

Arbeitsbericht NAB 22-49

**Long-term monitoring system
of the Bözberg-1 borehole:
Installation Report**

March 2023

M. Schoenball, T. Vogt, M. Kech & U. Rösli

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

Hardstrasse 73
P.O. Box
5430 Wettingen
Switzerland
Tel. +41 56 437 11 11
nagra.ch

Arbeitsbericht NAB 22-49

Long-term monitoring system of the Bözberg-1 borehole: Installation Report

March 2023

M. Schoenball¹, T. Vogt¹, M. Kech² & U. Rösli²

¹Nagra

²Solexperts AG

KEYWORDS

Tiefbohrungen, TBO, Langzeitbeobachtung, LZB, Jura Ost,
JO, Bözberg-1, BOZ1

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

Hardstrasse 73
P.O. Box
5430 Wettingen
Switzerland
Tel. +41 56 437 11 11
nagra.ch

Nagra Arbeitsberichte ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information.

Copyright © 2023 by Nagra, Wetztingen (Switzerland) / All rights reserved.

All parts of this work are protected by copyright. Any utilisation outwith the remit of the copyright law is unlawful and liable to prosecution. This applies in particular to translations, storage and processing in electronic systems and programs, microfilms, reproductions, etc.

Table of Contents

Table of Contents	I
List of Tables.....	II
List of Figures	II
List of Acronyms.....	III
1 Introduction	1
1.1 Borehole Bözberg-1-1	2
1.2 Planning of the Multi-Packer System	4
1.3 Companies involved	6
2 Description of the Multi-Packer-System.....	7
2.1 Components	7
2.2 As-built record.....	15
3 Field work.....	19
3.1 Workover Rig	19
3.2 Preparation of the borehole.....	20
3.3 System installation.....	22
3.4 Quality assurance.....	23
4 Operation.....	25
5 References.....	28
App. A Specifications.....	A-1

List of Tables

Tab. 1-1:	General borehole information.....	2
Tab. 1-2:	Casing scheme and open hole intervals	6
Tab. 2-1:	Summary of the observation intervals and packer locations of the MPS	16
Tab. 3-1:	Summary of preparatory work.....	21
Tab. 3-2:	Summary of the installation activity.....	22
Tab. A-1:	Packer specifications	A-1
Tab. A-2:	Sensor specifications	A-2

List of Figures

Fig. 1-1:	Tectonic overview map with the three investigated siting regions.....	1
Fig. 1-2:	Location of the drill site BOZ1	3
Fig. 1-3:	Simplified lithostratigraphic profile, casing scheme and summary of the MPS for the BOZ1-1 borehole	5
Fig. 2-1:	Hanger sub with monitoring and inflation lines below and standpipes above, respectively.....	8
Fig. 2-2:	Installation of a packer element on the central tubing with a centralizer below.....	9
Fig. 2-3:	Connections of monitoring and packer inflate lines on a packer.....	10
Fig. 2-4:	Filter port with burst disc above, installed on the central tubing with metal banding straps	11
Fig. 2-5:	Installation of a sliding sleeve on the central tubing	12
Fig. 2-6:	Schematic drawing of a sliding sleeve in open and closed position	12
Fig. 2-7:	View of the opened splice box with three splices of the FO cable	13
Fig. 2-8:	Lowering of the landing spool with fittings for standpipes and packer inflate lines.....	14
Fig. 2-9:	Sketch of the configuration for two standpipes and pressure sensors with sub-artesian conditions (left) and artesian condition (right), respectively.....	15
Fig. 2-10:	Installation record and schematic layout of the MPS, as built.....	17
Fig. 2-11:	Installation record of centralizers in the MPS, as built.....	18
Fig. 3-1:	Setup of the workover rig during installation of the MPS	20
Fig. 4-1:	Panoramic view of the borehole cellar	25
Fig. 4-2:	Packer pressures in the first six months of operation	26
Fig. 4-3:	Hydraulic heads in the observation intervals in the first six months of operation	27

List of Acronyms

AISI	American Iron and Steel Institute
API	American Petroleum Institute
BTC	Buttress thread connection
DAS	Data acquisition system
DTS	Distributed temperature sensing
ELB	Disposal canister
FO	Fibre optics
HLW	High-level waste
ID	Inner diameter
L/ILW	Low- and intermediate level waste
LTMS	Long-term monitoring system
MPS	Multi-packer system
OD	Outer diameter
OPA	Opalinus Clay
OTDR	Optical time-domain reflectometry
POOH	Pull out of hole
RIH	Run in hole
TBO	Nagra deep borehole
TU	Tubing

1 Introduction

To provide input for site selection and the safety case for deep geological repositories for radioactive waste, Nagra has drilled a series of deep boreholes in Northern Switzerland. The aim of the drilling campaign was to characterise the Mesozoic sediments of the three remaining siting regions located at the edge of the Northern Alpine Molasse Basin (Fig. 1-1).

In this report, we describe the installation of a multi-packer-system (MPS) for long-term observation in the Bözberg-1-1 borehole. The details of the drilling and characterization of the borehole are given in Ammen et al. (2022).

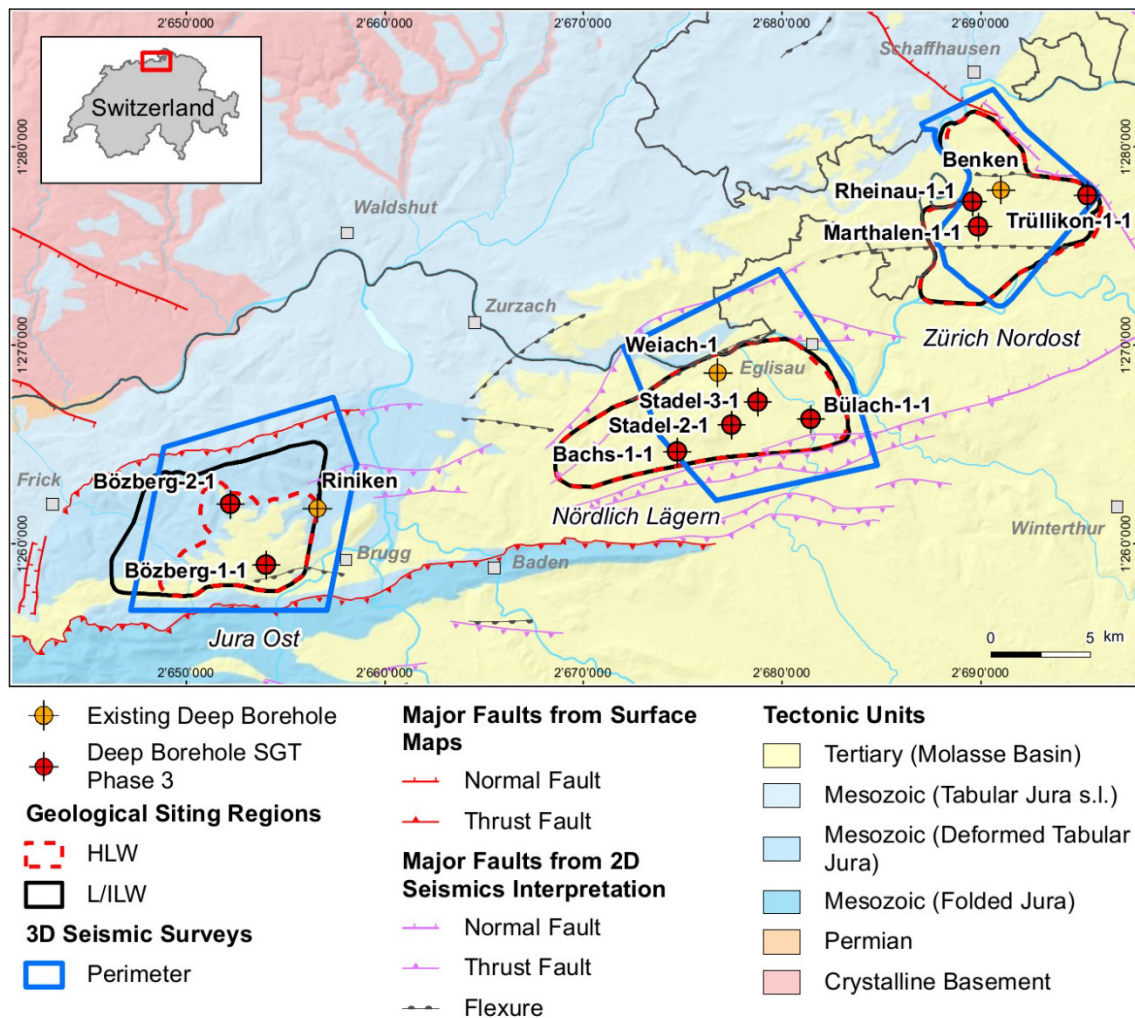


Fig. 1-1: Tectonic overview map with the three investigated siting regions

1.1 Borehole Bözberg-1-1

The general information on the borehole is given in Tab. 1-1, Fig. 1-2 shows a map with the location of the drill site.

