Multi-sites EGS Demonstration

DELIVERABLE D6.5

SUMMARY OF ADDITIONAL HEAT PRODUCTION CAPACITIES AT THE SOULTZ-SOUS-FORÊTS SITE

WP6: DEMONSTRATION OF ELECTRICITY AND POWER GENERATION

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CONTENT

LIST OF FIGURES

LIST OF TABLES

1 EXECUTIVE SUMMARY

1.1 DESCRIPTION OF THE DELIVERABLE CONTENT AND PURPOSE

This deliverable D6.5 is done in the framework of the Horizon 2020 MEET project aiming to boost and upscale the development of geothermal energy in Europe. It briefly presents the Soultz-sous-Forêts geothermal site, then the prototype heat exchanger used for the test, the test operational data and results as well as an analysis of the results obtained in order to set a new injection temperature lower limit for the geothermal plants implemented in the Upper Rhine Graben (URG).

1.2 BRIEF DESCRIPTION OF THE STATE OF THE ART AND THE INNOVATION BREAKTHROUGHS

Several projects in the URG, both in France and Germany, have been developed over the last decade thanks to knowledge gathered at the Soultz-sous-Forêts power plant. These plants produce very saline geothermal fluids (Total Dissolved Solids (TDS) of 100 g/L) at 150-170°C with similar physico-chemical characteristics, and reinject them at about 70°C, a temperature equivalent to the production temperature in the Paris Basin. Growing knowledge surrounding EGS and reservoir exploitation suggests that higher energy use would be sustainable, by reinjecting the geothermal fluid at a lower temperature than the current limit set at 60°C, which is to be further investigated through parallel simulations of the impact that a colder reinjection would have on the reservoir. This deliverable and the tests it describes allow considering to further decrease the theoretical injection temperature lower limit to 47.5°C for the deep geothermal power plants in the URG.

2 DELIVERABLE REPORT

2.1 CONTEXT

2.1.1 The Soultz-sous-Forêts geothermal plant

The Soultz-sous-Forêts EGS (Enhanced Geothermal System) power plant is located in Northern Alsace in the Upper Rhine Graben (URG). It consists of several deep wells drilled in a Palaeozoic granite reservoir at a depth of 5km (Genter et al., 2010). The owner of the Soultz plant is the "GEIE Exploitation Minière de la Chaleur", while the geothermal plant operation and maintenance is performed by ES-Géothermie.

Currently, the geothermal site exploits around 30 L/s of geothermal water with a very high salinity of 100 g/L. The brine is produced at 150°C from the production well GPK-2 and conveyed after filtration to three heat exchangers supplying heat to a 1.7 MW ORC unit. This electricity production unit is the only heat user of this geothermal plant, and uses the ambient air as a heat sink, through an Air-Cooled Condenser. The ambient air temperature variations throughout the day and the year impact the geothermal brine reinjection temperature, ranging from 60°C to 80°C. The geothermal brine is reinjected into two different wells, GPK-3 and GPK-4. The geothermal plant is fully operational since mid-2016, when a new ORC unit was erected and the geothermal loop refurbished. A view of the Soultz-sous-Forêts geothermal power plant is shown in Figure 1.

Figure 1: View of the Soultz-sous-Forêts geothermal power plant [source és].

2.1.2 Prototype heat exchanger

Over the last few years, the injection temperature of all the geothermal plants in operation in the URG has been limited to 60°C, and varied between 60°C and 80°C. So far, the lack of experiments with regards to the formation of scaling at a temperature lower than 60°C has led to setting this temperature as the admitted lower injection temperature limit. Therefore, a prototype heat exchanger has been designed to evaluate the feasibility of increasing the heat extraction from the brine in the URG by lowering the brine injection temperature to 40°C (Ravier et al., 2019). Information about scale formation at a temperature lower than 60-70°C is critical for this goal.

It has been proven that cooling down an URG brine modifies the geochemical equilibrium of the said brine, which triggers the formation of scaling, such as barium sulphate and metal-rich sulphides (Scheiber et al., 2013). To fight this phenomenon, scaling and corrosion inhibitors are currently injected into the geothermal brine on the production side, protecting the surface installations from excessive fouling and generalised corrosion issues. The scaling formation process at the geothermal power plant of Soultz-sous-Forêts has been investigated for several years (Mouchot et al, 2018); however, these studies were focussed on temperatures higher than 70°C and the scaling formation process is not well known below this temperature.

