Interreg North-West Europe

DGE-ROLLOUT

Evaluation of production strategies and technologies for long-term production optimization for a Carboniferous carbonate reservoir

2020/RMA/R/2130 v2.0

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List of Acronyms

ESP	Electric Submersible Pump
ORC	Organic Rankine Cycle
BRGM	Bureau de Recherches Géologiques et Minières

Summary

Introduction

The geothermal loop at the geothermal plant of VITO in Mol, Belgium is build out of the following components: Inhibitor lines against corrosion and scaling - electric submersible pump – gas and particle separator – heat exchangers – gas injection column – filter units – injection pumps. The flow in the geothermal loop is kept as constant as possible during operation and the system pressure is kept above bubble point to avoid degassing.

The plant was started up for the first time on 22 November 2018. The plant has been operational for 14 test periods between 0,5 and 240 hours. During these test periods, around 50.000 m³ of geothermal brine has been pumped from the production well towards the injection well and 3200 MWh of heat was extracted from the geothermal brine. The heat was used for heating purposes or the production of electricity via an organic rankine cycle or ORC.

D.1.2 Observations

The following observations have been made during the different test periods:

1. Free gases were present in the surface installation despite the high system pressure of 40 bar. Free gases could be observed via 1) low fluid levels in gas injection column and gas and particle separator 2) measurements of the gas flow in gas venting pipes 3) periodic pressure and flow oscillations within the surface installations and 4) the presence of gases on top of the injection well.
2. The number of particles and the particle size of the suspended solids was measured via millipore filtration. The results indicated that 25,4 mg of suspended solids were present per liter geothermal brine and 92% of these particles had a size smaller then 1,2 µm.
3. The proper functioning of the corrosion inhibitor was evaluated conducting corrosion inspections. No pits, cracks, crevices or uniform corrosion was observed during these inspections.
4. The proper functioning of the scaling inhibitor was evaluated through the amount and type of material in the filter elements. The material captured in the filter elements were analyzed via XRD analysis, XRF analysis, TICTOC analysis and rock-eval pyrolysis. The main precipitate that was found in the filter elements was lead sulfide or Galena.
5. The injection pressure reached a stable value only after 7 days of operation and was higher than initially expected.

D1.3-D1.4 Adaptations

Based on the observations summarized above, the following adaptations have been made:

1. Automatic deaerators, seals injection pumps and the rupture disc have been adapted to be able to reach higher system pressures then 40 bar. A higher system pressure should avoid the formation of free gases in the system.
2. An injection tubing was installed until a depth of 200 meter. This should avoid turbulent flow on the crossing between the surface installations and the casing of the injection well.
3. The mesh of the filter elements has been adapted from 10 µm towards 1 µm.
4. The inhibitors have been adapted with the goal to avoid the formation of Galena in the surface installation and possible also the geothermal wells.

5. The protection of the medium voltage circuit breakers has been removed to avoid shut down of the ESP in case of (short) drops in voltage.

D1.5 Implementation

The changes listed under D1.3-D1.4 were implemented in 2019 and 2020. Some further changes are planned for later in 2020. These include primarily a pressure sustaining system on the injection well (preventing a quick pressure drop in case of sudden shutdown), and the installation of a new ESP allowing production at a lower flow rate.

CHAPTER 1: Introduction

1.1. System configuration

The mass and heat balance of the geothermal loop is given in Figure 2. The following main components could be distinguished.

1.1.1. Electric submersible pump or ESP

Geothermal brine is pumped out of the production well via an electric submersible pump or ESP. The pump intake is placed at a depth of 875 meter below ground level. The pump has a high voltage electric motor controlled by a frequency drive, which will control the flow depending on the heat that can be dissipated. Since the ESP is working in harsh conditions, it is best to run the ESP as stable as possible (i.e. constant speed), and at the best efficiency point.

1.1.2. Inhibitor lines against corrosion and scaling

As the geothermal brine contains a lot of minerals and chlorides, two inhibitor lines are foreseen 1) an inhibitor line to inject chemicals against corrosion is foreseen just above the screens in the production well until a depth of 3000 meter. The anti-corrosion inhibitor is used to protect the casings of the production well against corrosion and 2) an inhibitor line to inject chemicals against scaling is foreseen just below the ESP intake until a depth of 900 meter. The anti-scaling inhibitor is used to prevent minerals from scaling (precipitation) in the production well and the surface installations.

1.1.3. Gas and particle separator

In order to remove possible free gases, the brine lead through a horizontal separator tank where the flow is slowed down to allow free gas bubbles to rise to the top of the tank, and particular matter (sand, clay > 50µg) to sink to the bottom. The tank is inclined by 1,5° to enable gas to accumulate near the topmost end where it is evacuated through a combined bleeding and venting valve. At the bottom of the tank, a purging system is foreseen to remove the particles.

1.1.4. Heat exchangers

Two identical shell and tube heat exchangers are coupled in series. In these heat exchangers:

- Clear water is heated from 70°C to 114°C on the shell side;
- Geothermal brine is cooled from 126°C to 82°C in the tubes;

The heat exchanger comprises 2x3 one pass shell and tube heat exchanger packs, coupled in series to form one continuous heat exchanger unit. Each heat exchanger can be taken into bypass e.g. for maintenance purposes.

1.1.5. Gas injection column

The solubility of some gases released from the gas and particle separator in the geothermal brine is higher at lower temperatures. Therefore, a vertical tank is foreseen to inject possible free gases in the brine loop coming from the free gas and particle separator. The gases could be injected via 2 spargers in the brine flow.

1.1.6. Filter units

The purpose of these filters is filtering the suspended solids from the geothermal brine before re-injection. During normal operation, the flow is directed to three parallel units, where one is online and two are offline for cleaning or as standby. Cleaning is required when the pressure difference over the filter unit is higher than 2 bar.

1.1.7. Injection pumps

The purpose of the injection pumps is to return used geothermal brine to the ground reservoir when required injection pressures are higher as the system pressure in the above ground installations. The pumps are used to maintain stable system pressure in the geothermal loop. Therefore, these pumps are frequency controlled.

1.1.8. Condenser/silencer

The purpose of this pit is to collect all drained brine. Most of the brine will be drained during filter exchangers. The hot brine will depressurize and flashes in the condenser/silencer. Gasses and steam will escape via the chimney.

1.2. Overview test periods

Figure 1 gives an overview of the pumped volumes during the several test phases until 01/01/2020. As can be seen, 14 test phases have been conducted with periods between 0,5 hour and 240 hours. During these test periods, around 50.000 m³ of geothermal brine has been pumped from the production well towards the injection well and 3200 MWh of heat was extracted from the geothermal brine. This heat was used for heating purposes or the production of electricity via an organic rankine cycle or ORC.