The borehole initially drilled to 882 m where it had to be abandoned due to lost equipment in the hole. The borehole was cemented to the shoe of the 9 5/8" casing and a sidetrack was drilled at 709 m. The sidetrack, named BOZ1-1B was drilled to 1038.39 m depth. Hereafter, the completed well be named BOZ1-1 throughout.

After drilling, the borehole was cemented back to 880 m depth. The borehole was stabilised with a telescopic casing system and liner hanger to 824 m MD (Fig. 1-3).

Tab. 1-1: General borehole information

Borehole name	Bözberg-1-1 (BOZ1-1)
Siting region	Zurich Nordost, Switzerland
Wellhead coordinates (for log headers)	X (m) 2'653'995.815 Y (m) 1'258'925.446 (Geodetic Datum: CH1903+/LV95)
Ground level	513.29 m AMSL (top of rig cellar)
Drilling period (start – end rig release)	27.04.2020 – 03.12.2020
Drilling company	PR Marriott Drilling Ltd.
Drilling rig	Rig-16 Drillmec HH102
Borehole maximum total depth	1037.39 m
Maximum deviation	3.12° at 709 m MD (borehole is vertical)
Maximum dogleg severity	7.5°/30 m at 518.31 m MD

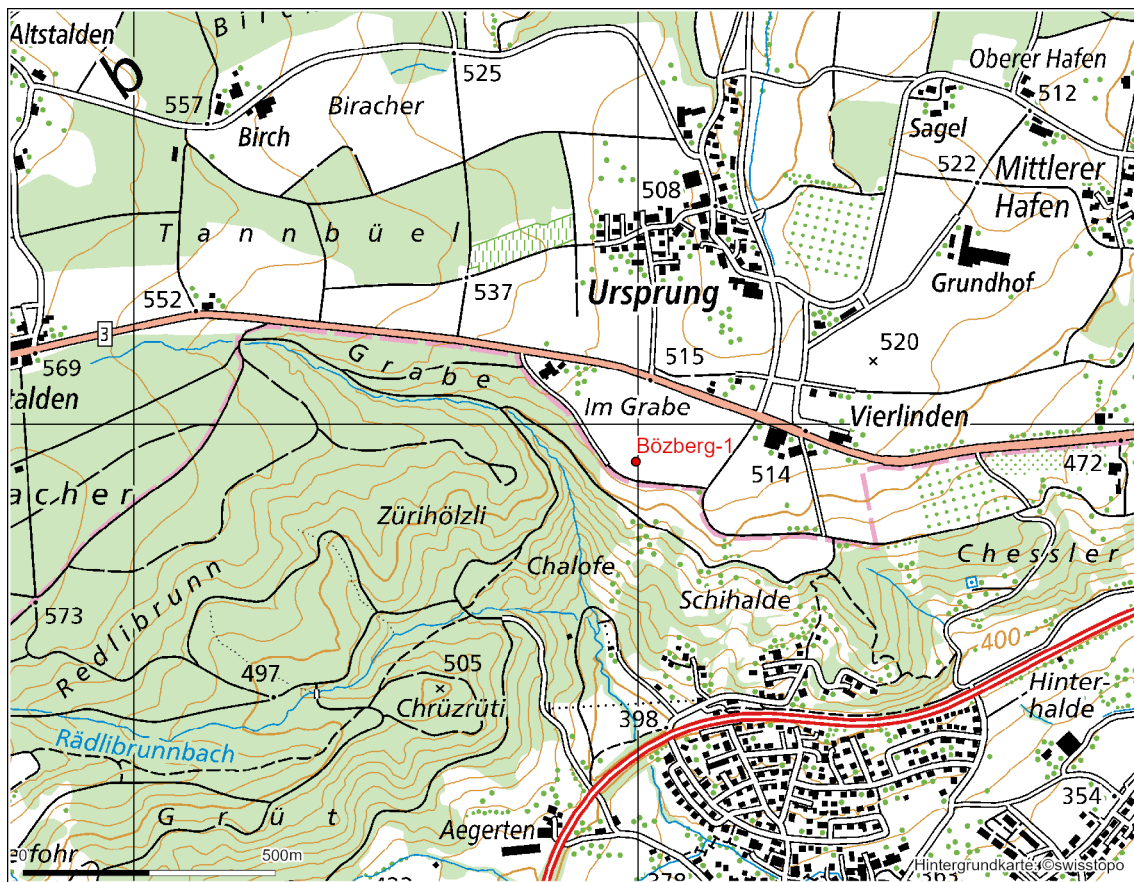


Fig. 1-2: Location of the drill site BOZ1

1.2 Planning of the Multi-Packer System

The MPS is intended to measure the undisturbed hydraulic heads and their temporal fluctuations in the Opalinus Clay, its surrounding rock units and the deep aquifers. The measurements represent a part of the environmental baseline monitoring according to Fanger et al. (2021).

If required, simple hydraulic tests and groundwater sampling in the deep aquifers will also be possible during the monitoring phase at selected observation intervals of the MPS. Furthermore, measurements of undisturbed formation temperatures are also foreseen.

Finally, with the long time series, the hydraulic heads in the clay-rich and very low-permeability formations can be recorded precisely and thus large-scale, undisturbed hydraulic properties of the rock can be mapped. This means that the database for regional and local hydrogeological models can be further expanded.

The MPS was planned considering the hydraulic tests conducted during drilling of the borehole, the recovered core and image logs as well as logs that provide information on the cementation quality.

Nine observation intervals were foreseen: one in each of the aquifers (Malm and Muschelkalk), three zones in the Opalinus Clay sections and four zones in the rock units surrounding the Opalinus Clay: Hauptrogenstein and Passwang formation of the Dogger group, the Staffelegg formation in Lias and the Klettgau formation in Keuper (Fig. 1-3). Note that the Keuper and Hauptrogenstein units showed low permeability in the TBO hydraulic testing and are not considered aquifers at BOZ1.

The details of the borehole casing are given in Tab. 1-2 and had to be considered for the planned perforation and selection of suitable packer elements. Perforation of the casing prior to MPS installation was required to create a hydraulic connection to the formations behind the casing where observation intervals of the MPS were planned.

