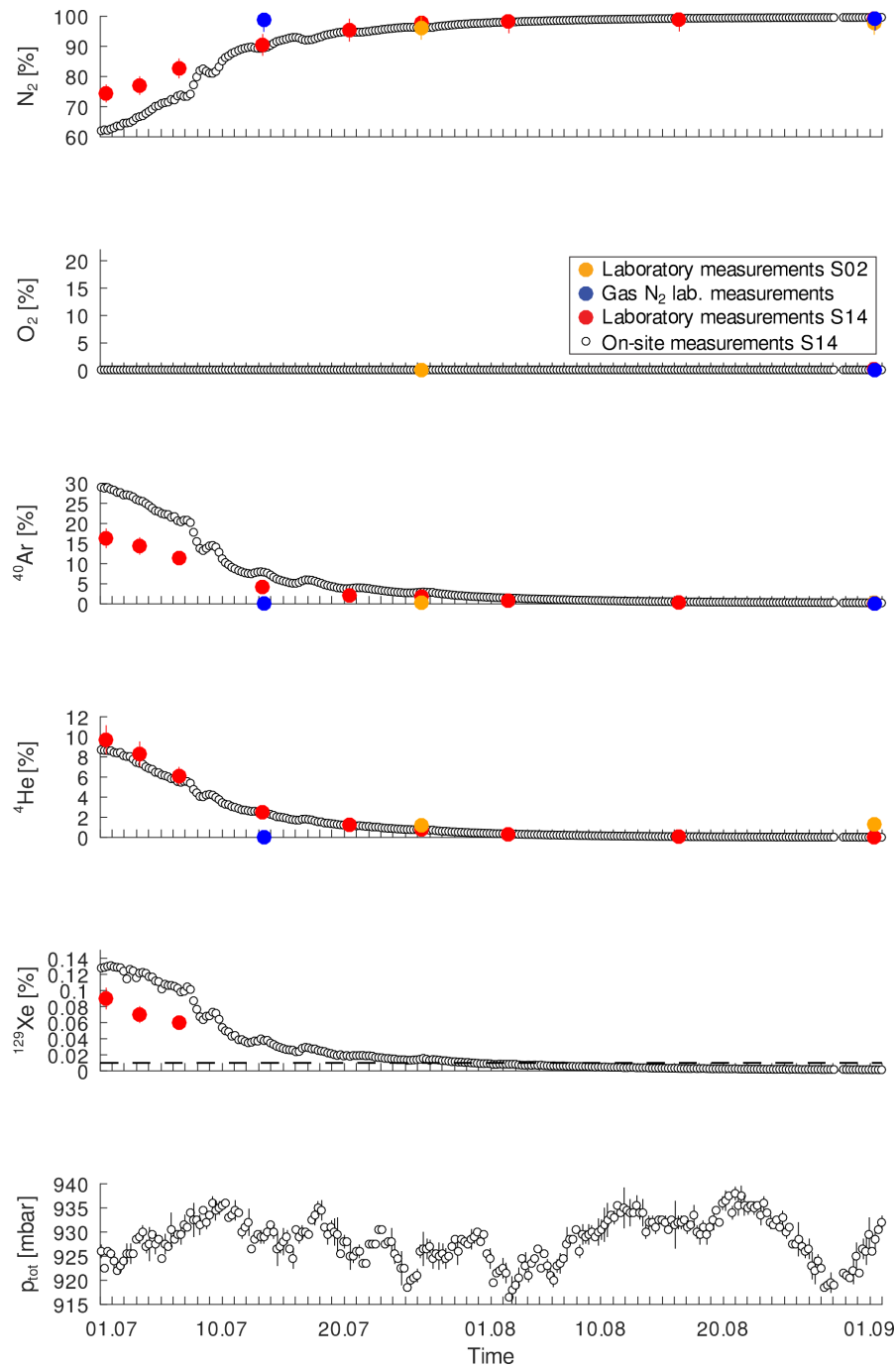


Fig. 4-79: Evolution of the gas composition with on-site and off-site measurements between 29 June 2023 and 01 September 2023 (Phase 9)

Empty circles: qualitative on-site measurements with miniRUEDI; red dots: quantitative off-site laboratory measurements of samples from PL_S14_L1; orange dots: off-site laboratory measurements on samples from PL_S02_L1; blue dots: off-site laboratory measurements of Gas N_2 samples. Vertical error bars indicate the respective analytical uncertainties. Horizontal error bars indicate the sampling time span. Results from off-site laboratory analyses are plotted only if above the respective detection limits. Horizontal dashed lines indicate the detection limit of off-site analyses.

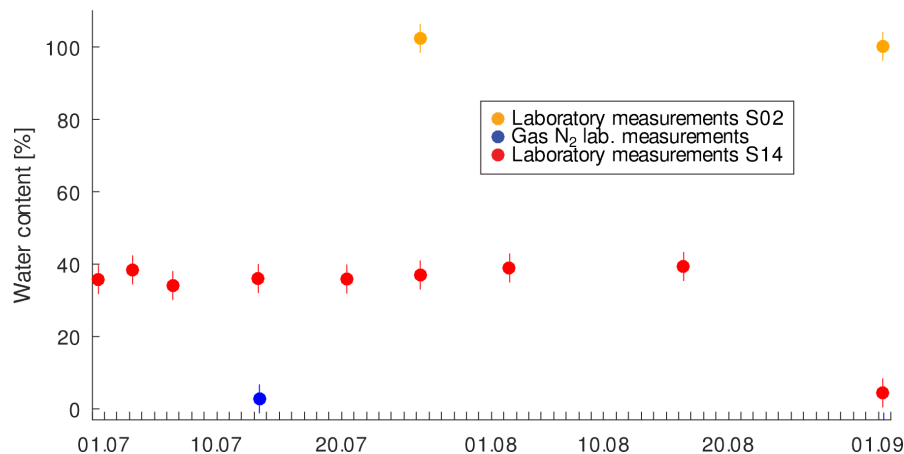


Fig. 4-80: Estimated water content in the samples for off-site analyses

The water content was calculated using the difference between the full and empty weights of the samplers normalised by the average volume of the used Swagelok cylinders.

4.6.7.2 Gas concentrations of PPE samples

Samples for off-site laboratory analyses were collected from the PPEs during the second cleaning with pure N₂ (Phase 9) to quantify and characterise the removal dynamics of the Gas Mix #2 tracers being injected during the second GFT (i.e., He, Ar, and Xe) inside the S/B layers. As for the preceding Phase 8, a parallel sampling was conducted at PPE_S06_L6H-2 and PPE_S10_L4, and three samples were collected at both PPEs during the same time periods to better investigate the temporal and spatial distributions of the gas tracers.

Off-site laboratory analyses conducted on PPE samples are summarised in Tab. 4-39.

Whenever detectable, only traces of O₂ were observed in the collected samples which supports the quality of the sampling within the experimental scopes.

The parallel sampling at PPE_S06_L6H-2 and PPE_S10_L4 illustrates the effect of the cleaning with pure N₂, and the related decrease in gas tracer concentrations over time. The fast response of the system to the N₂ injection is exemplified by rather low gas tracer concentrations already found in the first PPE samples to have been collected, compared to the respective concentrations at the end of Phase 8 (see Section 4.5.6.2). However, a slightly different behaviour characterises the two PPEs: the responsiveness of PPE_S06_L6H-2 to the N₂ injection is faster than that of PPE_S10_L4, hinting at a different degree of connection of the two PPEs with the main gas flow pathways. At PPE_S06_L6H-2, the He concentrations were already below the respective detection limit by 02 August 2023. On 24 August 2023, the gas signature at this PPE equalled that of injected pure N₂. Conversely, at PPE_S10_L4, the removal of the gas tracers was more gradual. At the end of the cleaning with N₂, traces of He (0.3%) and Ar (0.9%) were still detectable. On a side note, the last sample collected at PPE_S10_L4 showed low but quantifiable amounts of Xe (0.02%). As a significant increase of Xe does not seem reasonable with respect to the decreases in He and Ar, the quantification of Xe most likely occurred at the edge of the analytical detection limit, which would explain the impossibility to determine the Xe concentrations in the preceding samples.

One sample was collected from PPE_S08_L4 on 01 September 2023, coinciding with the end of N₂ injection. The gas composition of PPE_S08_L4 resembled that of PPE_S06_L6H-2, and the He share reached the lowest quantified value among all PPEs (0.04%), hinting at the presence of an active gas flow in proximity of this PPE inside the S/B. The presence of 0.2% of Ar (i.e., about twice the concentration found in the injected pure N₂) indicates that a small share of Gas Mix #2 is still likely to be present in the proximity of PPE_S08_L4.

At PPE_S03_L6L-1, an He share of 1.5% was determined, coinciding with the highest He concentration measured among all the PPEs, along with some Ar excess (0.6%). Notably, the sample was collected on 01 September 2023 (i.e., at the end of the flushing with pure N₂) suggesting again that this PPE is somehow isolated from the main gas flow pathways (see Section 4.5.6.2). The additional presence of a significant share of CH₄ (29%, see Enclosure J) is a further indication of the isolation of this PPE, and its samples might be biased by artifacts related to the sampling line (e.g., the use of bentogel).

Tab. 4-39: Gas composition in PPE samples collected during the second flushing with pure N₂ (Phase 9)

Water content: approximate percentage of the sampler volume filled with water. Tot.: total amount of dissolved gases in cm³_{STP}/kg. The relative composition in [%] was calculated from dissolved species abundance for samples where a direct measurement of a gas phase was not possible (numbers in italics). Full dataset of analytical results available in Enclosure J, full details of sample collection available in Enclosure K.

PPE	Start of collection (*)	Sampling date (*)	Water content	He	Ar	O ₂	N ₂	Tot.	He	Ar	Xe	O ₂	N ₂
			[%]	[cm ³ _{STP} /kg]					[%]				
S03_L6L-1	24.08.23 10:16	01.09.23 06:30	1						1.50	0.6	n.d.	0.06	68.3
S06_L6H-2	29.06.23 12:30	20.07.23 09:55	2						0.20	0.7	n.d.	0.10	99.3
S06_L6H-2	26.07.23 12:40	02.08.23 09:57	0						n.d.	0.3	n.d.	0.08	99.0
S06_L6H-2	16.08.23 13:30	24.08.23 07:17	0						n.d.	0.1	n.d.	0.10	99.3
S08_L4	24.08.23 10:16	01.09.23 06:30	1						0.04	0.2	n.d.	n.d.	98.6
S10_L4	29.06.23 12:30	20.07.23 09:55	2						1.30	3.5	n.d.	n.d.	94.7
S10_L4	26.07.23 12:40	02.08.23 09:57	4						0.50	1.7	n.d.	0.18	98.2
S10_L4	16.08.23 13:30	24.08.23 07:17	5						0.28	0.9	0.02	0.15	97.5

Tab. 4-41: Notes

- (*) Sampling date needs to be calculated back into S/B to account for PPE line length and extraction volumes, under piston flow model assumption and for samples not collected under vacuum:

PPE_S10_L4: line length 19.53 m, diameter 2.4 mm, approx. volume 88.4 cm³. Using an average extraction rate of 0.01 ml/min, the samples date back about 6 days in S/B compared to sampling date. Sample collected on 20 July 2023: line was purged from 29 June 2023 to 13 July 2023 at 0.01 ml/min, then sampler was reinstalled and about 99 additional ml were flushed until sample collection was complete. Successive samples were collected in sequence and line was not purged, with extraction rates kept at 0.01 ml/min.

PPE_S06_L6H-2: line length 22.84 m, diameter 2.4 mm, approx. volume 103.3 cm³. Using an average extraction rate of 0.012 ml/min, the samples date back about 6 days in S/B compared to sampling date. Sample collected on 20 July 2023: line was purged from 29 June 2023 to 13 July 2023 at 0.012 ml/min, then the sampler was reinstalled and about 118 additional ml were flushed until sample collection was complete. Successive samples were collected in sequence and line was not purged, with extraction rates kept at 0.012 ml/min.

PPE_S03_L6L-1: line length 25.32 m, diameter 2.4 mm, approx. volume 114.5 cm³. Using an extraction rate of 0.02 ml/min, samples date back about 4 days before in S/B compared to sampling date. Line cleaning was operated from 24 August 2023 to 29 August 2023, with 141 ml extracted. The sampler was inserted on 29 August 2023 and 80 – 90 additional ml were extracted until sampling was concluded.

PPE_S08_L4: line length 21.88 m, diameter 2.4 mm, approx. volume 98.9 cm³. Using an extraction rate of 0.02 ml/min, samples date back about 3 days before in S/B compared to sampling date. Line cleaning was operated from 24 August 2023 to 29 August 2023, with 141 ml extracted. The sampler was inserted on 29 August 2023 and 80 – 90 additional ml were extracted until sampling was concluded.

4.6.7.3 Gas sniffing results

The gas sniffing at the GAST plug did not reveal any measurable gas egressions from the experiment throughout the whole second N₂ flushing (i.e., the concentrations of all measured gas species did not fluctuate significantly, see Fig. 4-81).

No event resulting in experimental artifacts for the gas sniffing of the GAST plug is known for the second N₂ flushing.

4.6.8 Phase 9 summary

During Phase 9, continued rate-controlled gas injection into S02 and extraction from S14 resulted in the further development of the gas path with a reduction in the pressure gradient across the seal section with a constant rate injection (1,000 mln/min).

The stable gas path allowed continued sampling from the S14 extraction and from selected piezometers. These samples clearly showed the tailing of the Gas Mix #2 tracers (He, Ar and Xe) caused by flushing with nitrogen.

Continuous extraction and regular sampling from two piezometers showed differences in gas tracer transport within the seal, complementary to those observed during Phase 8.

Hydraulic index tests (PW) performed in the PPEs within the seal section were used to monitor compressibility changes around the piezometers in the seal section.

Total pressure measurements demonstrated that overall compressive stress was maintained within the seal section during the phase.

No leakage of gas into the WT tunnel was detected during the period.

4.7 Gas Flow Test flow path diagnostics (Phase 10)

4.7.1 Phase 10 aims

Section 4.7 describes the field work and results obtained during GFT Phase 10.

Phase 10 focused on characterisation of the gas flow path using step-rate nitrogen injections and operations to remove gas from the filters and buffer to accelerate eventual resaturation. The objectives for Phase 10 were to:

- Test the robustness of the gas path after an extended shut-in
- Examine rate dependence by using a series of step rate injections

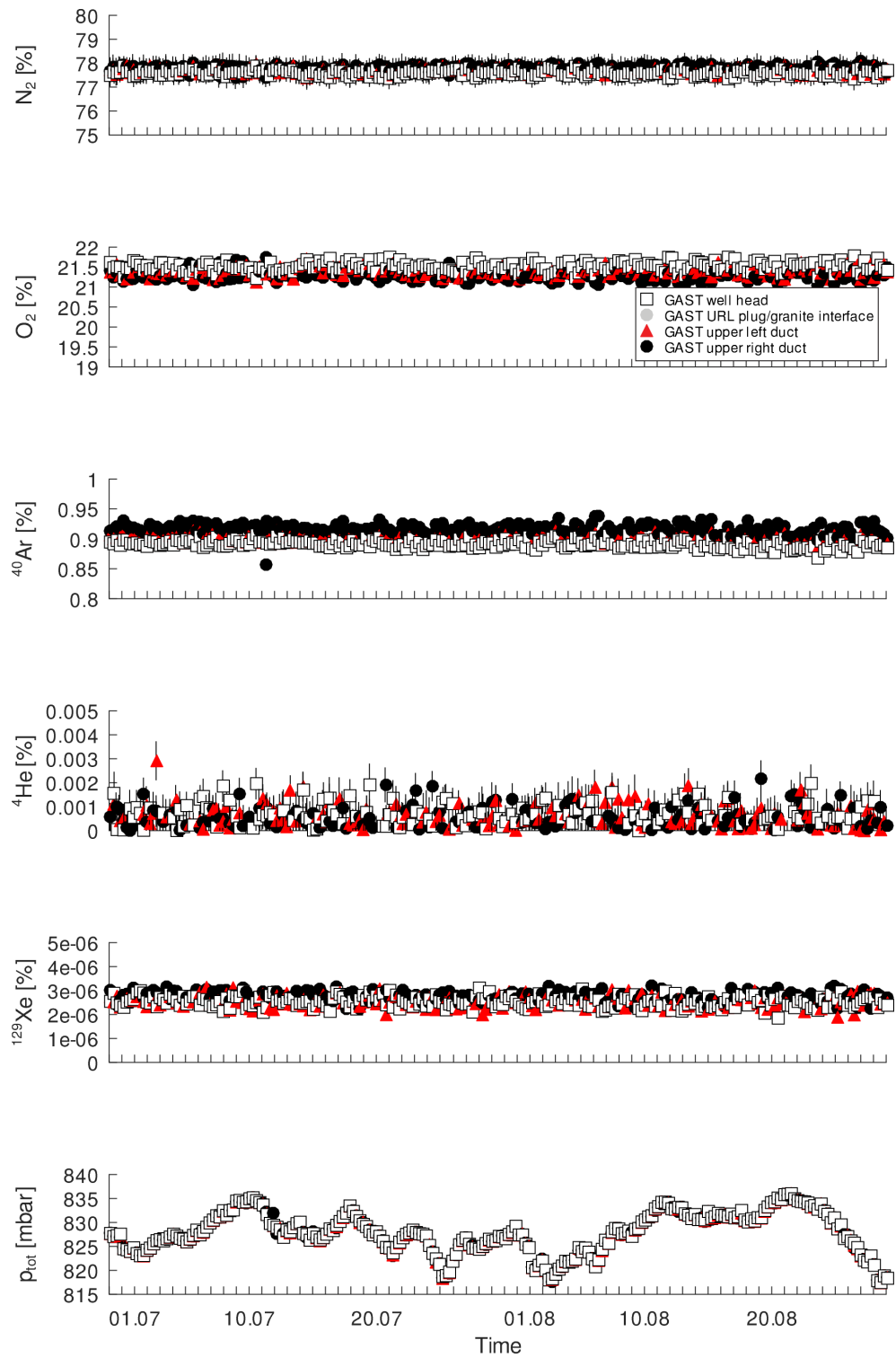


Fig. 4-81: Gas composition at the GAST plug between 29 June 2023 and 01 September 2023 (Phase 9)

Empty squares: well head; grey circles: URL plug/granite interface; red triangles: ULD; black dots: URD.

4.7.2 Field activities

The injection of pure nitrogen N₂ in PL_S02_L6L-2 was shut in on 01 September 2023 at 11:00. Between 22 September and 27 October 2023, a step rate test was conducted with the injection in PL_S02_L6L-2 and the extraction from PL_S14_L1. The events on the injection and extraction sides are summarised in Tab. 4-40. The layout of the surface equipment is given in Fig. 4-82. The surface equipment was not changed during Phase 9 except for the removal of the diffusion module.

During this phase, the N₂ gas injection rate was decreased from 1,380 to 45 mln/min. The corresponding overview graph is given in Fig. 4-84.