Silica has been identified as one of the elements dissolved in the brine, at about 180 mg/l (Sanjuan et. al, 2010), and it is expected that cooling the brine down to 40°C might trigger the deposition of new amorphous scaling containing silica (Ngo et al., 2016) that is very hard to clean. The solubility of amorphous silica and quartz shown in the curve presented in Figure 2 shows that scales containing silica can be expected for a similar silica concentration as Soultz's brine when cooling it down below 45-50°C.

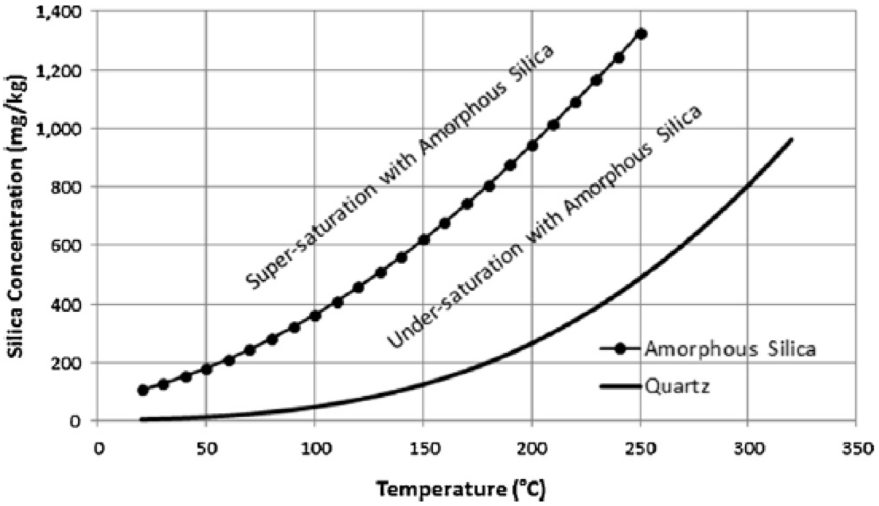

Figure 2: Temperature dependence of the solubility of quartz and amorphous forms of silica [Fournier and Rowe, 1977]

The prototype heat exchanger has been designed to be able to cool down about 10% of the total geothermal production flowrate, hence 3.0 L/s, from 70°C to 40°C using an existing cooling loop at 15°C. Using the HTFS software developed by ASPEN, the theoretical temperature drop could be calculated at the inlet and outlet of each pass of the heat exchanger. The results of these calculations are given in Table 1.

Pass	T_{inlet} (°C)	T_{outlet} (°C)
1	70	59.3
2	59.3	51.6
3	51.6	45.4
4	45.4	40.0

Table 1: Calculated temperature drops in the tubes of the prototype heat exchanger

Geothermal plants located in the URG are usually designed to withstand 22-25 bar with service temperatures higher than 150°C, which lead to designing the prototype heat exchanger with shell and tubes. The prototype heat exchanger was designed with four passes of 8 to 9 tubes, using 6 different metallurgies: 1.4539 (904L), 1.4547 (254 SMO), 1.4462 (DX 2205), 1.4410 (SDX 2507), 2.4858 (Alloy 825) and 3.7035 (Ti Gr.2). Figure 3 presents the drawing of the prototype heat exchanger as well as its end plate and shows how the different alloys for the tubes were implemented.