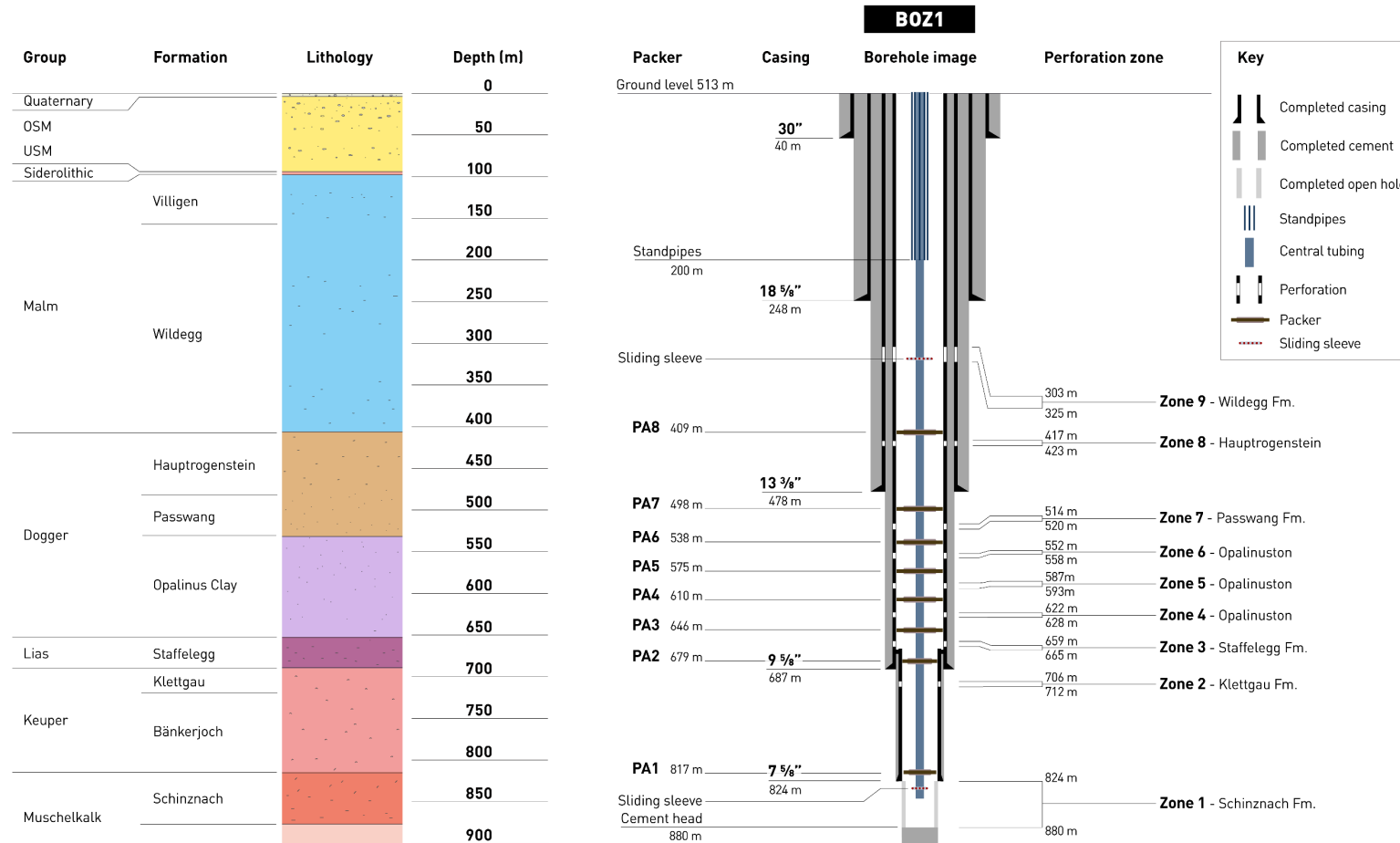


Fig. 1-3: Simplified lithostratigraphic profile, casing scheme and summary of the MPS for the BOZ1-1 borehole
For clarity, the abandoned well section is not shown. All depths are rounded to full meters.

Tab. 1-2: Casing scheme and open hole intervals

Section	Cased hole	Open hole
0 – Conductor	OD: 30"; Interval: 0 to 40 mMD Construction steel (S 355)	OD: 35 1/2"; Interval: 0 to 40.5 mMD
1 – Surface casing	OD: 18 5/8"; Interval: 0 to 247.85 mMD K-55, 87.5 lbs/ft, BTC	OD: 23"; Interval: 40.5 to 247.9 mMD
1 – Intermediate casing	OD: 13 3/8"; Interval: 0 to 478.08 mMD K-55, 68.0 lbs/ft, BTC	OD: 17 1/2"; Interval: 247.9 to 478.2 mMD
2 – Production casing	OD: 9 5/8"; Interval: 0 to 687.40 mMD K-55, 40.0 lbs/ft, BTC ID: 224.41 mm, Drift 220.45 mm	OD: 12 1/4"; Interval: 478.2 to 687.4 mMD
3 – Liner hanger	OD: 7 5/8"; Interval: 667.80 to 824 mMD K-55, 29.7 lbs/ft, BTC ID 174.63 mm, Drift 171.45 mm,	OD: 9 1/2"; Interval: 687.4 to 824 mMD
4 – Open hole	OD: 6 3/8"; Interval: 824 to 1037.4 mMD Cement backfilled from 1037.4 to 880.3 mMD	

1.3 Companies involved

The following companies were involved in the installation activities:

- Nagra: project management, coordination, and organisation of the well site
- Daldrup & Söhne AG: drilling contractor
- Schlumberger: wireline logging and perforation
- Société Suisse des Explosifs: supervising work with explosives during perforation
- Solexperts: Installation of the MPS
- Well Engineering Partners BV (WEP): drilling supervisors
- AFRY Switzerland Ltd: Quality control of the installation work performed in the borehole
- Ad Terra Energy: technical supervision of all the perforation and logging work performed in the borehole

2 Description of the Multi-Packer-System

The MPS isolates nine observation intervals in the 1037.4 m deep borehole BOZ1-1. The borehole is fully cased until 824 m MD. The open borehole section extends down to 880.3 m MD to the cement head, isolating the lowermost borehole section until borehole end. The casing outer diameter in the section instrumented with the MPS is $7 \frac{5}{8}$ " and $9 \frac{5}{8}$ ". The observation intervals are perforated to create a hydraulic connection to the formations. The casing was perforated in August 2021, almost one year before the MPS installation. The delay from perforation to installation was due to the issues with the first installation in MAR1, after which a significant gap was necessary in order to change the packer design and the availability of a suitable workover rig.

The system consists of the following main components:

- central tubing string;
- hydraulically inflatable packers; each with one packer inflation line;
- monitoring lines with ports/filters to measure the hydraulic head in the observation intervals;
- sliding sleeves to guarantee individual additional access to aquifers for groundwater sampling;
- pressure sensors for pressure measurements in the observation intervals and of the packer pressures;
- packer pressure control system at the surface;
- data acquisition system.

2.1 Components

Central tubing string

A $2 \frac{7}{8}$ " outer diameter L80, 6.5 lbs/ft tubing with API standard connections and an inner diameter of 62 mm is used. The length of the individual tubings is about 9.34 m. Protector couplings are used to protect and guide the packer and observations lines at the position of the couplings. In addition, one banding strap Alloy400 (Monel® 400) was used to fix the lines in the middle of each ~9.34 m long tubing.

A bullnose with a diameter of 140 mm is mounted as end cap at the bottom of the system and is sealed by Loctite adhesive.

The protector couplings protect and guide the packer and observation lines at the position of the tubing couplings. Two types of protector couplings are used, one type for the tubing below 200 m depth with packer and observation lines and the other type for the upper 200 m of tubing with packer lines and standpipes (Fig. 2-1). The protector couplings above 200 m depth are custom-made for 9 standpipes from the observation intervals, the 8 packer inflation lines and the fibre optic cable.

For the centralization of the whole downhole assembly in the borehole, centralizers are installed wherever it is appropriate to guarantee a smooth installation in critical sections (e.g. in the area of the liner hanger).



Fig. 2-1: Hanger sub with monitoring and inflation lines below and standpipes above, respectively

Sliding-end packers

Two types of sliding end packers are used, 154 mm (6.06") packer for the 7 ⁵/₈" diameter casing and 184 mm (7.24") packer for the 9 ⁵/₈" diameter casing. The packer connections were sealed with Loctite adhesive during installation (Fig. 2-2). The packers are individually inflated with water and in the uppermost part of the packer inflation lines with antifreeze (to protect from freezing during cold winter time). All packer pressure lines are run through the mandrels of the upper packers and are connected to a packer pressure maintenance system in the bore cellar. Full packer specifications are given in App. A. The packers fulfil the following requirements:

- Length of packer sleeve = 1.00 m;
- Natural rubber type for long-term stability;
- Integrated steel wire reinforcement in sleeves;
- Packers hold a differential pressure (pressure difference across a packer element) of 6'000 kPa for the defined casing diameters;
- Individual hydraulic inflation line for each packer with fluid (OD ¼");
- The pressure of each packer is kept stable with a pressure maintenance system in the bore cellar.



Fig. 2-2: Installation of a packer element on the central tubing with a centralizer below

Packer inflation lines

Each packer is connected via a packer line to the packer pressure maintenance system installed in the bore cellar. The packer lines are made of stainless steel 1.4404 (AISI 316 L), with inner diameter (ID): 4.55 mm, and outer diameter (OD) 6.35 mm. They are connected by Swagelok-type (Hy-Lok), stainless steel 1.4401 (316) fittings (Fig. 2-3).