The volumetric extraction from S14 was started at 99.36 ml/min and was eventually decreased to 12.96 ml/min prior to shut-in. The extraction rate was adjusted at each injection rate step to be approximately equivalent to the S02 gas mass injection rate accounting for the pressure and temperature at the S14 extraction. The corresponding overview graph is given in Fig. 4-85. The overview of the injection and extraction parameters and the corresponding volumes is given in Tab. 4-41. On 27 October 2023, a one-hour slug extraction was conducted at port PL_S02_L6L-2 to estimate the S02 filter gas volume. The graph with pressure, flow rate and total volume is shown in Fig. 4-86. The corresponding volumes are given in Tab. 4-41.

In addition, short rate withdrawal tests (RW) were performed in the following ports: PPE_S03_L6L-1, PPE_S10_L4, PPE_S08_L4, PPE_S06_L6H-2 and PPE_S12_L6L-1. The aim of these ~1-hour tests was to assess the ability to remove gas from the seal section via the port lines.

Tab. 4-40: Main field activities during GFT flow path diagnostics (Phase 10) between 01 September 2023 and 01 November 2023

Date & time	Gas injection PL_S02_L6L-2	Extraction PL_S14_L1 Total gas + water flow	Comments
01.09.23 11:00	Shut-in N ₂ injection	Shut-in extraction	Final shut-in
22.09.23 05:00	Start N ₂ injection 1,380 mln/min		Start step rate test
22.09.23 10:00		Start extraction 99.36 ml/min	
29.09.23 10:03	540 mln/min	38.88 ml/min	
09.10.23 07:00	45 mln/min		
10.10.23 09:05		12.96 ml/min	
10.10.23 07:00	180 mln/min		
12.10.23 09:06	45 mln/min	Shut-in extraction	
18.10.23 14:35	Shut-in N ₂ injection		Stop shut-in test
27.10.23 12:40	Start slug extraction		PL_S02_L6L-2
27.10.23 13:44	Stop slug extraction		

Tab. 4-41: Overview of injection and extraction parameters during GFT flow path diagnostics (Phase 10)

	P from [bar]	P to [bar]	Flow rate from	Flow rate to	Volume STP [ln]	Volume @ T, P [l]	Comments
GFT step rate test with N ₂ : 22.09.23 05:00 – 27.10.23 12:40							
Injection S02 N ₂	17.2	18.0	1,380 mln/min	45 mln/min	21,560.74	1,327.48	Step rate
Extraction S14 gas	15.0	14.3	99 ml/min	13 ml/min	20,093.66	1,475.56	Step rate
Extraction S14 water						2.58	
GFT slug extraction test in PL_S02_L6L-2: 27.10.23 12:40 – 13:44							
Extraction gas	15.5	14.5	181 ln/min	6.8 ln/min	359.85	25.75	Slug test

T: Temperature of 16 °C

P: Pressure at the time stamp

STP: Standard conditions (T = 273.15 K, P = 101.325 kPa)

4.7.3 Flow control

After the shut-in of GFT Phase 9, the diffusion module was removed from the surface equipment.

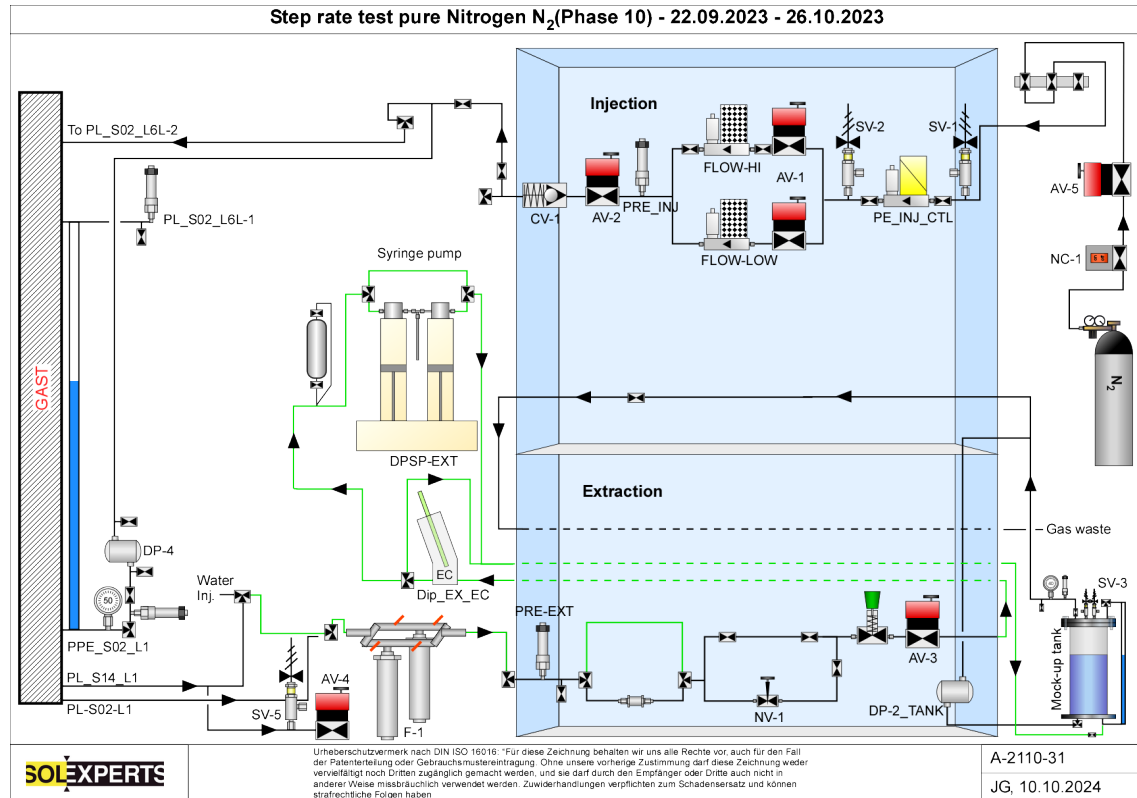


Fig. 4-82: Layout of surface equipment for GFT between 22 September 2023 and 26 October 2023

4.7.4 Index testing

During GFT flow path diagnostics (Phase 10), two PW test campaigns were performed on 21 September 2023 and on 26 October 2023, respectively. The applied procedure is described in Section 4.1.5.

The test parameters are summarised in Tab. 4-42 and Tab. 4-43. The graphs of the PW tests are shown in Enclosure N.5. An overview of the calculated compressibilities between July and October 2023 is shown in Fig. 4-83.

Please note that the filling volume of the 2 ml volume line piece could not be controlled during the tests. Therefore, the ΔV in Tab. 4-42 and Tab. 4-43 might overestimate the true extracted volume.

Tab. 4-42: Results of PW tests from PPE lines in September 2023

Date	Time	Sensor	ΔP [kPa]	$\Delta V^{(1)}$ [ml]	C [m ³ /Pa]	
21.09.23	7:05	PPE_S06_L6L-1	205.61	2.00	9.73E-12	Very slow increase
21.09.23	7:15	PPE_S09_L4	347.36	2.00	5.76E-12	
21.09.23	7:36	PPE_S03_L4	1,314.93	2.00	1.52E-12	Fast increase
21.09.23	9:15	PPE_S04_L3	1,501.60	2.00	1.33E-12	
21.09.23	9:17	PPE_S06_L4	196.82	2.00	1.02E-11	Very slow increase
21.09.23	9:19	PPE_S07_L2	1,410.10	2.00	1.42E-12	Fast increase
21.09.23	9:55	PPE_S12_L2-1	1,420.35	2.00	1.41E-12	Slow increase
21.09.23	10:05	PPE_S10_L6L-1	181.17	2.00	1.10E-11	
21.09.23	10:12	PPE_S03_L2-1	1,388.46	2.00	1.44E-12	Very fast increase
21.09.23	10:24	PPE_S06_L3	1,453.00	2.00	1.38E-12	Slow increase
21.09.23	10:28	PPE_S07_L4	425.72	2.00	4.70E-12	Very fast increase
21.09.23	10:43	PPE_S12_L2-2	1,429.52	2.00	1.40E-12	Fast increase
21.09.23	10:48	PPE_S03_L3	1,255.89	2.00	1.59E-12	Slow increase
21.09.23	10:55	PPE_S06_L2	1,468.66	2.00	1.36E-12	
21.09.23	12:07	PPE_S08_L2	1,424.40	2.00	1.40E-12	
21.09.23	12:13	PPE_S08_L6L	715.39	2.00	2.80E-12	
21.09.23	12:16	PPE_S09_L2	1,423.92	2.00	1.40E-12	
21.09.23	12:32	PPE_S11_L3	1,420.83	2.00	1.41E-12	
21.09.23	12:36	PPE_S10_L3	1,423.53	2.00	1.40E-12	
21.09.23	12:44	PPE_S12_L3	1,401.31	2.00	1.43E-12	Fast increase
21.09.23	12:46	PPE_S12_L4	460.98	2.00	4.34E-12	Very fast increase
21.09.23	13:02	PPE_S10_L6H-2	267.64	2.00	7.47E-12	Slow to fast increase
21.09.23	13:04	PPE_S10_L2	1,298.31	2.00	1.54E-12	
21.09.23	13:07	PPE_S03_L6H-2	107.35	2.00	1.86E-11	Very slow increase with jumps
21.09.23	13:11	PPE_S12_L6H-2	222.52	2.00	8.99E-12	Very fast increase
21.09.23	13:15	PPE_S03_L2-2	1,065.84	2.00	1.88E-12	Fast increase
21.09.23	13:24	PPE_S08_L3	1,421.99	2.00	1.41E-12	
21.09.23	13:26	PPE_S12_L6L-1	60.39	2.00	3.31E-11	
21.09.23	13:47	PPE_S03_L6L-1	20.39	2.00	9.81E-11	Fast increase
21.09.23	14:02	PPE_S06_L6H-2	27.73	2.00	7.21E-11	
21.09.23	14:02	PPE_S08_L4	17.10	2.00	1.17E-10	
21.09.23	14:06	PPE_S10_L4	33.43	2.00	5.98E-11	

⁽¹⁾ Line piece with about 2 ml volume connected to PPE port, true volume unknown

Colours: red: higher compressibility $C > 5E-12$ m³/Pa, green: very slow increase, blue: very fast increase

Tab. 4-43: Results of PW tests from PPE lines in October 2023

Date	Time	Sensor	ΔP [kPa]	$\Delta V^{(1)}$ [ml]	C [m ³ /Pa]	
26.10.23	8:18	PPE_S06_L6L-1	180.30	2.00	1.11E-11	Very slow increase
26.10.23	8:24	PPE_S03_L6L-1	18.17	2.00	1.10E-10	
26.10.23	8:46	PPE_S08_L4	31.21	2.00	6.41E-11	Fast increase
26.10.23	9:07	PPE_S09_L4	295.76	2.00	6.76E-12	
26.10.23	9:23	PPE_S03_L4	1,228.45	2.00	1.63E-12	Fast increase
26.10.23	9:24	PPE_S04_L3	1,501.60	2.00	1.33E-12	
26.10.23	9:31	PPE_S06_L4	169.38	2.00	1.18E-11	Very slow increase
26.10.23	9:33	PPE_S07_L2	1,420.25	2.00	1.41E-12	Fast increase
26.10.23	10:01	PPE_S12_L2-1	1,419.28	2.00	1.41E-12	
26.10.23	10:03	PPE_S10_L6L-1	167.64	2.00	1.19E-11	
26.10.23	10:05	PPE_S03_L2-1	1,471.21	2.00	1.36E-12	Very fast increase
26.10.23	10:07	PPE_S06_L3	1,461.22	2.00	1.37E-12	
26.10.23	10:35	PPE_S07_L4	364.85	2.00	5.48E-12	Very fast increase
26.10.23	10:36	PPE_S12_L2-2	1,445.95	2.00	1.38E-12	
26.10.23	10:38	PPE_S03_L3	1,264.69	2.00	1.58E-12	Slow increase
26.10.23	10:41	PPE_S06_L2	1,477.35	2.00	1.35E-12	Fast increase
26.10.23	10:43	PPE_S08_L2	1,433.10	2.00	1.40E-12	
26.10.23	10:45	PPE_S08_L6L	553.36	2.00	3.61E-12	Very slow increase
26.10.23	10:47	PPE_S09_L2	1,442.67	2.00	1.39E-12	
26.10.23	10:52	PPE_S11_L3	1,437.35	2.00	1.39E-12	
26.10.23	10:54	PPE_S10_L3	1,438.70	2.00	1.39E-12	
26.10.23	12:18	PPE_S12_L3	1,392.90	2.00	1.44E-12	Very fast increase
26.10.23	12:20	PPE_S12_L4	389.97	2.00	5.13E-12	Very fast increase
26.10.23	12:22	PPE_S10_L6H-2	234.70	2.00	8.52E-12	
26.10.23	12:27	PPE_S10_L2	1,306.33	2.00	1.53E-12	
26.10.23	12:38	PPE_S03_L6H-2	102.23	2.00	1.96E-11	Very slow increase with jumps
26.10.23	12:48	PPE_S12_L6H	198.56	2.00	1.01E-11	Very fast increase
26.10.23	12:50	PPE_S03_L2-2	1,221.50	2.00	1.64E-12	Fast increase
26.10.23	12:57	PPE_S08_L3	1,431.07	2.00	1.40E-12	
26.10.23	13:00	PPE_S12_L6L	64.35	2.00	3.11E-11	
26.10.23	13:03	PPE_S03_L6L-1	22.90	2.00	8.73E-11	Fast increase

Tab. 4-43: Cont.

Date	Time	Sensor	ΔP [kPa]	$\Delta V^{(1)}$ [ml]	C [m ³ /Pa]	
26.10.23	13:48	PPE_S06_L6H-2	28.41	2.00	7.04E-11	
26.10.23	13:50	PPE_S08_L4	31.02	2.00	6.45E-11	
26.10.23	13:53	PPE_S10_L4	35.27	2.00	5.67E-11	

⁽¹⁾ Line piece with about 2 ml volume connected to PPE port, true volume unknown

Colours: red: higher compressibility $C > 5E-12$ m³/Pa, green: very slow increase, blue: very fast increase

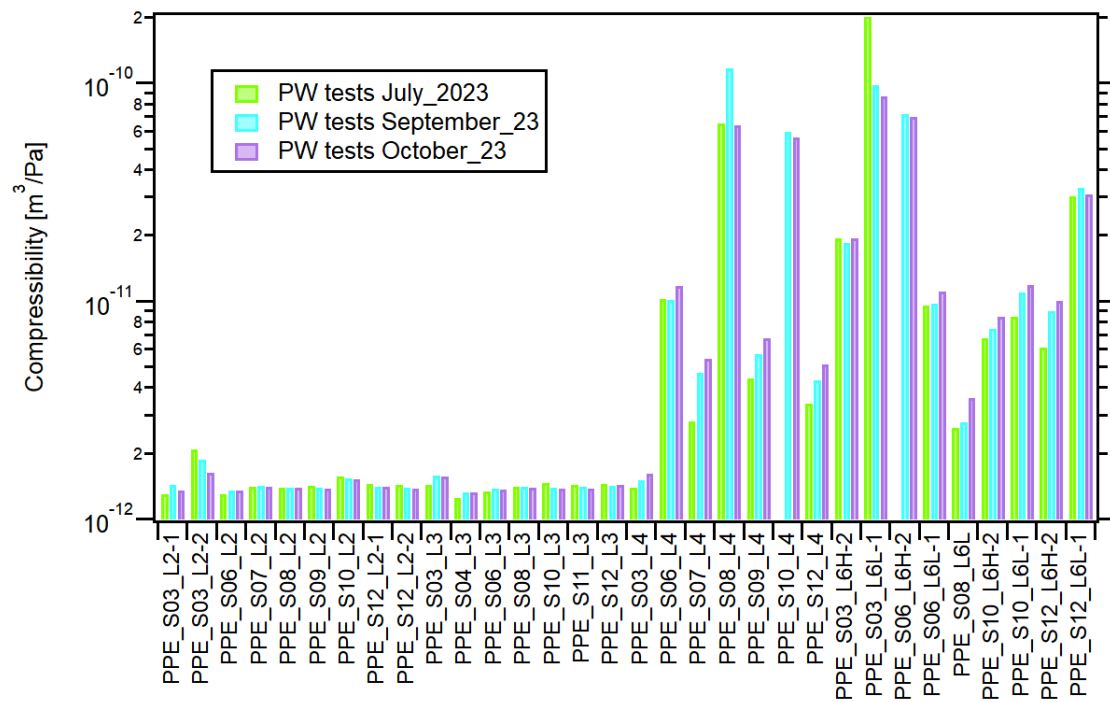


Fig. 4-83: Overview of calculated compressibilities from PW tests in July 2023 (Phase 7), September 2023 and October 2023 (Phase 10)

4.7.5 Monitoring data

The monitoring data for Phase 10 are shown in Fig. 4-84 (injection side) and Fig. 4-85 (extraction side). Flow rates were adjusted as a series of constant mass rate steps (mln/min) in S02 and constant volumetric rate steps (ml/min) in S14 (see Tab. 4-40). During this phase, pressures in S02 were controlled by the step rate changes with an initial rising transient followed by stabilisation for each step. Pressure in S02 showed comparable variations again with an initial transient at the start of each step. Fig. 4-86 shows the S02 response to the slug extraction test.

Many of the point TDRs (TDP sensors) showed no changes during Phase 10. As in the previous phases, the responses of some TDPs were not straightforward enough to directly infer physical changes resulting from the nitrogen injection performed in Phase 9. The TDL sensors showed a stable gas accumulation in the S14 filter during Phase 9 without major dynamic changes (Enclosure M).