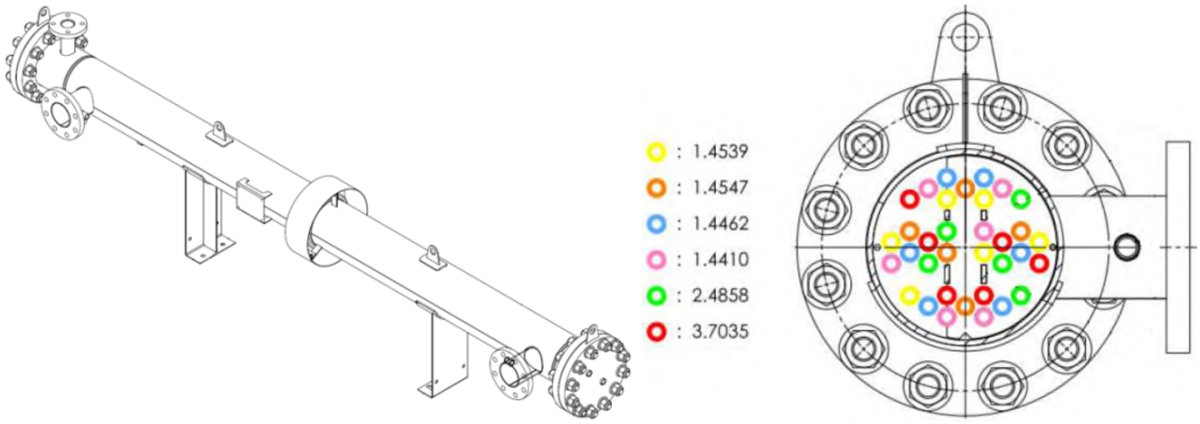

Figure 3: Drawings of the prototype heat exchanger (left) and of the end plate design showing the metallurgies used (right)

2.2 TEST DESCRIPTION

2.2.1 Installation

The prototype heat exchanger was manufactured by KAPP and delivered on site in Soultz-sous-Forêts in early-January 2019, which allowed ES-Géothermie to check the initial condition of the pipes before installing the equipment and its auxiliaries and start its operation. A glycol water based closed cooling loop, already present on site, was adapted to connect the prototype heat exchanger to additional piping and a circulating pump. The prototype heat exchanger was connected to the injection line between the ORC unit outlet and the injection wells GPK-3 and GPK-4, in place of a former filtering unit that had been dismantled in October 2018, hence minimizing the modifications to perform on the geothermal loop.

Figure 4: Prototype heat exchanger inspection (left) and final installation (right) [source és]

Since the prototype heat exchanger was designed to cool down the geothermal brine from 70°C to 40°C with four passes, it was possible to accurately monitor the temperature drops through the heat exchanger by adding thermowells and temperature sensors (TT) after each pass, as shown in Figure 5. The temperature was also monitored at the inlet and outlet of the prototype heat exchanger shell side along with the flow with an existing flowmeter on the closed cooling water loop, and a flowmeter was added on the tube side.

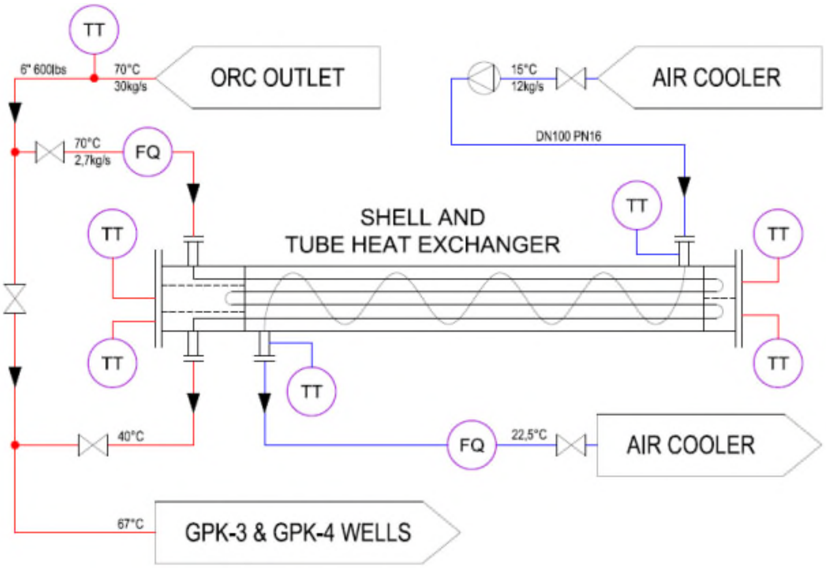

Figure 5: Piping & Instrumentation Diagram of the test

2.2.2 Three-month test operation

The prototype heat exchanger operation started on January 31st 2019 and lasted for three months until April 29th 2019. During this period of time, the water treatment of the brine remained normal, with the injection of both corrosion and scaling inhibitors, which definitely affected the deposition of scales on the prototype heat exchanger but operating without them would not be an option on any geothermal plant in the URG. Therefore, the use of inhibitors during the test actually allowed the effect of further decreasing the brine injection temperature in real operating conditions to be evaluated.