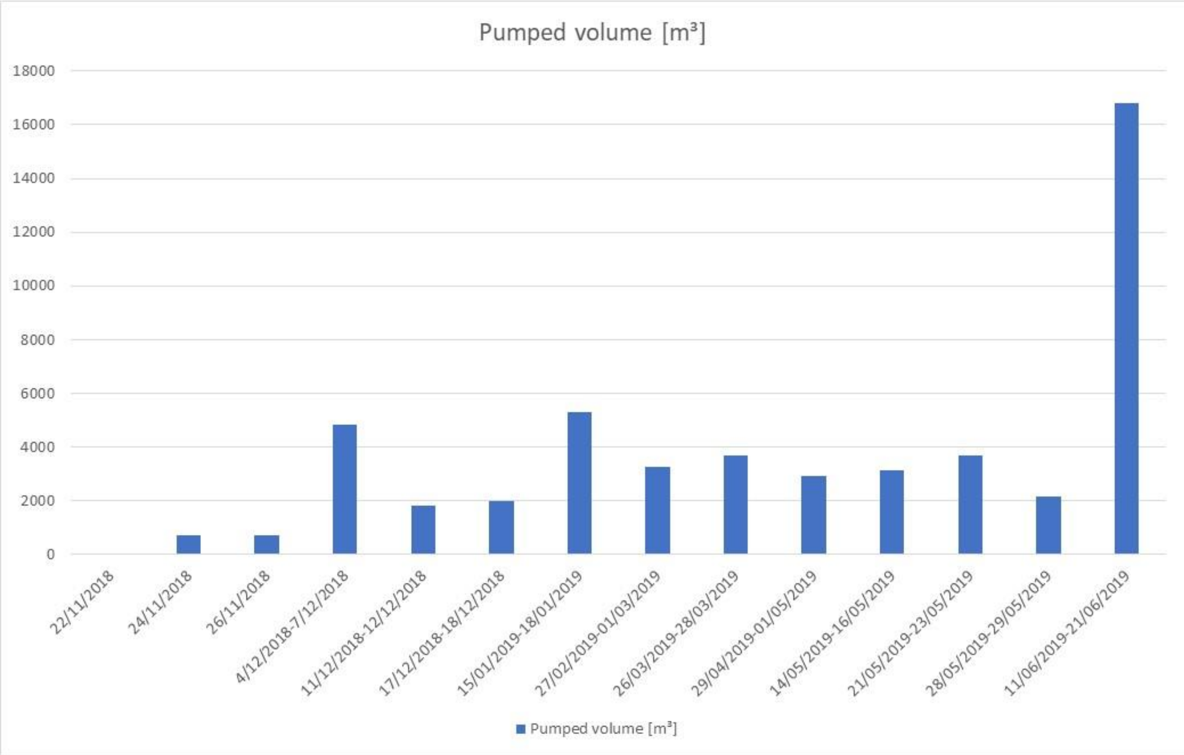
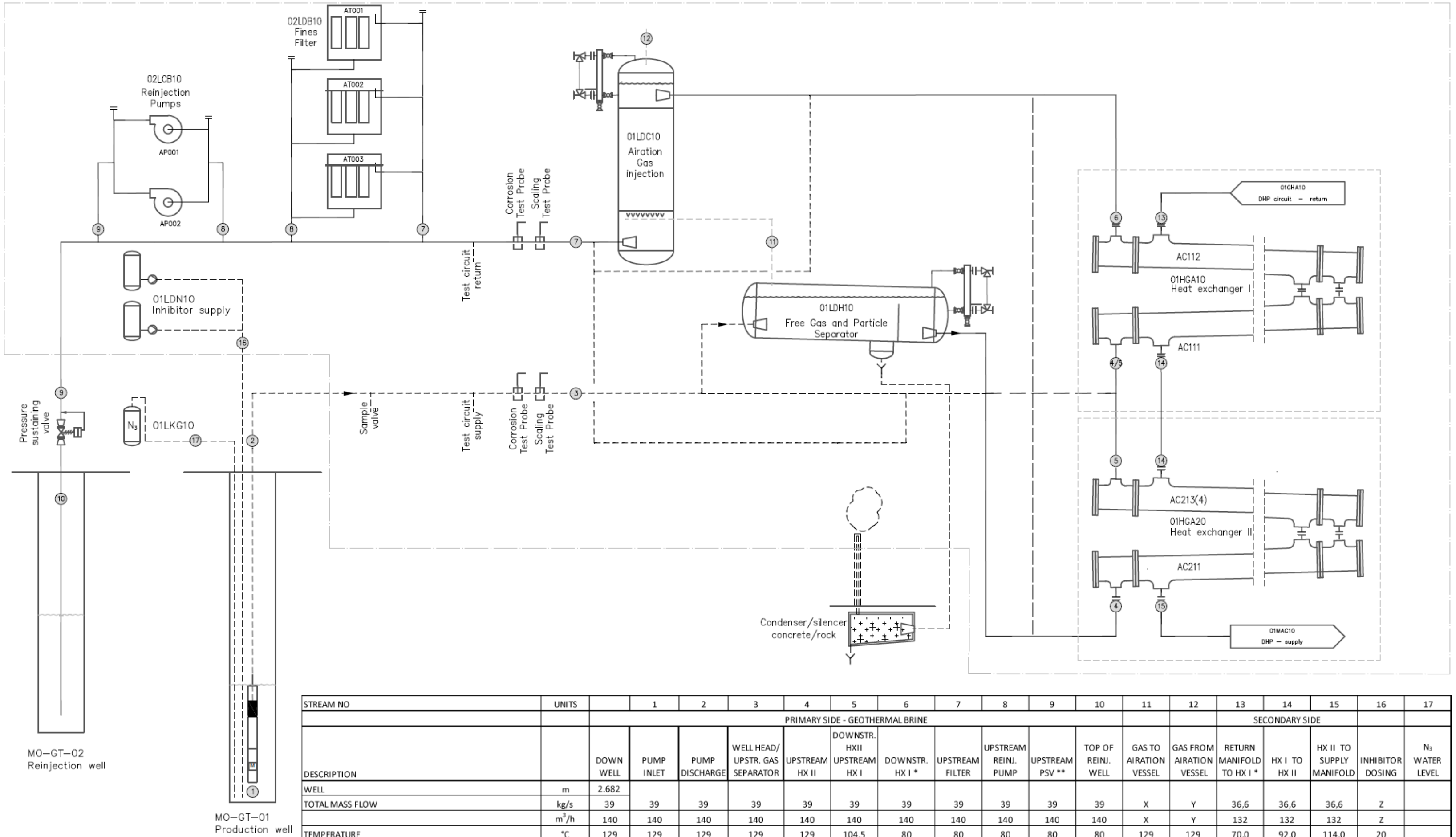


Figure 1: Pumped volume during the several test phases

Adaptations have been made on the installation and different production strategies have been applied during the several test phases based on new insights gathered during previous test phases. This chapter describes the observations in the surface installations.