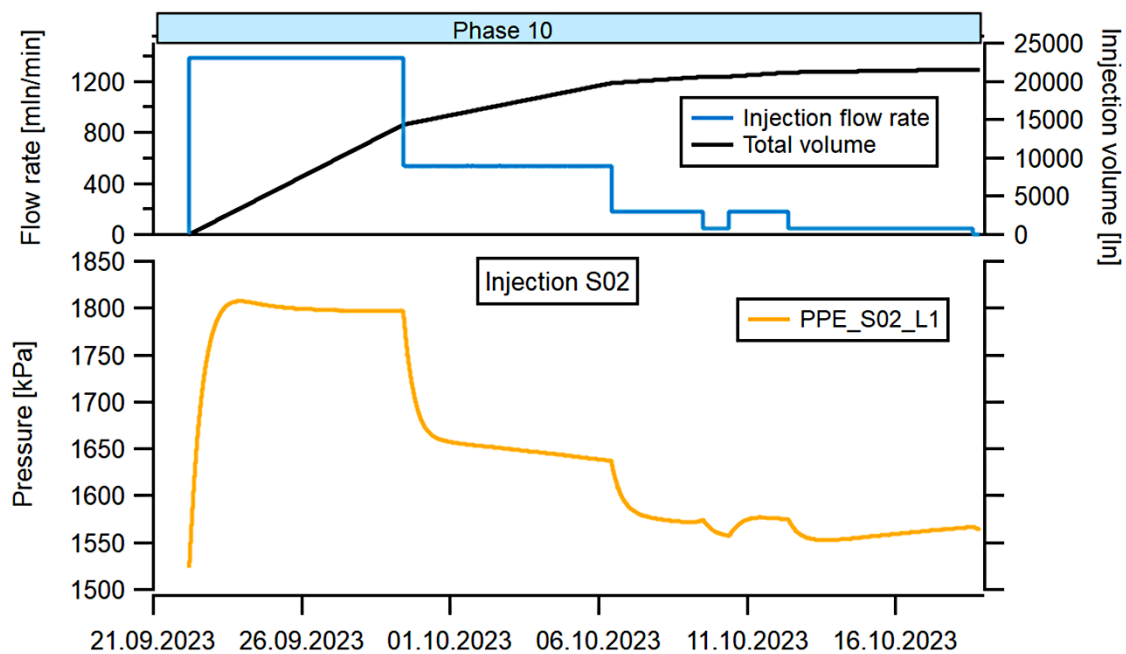


Fig. 4-84: Injection pressures, flow rate and total volume for GFT step rate test (Phase 10)

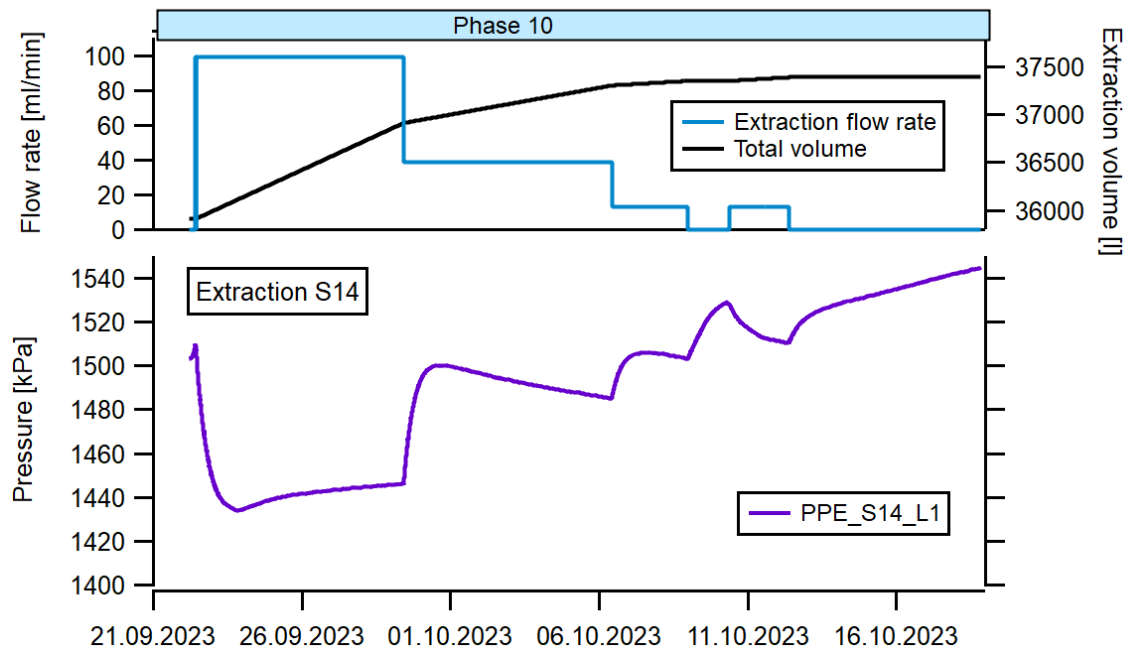


Fig. 4-85: Extraction pressures, flow rate and total volume for GFT step rate test (Phase 10)

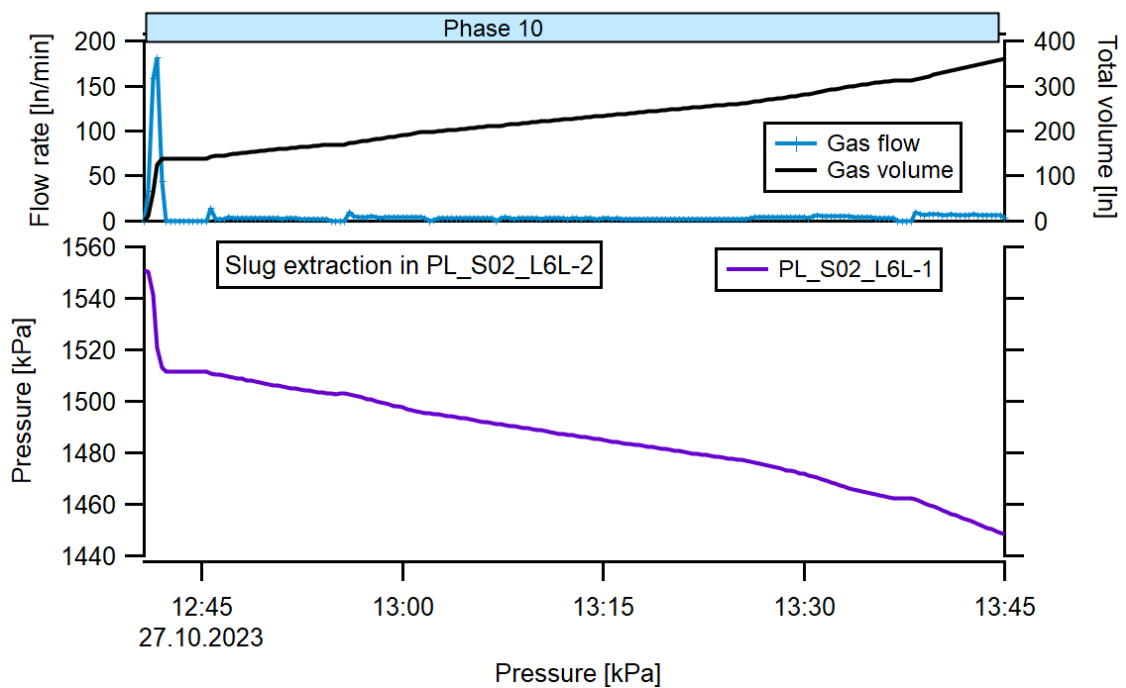


Fig. 4-86: Pressures, flow rate and total volume for GFT slug extraction test (Phase 10)

4.7.6 Sampling

Following the Phase 9 flushing with N₂ of the Gas Mix #2 tracers injected during Phase 8, all gas tracer activities were completed and no samples were taken during Phase 10.

4.8 Gas Flow Test gas removal (Phase 11)

4.8.1 Phase 11 aims

Section 4.78 describes the field work and results obtained during GFT Phase 11. The objective for Phase 11 was to remove as much gas as possible from the system prior to the resaturation phase. In order to do so for the S14 filter, the gas flow direction was reversed with gas and then water was injected into S14 and gas was extracted from S02. Although the primary aim was the removal of gas, these activities also provided valuable characterisation data regarding the gas path around S14.

4.8.2 Field activities

Different tests were performed during Phase 11 to remove gas from the system. The events on the injection and extraction sides are summarised in Tab. 4-44. The corresponding volumes are given in Tab. 4-45. The layout of the surface equipment for the reverse flow test (gas flow from S14 to S02) is given in Fig. 4-87, for the G-WX in Fig. 4-88.

On 01 November 2023, the reverse flow test was started with the injection of gas in PL_S14_L1 and extraction from PL_S02_L6L-2. On 07 November 2023, gas injection was stopped, and water injection was started to displace gas from the S14 filter (Fig. 4-89 and Fig. 4-90).

After the gas path out of S14 closed, preventing further displacement of gas from the S14 filter, the S02 filter G-WX was performed between 24 and 27 November 2023 with injection in PL_S02_L1 and extraction from PL_S092_L6L-2. The corresponding overview graphs are given in Fig. 4-91 and Fig. 4-92.

On 29 November 2023, a short pulse injection test was performed in PL_S02_L1 (Fig. 4-93) to determine the remaining gas volume within the filter.

On 29 and 30 November 2023, a test with alternating injection and extraction and a pulse extraction was conducted in PL_S14_L1 (Fig. 4-94) to check whether more gas could be extracted and determine the gas volume trapped within S14.

On 30 November 2023, a short pulse extraction test was performed in PL_S14_L1 (Fig. 4-95).

An additional gas extraction test was performed in S02 on 15 December 2023 with almost no gas extracted (Fig. 4-96, Fig. 4-97).

Gas extraction tests were additionally made in PPE_S10_L4 and PPE_S06_L6H-2.

Tab. 4-44: Main field activities during GFT gas removal (Phase 11) between 01 November 2023 and 31 December 2023

Date & time	PL_S02_L1 [ml/min]	PL_S02_L6L-2 [ml/min]	PL_S14_L1 [mln/min / ml/min]	Comments
01.11.23 10:00			Gas injection with 1,200	Start reverse flow with gas injection
01.11.23 15:33		Extraction 80		
01.11.23 10:00			Shut -in gas injection	
06.11.23 08:24		Extraction 80	Gas injection 1,000	
07.11.23 12:00		Extraction 80	Shut-in gas injection Start water injection 63.29	Reverse flow with water injection
08.11.23 12:00		Extraction 72		
10.11.23 12:00		Extraction 65		
13.11.23 09:08		Extraction 60 → 12	Water injection 28 → 20 → 9	Step rate injection
14.11.23 15:02			Water injection 400	Short pulse injection test
14.11.23 15:50		Shut in	Shut in	
24.11.23 10:41	Injection 80 → 40			Start G-WX
24.11.23 11:22		Extraction 80 → 40		
27.11.23 06:43	Shut-in	Shut-in		Shut-in G-WX
29.11.23 09:15 – 11:30	Pulse injection 80			
29.11.23 14:13 – 15:48			Alternating injection and extraction with 100	
30.11.23 07:59 – 11:33			Pulse extraction with 80	
15.12.23 11:44 – 15:12	Injection 80	Extraction 80		Gas extraction, but almost no gas

Tab. 4-45: Overview of injection and extraction parameters during GFT gas removal (Phase 11)

	P from [bar]	P to [bar]	Flow rate from	Flow rate to	Volume STP [ln]	Volume @ T, P [l]	Comments
Reverse flow test: 01.11.23 10:00 – 14.11.23 15:50							
Injection S14 N ₂	15	16.3	1,200 mln/min	1,000 mln/min	3,869.90	263.92	PL_S14_L1
Injection S14 water	14.8	16.6	63 ml/min	9 ml/min		457.88	PL_S14_L1
Extraction S02 gas	15.0	10.8	80 ml/min	12 ml/min	8,625.66	743.20	PL_S02_L6L-2
G-WX in PL_S02_L6L-2: 24.11.23 10:41 – 27.11.23 06:43							
Injection S02	11.2		80 ml/min	40 ml/min		277.37	PL_S02_L1
Extraction S02 gas	11.2		80 ml/min	40 ml/min	2,022.21	192.66	PL_S02_L6L-2
Extraction S02 water						73.90	PL_S02_L6L-2
Pulse injection in PL_S02_L1 29.11.23 09:15 – 11:30							
Injection water	11.3	12.3	80 ml/min			10.98	PL_S02_L1
Injection / extraction PL_S14_L1: 29.11.23 14:13 – 15:48							
Injection S14	16		100 ml/min			2.87	PL_S14_L1
Extraction S14 gas	16		100 ml/min	80 ml/min	21.58	1.44	PL_S14_L1
Extraction S14 water						4.37	
Injection / extraction S01_L1: 15.12.23 11:44 – 15:12							
Injection water	12.2	12.3	80 ml/min			15.93	PL_S02_L1
Extraction water			80 ml/min			15.37	PL_S02_L6L-2

T: Temperature of 16 °C

P: Pressure at the time stamp

STP: Standard conditions (T = 273.15 K, P = 101.325 kPa)

4.8.3 Flow control

For the reverse flow phase, the injection side of the surface equipment was connected to PL_S14_L1 and the extraction side to PL_S02_L6L-2. Gas was injected from the N₂ bottle with FLOW_HI. Water injection was made with water from BOADUS and a water flow controller named S14_INJ_HI. Extraction was made through the double piston syringe pump and mock-up tank.

For the S02 G-WX phase, BOADUS water was injected in PL_S02_L1 via a downstream pressure regulator and a piston tank, with the same water flow controller to control water injection. For extraction from PL_S02_L6L-1, the previously used setup was used.

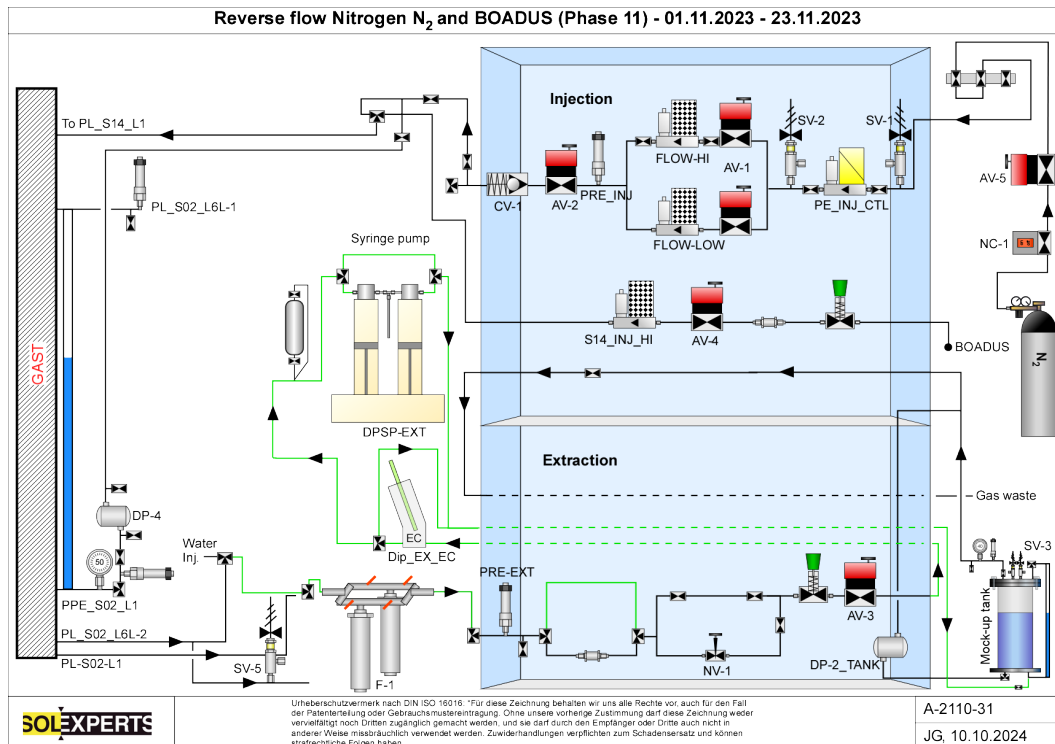


Fig. 4-87: Layout of surface equipment for the GFT between 01 November 2023 and 23 November 2023

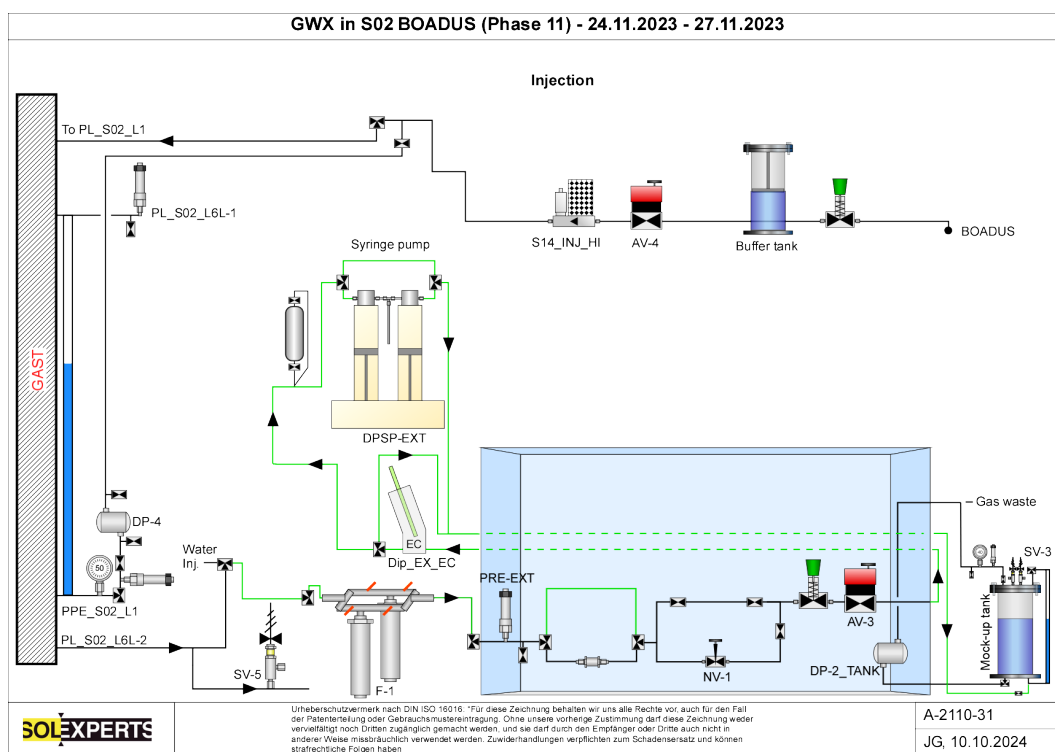


Fig. 4-88: Layout of surface equipment for the GFT for G-WX between 23 November 2023 and 27 November 2023

4.8.4 Monitoring data

The monitoring data for the Phase 11 reverse flow period are shown in Fig. 4-89 (S14 injection side) and Fig. 4-90 (S02 extraction side). The different steps of the reverse flow procedure are listed in Tab. 4-44. The reversal of flow gradient direction with higher pressure in S14 and lower pressure in S02 was achieved after injection and extraction were resumed on 06 November 23. Flow rates and pressures were adjusted to maximise the gas outflow from S02 once the injection into S14 was switched to water. The reverse flow was halted when it became clear that the gas path from S14 had closed, and pressures rose strongly when further water was injected.

Fig. 4-91 shows the measured flow rates, volumes and pressure during the final S02 gas water exchange.