The packer inflation lines were delivered in 250 m rings. Each ring was tested on tightness with 7 bar compressed air in a water basin. Afterwards, the packer inflation lines were wound up on a bobbin and the rings were connected with Swagelok-type compression fittings. The entire line for each packer was saturated with water and pressurized with 100 bar water pressure.

Above each packer inflation port, a burst disc is included in the packer inflation line to avoid packer inflation during system installation (the packer inflation lines are saturated with water before system installation). They were also used to test the tightness of the packer inflation lines and their couplings at the end of the system installation before packer inflation.

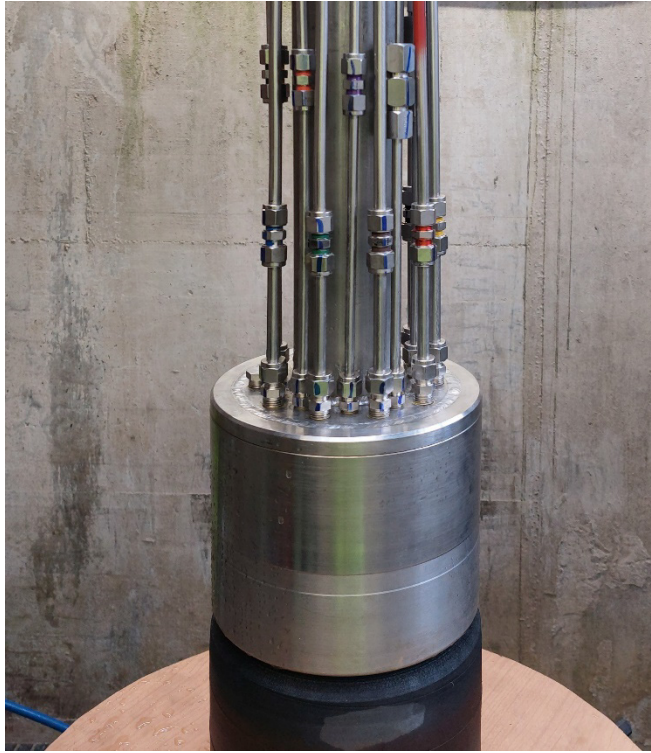


Fig. 2-3: Connections of monitoring and packer inflate lines on a packer
Lines are identified by a colour code.

Monitoring lines with filter ports

Each observation interval is equipped with an individual monitoring line for pressure monitoring.

The monitoring lines from the observation intervals until 200 m below ground level have an inner diameter of 6.00 mm and an outer diameter of 8.00 mm.

The monitoring lines were delivered in 350 m rings. Each ring was tested on tightness with 7 bar compressed air in a water basin. Afterwards, the monitoring lines were wound up on a bobbin and the rings were connected with Swagelok-type compression fittings. The entire line for each packer was saturated with water and pressurized with 100 bar water pressure.

Each monitoring line is equipped with a filter piece located in the corresponding observation interval. The filter piece consists of a tube with an outer diameter of 20 mm mounted to the monitoring line with Swagelok-type fittings (Fig. 2-4).

Above each filter piece, a burst disc is included in the monitoring line. They were used for pressure testing the monitoring lines with water up to 20 bar.

At about 200 m below ground level, each monitoring line is connected to a stainless-steel standpipe up to the wellhead. A specific hanger sub was used to connect the monitoring lines and the standpipes (Fig. 2-1). The standpipes have an ID of 16.05 mm and an OD of about 19.05 mm and a standard length of 6 m. They are connected by $\frac{3}{4}$ " Swagelok fittings. For artesian conditions, the monitoring standpipes have a valve at the top end such that the pressure transmitter and manometer can be removed without outflow or pressure decrease in the standpipe.



Fig. 2-4: Filter port with burst disc above, installed on the central tubing with metal banding straps

Sliding sleeves

To be able to take water samples from selected aquifers, two sliding sleeves are installed into the central tubing string (Fig. 2-5 and Fig. 2-6) at the depth of the aquifers (Tab. 1-2). The connection is sealed by Loctite adhesive. By opening the sliding sleeve, the access to the observation interval is established and the water can be pumped to the surface by installing a 2"-pump or similar into the central tubing string.

The sliding sleeve has an opening and closing mechanism which is activated by a wireline operation tool. The operation tool is designed to be run using wireline methods. The sliding sleeve has the ability to operate numerous times over a long period of time.



Fig. 2-5: Installation of a sliding sleeve on the central tubing

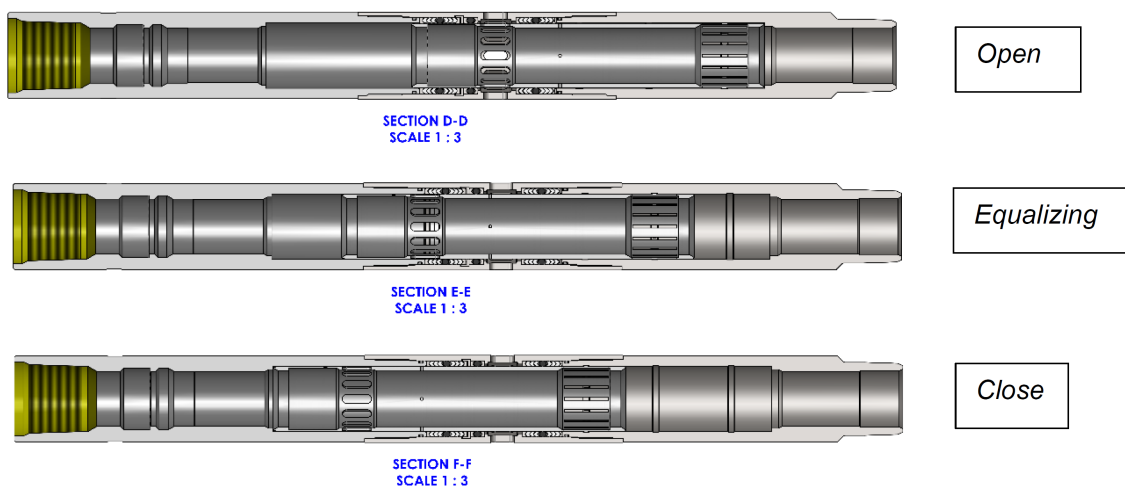


Fig. 2-6: Schematic drawing of a sliding sleeve in open and closed position

Fibre optic cable

A fibre optic cable is run along the multi-packer-system along with the packer and monitoring lines. The used fibre-optic cable is a stainless-steel loose tube-in-tube sensing cable, with carbon-coated fibres. One single-mode fibre and two multi-mode fibre strands are integrated. The multi-mode fibers are connected at the bottom at 820.94 m depth to make one continuous loop.

The cable has to be spliced below each packer using a splice box designed by Solexperts (Fig. 2-7), which is tightly sealed with sealing glands (CONAX compression seal fittings). Before installation of the splice box in the borehole, the quality of each splice was verified with an OTDR-measurement. Additionally, the exact position of each splice box and the cable meters deployed in the borehole were documented during the installation.

In the borehole cellar a reference box with thermal isolation material and about 50 m of cable is mounted to the wall. This can be used for calibration during each measurement.



Fig. 2-7: View of the opened splice box with three splices of the FO cable

Landing Spool – Wellhead flange

The wellhead flange is a standard 11" API flange (3'000 psi) with a soft iron ring as seal (Fig. 2-8). Two 2 7/8" EU pup joints (0.5 m at the top, 1.0 m at the bottom; both screwed in with optimum torque) are screwed in the landing spool, together with NPT connections for the 8 packer inflation lines, one FO cable and 9 monitoring standpipes (through-hole tube fitting for the 3/4" observation standpipes).



Fig. 2-8: Lowering of the landing spool with fittings for standpipes and packer inflate lines

Deployed sensors

Different pressure sensors were deployed in the system. A barometric sensor to measure atmospheric pressure and a temperature sensor for ambient temperature are installed in the bore cellar. The sensor specifications are given in Tab. A-2.