STREAM NO	UNITS		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		PRIMARY SIDE - GEOTHERMAL BRINE													SECONDARY SIDE				
DESCRIPTION		DOWN WELL	PUMP INLET	PUMP DISCHARGE	WELL HEAD/ UPSTR. GAS SEPARATOR	UPSTREAM HX II	DOWNSTR. HXII UPSTREAM HX I	DOWNSTR. HX I *	UPSTREAM FILTER	UPSTREAM REINJ. PUMP	UPSTREAM PSV **	TOP OF REINJ. WELL	GAS TO AIRATION VESSEL	GAS FROM AIRATION VESSEL	RETURN MANIFOLD TO HX I *	HX I TO HX II	HX II TO SUPPLY MANIFOLD	INHIBITOR DOSING	N_3 WATER LEVEL
WELL	m	2.682																	
TOTAL MASS FLOW	kg/s	39	39	39	39	39	39	39	39	39	39	39	X	Y	36,6	36,6	36,6	Z	
	m^3/h	140	140	140	140	140	140	140	140	140	140	140	X	Y	132	132	132	Z	
TEMPERATURE	°C	129	129	129	129	129	104,5	80	80	80	80	80	129	129	70,0	92,0	114,0	20	
HEAT DELIVERY	kW						3383	3383								3382	3382		
PRESSURE	Bara	271,5	36	83	39	39	38	37	37	37	80,0	79,8						36	36
ESTIMATED DRY GAS FLOW FROM WELL	Nm^3/h	313																	
FREE GAS/WATER RATIO	Nm^3/m^3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	NA	0,0	0,0					
Ph-value		5,4																	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

Figure 2: Mass and heat balance geothermal loop

CHAPTER 2: Evaluation of adapted production strategies

This chapter describes the observations during the operational periods between 22/11/2018 and 2020. The following chapter describes the approach that was followed to tackle the issues to optimize the production.

1.1. System pressures and degassing

During the well tests of the production well, a bubble point determination (pressure from which the gases come out of solution and become free gases) has been conducted and the bubble point appeared to be 35 bar. By keeping the system pressure in the production well and the surface installations above 35 bar, no gases where expected during production. As can be seen on the mass and heat balance, it was intended to keep the pressures in the above ground installation between 36 and 39 bar to avoid degassing.

1.1.1. Presence of free gases

During the first tests in November and December 2018, it became clear that free gases were present in the surface installations despite the high system pressure:

- Fluid levels in gas and particle separator and gas injection tank were rather low;
- Gases were observed via the sight glass of the gas injection column;
- Constant degassing via automatic deaerators has been detected with gas flow meters;
- Periodic flow and pressure resonances entered the system as can be seen in the figure below;

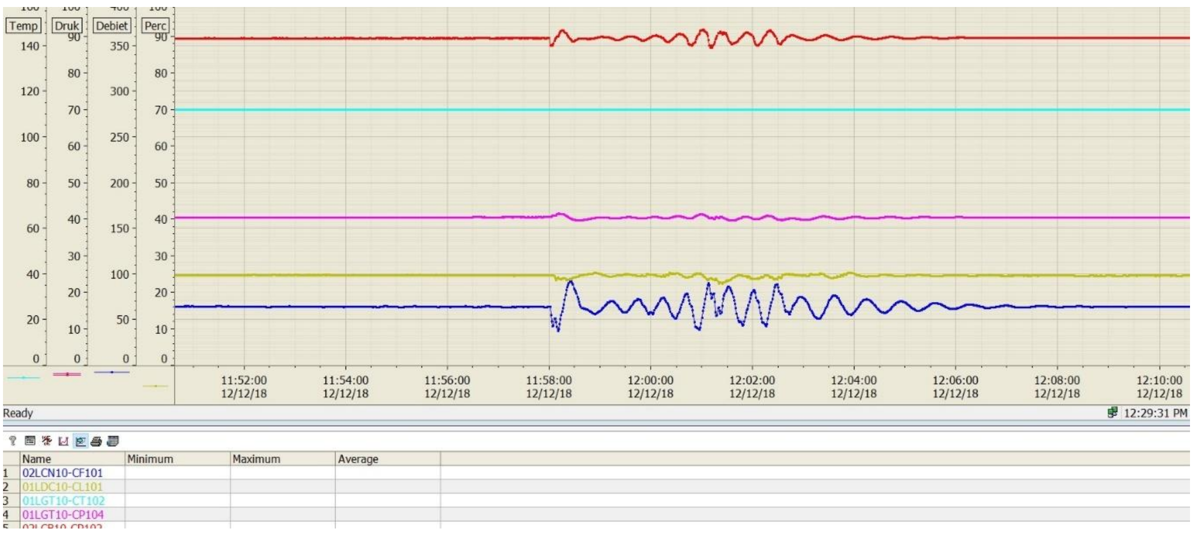


Figure 3: Pressure and flow resonances

The blue line indicates flow rate while the red line indicates the injection pressures. The resonances were caused by gas bubbles transferred from the gas and particle separator throughout the complete surface installation into the injection well.

1.1.2. Amount of free gases with several system pressures

Once the phenomena of degassing became clear, a bypass was installed to release the gases from the gas and particle separator directly towards the condenser/silencer instead of leading them towards the gas injection column. System pressures were increased during next operational phases and gas release was measured. The average amount of gas that was released at system pressures of 36, 40 and 42 bar is shown in Figure 4. It is clear that there is a decreasing trend of the gas release when system pressure is increasing. It was however not possible to test higher system pressures as some components (rupture disc, automatic deaerators, seals injection pumps, …) were not designed for higher system pressures. During the well test, the gas/water ratio was also determined for gas release towards atmospheric conditions and equaled 2,5 Nm³ gas/m³ brine.

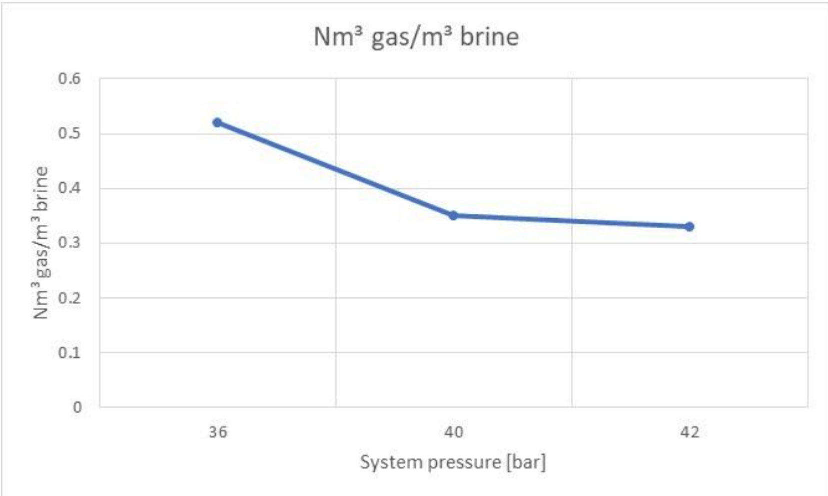


Figure 4: Degassing in function of system pressure

1.1.3. Gas composition released gases

The gases were sampled under pressure and analyzed. The results are given in the figure below.