Since the closed cooling water loop used as a heat sink for the test was cooled down with ambient air, the first period of the test allowed for a brine flowrate higher than expected. Effectively, as the ambient temperature is colder in winter, the temperature of the closed cooling water loop was lower than expected and allowed the brine flowrate to be increased to 4,0 L/s for 15 days before reducing it to the anticipated flowrate of 3,0 L/s. Moreover, daily variations of the brine temperatures can be noticed in Figure 6, clearly identifying the difference between the day and night, due to the air-cooled closed cooling loop. A total of about 22 000 m^3 of brine was cooled down by the prototype heat exchanger during the test.

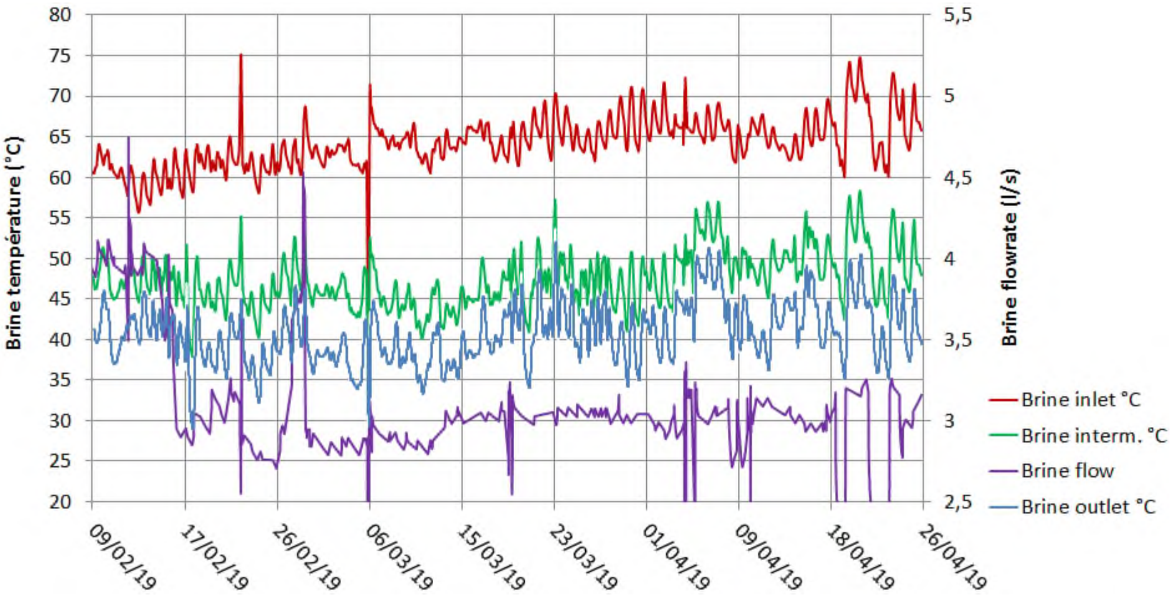

Figure 6: Evolution of the brine temperatures and flow in the prototype heat exchanger throughout the 3-month test

Figure 6 also shows that all the brine temperatures measured on the tube side of the prototype heat exchanger increased over the length of the test, due to an increasing ambient temperature impacting the ORC unit outlet temperature, which fed the heat exchanger for this test. However, the temperatures at the inlet, after the 2nd pass and at the outlet of the brine side of the prototype heat exchanger generally follow the expected trends, with standard deviations around 4°C for each pass. This is mainly explained by the daily variations observed due to the ambient air-cooling systems.