In case the hydraulic head lies below ground level, the fluid level in the interval observation lines is monitored by submersible water level probes (downhole pressure probes), which are installed in the standpipes below the expected hydraulic head (water level), see Fig. 2-9. The fluid level in the standpipes can lie between 0 – 200 m below ground level. The standpipe is open to the atmosphere. If a pumping test with groundwater sampling will be performed in one of the aquifers, the probe depth can easily be adjusted. Moreover, sensors can be easily repaired or replaced when they have a problem.

If an observation interval shows artesian conditions, the hydraulic head is measured at the wellhead level at the end of the standpipe with a pressure transmitter and with a manometer, see Fig. 2-9. In case of sensor failure, both, the submersible water level probes and the pressure transmitters are easily replaceable.

The downhole sensors are slim, short and very light. To avoid any problems with the lowering of the downhole sensors in the standpipes to the desired depths, ten sinker bars are available which can be screwed to the bottom end of each sensor. The sinker bars have a length of 0.5 m and a weight of 0.3 kg each. Several sinker bars can be connected together, if necessary.

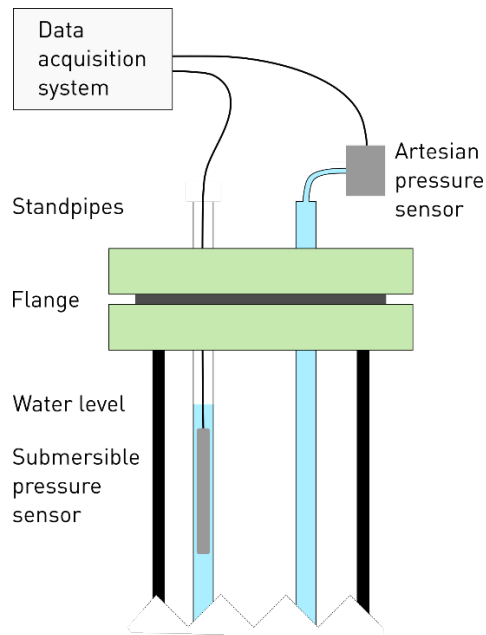


Fig. 2-9: Sketch of the configuration for two standpipes and pressure sensors with sub-artesian conditions (left) and artesian condition (right), respectively

Packer pressure control system

The pressure of each packer should be kept constant with a pressure vessel connected to a 20-litre nitrogen gas bottle with high precision pressure reduction valve. The vessel is filled up to $\frac{2}{3}$ with water and $\frac{1}{3}$ with gas and the pressure is monitored with a pressure sensor. The nitrogen gas bottle contains a small amount of a non-toxic tracer gas with a strong odour, so that leakages in the high-pressure maintenance system can be detected easily when entering the bore cellar.

Data acquisition system

The DAS consist of an industrial PC, screen and keyboard. Data acquisition is performed through the Solexperts GeoMonitor II software. The connected sensors include packer pressure, interval pressure, ambient pressure and temperature and weight readings from the scales with the pressure vessels. Data is transmitted via FTP to a database for remote access to the monitoring data.

2.2 As-built record

The lengths of the $2 \frac{7}{8}$ " central tubing vary slightly from one piece to another. Hence, there are minor deviations in the geometry as-built over the planned location of all elements of the MPS. Tab. 2-1 summarizes the as-built record for the sub-surface components, i.e. the depths of packers and sliding sleeves together with the perforation zones. The perforation zones were realized according to the planned depth with an accuracy of around 0.1 m and confirmed by logs. Fig. 2-10 contains the detailed installation record and schematic layout of the MPS, and Fig. 2-2 provides further detail on the centralizers deployed.

Tab. 2-1: Summary of the observation intervals and packer locations of the MPS

	Formation	Interval [m MD]	Length [m]	Sliding sleeve [m MD]	Perforation [m MD]
Interval 9	Wildegge Fm. (Malm)	0 – 408.91	408.91	322.33-323.24	303.00 – 309.99 310.97 – 316.97 319.02 – 325.02
Packer 8		408.91 – 409.91	1.0		
Interval 8	Hauptrogenstein (Dogger)	409.91 – 497.79	87.88		416.99 – 422.99
Packer 7		497.79 – 498.79	1.0		
Interval 7	Passwang Fm. (Dogger)	498.79 – 539.42	39.63		514.00 – 520.00
Packer 6		538.42 – 539.42	1.0		
Interval 6	Opalinus Clay (Dogger)	539.42 – 574.89	35.47		552.01 – 558.01
Packer 5		574.89 – 575.89	1.0		
Interval 5	Opalinus Clay (Dogger)	575.89 – 610.37	34.48		587.00 – 593.00
Packer 4		610.37 – 611.37	1.0		
Interval 4	Opalinus Clay (Dogger)	611.37 – 645.70	34.33		622.01 – 628.01
Packer 3		645.70 – 646.70	1.0		
Interval 3	Staffelegg Fm. (Lias)	646.70 – 678.81	32.11		659.00 – 665.00
Packer 2		678.81 – 679.81	1.0		
Interval 2	Klettgau Fm. (Keuper)	679.81 – 817.00	137.19		706.00 – 712.00
Packer 1		817.00 – 818.00	1.0		Open hole
Interval 1	Schinznach Fm. (Muschelkalk)	818.00 – 880.00	62.00	828.01 – 828.92	