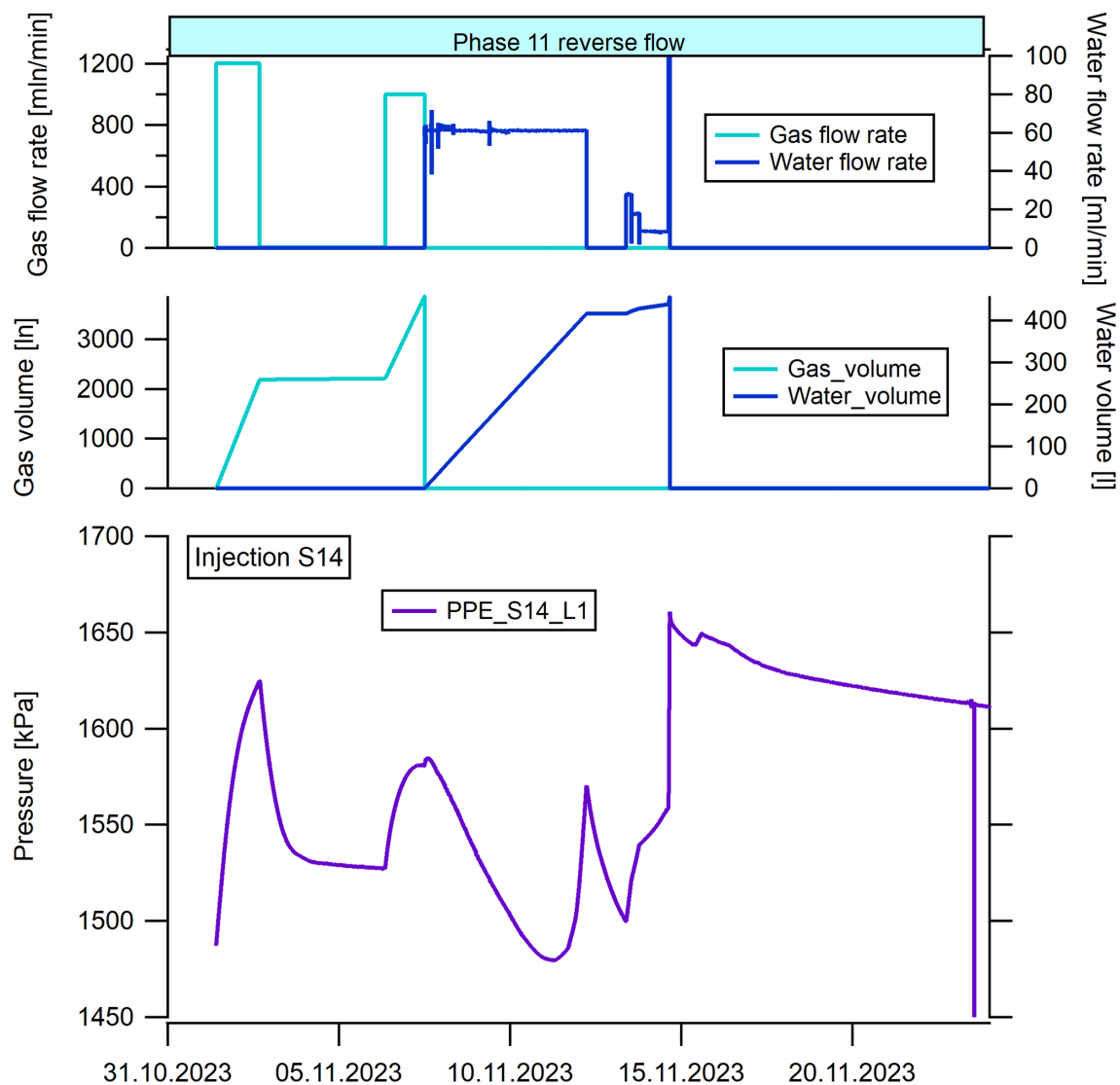


Fig. 4-89: Injection pressures, flow rates and total volumes for reverse flow test (Phase 11) with injection into S14 and extraction from S02

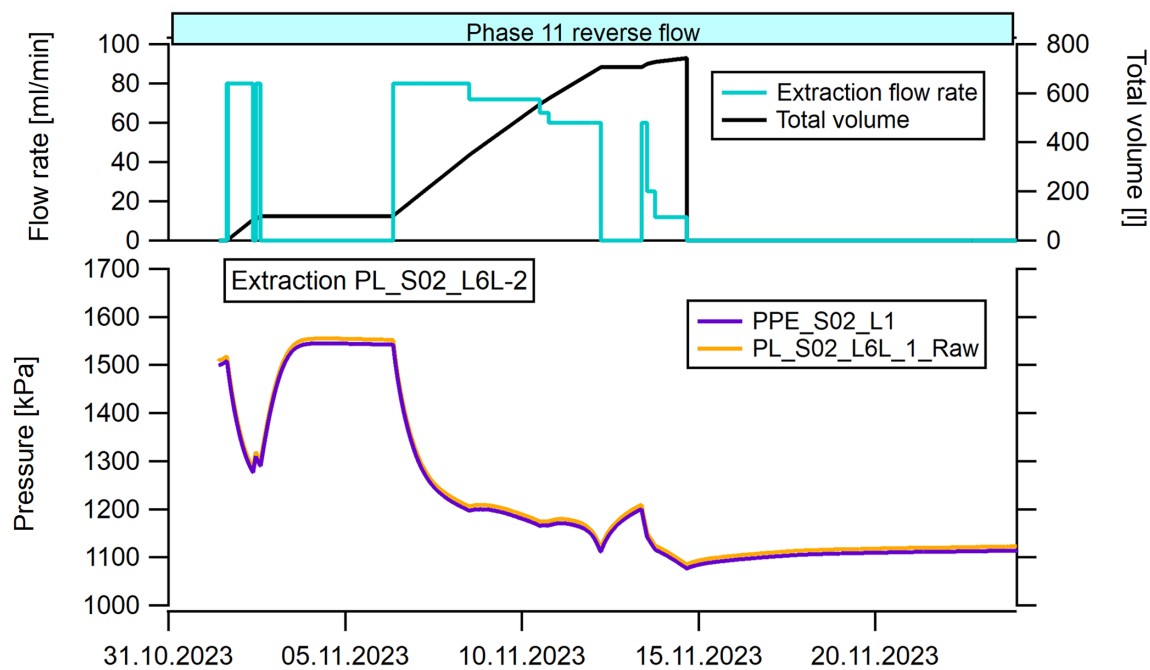


Fig. 4-90: Extraction pressures, flow rates and total volume for reverse flow test (Phase 11) with injection into S14 and extraction from S02

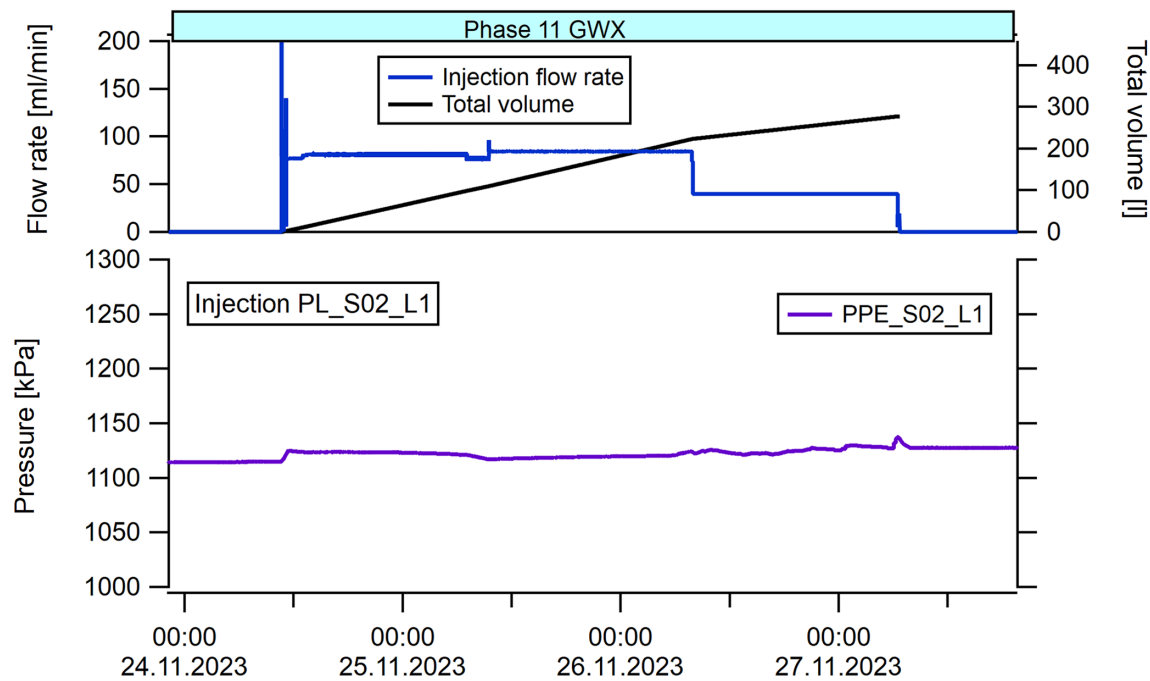


Fig. 4-91: Injection pressures, flow rates and total volumes for S02 G-WX test (Phase 11)

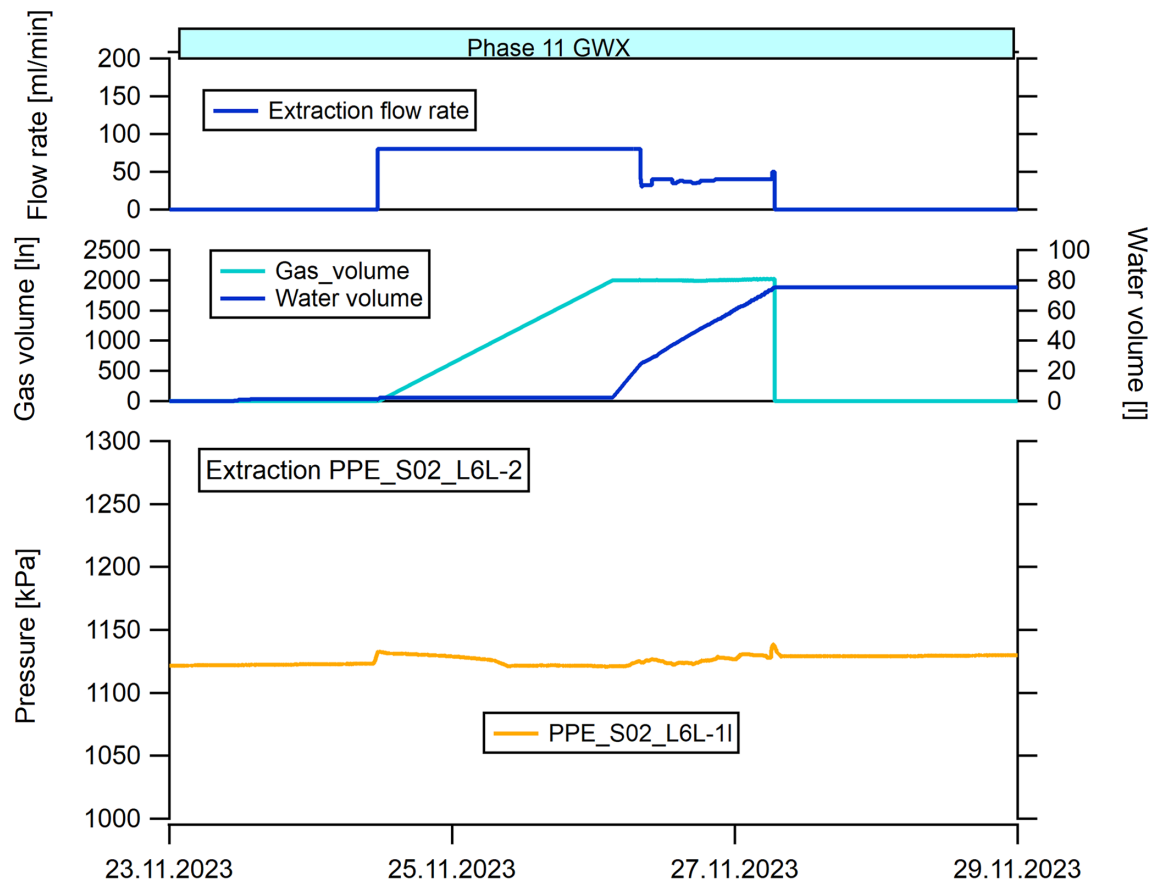


Fig. 4-92: Extraction pressures, flow rates and total volumes for S02 G-WX test (Phase 11)

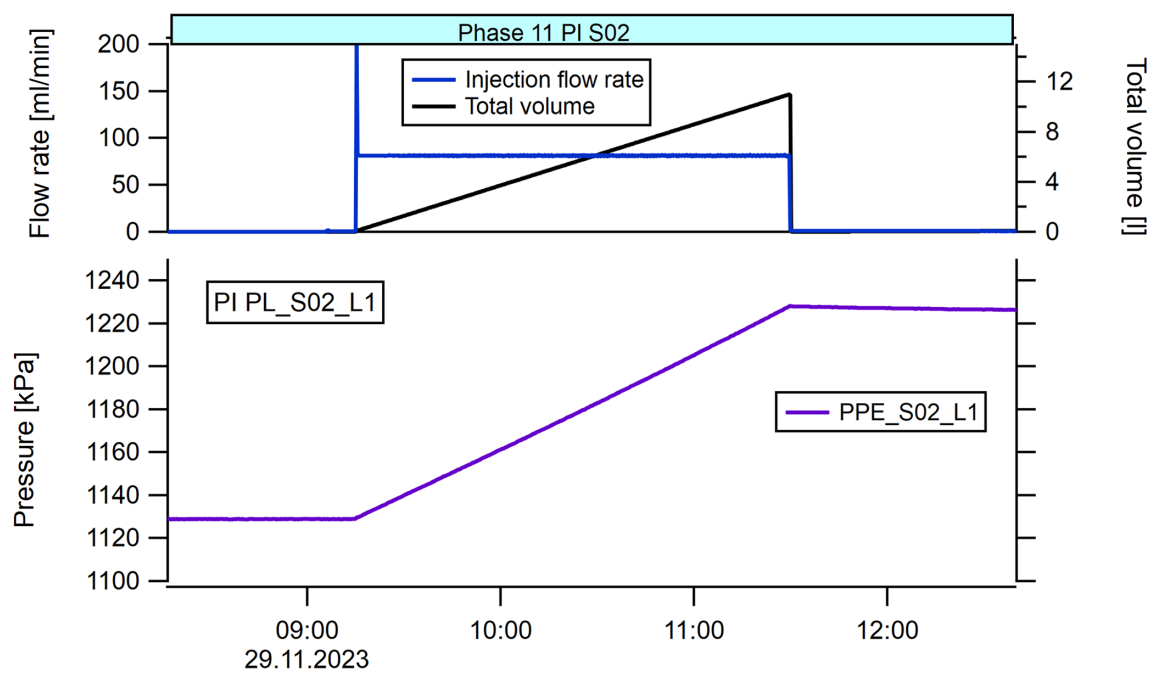


Fig. 4-93: Pressure, flow rate and total volumes for PI test in PL_S02_L1 (Phase 11)

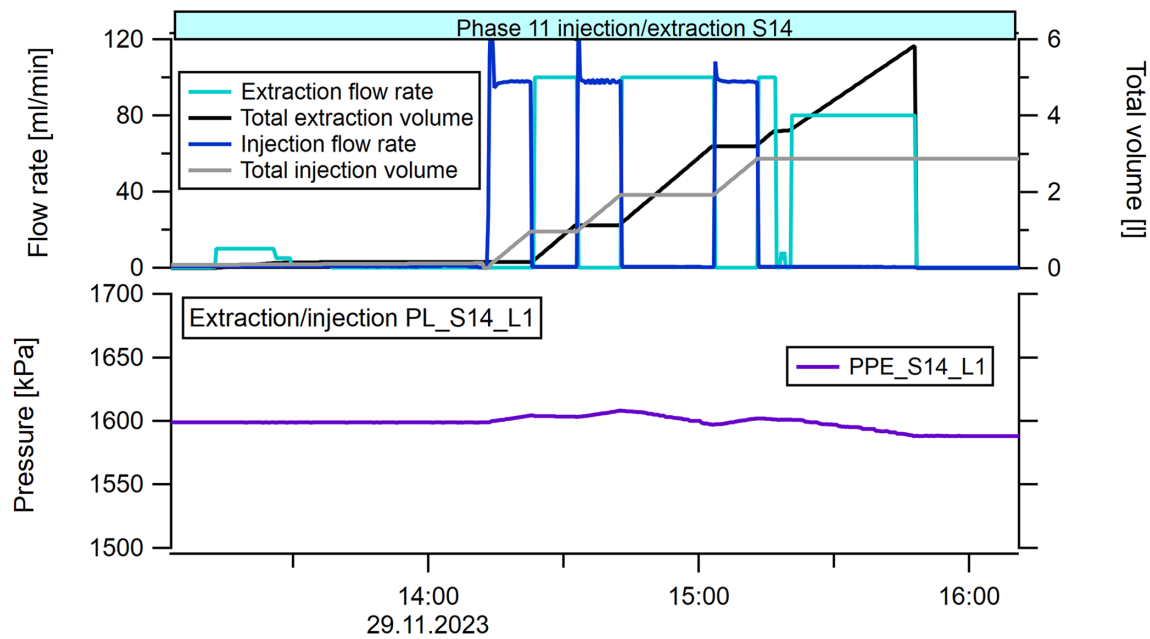


Fig. 4-94: Pressures, flow rates and total volumes for injection/extraction test in PL_S14_L1 (Phase 11)

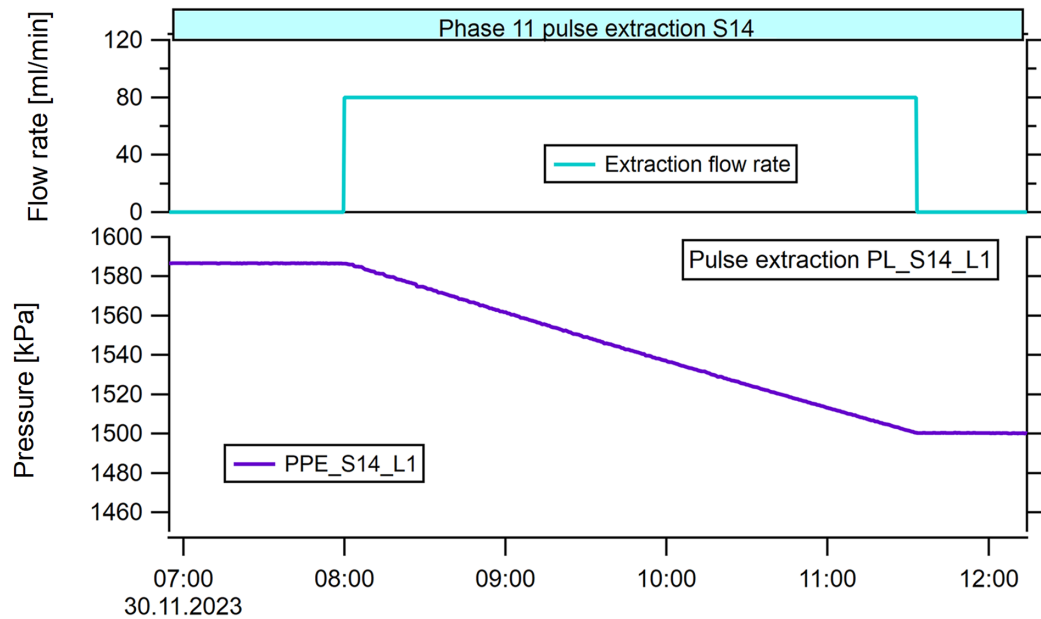


Fig. 4-95: Pressure and flow rate for pulse extraction test in PL_S14_L1 (Phase 11)