		Average value	Standard deviation
Tube side	Brine flow	3.1 L/s	0.4 L/s
	HEX inlet temperature	64,2 °C	3,6 °C
	1st pass outlet temperature	54,6 °C	3,8 °C
	2nd pass outlet temperature	47,5 °C	3,8 °C
	3rd pass outlet temperature	43,6 °C	4,1 °C
	4th pass outlet temperature	40,8 °C	4,2 °C

Table 2: Average brine temperature on the prototype heat exchange tube side

During the first week of operation, the efficiency of the 2nd pass of the prototype heat exchanger appeared to be very poor, as shown in Table 3, and that of the 1st pass was much better than expected. Even though the 2nd pass was supposed to be less efficient than the 1st and the 3rd passes, due to the fact that the brine was not flowing in counter flow with the closed cooling water in the 2nd and 4th passes, such a low heat transfer was very surprising. It led to a short operation stop to check the state of the waterbox and revealed that the gasket ensuring the water tightness of the three compartments of the inlet waterbox was damaged. This gasket was immediately changed and the operation resumed with measured temperatures much closer to the calculated ones.

Temperature point		Calculated temperature	Measured temperature
Tubes @ 3,1 L/s	HEX inlet	61.7 °C	61.7 °C
	1st pass outlet	55.6 °C	51.4 °C
	2nd pass outlet	51.4 °C	51.2 °C
	3rd pass outlet	48 °C	48.8 °C
	4th pass outlet	45 °C	44.8 °C
Shell @ 11 L/s	Inlet	31.3 °C	
	Outlet	39.2 °C	

Table 3: Calculated temperature drops in the tubes of the prototype heat exchanger, revealing a damaged gasket in the waterbox

The thorough monitoring of the temperatures and flowrates on both the tubes and shell sides is very important to perform, not only to identify a potential leak in a gasket or a hole in a tube, but also to investigate the heat transfer coefficient of the prototype heat exchanger. Effectively, scaling accumulated in the tubes has a lower thermal conductivity than metals, and reduces the circulation section for the brine, increasing its velocity. Therefore, the heat transfer coefficient provides an excellent indication of the fouling in the tubes, and therefore the scaling formation (Mouchot et al., 2019). In a clean heat exchanger under design conditions, this heat transfer coefficient has been calculated to be 1 843.2 W/m^2/K. Figure 7 shows the evolution of this parameter over the length of the test, starting from February 9th 2019 after the damaged gasket in the inlet water box was replaced. A regular decrease in the heat transfer coefficient can be identified over the whole length of the test, showing an accumulation of scaling in the tubes.