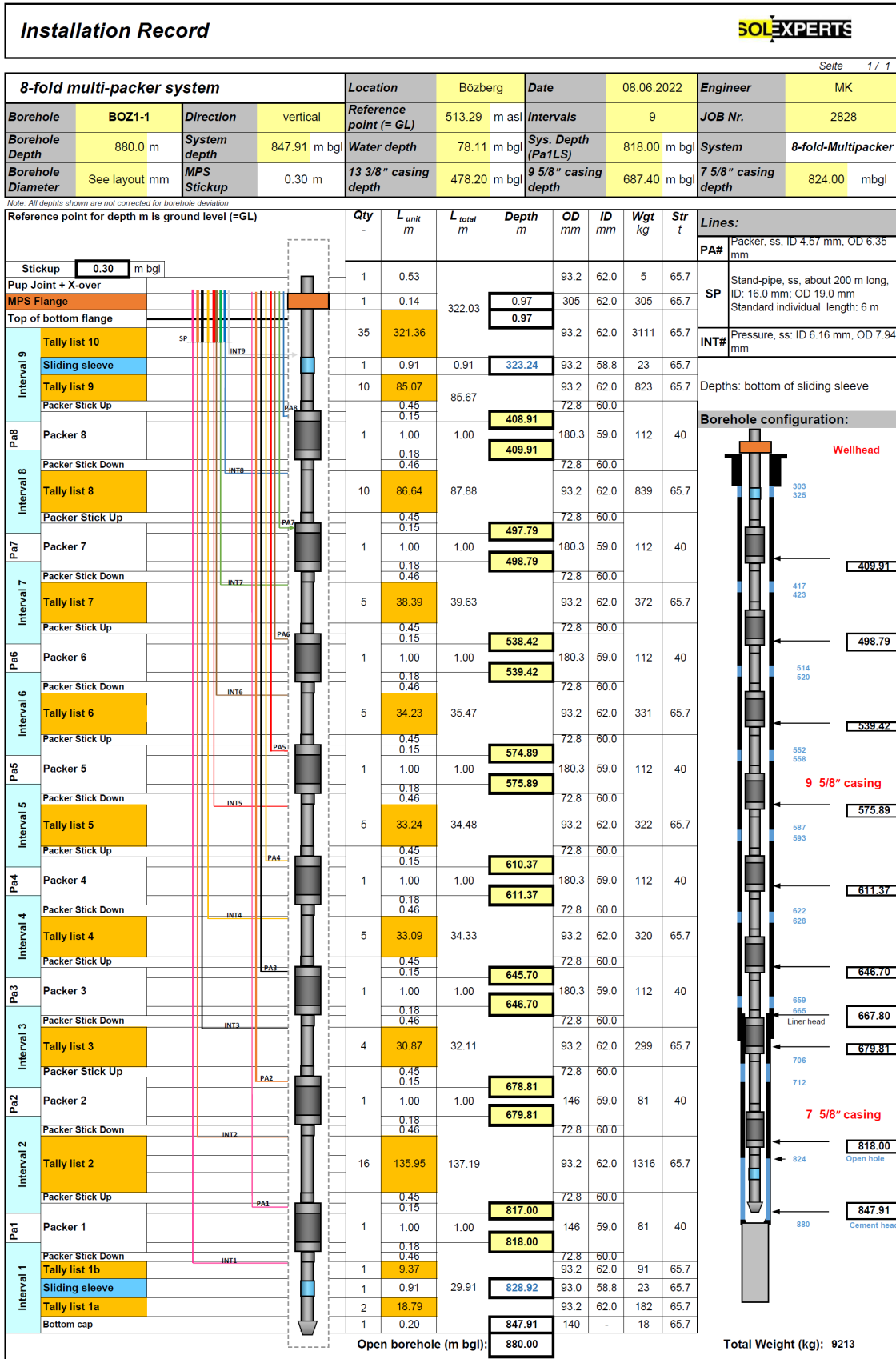


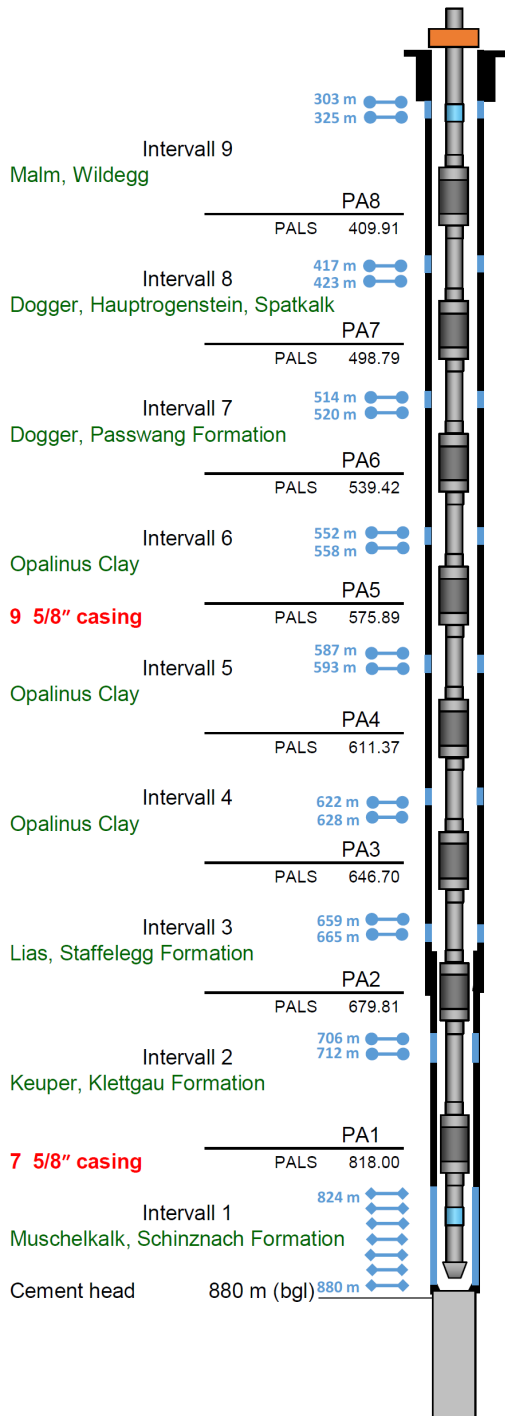
Fig. 2-10: Installation record and schematic layout of the MPS, as built

Add-on Installation Record SOLExperts

Borehole: BOZ1-1
Open Borehole Depth: 880 m

Date: 08.06.2022
Location: Bözberg

WC: welded positive cased hole centralizer
BC: bow-spring centralizer



Centralizer		
No.	Type	Tubing
C22	WC 8 3/8"	TU63
C21	WC 8 3/8"	TU43
C20	WC 8 3/8"	TU42
C19	WC 8 3/8"	PJ11_3m
C18	WC 8 3/8"	TU33
C17	WC 8 3/8"	TU30
C16	WC 8 3/8"	TU29
C15	WC 8 3/8"	PJ8_3m
C14	WC 8 3/8"	TU26
C13	WC 8 3/8"	PJ6_3m
C12	WC 8 3/8"	TU23
C11	WC 8 3/8"	PJ4_3m
C10	WC 8 3/8"	TU20
C9	WC 6 1/2"	PJ3_3m
C8	WC 6 1/2"	TU17
C7	WC 6 1/2"	TU17
C6	WC 6 1/2"	PJ1_3m
C5	WC 6 1/2"	TU3
C4	WC 6 1/2"	TU3
C3	BC 6"	TU2
C2	BC 6"	TU1
C1	BC 6"	TU1

TU: Tubing #
PJ: Pup Joint #_length

●—● perforated borehole section
— open borehole section

Fig. 2-11: Installation record of centralizers in the MPS, as built

3 Field work

3.1 Workover Rig

The preparation of the borehole and installation of the MPS was conducted using a workover rig Schäfer C14 8.10 operated by Daldrup (Fig. 3-1). The specifications are detailed below.

Work over rig details

General

- Max. Load: 470 kN
- Working Load: 410 kN
- Auxiliary winch: 20 kN
- Workover rig height: 13.8 m (overall); 11.8 m (free working)

Top Drive hydraulic

- Power: 140 kW
- Max. Torque: 15000 Nm
- Max. RPM: 300 1/min
- Constant Torque: 6000 Nm
- Constant RPM: 280 1/min

Mud pumps

- Power: 84 kW
- Max. pressure: 210 bar
- Max. flow rate: 500 l/min

Mud mixing system

- Volume: 40 m³ mud tanks+ 12 m³ mixing tank



Fig. 3-1: Setup of the workover rig during installation of the MPS

3.2 Preparation of the borehole

Before installation of the MPS, the borehole had to be prepared. The first step was to replace the completion fluid with a synthetic porewater, that resembles the composition of the pore water found in the Opalinus Clay formation of the borehole. A batch of 10 m³ of tap water mixed with salts according to the following list:

- 32 kg NaCl
- 0.6 kg KCl
- 60 kg Na₂SO₄
- 0.6 kg NaHCO₃
- 8 kg MgCl₂ * 6 H₂O
- 13.6 kg CaCl₂ * 2H₂O
- 0.25 kg SrCl₂ * 6 H₂O

Uranine tracer fluid at 1 ppm concentration was added just before pumping of the brine in order to not lose the dye effect which fades with exposure to sunlight.

Subsequently, the borehole was perforated at the selected intervals. Each perforation section was about 6 m long and contained 100 shots of shaped charges (5 shot/ft).

The preparation work is summarized in Tab. 3-1.

Tab. 3-1: Summary of preparatory work

Date	Activity
13.08.21 – 17.08.21	Delivery of workover rig and other equipment Rig-up workover rig
18.08.21 – 18.08.21	Run in hole (RIH) of 3 1/2" drill pipe to 877 m depth. Last 3 drill pipes in open hole section were installed under circulation Total depth is reached at depth 877 m, stand-up load was 3 tons Circulating tap water to check for returns, fluid returns were received Mixing of 40 m ³ of synthetic pore fluid Fluid returns were salt completion fluid and about 2 m ³ of bentonite mud from the open hole section Synthetic pore fluid returned after 33 m ³ pumped volume Stopped pumping after 35 m ³ total Pull out of hole (POOH)
19.08.21 – 23.08.21	Preparation for perforations Running Casing Collar Locator log for depth reference during perforations. Ten perforation runs according to Tab. 2-1 Confirmation of perforations using USIT log
23.08.21 – 25.08.21	Scraper runs in 9 5/8" casing, then in 7 5/8" liner, respectively, to clean the hole. At the bottom of the scraper the borehole fluid was exchanged again for a fresh batch of synthetic pore water with the composition as detailed above.
26.08.21	Begin of rig down of workover rig

The installation of the MPS was originally foreseen to occur immediately after the perforations. However, due to the problems with the system in MAR1 the installation was cancelled and postponed indefinitely. The borehole was closed with the original wellhead.

In February 2022 fluid sampling was performed in BOZ1 in order to verify the stability of the fluid column of synthetic pore water. A fluid sample at depth of the middle OPA interval was taken and analysed in a laboratory. It was found that the fluid composition was very close to the specifications and hence the fluid column indeed was stable. It was decided that the installation of the MPS could be performed without any further actions in regard to the completion fluid.

3.3 System installation

The MPS as detailed in Section 2 was installed in Summer 2022, immediately after the MPS installation in MAR1 was finished.