Component		Mole%	Weight%
H_2	Hydrogen	0.000	0.000
H_2S	Hydrogen Sulphide	0.000	0.000
CO_2	Carbon Dioxide	83.311	91.635
N_2	Nitrogen	5.022	3.516
C1	Methane	11.549	4.631
C2	Ethane	0.004	0.003
C3	Propane	0.009	0.009
C4	i-Butane	0.005	0.007
C4	n-Butane	0.019	0.028
C5	i-Pentane	0.011	0.019
C5	n-Pentane	0.025	0.045
C6	Hexanes	0.026	0.054
	MC Pentane	0.002	0.005
	Benzene	0.000	0.001
	Cyclohexane	0.001	0.003
C7	Heptanes	0.007	0.017
	MC Hexane	0.001	0.003
	Toluene	0.001	0.001
C8	Octanes	0.002	0.005
	E-Benzene	0.000	0.000
	M/P Xylene	0.000	0.000
	O-Xylene	0.000	0.000
C9	Nonanes	0.001	0.003
	1,2,4 TMB	0.000	0.000
C10	Decanes	0.001	0.004
C11+	Undecanes +	0.003	0.010
	Total	100.000	100.000

Calculated Gas Properties	
Gas Density (kg m^{-3} @ 15°C)	1.795
Gas Mole Weight (g mol^{-1})	40.012
Real Relative (to air) Density of Gas	1.388
Mole weight of Heptanes Plus (g mol^{-1})	104.873
Density of Heptanes plus (g cm-3 at 60°F)	0.759
Mole Weight of Undecanes plus (g mol^{-1})	147.000
Density of Undecanes plus (g cm-3 at 60°F)	0.789
Calorific Value (MJ m^{-3})	4.800

Air content: 3.96%
Gas Water Ratio (GWR): 1.83 sm^3/m^3

Figure 5: Gas composition released gases

1.1.4. Release of gases near the injection well

As an injection tubing was not installed, a test setup was prepared to evaluate the presence of gases on top of the injection well. A schematic of this test setup is given in Figure 6. Two manual valves of the wellhead are coupled with the condenser/silencer via 1) an adaptor piece to release pressure 2) a sight glass and 3) a flexible connection between the injection well and the condenser silencer. Through opening the manual valves, looking into the sight glass and keep an eye on the fluid level in the condenser/silencer, it could be detected if gases or fluids were present on top of the injection well.

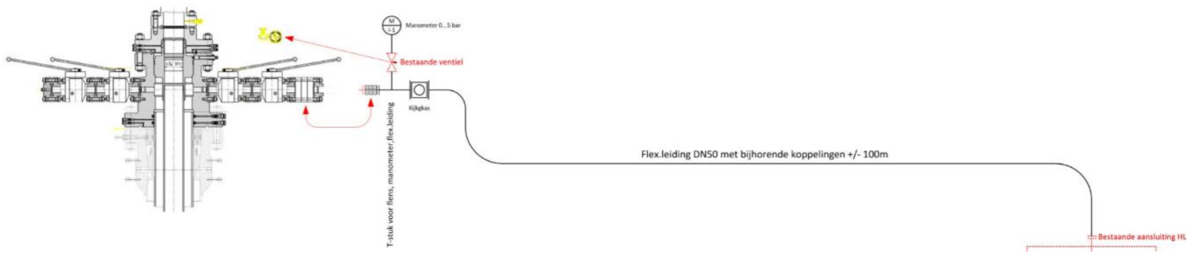
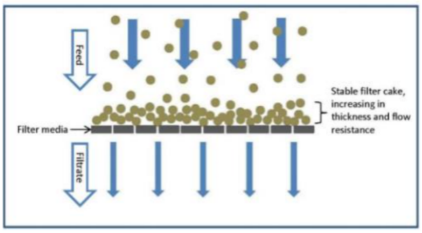


Figure 6: Test setup gas release injection well

Dependent on the time that the geothermal plant was operational, it took several minutes up to some hours that only gases escaped on top of the injection well when opening the manual valves of the wellhead. It could be concluded that a gas bubble and turbulent flow was present on top of the injection well during production.

1.2. Total suspended solids

As water is extracted from a limestone reservoir, it was expected that the total suspended solids were rather limited. Bag filters with a filter mesh of 10 µm were used during startup. It appeared that the lifetime of these filter units was only several hours. To determine the amount and size of the particles in the geothermal brine, a millipore filtration was conducted. The results are given below. The majority of the particles appeared to be smaller then 1,2 µm.



MATIERES EN SUSPENSION	mg/l	%
0,22 à 0,45 µm	17,1	67,3
0,45 à 1,20 µm	6,272	24,7
1,20 à 3 µm	0,358	1,4
3 à 5 µm	0,253	1
5 à 8 µm	0,135	0,5
sup. à 8 µm	1,282	5
TOTAL	**25,4**	**100**

Figure 7: Results of millipore filtration on the geothermal brine

1.3. Inhibitors

1.3.1. Corrosion inhibitor

Geoprotect100 of Aquaprox was selected as initial corrosion inhibitor. According studies of BRGM (Bureau de Recherches Géologiques et Minières), results show a corrosion inhibition efficiency of 93% for predefined laboratory conditions. The advised dosing concentration of the product amounts 3 ppm, at low production rates this may rise to 5 ppm. Chemical stability has been tested at a temperature of 126°C. The pH, density and viscosity of the products before and after temperature exposure do not vary much (less than 5%). This generally indicates that the product performance is not hampered by temperature exposure.

Metalogic, a company specialized in corrosion and corrosion inspections has performed 2 corrosion inspections on 1) the filter units and 2) the geothermal brine shell and tube heat exchanger. A picture taken during the inspection of the heat exchanger is shown in Figure 8. No pits, cracks, crevices or corrosion were observed during the inspections.

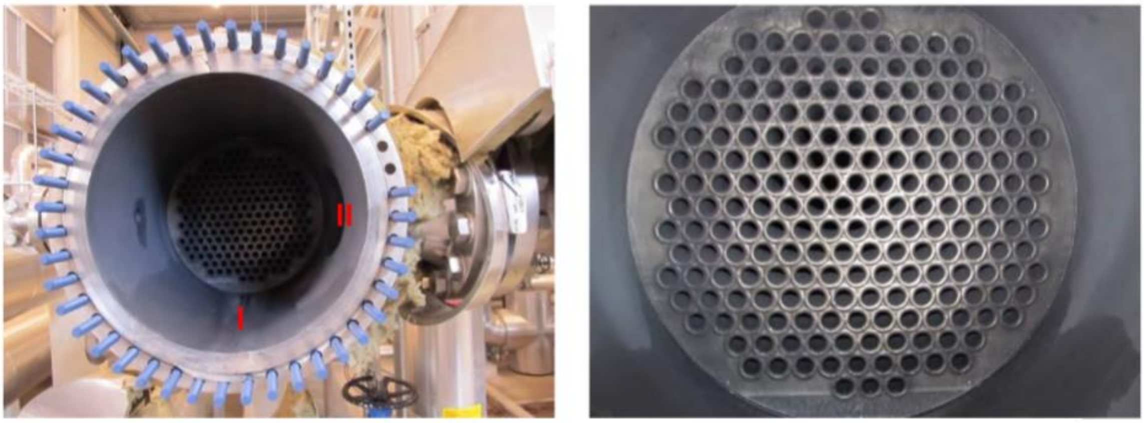


Figure 8: Corrosion inspection heat exchanger

1.3.2. Scaling inhibitor

Aquaprox TD1100 was selected as scaling inhibitor. The approach of Aquaprox is to prevent scale inhibition of carbonates (e.g. $CaCO_3$). The reason for this is that the ionic content of Ca and Fe is high, and that spurious degassing may occur (e.g. due to ESP failure or momentaneous increase in bubble point). To be sure that carbonate deposition doesn't occur, a carbonate scavenger was selected at the start. Aquaprox uses a formulation based on polyacrylates. When possible carbonate deposition is under control, the minor scaling risks of e.g. sulfates is further tackled by adding other polyacrylates with other side chains that can defeat these compounds. This is the common approach that Aquaprox follows and will result for the customer in a site-specific formulation. The product was heated for 300 hours at 126°C in order to test the chemical stability at long exposure time. The pH, density and viscosity of the products before and after temperature exposure did not vary much (less than 5%). This generally indicates that the product performance is not hampered by temperature exposure.