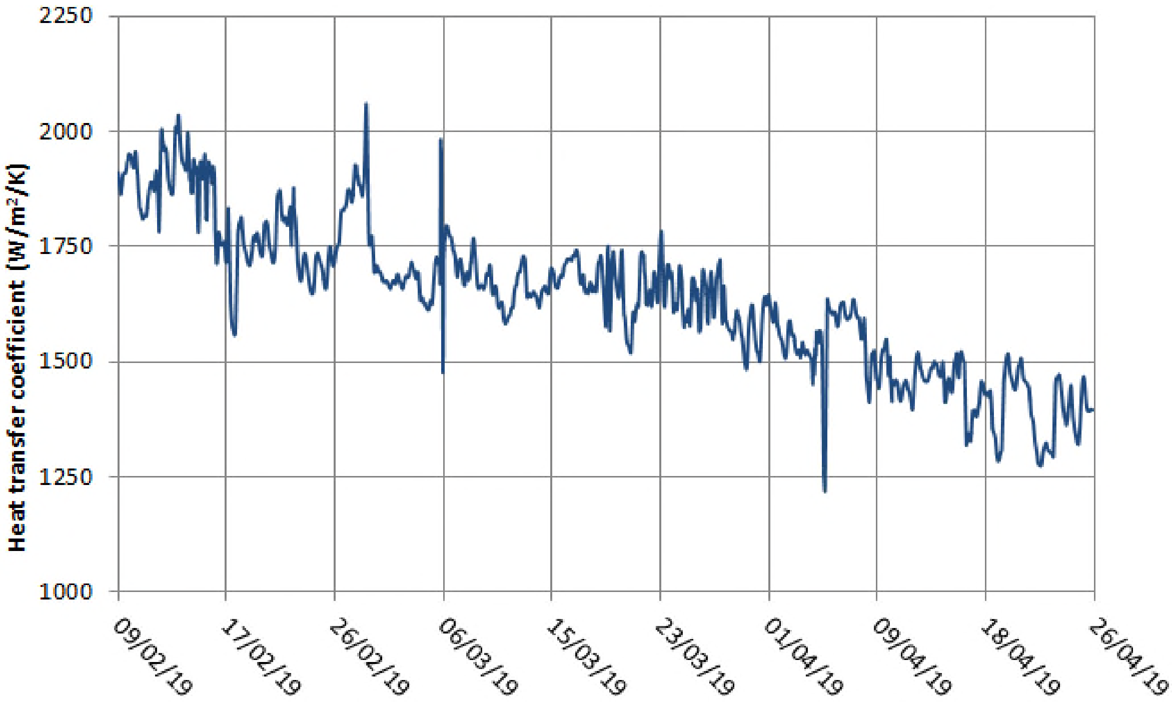

Figure 7: Evolution of the prototype heat exchanger heat transfer coefficient

Unfortunately, it was not possible to distinguish a cooling water temperature and flow around each pass, since the shell side was designed in one piece. Therefore, the heat transfer coefficient for each pass of the prototype heat exchanger could not be evaluated, which would have provided valuable information about the scaling formation during the test depending on the brine temperature.

2.3 ANALYSIS

2.3.1 Dismantling of the prototype heat exchanger

After three months of continuous operation, the prototype heat exchanger has been stopped, and drained in order to open it and start investigating its behaviour throughout the test. A view of the state of the prototype heat exchanger is given in Figure 8.

Figure 8: Prototype heat exchanger opening after 3 months of operation; waterbox flange (left) and tubes (right) [source és]

For the sake of these investigations, the prototype heat exchanger was partially dismantled, as shown in Figure 10, in order to provide ICI (Innovation Center Iceland) and UCP (Université de Cergy-Pontoise) with material to analyse. A selection of 18 pieces of tubes was cut from the heat exchanger. These pieces of tubes were taken from the inlet of the 1st pass, where the average brine temperature over the test was 64.2°C, the outlet of the 2nd pass, where the average temperature was 47.5°C, and the outlet of the 4th pass with an operating average temperature of 40.8°C. At these locations, tubes from all six metallurgies were cut out and opened in halves along their length (Figure 9). Scaling was also sampled at these locations, in order to analyse both the corrosion and the scaling and compare their interactions.

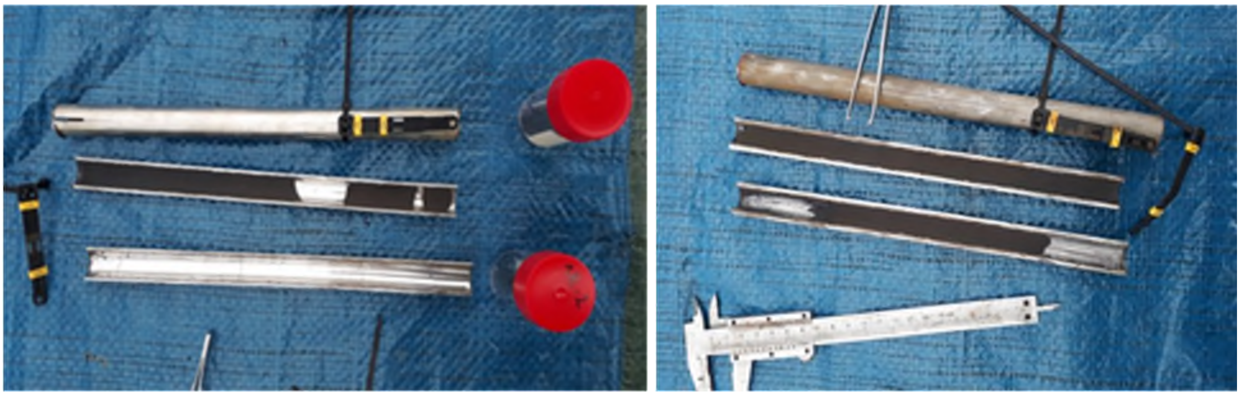

Figure 9: Scaling observation and sampling from 254 SMO tube (left) and DX 2205 (right) [source és]

With these samples, X-Ray Fluorescence and Scanning Electronic Microscope analytical methods was chosen to better characterise the elements contained in each sample and relate them to the temperature at which they appeared as well as the material on which they grew.