Tab. 3-2: Summary of the installation activity

Date	Activity
23.05.22 – 27.05.22	Delivery of workover rig and other equipment Rig-up workover rig
30.05.22	Preparatory work for the MPS installation (e.g. measuring of tubing, setup of scaffolding for steel lines, preparation of tools)
31.05.22	Finish of preparatory work Installation to tubing (TU) 4, incl. packer 1
01.06.22	Installation to TU21, incl. packers 2 and 3
02.06.22	Installation to TU26, incl. packer 4
03.06.22	Installation to TU29, incl. packer 5
07.06.22	Installation to TU33, incl. packers 6 and 7
08.06.22	Installation to TU42, incl. packer 8
09.06.22	Installation to TU51
10.06.22	Installation to TU65, incl. standpipe series no. 1
13.06.22	Installation to TU70, incl. standpipe series no. 9
14.06.22	Installation to TU78, incl. standpipe series no. 23
15.06.22	Installation to landing spool, incl. remaining standpipes
16.06.22 – 21.06.22	Connect lines to pressure vessels and data acquisition in borehole cellar
22.06.22	Breaking of burst discs in monitoring lines
23.06.22	Breaking of burst discs and inflation of packers 8 to 3 (top to bottom)
24.06.22	Re-inflation of packers 8 to 3 Breaking of burst discs and inflation of packers 2 and 1
27.06.22 – 04.07.22	Finish of installation work in the borehole cellar Clean-up

3.4 Quality assurance

The system installation was performed by Solexperts, Nagra provided AFRY for QC and the workover rig from Daldrup (with personnel). Each activity was checked based on the 4-eyes principle by the Solexperts test engineer / Solexperts technician / Solexperts-GTC Geophysicist. In addition, AFRY performed independent QC. All relevant activities were documented by the Solexperts test engineer and by the AFRY in separate logbooks. All actions concerning the FO cable installation and verification were made by the FO specialist from the Solexperts subsidiary Solexperts GmbH Karlsruhe (brand name GTC Kappelmeyer).

Before delivery of all components, they were tested by the manufacturer or in the lab by Solexperts.

- The 2 7/8" central tubing were checked for checked against API requirements and dimensional accuracy (tubing and threads)
- The tightness of threads was verified using the actual hydraulic tongs used during installation with nitrogen gas and water
- The inflatable packers were checked by the manufacturer as well as Solexperts in pieces of casing provided by Nagra, Tests were run for at least 1 day on each packer
- Stainless steel lines and standpipes were checked by the manufacturer for conformity with specifications and pressure tested, including necessary couplings, by Solexperts
- Samples of the burst discs were tested in the lab to verify burst pressure and the burst pattern, to exclude future clogging of potential restrictions
- The sliding sleeves were pressure tested with nitrogen gas and there opening operation checked
- The FO cables were checked for attenuation at two different wavelengths
- The FO splice boxes and feed-throughs were pressure tested at 99.5 bar
- The pressure sensors were calibrated by the manufacturer

The quality assurance on site – before, during and after system installation – comprised the following procedures:

- Each 2 7/8" central tubing rod to be installed was numbered with a permanent marker and was measured with a measuring tape. Each length was documented in the installation list.
- The inner diameter of each tubing rod was checked with a dummy at a fibreglass stick (OD dummy 58 mm)
- Each tubing was cleaned with a high-pressure cleaner, each tubing coupling was cleaned with rags.
- The final installation list with the tally list and the installation record was proved and accepted by AFRY.
- The grease for connecting the system parts was provided by Nagra.
- The tightening torque of each system part connection (central tubing, sliding sleeves, packer) was checked by AFRY (optimum torque: 2250 lbf-ft = 3050 Nm).
- The connected system parts did not show a thread turn when connected which corresponds to the measured system part length.
- Each installed system part was protocolled by the Solexperts test engineer and by AFRY.

- Each coupling of the FO cable, packer and interval lines and standpipes was checked by the Solexperts test engineer and by AFRY. Each tightened coupling was marked and photographed by AFRY.
- The couplings of the FO cable were tightened with a torque wrench (30 Nm), the ¼" and 8 mm lines were tightened with suitable spanners and were checked with the corresponding control gauges of the coupling suppliers. The standpipe couplings were mounted onto the standpipes with a hydraulic pre-assembly device and were tightened with suitable spanners and a torque wrench (49 Nm) and were checked with the corresponding control gauge for the specific coupling.
- Each packer was checked on the workbench before installation (visual and coupling check).
- Each line and the FO cable were visually controlled during the system installation.
- Each burst disc unit was controlled during system installation (if installed in the right direction).
- The colour codes of the lines and standpipes were checked before connecting the lines and standpipes.
- When the lines and the 1/8" FO cable were fixed to the central tubing string with Monel® banding straps, a guide bar made out of corn starch (produced with a 3-D printer) was used to clamp and protect the FO cable. It was also checked that no lines were crossed over while tightening the strap.
- The borehole annulus between the installed system string part and the casing was covered during any actions at the system with thin slotted plywood discs movable between each other and with rags.
- The exact position of each installed filter piece and of each splice box was measured with a meter stick.
- The functionality of the FO cable was checked after each splicing and also during system installation. Splicing and verification was made by the FO specialist.
- The tightness of the central tubing was checked by filling up the tubing to the top during and after system installation.
- Packer lines and interval lines / standpipes were pressurized with 20 bar water pressure after system installation and before bursting the burst discs to detect major leaks.
- During packer inflation, the interval pressures were already monitored online with downhole or artesian pressure sensors.
- The inflation pressure of the packer was monitored by a manometer and, when the packer inflation lines were connected to the corresponding pressure vessel, additionally by packer pressure sensors mounted on top of each vessel.
- The weight of each pressure vessel was measured with individual scales. The weights are shown on the displays. In the beginning the scale weights were manually read out. Since 25 August 2022, the scale weights are automatically recorded by the DAS.

4 Operation

Fig. 4-1 contains an overview of the system installation in the borehole cellar. The packers were inflated on June 23 and 24, 2022, which initiated zonal isolation and hydraulic heads between the observation intervals started to separate.

Data is recorded by the DAS. The sampling rate can be adjusted as needed and is set to 5 minutes for long-term monitoring. Daily files include pressure readings (monitoring zones and packers), weights of the pressure vessels (added on August 25, 2022) and ambient air temperature and air pressure in the borehole cellar. They are uploaded via FTP to a server for long-term storage and access. In addition, the sensor depths and any changes performed as part of the system maintenance are recorded in a logbook. This ensures that all necessary corrections can be performed on the recorded raw data for the evaluation of hydraulic heads of the observation intervals.



Fig. 4-1: Panoramic view of the borehole cellar

from left to right: the pressure control system with pressure vessels, the DAS (blue box), wellhead and monitoring lines, second set of pressure control units with inflate and gas bottles.

For verification and initial data recording, a DTS measurement was conducted after installation. No calibration was applied to this measurement since this was conducted primarily to validate that the fibre optic cable fully functional. The measurement showed that the multi-mode fibre has strong signal artefacts (high loss) below about 680 m. This section needs to be discarded from measurements.

The packers were inflated and re-inflated in several steps needed to reach stable conditions. Due to transient expansion of the packer sleeve and solution of trapped air in the fluid, pressure decreased and was compensated by re-inflation. After the initial phase most packers have stabilized. Packer 8 slowly loses pressure and has to be re-inflated periodically in order to guarantee separation of the observation intervals. An alarm system is implemented that sends out notifications when the packer pressure falls below a certain threshold to allow sufficient mobilisation time for a maintenance intervention. The time series of the packer pressures is shown in Fig. 4-2.

Fig. 4-3 shows the measured hydraulic heads of the observation intervals during the same time period. The ground surface is outside of the plotting range at 513 m, thus all zones are subartesian. It is evident that the Schinznach and Keuper formations are close to equilibrium. The other zones are still declining and recovering from the perturbation by the drilling operations and installation

of the MPS. Note that the pressure sensors had to be lowered inside the standpipes several times in order to adapt to the falling measured heads. For the low permeability formations the displacement by the additional cable length resulted in an apparent instantaneous head increase.

A more detailed discussion of the initial observations will be given in the first annual data trend report.