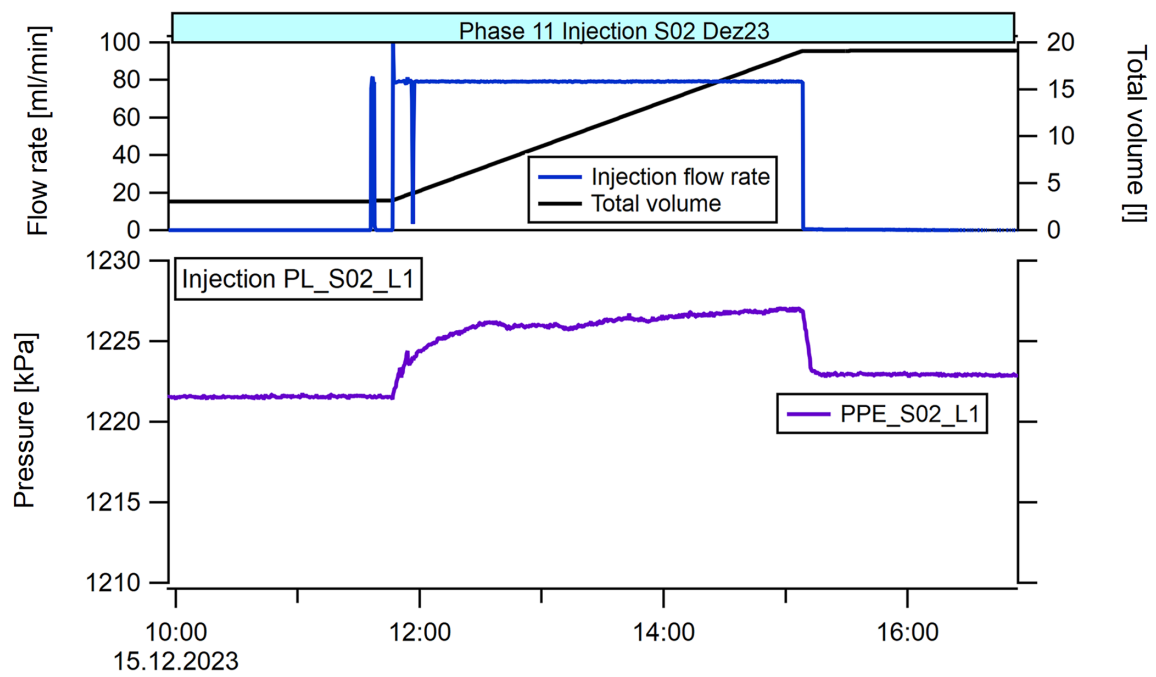


Fig. 4-96: Injection pressures, flow rates and total volume for injection/extraction test in S02 (Phase 11)

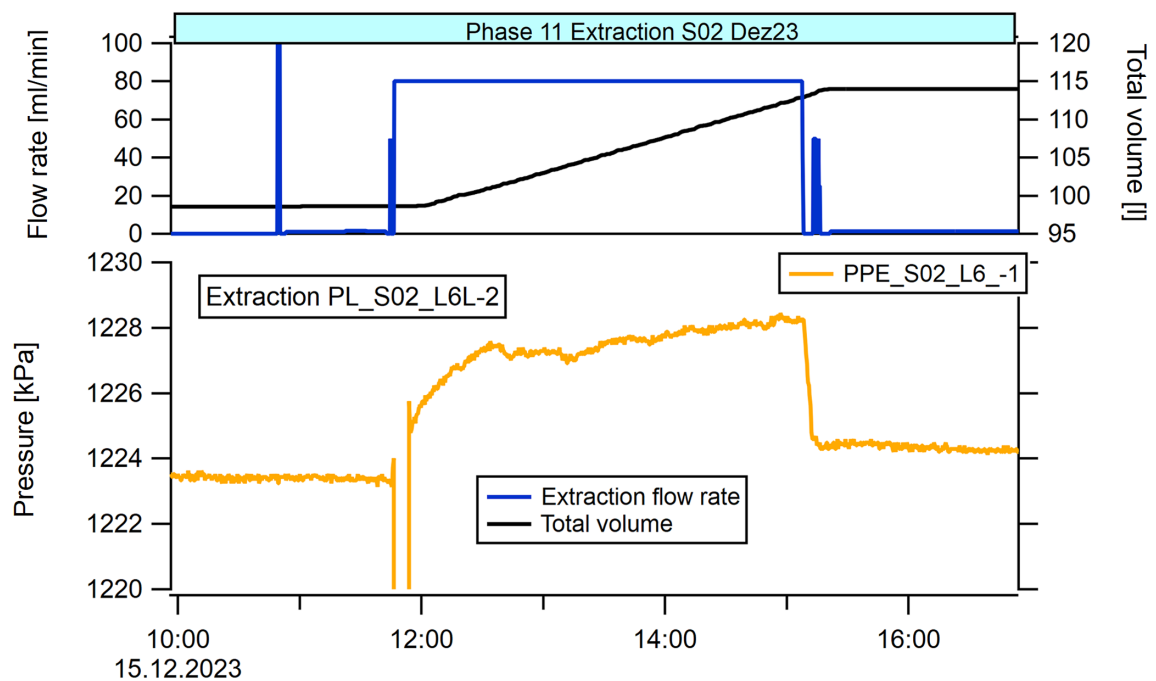


Fig. 4-97: Extraction pressures, flow rates and total volumes for injection/extraction test in S02 (Phase 11)

Many of the point TDRs (TDP sensors) showed no changes during Phase 11. As in the previous phases, the responses of some TDPs were not straightforward enough to directly infer physical changes due to the gas extraction and water injection performed in Phase 11. The TDL sensors, on the other hand, showed relatively sharp resaturation in the S14 filter, which progressively appeared from lower layers to higher ones (Enclosure M.5). It is also worth noting that there was a very minor increase in travel time for TDLs in L2 after a very slow gradual desaturation from Phase 5. This de- and resaturation could have been affecting part of the long ribbon electrodes, as seen in Fig. 4-98.

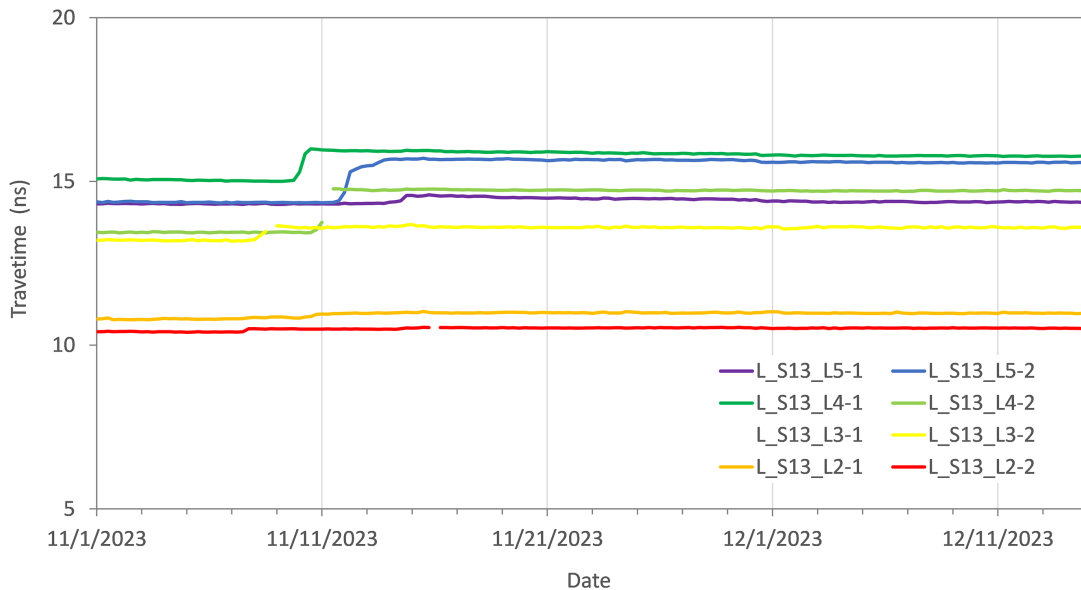


Fig. 4-98: Changes in travel time with TDLs due to water injection in S14 filter during Phase 11

4.8.5 Index testing

During GFT flow path diagnostics (Phase 11), one PW test campaign was performed on 30 November 2023. The applied procedure is described in Section 4.1.5.

The test parameters are summarised in Tab. 4-46. The graphs of the PW tests are shown in Enclosure N.6. An overview of the calculated compressibilities between September, October and November 2023 is shown in Fig. 4-99.

Please note that the filling volume of the 2 ml volume line piece could not be controlled during the tests. Therefore, the ΔV in Tab. 4-46 might overestimate the true extracted volume.

Tab. 4-46: Results of PW tests from PPE lines in November 2023

Date	Time	Sensor	ΔP [kPa]	$\Delta V^{(1)}$ [ml]	C [m ³ /Pa]	
30.11.23	10:10	PPE_S06_L6L-1	133.82	2.00	1.49E-11	Very slow increase
30.11.23	10:13	PPE_S03_L6L-1	25.70	2.00	7.78E-11	
30.11.23	10:16	PPE_S08_L4	26.86	2.00	7.45E-11	Fast increase
30.11.23	10:18	PPE_S09_L4	215.66	2.00	9.27E-12	Fast increase
30.11.23	10:39	PPE_S03_L4	1,092.89	2.00	1.83E-12	
30.11.23	10:45	PPE_S04_L3	1,242.37	2.00	1.61E-12	
30.11.23	10:48	PPE_S06_L4	105.80	2.00	1.89E-11	Very fast increase
30.11.23	10:52	PPE_S07_L2	1,250.48	2.00	1.60E-12	
30.11.23	10:56	PPE_S12_L2-1	1,400.94	2.00	1.43E-12	Very fast increase
30.11.23	11:00	PPE_S10_L6L-1	103.48	2.00	1.93E-11	
30.11.23	11:02	PPE_S03_L2-1	1,173.67	2.00	1.70E-12	Slow increase
30.11.23	11:21	PPE_S06_L3	1,275.89	2.00	1.57E-12	Fast increase
30.11.23	11:23	PPE_S07_L4	1,229.48	2.00	1.63E-12	
30.11.23	11:30	PPE_S06_L6H-2	21.96	2.00	9.11E-11	
30.11.23	11:44	PPE_S12_L2-2	1,452.42	2.00	1.38E-12	Very slow increase
30.11.23	11:46	PPE_S03_L3	986.13	2.00	2.03E-12	
30.11.23	11:57	PPE_S06_L2	1,259.66	2.00	1.59E-12	
30.11.23	13:01	PPE_S08_L2	1,270.00	2.00	1.57E-12	
30.11.23	13:11	PPE_S08_L6L	377.60	2.00	5.30E-12	Very fast increase
30.11.23	13:17	PPE_S09_L2	1,303.63	2.00	1.53E-12	Very fast increase
30.11.23	13:23	PPE_S11_L3	1,329.13	2.00	1.50E-12	
30.11.23	13:26	PPE_S10_L3	1,319.38	2.00	1.52E-12	
30.11.23	13:51	PPE_S12_L3	656.68	2.00	3.05E-12	Very slow increase with jumps
30.11.23	13:54	PPE_S12_L4	293.15	2.00	6.82E-12	Very fast increase
30.11.23	14:15	PPE_S10_L6H-2	154.89	2.00	1.29E-11	Fast increase
30.11.23	14:18	PPE_S10_L2	1,191.74	2.00	1.68E-12	
30.11.23	14:22	PPE_S03_L6H-2	93.43	2.00	2.14E-11	
30.11.23	14:31	PPE_S12_L6H	147.35	2.00	1.36E-11	Fast increase
30.11.23	14:33	PPE_S03_L2-2	1,034.63	2.00	1.93E-12	
30.11.23	14:37	PPE_S08_L3	1,252.90	2.00	1.60E-12	
30.11.23	14:41	PPE_S12_L6L	28.41	2.00	7.04E-11	
30.11.23	14:44	PPE_S10_L4	18.07	2.00	1.11E-10	Very slow increase

⁽¹⁾ Line piece with about 2 ml volume connected to PPE port, true volume unknown

Colours: red: higher compressibility $C > 5E-12$ m³/Pa, green: very slow increase, blue: very fast increase

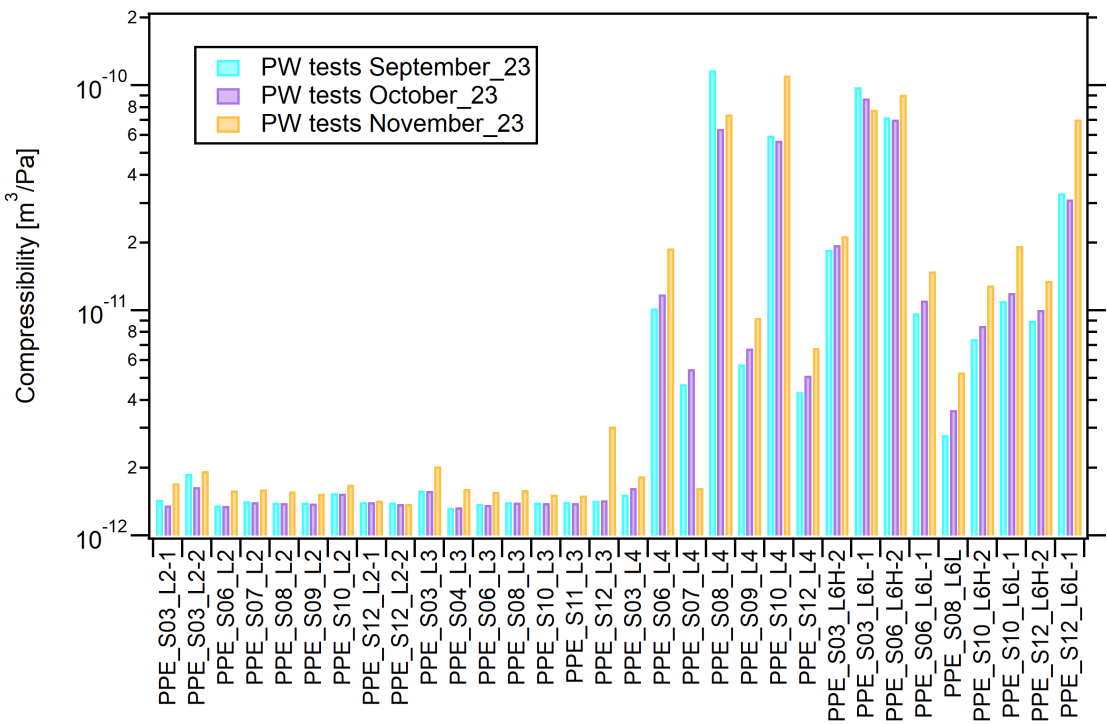


Fig. 4-99: Overview of calculated compressibilities from PW tests in September and October 2023 (Phase 10) and November 2023 (Phase 11)

4.8.6 Sampling

As in Phase 10, no samples were taken during Phase 11.

5 Database

5.1 Comments on the databases

The data presented in this report were recorded with the Solexperts DAS GeoMonitor II as described in Section 3.3.4, and with the miniRUEDI DAS as described in Section 3.5.2. Data were temporarily stored on GeoMonitor in a proprietary binary format and exported to an ASCII format on a daily basis (primary databases). The exports were then imported into the data management and visualisation software GAST-IS for quick online access and data visualisation. The data management system included also auxiliary data to provide the essential information for decision-making.

Based on the original data records with native resolution, secondary databases were assembled for interpretation and modelling purposes. Secondary databases include data channels that are derived from primary data channels, using e.g. pressure or temperature normalisation. Section 5.4 describes flow normalisation and separation from as-measured volumetric flow to mass fraction flow of fluid and gas phases.

5.2 DAS maintenance and primary databases

The DAS with the GeoMonitor II software was first installed on 16 March 2015. On 26 January 2017, the PC was found to be defective and was replaced with the same setup of the GeoMonitor software. On 30 November 2022, the GeoMonitor PC was replaced with a new one running Windows 10, and a new monitoring database was set up. Therefore, the DAS channels in the primary database changed as noted in the DAS list in Tab. D-1 in Enclosure D. All the DAS-related events are summarised in the data acquisition logbook in Tab E-1 in Enclosure E. Sensors that were added or changed during the observation period are marked in orange in Tab E-1.

Pressure sensors PPE_S02_L1, PPE_S02_L6L-1 and PPE_S03_L6L-1 were calibrated in 2018 and the results are documented in Roesli et al. (2019).

The repeated calibration of the flow controllers is described in Section 3.2.2. The calibration sheets of the new as well as the calibrated sensors are included in Enclosure C.

The miniRUEDI DAS installation started in January 2022 and was completed in February with its connection to the gas/water separation module. Gas sniffing tests conducted 14 – 16 March 2022 and fluid trial tests (21 – 31 March 2022) confirmed the installation's sensitivity to detect gas tracers from the plug surface capillary and from the separator module. From April 2022 to August 2023, miniRUEDI DAS provided qualitative data on gas composition as described in Section 3.5. All miniRUEDI DAS records were imported to the GAST-IS for visualisation and comparison with hydraulic measurements.

The Acoustic Emission DAS wrote event files containing information on AE events that triggered the system and on autolocated events. This information was copied to the GeoMonitor DAS for access and download by GAST-IS. GAST-IS facilitated comparisons of AE event rates with hydraulic and outflow data. Postprocessing the AE event data provided more precise location and magnitude estimates, which were collected in an AE database. Note that the description of the AE activity is beyond the scope of this report.

5.3 Monitoring and visualisation in GAST-IS

GAST monitoring data were imported into the GAST information system (GAST-IS) on a daily basis. Developed and operated by BetterDataSystems GmbH, the customised GAST-IS included a data pipeline collecting information from the DAS-connected sensors and provided client access to the GAST-IS server-based database (Fig. 5-1). The setup allowed differentiation between static sensors for long-term measurements and dynamic sensors that were only temporarily in use. A validation step cancelled noise and out-of-range data before validated entries were written into the database. GAST-IS also allowed for:

- Data management and combination of primary databases
- Visualisations in 2D (time series) and 3D (sensor positions, AE locations) for quality control and on-the-fly interpretations
- Monitoring and alerting in case of threshold exceedance (watchdog)

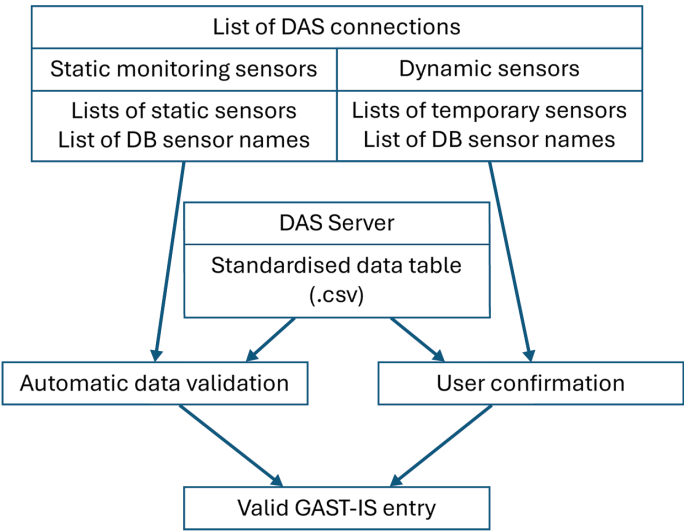


Fig. 5-1: Simplified schematic of the data flow from DAS to GAST-IS

5.4 Secondary database

Data from the Geomonitor system and previous monitoring from 2012 onwards were processed to provide a consistent database suitable for input to modelling projects. The data were organised according to measurement type with worksheets for:

- PPE: piezometers in the S/B, GBM, WT tunnel
- RH: relative humidity sensors in the GBM
- TP: total pressure sensors at L6, tunnel wall and concrete walls
- TE: temperature sensors both dedicated to and associated with RH sensors
- PS: psychrometers (disconnected 14 June 2016)
- TDR calculated travel time
- Flow: water and gas flows in/out of the S02 and S14 filters
- Disp: displacement and relative displacement measurements around the concrete plug

In addition, there were spreadsheets with information on sensor location and type and the relevant site logs. The data covered the period from 11 July 2022 to 14 September 2022 (V0), 22 March 2023 (V01) and 01 September 2023 (V02). Data were initially given at a 1-hr time resolution, and then at both a 1-hr and a 6-hr time resolution.