The amount and type of material that is captured in the filter elements is a good indication for the effectiveness of the scaling inhibitor. As the filter elements need to be replaced on a regular basis, it was expected that some scaling occurred. The filter elements were opened and analyzed via XRD analysis, TICTOC analysis, rock-eval pyrolysis and XRF analysis. Figure 9 shows a picture of the filter elements that where brought to a laboratory for analysis.

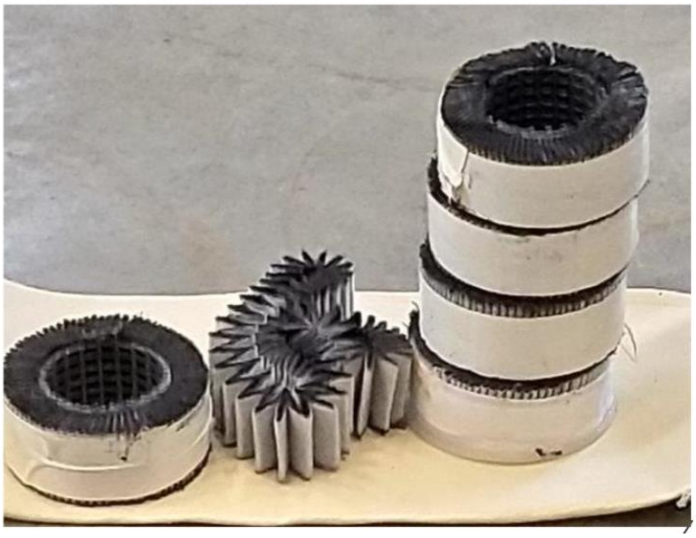


Figure 9: Black precipitation in filter elements

Figure 10 shows the output of the XRD analysis of the filter elements. The results showed the presence of PbS scale or Galena.

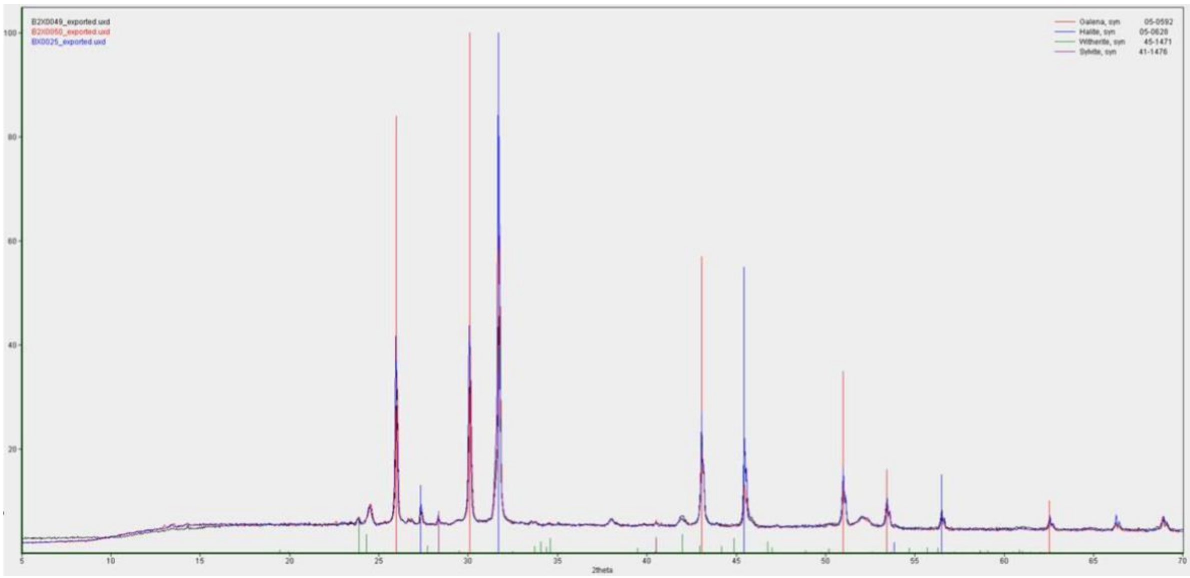


Figure 10: Results XRD analysis filter elements

1.4. Injection pressure

Figure 11 shows flow rate (black), injection temperature (orange), system pressure (red) and injection pressure (yellow) from the longest operational period. A stable injection pressure was reached at 115 bar which was higher than expected.

Figure 11: Injection pressure

1.5. Power outages

A power outage caused the end of an operational period of the geothermal plant on 12/12/2018, 29/05/2019 and 21/06/2019. At first instance, the cause of the power outage was not clear as the medium voltage circuit breakers automatically switch in when the voltage reappears. A logger was placed on the low voltage cabinets and automatic reopening of the medium voltage circuit breakers was switched off to investigate the problem. The results of the logging during the next power outage are shown in the figure below. The residual voltage appeared to be 41% during a time period of 0,4 seconds.

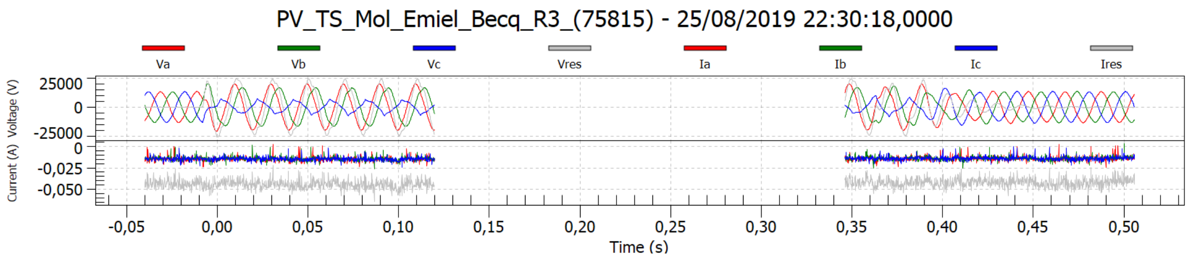


Figure 12: logging low voltage cabinet

1.6. Control parameters

During startup, switching in of the injection pumps, … some nervous behavior has been detected. This nervous behavior was tackled during the observations by adapting the parameters of the PID controllers. The initial values for the PID controllers were determined before startup of the geothermal plant as shown in the figure below:

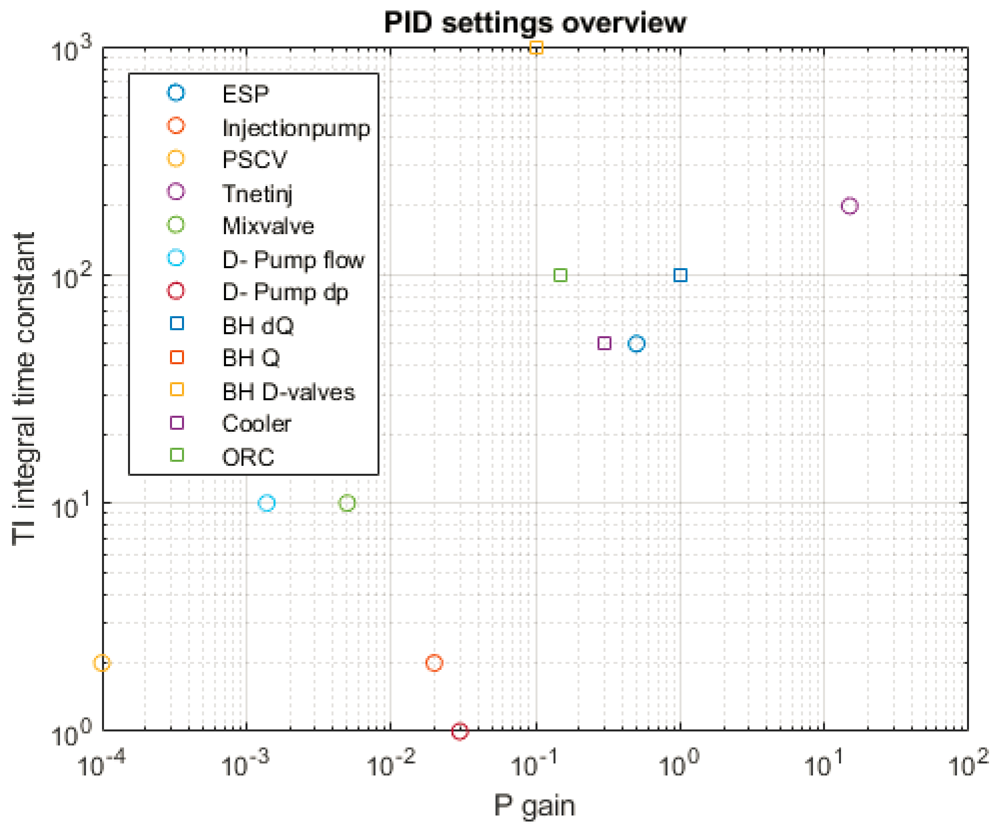


Figure 13: PID settings overview

One rate limiter is used to limit the change in frequency of the ESP and the rate limitation was set on 1 Hz/5min. It is however during operation that all hydraulic parameters (opening and closing times of valves, inertia of the system, …) become clearer and control parameters could be finetuned.

1.7. Seals injection pumps

The injection pumps have mechanical seals on the intake and outlet of the pump. The seals work with a cooling circuit on a higher pressure to prevent the leakage of brine towards other installations nearby the injection pumps. During normal operation, the pressure on the seals of the injection pumps remains fairly constant and increasing the pressure is only needed once a month or couple of months. The figure below shows the pressure in the cooling circuit during the operational phase from 11/06/2019 – 21/06/2019. During the last days, the pressure of the cooling circuit need to be increased every couple of hours indicating there was a problem with the seals of the injection pump.

Figure 14: Pressure cooling circuit seals injection pumps

CHAPTER 3: Technologies for long-term production optimization

This chapter describes the measures that were taken to tackle the observations as described in Chapter 2. In this way, the geothermal energy production at the Balmatt site was optimized. It must be noticed that adaptations on the installation are made based on lessons learned during previous operational periods until 01/01/2020.

3.1. Increase system pressure above bubble point

As mentioned in paragraph 1.1.1, free gases were observed during all operational phases in the period 22/11/2018 – 21/06/2019. As the piping of the geothermal loop has pressure class PN63, an analysis has been conducted on the components to evaluate which components need to be adapted to be able to work on a system pressure of 55 bar (this is the limit taking into account temperature derating on the piping PN63). The analysis showed out that the rupture disc, seals of the injection pumps and automatic deaerators need to be adapted. A picture of these components is shown in Figure 15.

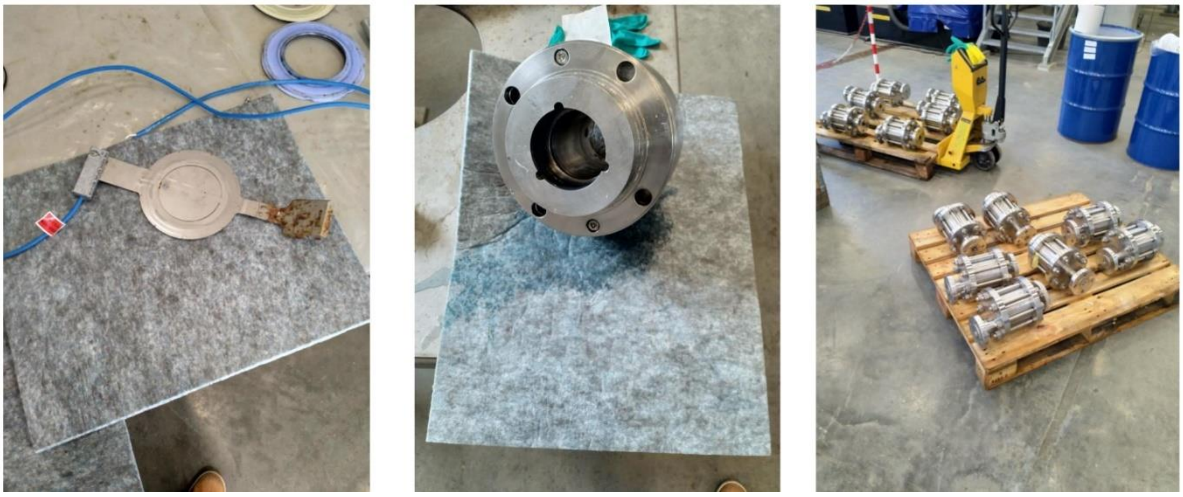


Figure 15: Rupture disc, seal injection pump and automatic deaerators

Besides the adaptations of these components, all setpoint values for the alarms high and low pressure need to be adapted towards the new system pressure. Keeping the system pressure above 55 bar should have a positive impact on the scale formation and possibly also on the high injection pressure.

3.2. Installation injection tubing

As mentioned in paragraph 1.1.4, free gases were present on top of the injection well. To reduce the amount of free gases, an injection tubing was installed. In this way, the diameter of the piping of the surface installations remains the same as the diameter of the first 200 meter piping of the injection well. If free gases are still present, they will accumulate in the annular space between the injection tubing and the casing of the injection, forming a cushion which will deliver an extra downward pressure. Pictures of the installation of the injection tubing are given in Figure 16.