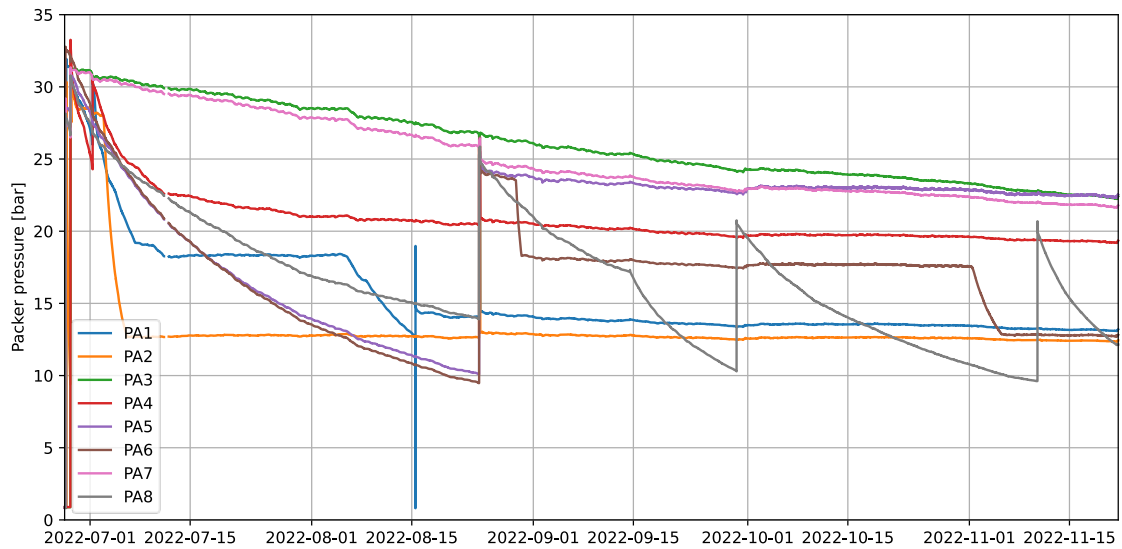


Fig. 4-2: Packer pressures in the first six months of operation
 PA8 was re-inflated several times when falling below 10 bar pressure to ensure interval separation.

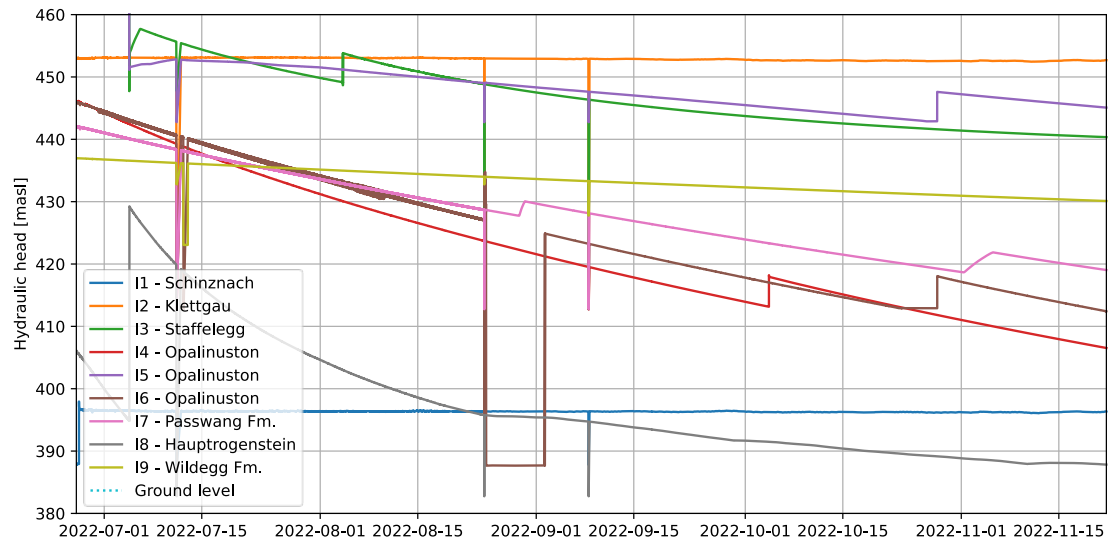


Fig. 4-3: Hydraulic heads in the observation intervals in the first six months of operation
 Ground level is at 513 m. Instantaneous vertical shifts correspond to the water displacement after manual changes of sensor installation depth.

5 References

Ammen, M., Palten, P.-J., Vlieg, J., Gollob, K. & Hilgendorf, K. (2022): TBO Bözberg-1-1: Data Report Dossier I Drilling. Nagra Arbeitsbericht NAB 21-21 I.

Fanger, L., Müller, H. & Vogt, T. (2021): Konzeptbericht Überwachung Umwelt und geologisches Umfeld. Nagra Arbeitsbericht NAB 20-28 Rev. 1.

App. A Specifications

Tab. A-1: Packer specifications

	Packer for 9^{5/8}" casing	Packers for 7^{5/8}" liner
Manufacturer	Inflatable Packers International, Perth, Australia	
Packer type	IPI 6.06" (154 mm)	IPI 7.24" (184 mm)
Rubber type	Natural rubber, sliding end	Natural rubber, sliding end
Reinforcement	Steel wire reinforced	Steel wire reinforced
Material	Stainless steel	Stainless steel
Drift casing diameter	171.5 mm	220.5 mm
Outer diameter not inflated	154 mm, max.	184 mm, max
Inner diameter	59 mm, min.	59 mm, min
Overall length	2.296 m	2.296 m
Installation length	2.239 m	2.239 m
Rubber sleeve length	1.00 m	1.00 m
Thread connections	2 ^{7/8} " EU pin × 2 ^{7/8} " EU box	2 ^{7/8} " EU pin × 2 ^{7/8} " EU box
Max. number of lines through packer	3 × ø 8 mm	10 × ø 8 mm
	2 × ø 6.35 mm	9 × ø 6.35 mm
	1 × ø 6.35 mm (inflation)	1 × ø 6.35 mm (inflation)
Packer inflation lines	6.35 mm stainless steel	6.35 mm stainless steel
Inflation method	Surface controlled	Surface controlled
Inflation fluid	Water	Water

Tab. A-2: Sensor specifications

Location	Interval lines submersible	Interval lines submersible	Interval lines surface	Packer lines	Atmosphere	Temperature
Pressure transmitter manufacturer	STS Sensor Technik	STS Sensor Technik	STS Sensor Technik	STS Sensor Technik	STS Sensor Technik	--
Type / model	MTM/N10	MTM/N10	ATM.1ST	ATM.1ST	PTM	PT1000
Pressure range (absolute)	0-200 kPa	0-600 kPa	0-1'600 kPa	0-10'100 kPa	85-125 kPa	--
Accuracy (characteristic curve deviation)	$\leq \pm 0.1 \%$ FS	$\leq \pm 0.1 \%$ FS	$\leq \pm 0.1 \%$ FS	$\leq \pm 0.1 \%$ FS	$\leq \pm 0.1 \%$ FS	$\pm 0.15 \text{ }^\circ\text{C}$ at $0 \text{ }^\circ\text{C}$ $\pm 0.35 \text{ }^\circ\text{C}$ at $100 \text{ }^\circ\text{C}$
Total error band			$\leq \pm 0.3 \%$ FS (max.)		$\leq \pm 0.3 \%$ FS	Class A
Measuring frequency	1 Hz	1 Hz	1 Hz	1 Hz	1 Hz	1 Hz
Temperature compensation	$-5 \dots 50 \text{ }^\circ\text{C}$	$-5 \dots 50 \text{ }^\circ\text{C}$	$0 \dots 70 \text{ }^\circ\text{C}$	$0 \dots 70 \text{ }^\circ\text{C}$	$-10 \dots 50 \text{ }^\circ\text{C}$	$-20 \dots 70 \text{ }^\circ\text{C}$
Outer diameter	10 mm	10 mm	--	--	--	12 mm
Output signal	4 – 20 mA	4 – 20 mA	4 – 20 mA	4 – 20 mA	4 – 20 mA	--
Material	Stainless steel 1.4435					
Cable length	173 m / PUR	210 m / PUR	10 m / PUR	10 m / PUR	1 m / PUR	1 m