Smoothing of the sensor data to remove anomalous data points or gaps was performed with a median filter over the relevant time step. The use of a 6-hr sampling rate resulted in under-sampling of the sinusoidal injection (period of 333 minutes) and extraction rate (period of 120 minutes) but this did not affect mean flow rates or cumulative totals.

The spreadsheet data used for mass-balance calculations were processed to provide the necessary input to the model at the 1-hr and 6-hr intervals. The injected gas tracer fractions in the spreadsheets used the laboratory characterisation of the gas mixes (see Sections 4.3.7.1, 4.4.7.1 and 4.6.7.1).

6 Gas volume estimation

6.1 Injection gas volume

To compensate for different hardware and gas properties, the injection gas flow measurements were corrected with calibration factors. Tab. 6-1 lists the hardware calibration factors and gas conversion factors as described in Section 3.2.2. Data from the mass flow meter FG_INJ_MASS were converted to volumetric flow to provide consistent normalised flow values. Prior to calculating the cumulative injected gas volume from the flow measurements, unrealistic readings such as virtual non-zero flow during shut-in phases were set to zero. The normalised measured injection flow rates and the cumulative injected volume are displayed in Fig. 6-1. The injected volumes $V_{g'}^I$ for injection conditions (P^I , T) were also calculated and integrated in the database.

Tab. 6-1: Details of injection flow rate calculation

Date & time	Flow controller	Medium	Factor	Comments
06.05.22 11:21	FLOW_HI [mln/min]	Tracer Gas Mix #1	0.98 * 1.007	Backward calibration and gas calculation
06.05.22 14:15	FLOW_LOW [mln/min]	Tracer Gas Mix #1	0.98 * 1.007	Backward calibration and gas calculation
12.05.22 07:20	FLOW_HI [mln/min]	Tracer Gas Mix #1	0.98 * 1.007	Backward calibration and gas calculation
01.12.22 07:05	FLOW_HI [mln/min]	Nitrogen N ₂	0.98	Backward calibration
26.01.23 13:49	FG_INJ_MASS [g/h]	Nitrogen N ₂	13.3	Based on literature values for N ₂ density at STP (*)
30.03.23 09:53	FLOW_HI [mln/min]	Nitrogen N ₂	1.0 * 0.9232	After calibration and gas calculation
18.04.23 07:20	FLOW_HI [mln/min]	Tracer Gas Mix #2	1.004	Backward calibration
29.06.23 12:16	FLOW_HI [mln/min]	Nitrogen N ₂	1.004 * 0.9232	Backward calibration and gas calculation
01.09.23 11:00	Shut-in			

(*) 1 g of nitrogen corresponds to 799.36 ml of nitrogen gas

6.2 Extraction volume

Extraction volumes were measured by syringe pumps and for a short while by a flow meter⁴ as detailed in Section 4.3.3. After interpolation of the flow measurements (Section 4.3.4), the cumulative and total extraction volumes were calculated from the syringe pump measurements at the extraction line PL_S14_L1. The measured extraction volume V^E and its cumulative sum are shown in Fig. 6-2.

Because water and gas may have contributed to V^E , separation of water and gas from the extracted fluid was realised by installation of the mock-up tank as a fluid separator (Section 4.3.3). Monitoring data indicated that essentially only water was extracted until 09 June 2022. Afterwards, the measured extraction volumes V^E consisted of gas and liquid phases. Gas volumes V_g^E were derived by subtraction of the measured water volume V_w^E from the total extraction volume V^E .

Since the syringe pump was kept under extraction pressure, extraction flow and volumes corresponded to the extraction pressure P^E . As for the injection volumes, the gas volumes were derived for ambient and standard STP conditions. The correction to standard pressure (STP) was made with the following equation:

$$V_{STP} = \frac{P \cdot T_{STP}}{P_{STP} \cdot T} \cdot V$$

where P is the measured pressure and temperature, T is the estimated ambient temperature in the WT tunnel where the syringe pump was located (289.15 K), T_{STP} is standard temperature (273.15 K), and P_{STP} is standard pressure (101.25 kPa or 1.0125 bar). STP stands for standard temperature and pressure conditions after Mass Flow Online B.V. (2024)⁵.

6.3 Mass-balance computations

Mass-balance spreadsheets were calculated for each of the different gas injections: Gas Mix #1, N₂ flushing, Gas Mix #2 and second N₂ flushing using high-resolution (20 s) data. Flow rates and cumulative volumes were calculated for both ambient conditions (ml/min and l) and at STP (mln/min and ln). STP was taken to be 101.3 kPa and 0 °C. Within the tunnel, an ambient temperature of 16 °C (289.15 K) was assumed for the purposes of the conversion. The quantities calculated and data sources are listed in Tab. 6-2.

The mass balances were used to estimate the recovery of injected gas and the “instantaneous effective permeability area” of the gas path. A separate mass balance was also calculated for the W-GX (see Section 4.2).

⁴ The flowmeter data were less reliable than the data from the syringe pumps which, at the time, were required for PPE sampling.

⁵ www.massflow-online.com, accessed in 2024

Tab. 6-2: Mass balance quantities and data sources

Property	Data source
S02 gas injection STP (mln/min, ln)	Gas flowmeter data using as-received calibrations (see Section 3.2.2 and Enclosure C)
S14 total volumetric extraction (ml/min, l)	Syringe pump volume plus interpolated data for period when unavailable
S14 water extraction (ml/min, l)	Water level in mock-up tank
S14 gas volumetric extraction (ml/min, l)	S14 volumetric extraction – water extraction
S14 gas norm volume extraction (mln/min, ln)	Norm volume (STP) calculated from S14 gas volumetric extraction, S14 pressure and temperature in tunnel

6.4 Volume comparison

A comparison of the cumulative injection (Vg^I) and extraction volumes (V^E) is given in Tab. 6-3. The cumulative volumes were derived for each gas mix injected. A simplified flow balance is possible when the normalised volumes Vg^I_{STP} and Vg^E_{STP} are compared (Tab. 6-4). It is important to note that the monotonically reducing volume differences indicate the high quality of the gas flow measurements. The differences may include gas losses to the environment, but gas accumulation in the filters, GB, and S/B must also be considered. A qualitative assessment of these effects is described in Nagra (2025).

Tab. 6-3: Corrected volume calculations for each gas injection phase

Phase	Gas	P^I [bar]	Injected volume Vg^I [l]	Injected volume Vg^I_{STP} [ln]	Extracted volume V^E [l]	Extracted water volume S14 Vw^E (*) [l]	Extracted gas volume Vg^E [l]	P^E [bar]	Extracted gas volume Vg^E_{STP} [ln]
2(WG-X)	Mix #1	18.5	301.6	5,525.1	-	2.9		14	0.0
2 – 5	Mix #1	19	7,763.1	136,776.1	9,794.8	641.1	9,153.7	14	119,643.9
6 – 7	N ₂	19 – 18	9,727.8	167,040.9	12,028.6	29.6	11,999.0	14	158,047.2
8	Mix #2	18	6,273.1	104,417.9	7,459.2	10.5	7,448.7	14	100,305.5
9	N ₂	18	5,589.3	92,195.3	6,629.8	6.9	6,622.8	14.6	90,101.5
10	N ₂	var	1,327.5	21,560.7	20,093.7	2.6	1,475.6	var	20,093.7
Total				527,516.0					488,191.7

T: Temperature of 16 °C

P: Pressure at the time stamp

STP: Standard conditions (T = 273.15 K, P = 101.325 kPa)

(*) 301.0 l of water extracted from S02 during Phase 1 are not shown

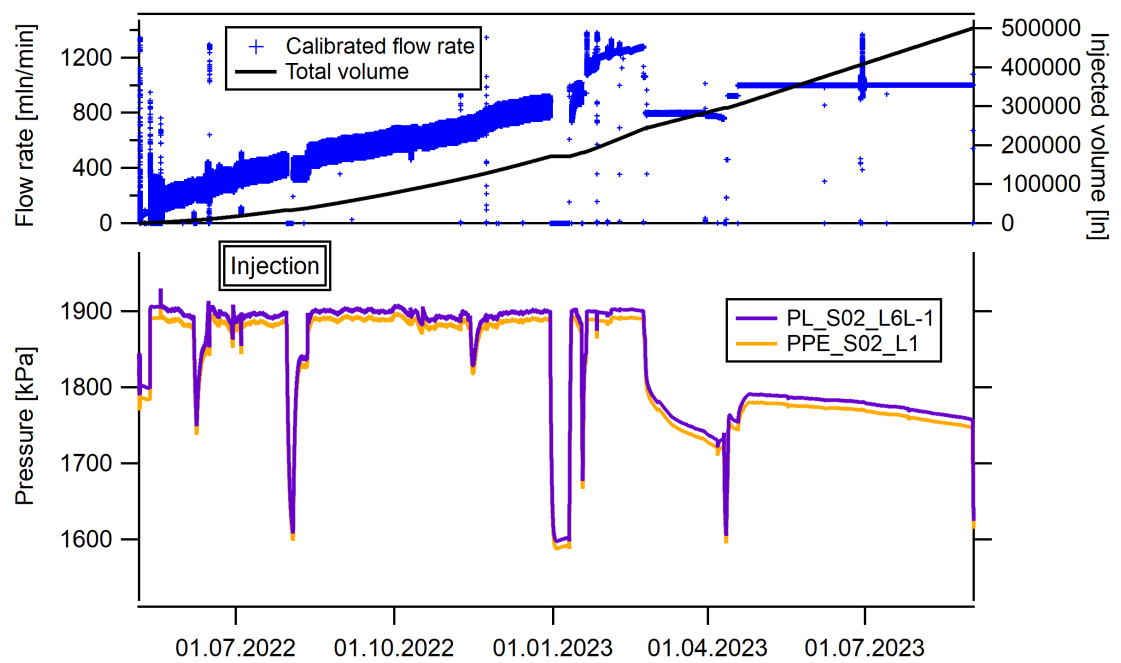


Fig. 6-1: Overview of the GFT injection measurements

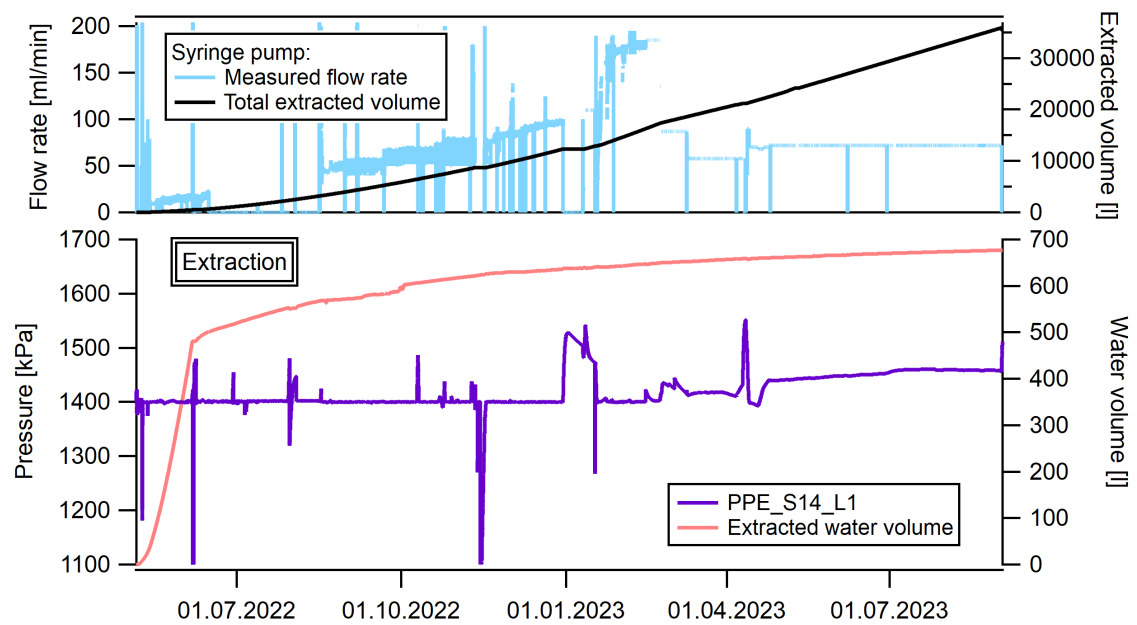


Fig. 6-2: Overview of the GFT extraction measurements

Tab. 6-4: Simplified flow balance

Phase	Gas	Injected volume Vg^I_{STP}	Extracted gas volume Vg^E_{STP}	Balance $\Delta V_{gSTP} = Vg^I_{STP} - Vg^E_{STP}$	
		[ln]	[ln]	[ln]	[%]
2(GW-X)	Mix #1	5,525.1	0.0		
2 – 5	Mix #1	136,776.1	119,643.9	17,132.21	13%
6 – 7	N ₂	167,040.9	158,047.2	8,993.76	5%
8	Mix #2	104,417.9	100,305.5	4,112.38	4%
9	N ₂	92,195.3	90,101.5	2,093.72	2%
10	N ₂	21,560.7	20,093.7	1,054.4	5%
All	All	527,516.0	488,191.74	38,911.6	6%

6.5 Index testing

An index testing routine was established and applied typically once per phase to detect changes in compressibility, which were interpreted as an indicator of possible accumulations of gas. Initially performed at selected PPEs, the index testing routine was later performed for all PPEs in the S/B body. The resulting compressibilities are tabulated in the previous sections (Tab. 4-6, Tab. 4-15, Tab. 4-25, Tab. 4-26, Tab. 4-37, Tab. 4-42, Tab. 4-43, Tab. 4-46), and Fig. 6-3 displays the test results for L4 and L6. Many sensors indicate a significant increase in compressibility in Phase 5 or Phase 6. Nagra (2025) visualised and interpreted the compressibility measurements to derive constraints for the evolution of the gas flow path.

This section illustrates the compressibility tests in a series of drawdown/recovery curves (Fig. 6-4 to Fig. 6-13) for the PW tests performed in Phase 2 to Phase 9. Note that all pressure response curves for a specific sensor are shifted to a common onset time and superimposed. The response curves can be summarised as follows:

- PPE_S03_L2-1 (Fig. 6-4), for example, consistently shows a fast pressure recovery and very similar recovery curves.
- The recovery curves for PPE_S03_L6H-2 (Fig. 6-5) are less similar. There is a fast and partial recovery, which slowed down at later times.
- PPE_S06_L3 (Fig. 6-6) is an example showing consistently slow recoveries.
- The recovery curves in L4 (Fig. 6-7, Fig. 6-9, Fig. 6-10 and Fig. 6-11) show a significant shape change: slow recovery for early tests at the beginning of the GFT and fast recovery at later phases. This is also reflected in the compressibility changes in Fig. 6-3.
- The recovery curves in L6 (Fig. 6-5, Fig. 6-11, Fig. 6-12 and Fig. 6-13) show considerable variability but the trend to very quick recovery over the GFT is generally visible.

The switch from slow recovery to quick recovery is believed to reflect the higher compressibility and higher gas mobility compared to water. This can therefore be interpreted as a further indication of a local free gas phase.

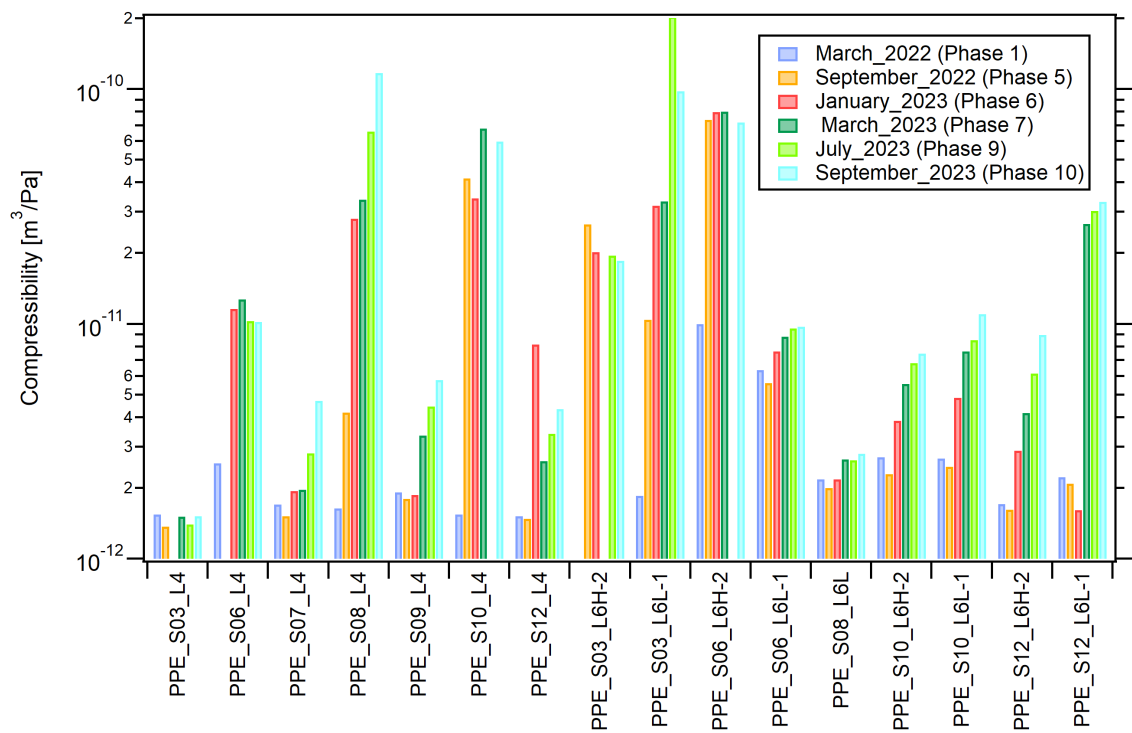


Fig. 6-3: Comparison of all calculated compressibilities from PW tests in L4 and L6 since March 2022