Figure 16: Installation injection tubing

The injection tubing is made of carbon steel and is placed until a depth of 200 meter. This is 60 meter below the static water level of the well.

3.3. Adapted filter elements

Based on the information given in paragraph 1.2, it was decided to switch from bag filters with a mesh of 10 µm towards cartridge filters with a mesh of 1µm. Cartridge filters have a bigger surface area and since the total suspended solids between 1µm and 10µm are limited, it is expected that filter elements will last longer before they have to be replaced. Figure 17 shows the pressure drop across the cartridge filters during operation. Instead of some hours, the cartridge filters could be operational for several days.

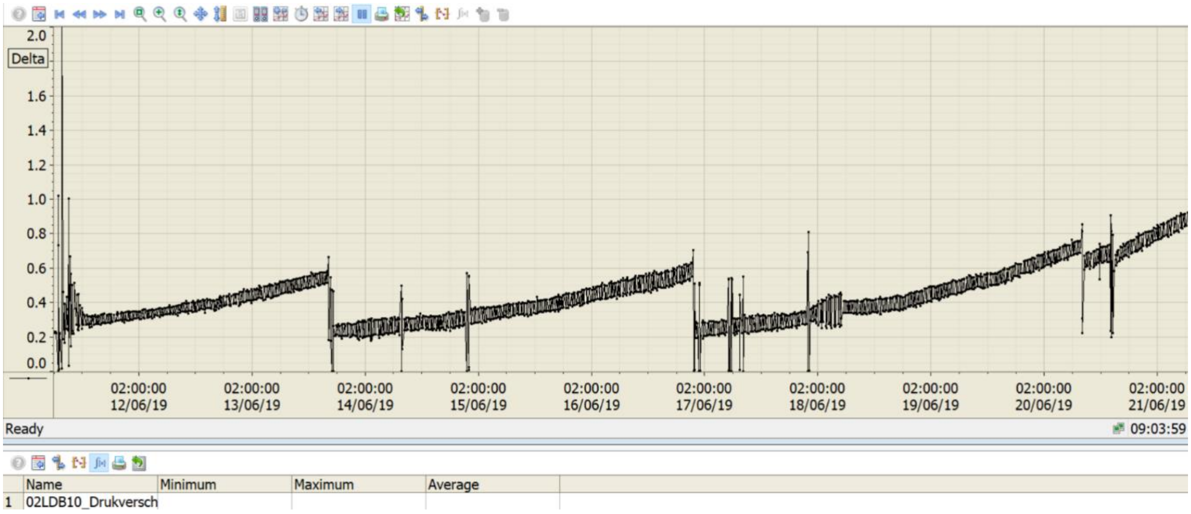


Figure 17: Lifetime cartridge filter elements

3.4. Adapted inhibitors

As 1) the support of Geofluid, the supplier of the aquaprox products was very poor and 2) Galena scale was observed in the filter elements, it was decided to switch from supplier for the anti-corrosion and anti-scaling inhibitor.

3.4.1. Anti-corrosion inhibitor

As corrosion Inhibitor, Inhibitor EF8600, will be dosed in the well, on reservoir level. Product stability and compatibility were tested thoroughly, and proved stability of the product at 126 °C. This corrosion inhibitor contains an agent that sequesters the lead ion, and therefore avoids Pb-ions based electrochemical reactions that otherwise may induce lead deposition and/or lead precipitation.

3.4.2. Anti-scaling inhibitor

ScaleTrol PDC9403, a diluted combination product which strongly acts against both calcite, sulphate and Fe-based deposition. It will be dosed on 900 m level. Product stability and compatibility were tested thoroughly, and also showed stability of the product at 126 °C.

3.5. Power outages

It became clear there was a minimum voltage protection on the medium voltage circuit breakers with automatic recoupling when the voltage reappears. This is no problem for non-critical devices like lightning, cooling applications, etcetera. However, when the ESP doesn't get power for a millisecond, it will be switched off (internal protection) and causes the geothermal plant to shut down. As this is not desired for small voltage dips, the protection of the medium voltage circuit breakers of the geothermal plant was removed.

3.6. Control parameters

The control parameters have been adapted during operations to become a smooth operation of the geothermal plant. The rate limiter of the ESP has been adapted to 1 Hz/30 min to become smooth transitions towards other flow rates in the geothermal reservoir.

3.7. Seals injection pumps

The seals of the injection pump have been replaced by another type of seal. The new type of seal should be able to cope with system pressures until 100 bar.

3.8. Soft (continuous) acidizing (still to be realized)

To clean up the tubular and near wellbore from scaling and deposits, it is possible to injection a (soft) acid. A proposal is made to add a soft acid at a concentration of 1% v/v for at least a period of 1 to 2 hours.

Injecting a fluid with low pH should have a positive impact on long term regarding the permeability off the reservoir as the reservoir is a limestone reservoir. Therefore, pH control could be conducted by adding a soft acid to the main stream at an injection concentration of 0,1 % v/v.

3.9. Pressure sustaining system injection well (still to be realized)

As the risk on seismic events increases with pressure variations in the underground, a system to keep the pressure on the reinjection well during outages of the geothermal plant has been worked out. At first instance, an analysis of the gas and brine flows in the reinjection well during outages of the geothermal plant has been conducted.