While the Scanning Electron Microscope examinations on the pipes to be performed by ICI would have provided more thorough analyses with the scaling still attached to the pipes, it was not possible to ship them in this state due to the presence of elements with ionising radiation.

Therefore, to ensure the health and safety of ICI staff, it was necessary to remove this residue, classified as NORM due to traces of 210Pb and 226Ra (Cuenot et al, 2013). On-site measurements applied on tubes and scaling are comparable to measurements on other surface facilities at the Soultz-sous-Forêts geothermal power plant. The dose rate is at background level, and the activity issued from 210Pb radionuclides mainly is of the same magnitude order for all temperature ranges and tubes metallurgies. Some tubes even had to be sand blasted in order to remove some strongly attached scaling, which will ultimately alter the quality of the results obtained by ICI for the sake of deliverable D6.6 but proved to be a necessary measure to ensure health and safety.

Figure 10: Prototype heat exchanger opening (left) and dismantling (right) [source és]

2.3.2 Quantitative analyses

Some preliminary results can already be drawn from the three-month test performed on the prototype heat exchanger at Soultz-sous-Forêts geothermal power plant. The idea behind the test was to identify the feasibility of harnessing more heat from existing deep geothermal wells in the URG by lowering the acceptable reinjection temperature of the geothermal fluid, currently set at 60°C. More details about the scaling and corrosion analyses are available in deliverables D3.5 and D6.6.

If the detailed results to be provided by ICI and UCP in these dedicated deliverables will be extremely interesting for operation purposes, the quantity of scales formed over time and the capacity to clean them are key parameters in determining whether implementing such an additional heat extraction solution is feasible or not. In terms of the operation of a thermal or power geothermal plant, the day-to-day focus is on the handling of the scales to treat and dispose of. Therefore, the preliminary observations made during the opening of the prototype heat exchanger after its three months of operation, and summarised in Table 4 and Table 5, are highly interesting, even though they tend to derive more from observations than purely qualitative analyses. Since no corrosion was visible on any pipe of the prototype heat exchanger after three months of operation, it was not possible to draw conclusions comparing the visual inspections regarding their likeliness to withstand the corrosiveness of the URG brine. However, all these materials were selected for their known corrosion resistivity, and further investigations are performed within the deliverable D6.6.

		Temperature		
		64,2°C ± 3,6°C	47,5 °C ± 3,8°C	40,8 °C ± 4,2°C
Tube material	904 L	**2**	**3**	**2**
	254 SMO	**2**	**1**	**3**
	DX 2205	**3**	**2**	**1**
	SDX 2507	**1**	**1**	**3**
	Alloy 825	**3**	**2**	**3**
	Ti Gr.2	**3**	**1**	**3**

Table 4: Rating of the quantity of scales formed in the tubes (1 = small quantities, 3 = large quantities)