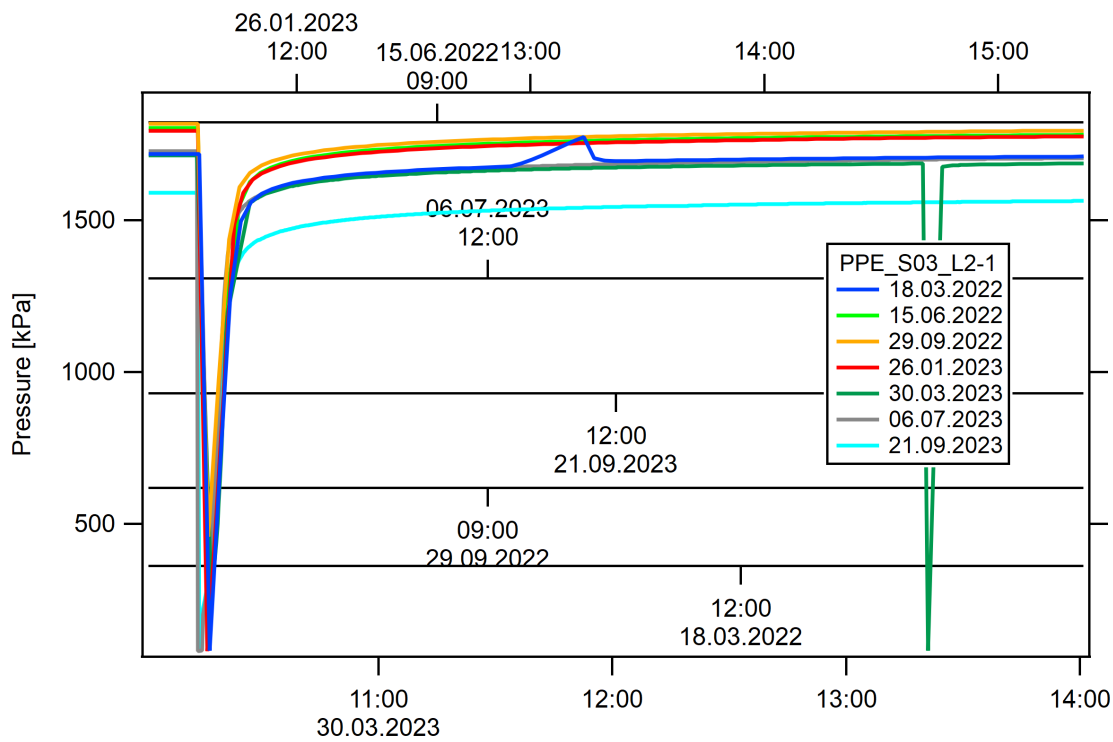


Fig. 6-4: Development of index tests in PPE_S03_L2-1 (time scale = 4 hours)

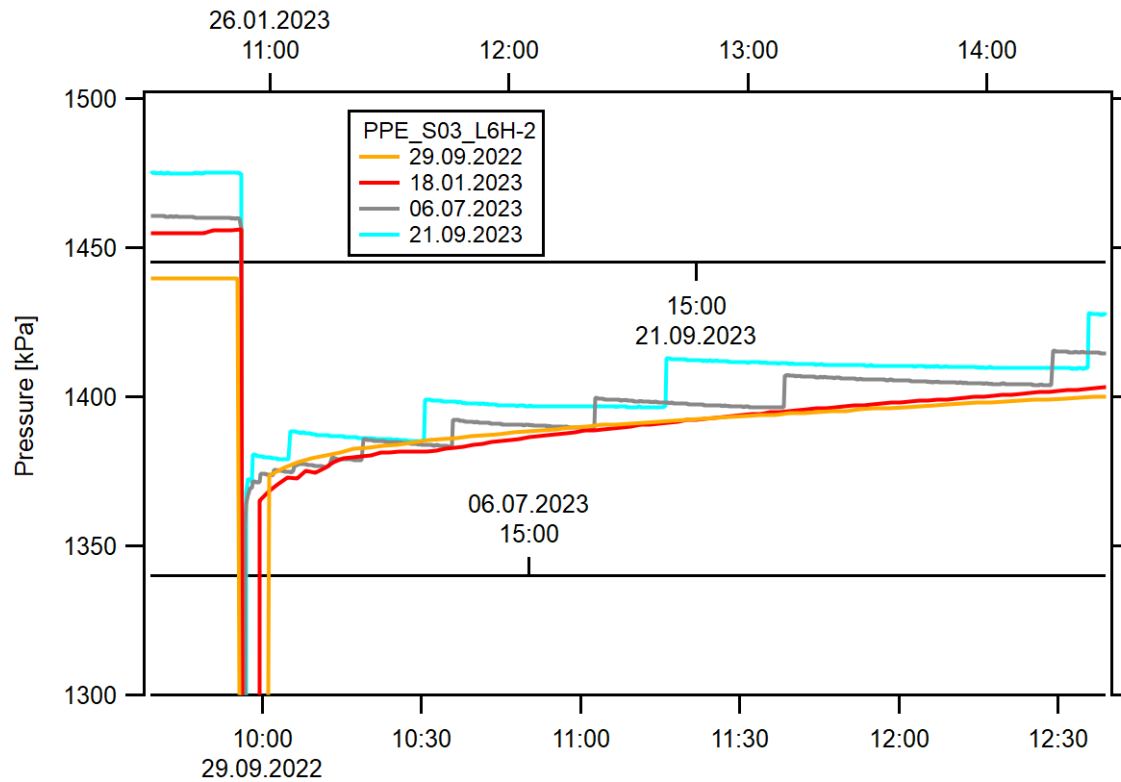


Fig. 6-5: Development of index tests in PPE_S03_L6H-2 (time scale = 4 hours), no test in March 2022

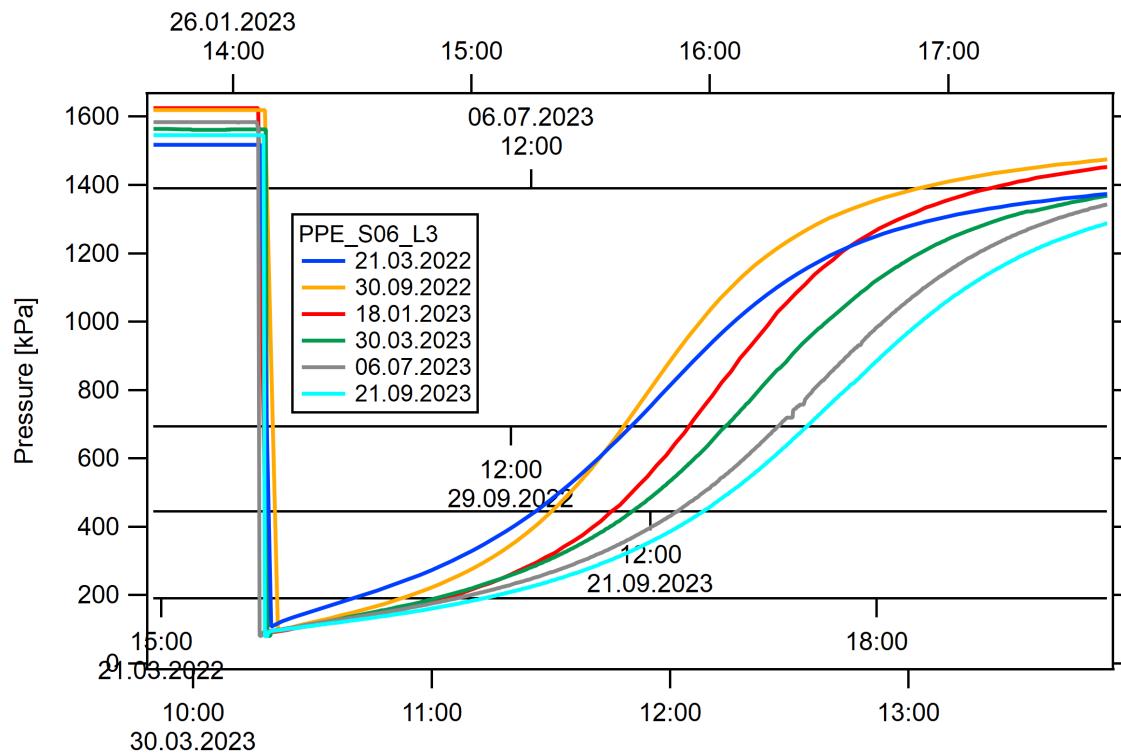


Fig. 6-6: Development of index tests in PPE_S06_L3 (time scale = 4 hours)

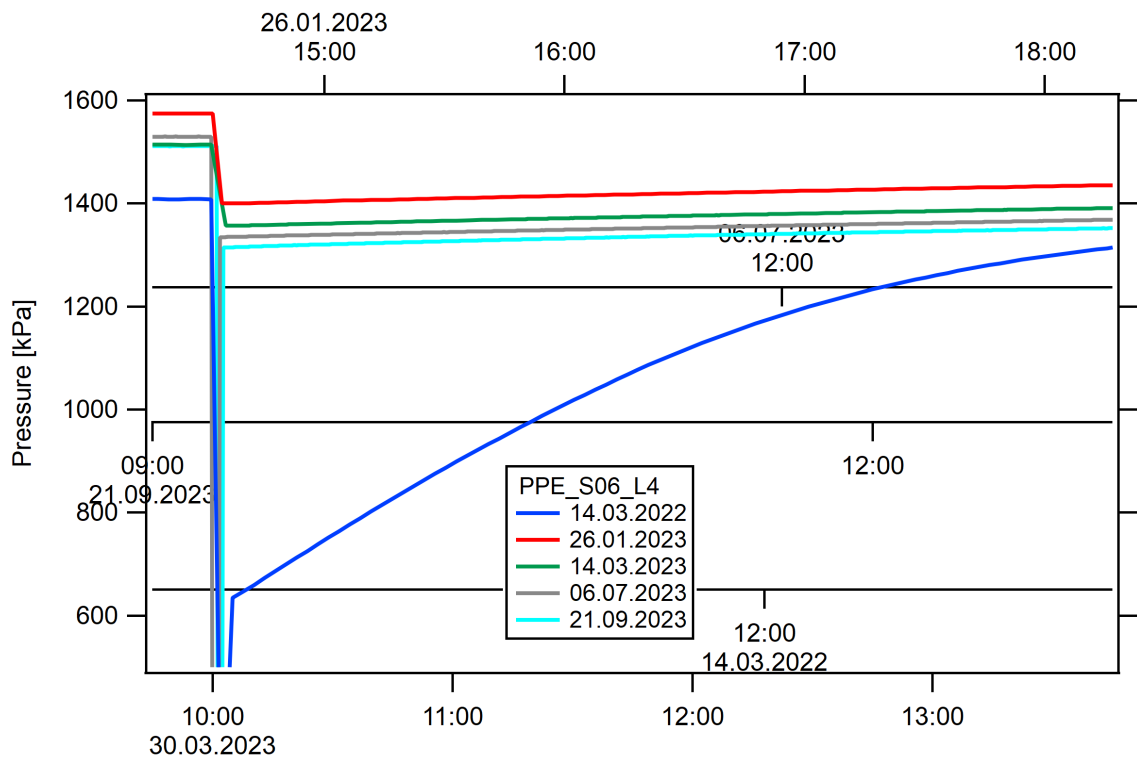


Fig. 6-7: Development of index tests in PPE_S06_L4 (time scale = 4 hours)

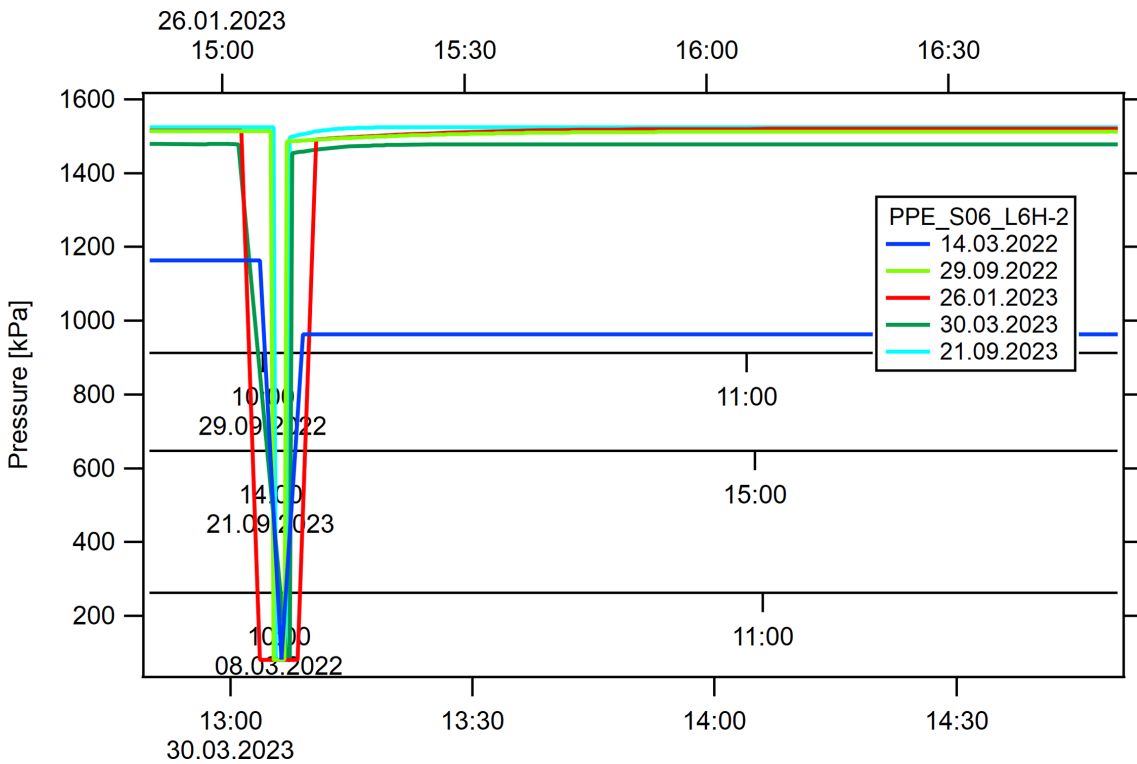


Fig. 6-8: Development of index tests in PPE_S06_L6H-2 (time scale = 2 hours)

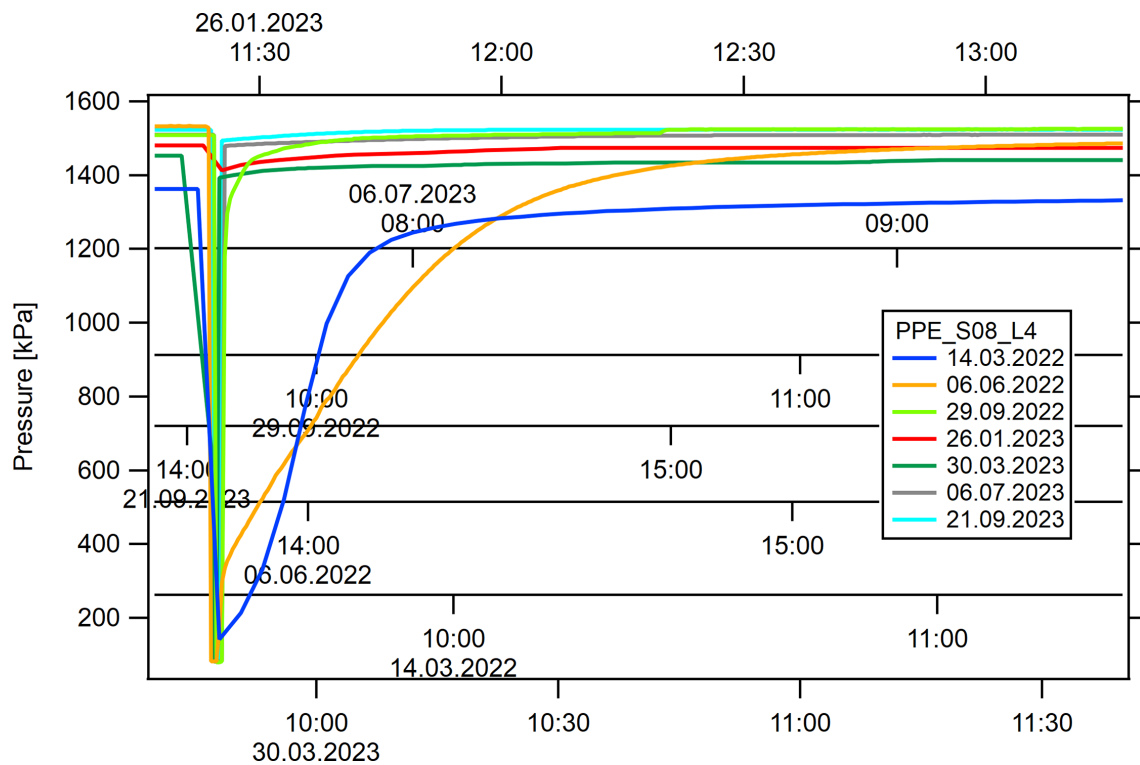


Fig. 6-9: Development of index tests in PPE_S08_L4 (time scale = 2 hours)

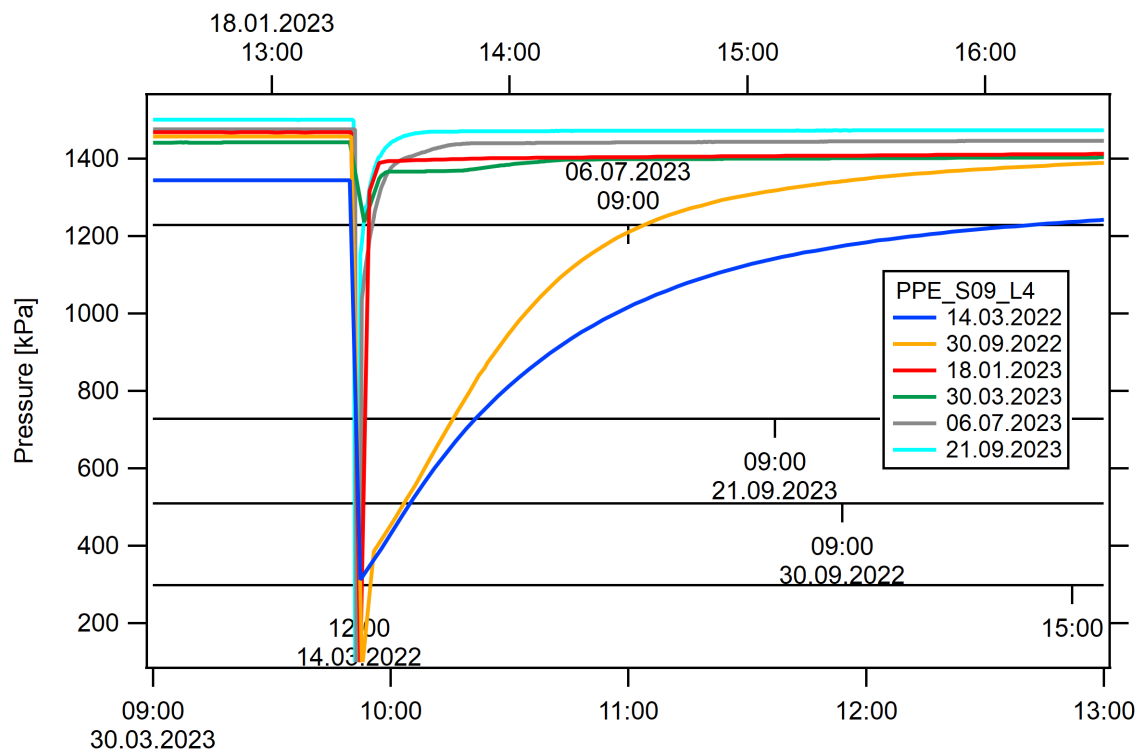


Fig. 6-10: Development of index tests in PPE_S09_L4 (time scale = 4 hours)