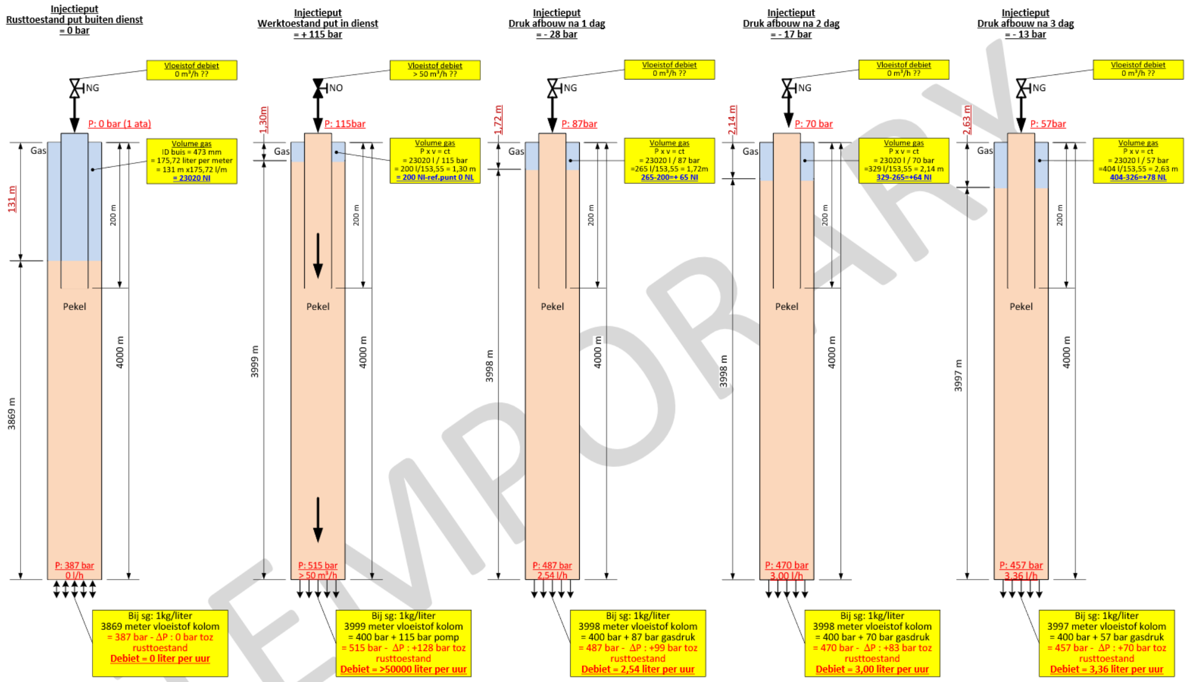


Figure 18: Schematic view of gas and fluid flows when the system (pumps) shut down.

Afterwards, a P&ID has been worked out to keep the pressure on the reinjection well during outages of the geothermal plant as shown in the figure below. Nitrogen bottles at a pressure of 200 bar are used to pressurize brine storage tanks. These tanks are discharged towards the injection well to compensate for the brine flowing into the reservoir at the bottom of the well. The flow is regulated to obtain a desired pressure in the injection well. The pressure could be kept constant or could be decreased very slowly at a ramp rate that could be selected.

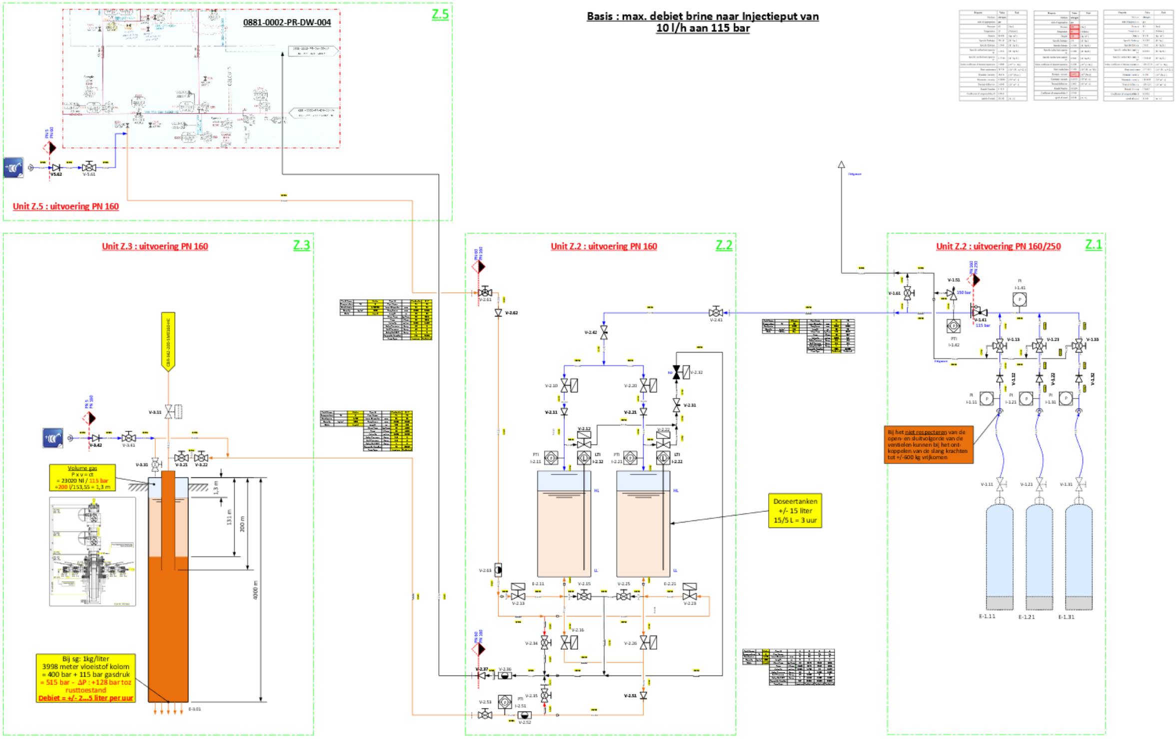


Figure 19: P&ID of the pressure sustaining system.

3.10. Adapted ESP (still to be realized)

During the previous operational periods, a stabilization of the injection pressure was only reached one time. This was at an injection pressure of 115 bar with flow rates around 65 m³/h. To limit the injection pressure an adapted ESP will be installed which is capable of handling flow rates between 10 and 50 m³/h. The pumps curves of the adapted ESP are given in the figure below.

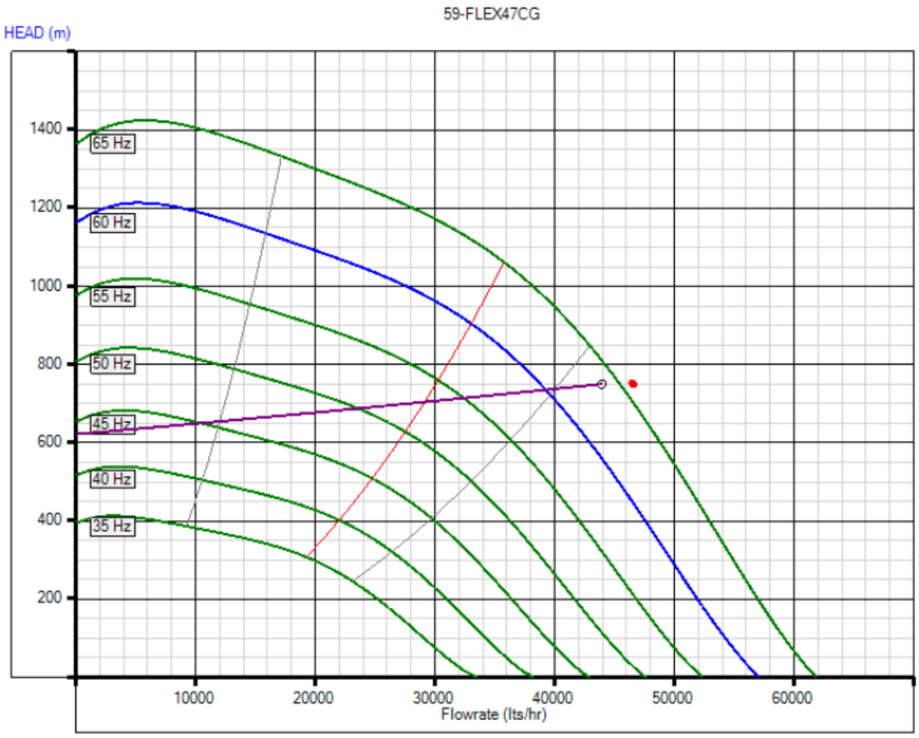


Figure 20: Pump characteristics for the adapted ESP (flow rate versus drawdown).

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