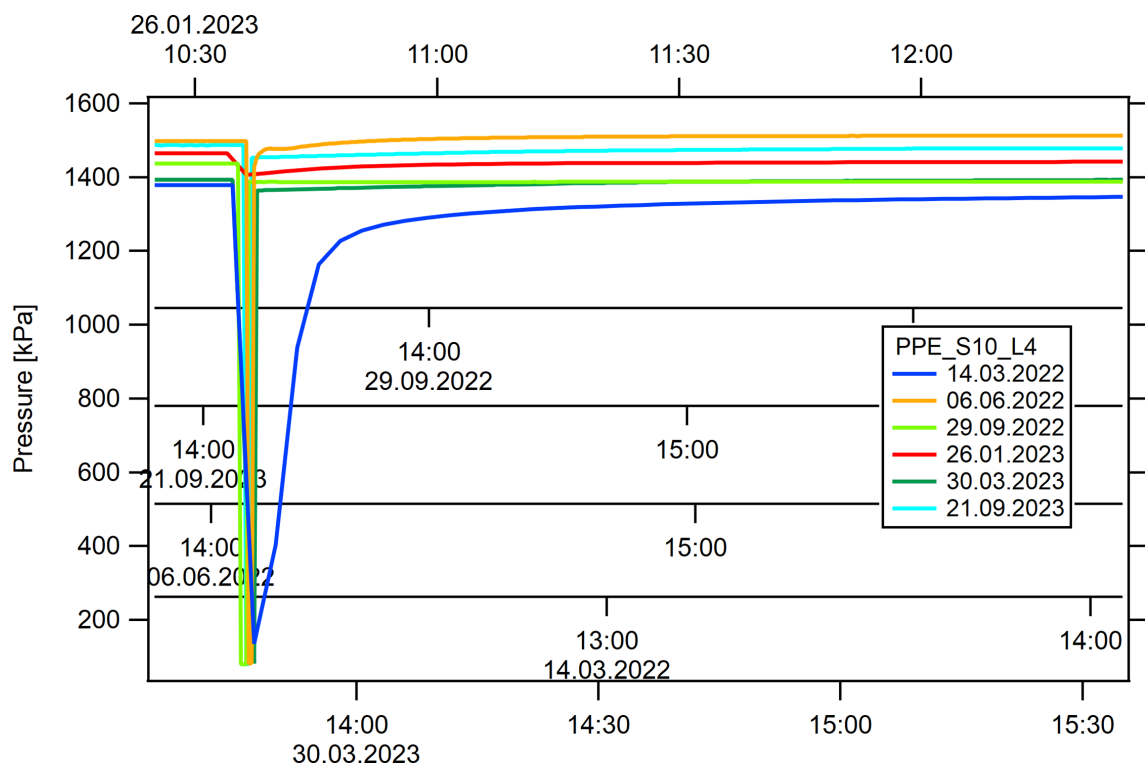


Fig. 6-11: Development of index tests in PPE_S10_L4 (time scale = 2 hours)

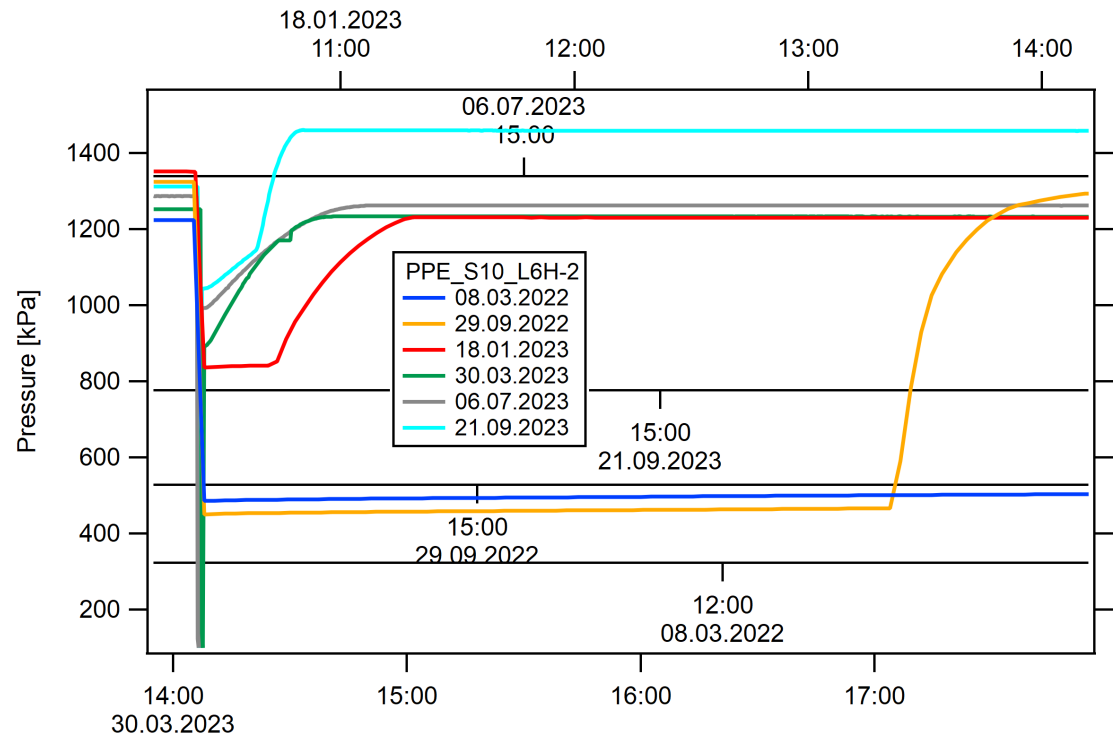


Fig. 6-12: Development of index tests in PPE_S10_L6H-2 (time scale = 4 hours)

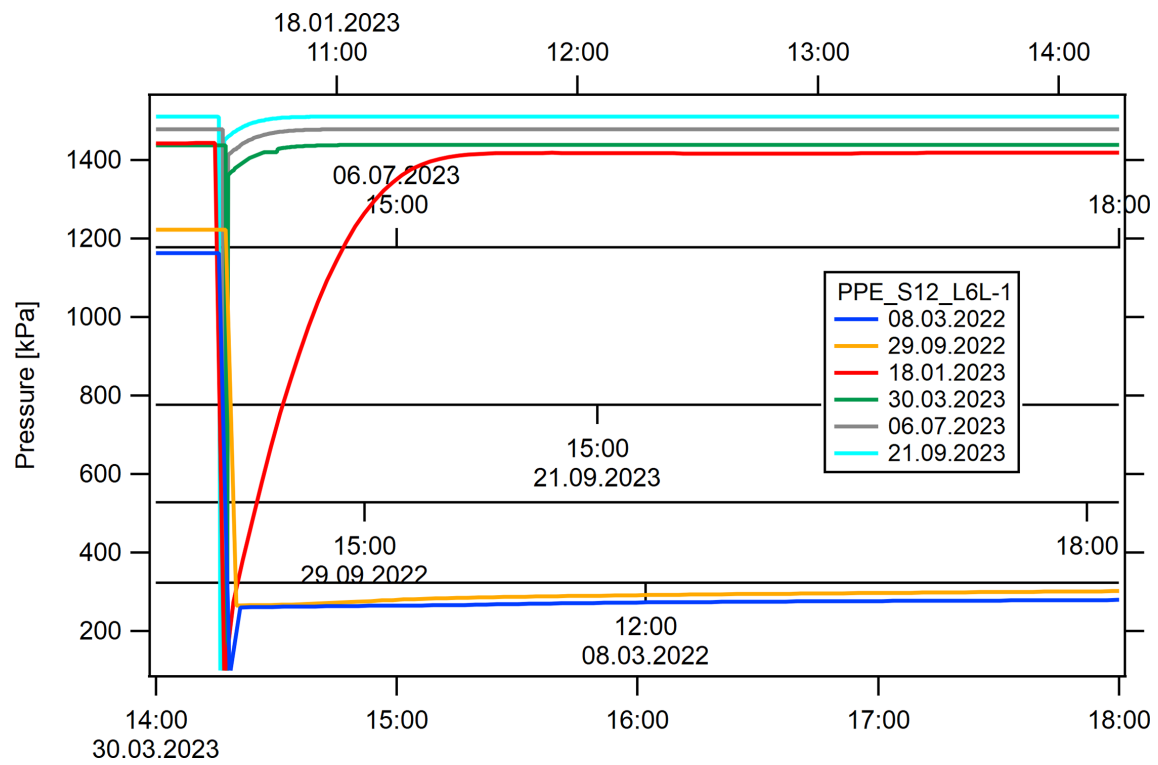


Fig. 6-13: Development of index tests in PPE_S12_L6L-1 (time scale = 4 hours)

7 Summary and conclusions

The Gas-Permeable Seal Test (GAST) was constructed in 2011 – 2012 and subsequently saturated during multi-stage water injections. In 2018, the one-sided gas property test (GPT1) demonstrated the feasibility of gas injections and derived a preliminary gas entry value valid for the S/B near the injection filter S02. Afterwards, the system was resaturated and pressurised using water injections from both filters S02 and S14 up to pressures around 2,200 kPa. Pressures were reduced stepwise in 2021 with the aim of establishing a monotonic pore pressure gradient from the injection point S02 (~1,800 kPa) to the extraction point S14 (~1,400 kPa). In parallel, the field equipment was upgraded to ensure a safe and successful performance of the Gas Flow Test (GFT). The upgrade included, most importantly:

- Equipment that is capable of fluid extraction (gas/water mixtures) at a controlled rate and pressure
- Installation of a gas/water separation module for online gas monitoring of extracted gas composition (providing qualitative results)
- Integration of sampling ports for taking gas and water samples for later laboratory analyses (providing quantitative results)

In preparation for the GFT, a 84-day dipole test (injection in PPE_S06_L2; extraction from PPE_S07_L2) was started at the end of 2021, demonstrating the feasibility of taking samples from the S/B piezometers and the low permeability to water of the sand/bentonite in the seal section. Test results indicated the need to manage very low flow rates in the range of tens of ml/week. Four baseline samples were taken, but no injection fluid/tracer was detected during the testing period. Additionally, an efficient and repeatable index testing methodology was developed that facilitated estimates of compressibility in S/B piezometers in a time-lapse manner.

7.1 GFT summary

The actual GFT activities were divided into multiple phases, data of which are presented and discussed in this report.

During Phase 1 (15 March 2022 – 01 May 2022), the site was prepared for the gas injection and gas monitoring/sampling (including equipment calibration and testing) and baseline data were acquired (filter pulses tests and PW tests in PPEs).

In Phase 2, the water-gas exchange (W-GX) in filter S02 started on 02 May 2022. While minimising pressure fluctuations in the system, about 300 l of water were replaced with Gas Mix #1 in injection filter S02.

The injection filter (S02) to extraction filter (S14) flow started on 06 May 2022 with extraction from S14 and, with a slight delay, injection of Gas Mix #1 in PL_S02_L6L-2 (injection started 3:28 hrs after extraction). The injection regime (Phase 3) began with constant pressure (1,800 kPa on 06 May 2022 at 11:22), increased to 1,900 kPa (on 12 May 2022 at 12:50) and changed finally to sinusoidal rate injection (19 May 2022) once flow rates were established. The sinusoidal injection regime was kept through Phases 3 to 5, but the mean flow rate was regularly increased to maintain the target pressures.

During Phases 4 and 5, practically stable conditions had been established with sinusoidal injection of Gas Mix #1 at ~1,900 kPa into the S02 filter and ongoing gas accumulation and water drainage from S14 which was maintained at ~1,400 kPa. These stable conditions allowed targeted sampling of PPEs, which required significant time due to the low water permeability and storage volumes associated with the PPE lines. Gas breakthrough to the S14 extraction (PL_S14_L1) occurred on

08 June 2022 after clogging of the outflow (probably due to disturbance of fine material near the base of the filter). Gas phase monitoring and sampling from the outflow showed an increasing fraction of the gas tracers, indicating the development of a gas path. Tracer-bearing gas samples were further extracted from two PPEs, one in the S/B (S10_L4) and one the S/B-GB interface (S06_L6H-2). Evolution of the path during Phase 5 resulted in increased injection and extraction rates to maintain the pressure boundary conditions in the filters, and the outflow tracer concentrations approached those of the injection gas mixture.

In Phase 6, the S02 gas injection was switched to N₂. Gas tracer sampling from the S14 outflow and PPEs allowed monitoring of the flushing of the gas tracers from the filters and gas path. During Phase 6, the S02 gas injection and S14 extraction rates continued to increase (maintaining constant pressure conditions). Towards the end of Phase 6, injection and extraction were shut in from 31 December 2022 to 10 January 2023. Once gas injection resumed, the flow path was quickly re-established.

To better manage the injection and extraction rates for the second gas tracer experiment, it was decided to switch to rate control to ensure that sufficient traced gas was available and to stay within the limits of the injection and extraction flow controllers. The switch to rate control occurred at the start of Phase 7 resulting in a reduction in N₂ injection pressure. Continued gas sampling during Phase 7 showed that the gas tracers had been largely flushed from the filters and the gas path during Phase 6.

The second gas tracer experiment using Gas Mix #2 was performed in Phase 8 at constant injection and extraction rates. Injection pressure reduced slightly as the gas path continued to develop. Extraction pressure also rose slightly. Gas sampling and monitoring of the S14 extraction showed the arrival of the Gas Mix #2 tracers, and the concentrations increased to close to the injection fractions by the end of the phase. Gas tracer arrival was also observed in samples taken from selected PPEs.

The gas injection was switched to N₂ at the start of Phase 9 to flush the Gas Mix #2 tracers from the filters and flow path. Injection and extraction rates were held constant, and injection and extraction pressures only changed slowly (ongoing flow path development). Gas sampling and monitoring of the S14 extraction showed the flushing of the Gas Mix #2 tracers. Flushing of the gas tracers was also observed in samples taken from selected PPEs.

The gas tracer experiments ended in Phase 9 with no further gas samples being taken from the filters or PPEs.

Phase 10 provided additional flow path diagnostics with N₂ injection into S02. Phase 10 included an extended shut-in of about 3 weeks (01 September 2023 – 22 September 2023) and a series of step rate injections from 1,380 mln/min down to 45 mln/min. Gas extraction tests were also performed to characterise the ability of the PPEs to remove gas from the flow path.

In preparation for the long-term resaturation of the seal section, Phase 11 concentrated on the removal of gas from the S14 filter by reversing the flow direction. While injecting water into the filter S14, gas was extracted from the S02 filter until flow resistance increased. A G-WX in filter S02 to extract gas from selected PPEs concluded Phase 11 and the GFT.

7.2 Monitoring and control of the GFT

Active testing during the GFT started on 11 May 2022 and continued until 30 November 2023, a period of over 18 months. During this time, multiple gas injection and extraction phases were successfully controlled and monitored.

The development of the end-to-end gas flow path through the seal section from S02 to S14 was successfully monitored over this time, using a range of sensors within the sand/bentonite and GBM. Tab. 7-1 outlines essential monitoring methods and their importance within the GFT. In addition, gas tracers from the two tracer experiments (Gas Mix #1 and Gas Mix #2) were sampled from the extraction and from selected PPEs within the gas flow path.

Tab. 7-1: Monitoring methods with associated achievements and observations during the GFT

Method/sensor	Achievements and observations
Gas injection flow control	• Continuous calibrated measurements of gas injection mass (mLN/min). • Allowed control of pressure and rate conditions during stable gas path evolution.
Gas/water extraction flow control	• Continuous controlled extraction of gas/water mix with phase separation in mock-up tank. • Syringe pumps (when available) provided high-quality volumetric outflow and controlled pressure and rate conditions during stable gas path evolution.
PL (S02) gas monitoring	• Successful quantitative monitoring of gas tracers injected.
S02 sinusoidal gas injection	• Sinusoidal injection allowed successful continuous estimation of S02 filter gas volume.
PL (S14) gas sampling	• Successful quantitative monitoring of arrival and tailing of gas tracers. • Large gas pore volumes in S02 and S14 resulted in significant mixing/tailing of the tracers
PL (S14) gas separation and monitoring	• Successful qualitative monitoring of arrival and tailing of gas tracers.
S14 sinusoidal extraction	• This initially provided a reliable estimate of the S14 gas volume but became less reliable as gas approached the L1 extraction level.
S02 and S14 filter pulse tests	• Pulse injection/extraction tests were performed in S02 and S14 to estimate the gas volumes within the filters and to characterise the seal section pressure response to these events.
W-GX and G-WX in S02	• It was possible to control the exchange of gas and water volumes in S02 without significant pressure changes. Overall, about 300 l of gas were present in S02 during the GFT.
PPE gas sampling	• Successfully controlled extraction of water and gas phases from low permeability seal using syringe pumps. • Identification and quantitative description of tracer gases in the sand/bentonite (L4) and sand/bentonite-GBM interface (L6). • Line volumes and low permeability to water limited the number of PPEs that could be sampled for water or gas.

Tab. 7-1: Cont.

Method/sensor	Achievements and observations
PPE PW tests	• Effective monitoring of local compressibility as indicator of gas presence. Used to target sampling.
TDP sensors	• TDP sensors showed only ambiguous changes during the GFT, probably due to the small and localised desaturation of sand/bentonite.
TDL sensors	• Successful monitoring of S14 filter drainage and resaturation. • L2 sensors showed only a very small effect, indicating incomplete drainage of the lower filter compartment
TP cells	• Continuous monitoring of stress conditions on the tunnel wall, end wall and plug (19 operating sensors). • Demonstration of overall compressive effective stress.
RH sensors	• Most RH sensors installed in GBM had been saturated and became inoperative as GBM RH increased close to 100%. Only 2 operating sensors in the GBM, both indicating RH >94% and only minimal changes during the GFT.

Besides using mature and robust technology, continuous learning and improvement of the field equipment enabled the success of the GFT. Maintaining sufficient redundancy in the monitoring system and spare parts to manage occasional equipment failure were other factors to success. Periodic maintenance and recalibration of flow meters were given high priority to assure sufficient data quality for subsequent quantitative interpretation.

7.3 Conclusions

In summary, the GFT demonstrated the ability of the sand/bentonite to transport large volumes of gas at significant flow rates across an 8-m-long sand/bentonite seal body.

Major achievements include:

- Successful, high recovery gas tracer tests performed over 1.5 years within the sand/bentonite seal section. A cumulative volume of about 527 m³ gases (Mix #1, Mix #2, N₂) was injected, whereof a volume of about 488 m³ was extracted or recovered as part of the flow test (volumes are considered under standard STP conditions).
- Development and application of real-time monitoring and sampling of tracer gases that allowed the unambiguous detection of end-to-end gas flow and of the injected gas within the sand/bentonite.
- Provision of point measurements/gas samples to constrain potential gas flow paths within the sand/bentonite seal section and its interfaces. Injected gas tracers were detected at various points within the S/B (at L4) and at the S/B-GBM interface (L6).
- Provision of high-quality dataset for further interpretation and modelling of gas flow in sand/bentonite.

A comparison of the small water flows established prior to the GFT (~0.1 ml/min; Section 4.1) with gas flow rates realised during stable GFT flow phases (~100 ml/min; Section 4.4) demonstrates the ability of a sand/bentonite seal to support significantly higher gas volumetric flows than water flows. Readers are referred to Nagra (2025) for a more quantitative analysis of the data that are presented in this report.

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