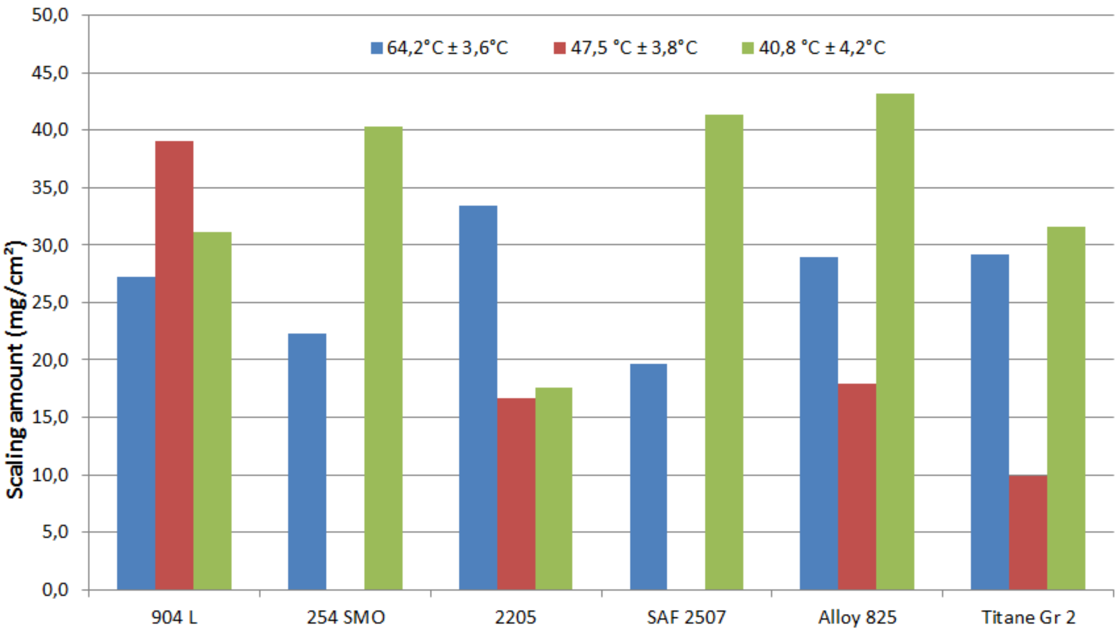

Figure 11: Amount of scaling deposition on tubes over the length of the three-month test at different temperatures

In terms of quantity of scales formed in the pipes, it appears to be unwise to reduce the temperature below 47°C (Figure 11), which happens to be the suspected temperature at which the formation of silica in Soultz brine is triggered. The DX 2205 seems to be the only material in which the quantities of scales sampled after three months of operation were acceptable at a low temperature. Unfortunately, the few scales formed in the pipe made of this material proved to be extremely hard to clean at all the temperatures tested, as shown in Table 5, and required sand blasting to be removed, which would be unacceptable during normal operations since it would generate huge amounts of waste to dispose of and this cleaning technique would definitely damage the heat exchangers beyond reason.

		Temperature		
		64,2°C ± 3,6°C	47,5 °C ± 3,8°C	40,8 °C ± 4,2°C
Tube material	904 L	**2**	**1**	**1**
	254 SMO	**1**	**1**	**1**
	DX 2205	**3**	**3**	**3**
	SDX 2507	**1**	**1**	**2**
	Alloy 825	**2**	**2**	**1**
	Ti Gr.2	**3**	**3**	**3**

Table 5: Rating of the adhesion of scales to the tubes (1 = easy to clean, 3 = extremely sticky)

Considering the temperature range selected, i.e. operating temperatures higher than 45°C, only three tube materials appear to present scales which are reasonably easy to clean: 904 L, 254 SMO and SDX 2507. These tube materials showed scales that could be removed by hand, needing only to lightly scratch the surface to remove them, and transforming the scales into powder or small slabs. The other materials, i.e. Alloy 825, Ti. Grade 2 and DX 2205 proved to be difficult to extremely difficult to clean and should be discarded when considering the design of a heat exchanger to harness geothermal brine at a temperature lower than 65°C. However, even though the quantity of scales formed was relatively high, the Alloy 825 showed scales that were easy to clean at a 40°C operating temperature.

The Table 7 shows the combination of both the quantities of scaling formed in the tubes and their stickiness, in order to rate the materials considering both aspects. It turns out that considering both parameters at the same time, SDX 2507 appears to be the best alternative to harness the brine temperature down to 47.5°C, whereas 254 SMO could be an interesting alternative when considering to reinject the brine at 40°C, even though the quantities of scaling formed in the tubes increase greatly at this temperature.

		Temperature		
		64,2°C ± 3,6°C	47,5 °C ± 3,8°C	40,8 °C ± 4,2°C
Tube material	904 L	**4**	**3**	**2**
	254 SMO	**2**	**1**	**3**
	DX 2205	**9**	**6**	**3**
	SDX 2507	**1**	**1**	**6**
	Alloy 825	**6**	**4**	**3**
	Ti Gr.2	**9**	**3**	**9**

Table 6: Rating of the combined quantity and adhesion of scales formed in the tubes (1-2 = reasonable, 3-4 = challenging, ≥5 = problematic)

2.3.3 Potential valorisation

Without considering the effect of further decreasing the brine injection temperature on the reservoir and the propagation of the cold plume towards the production well, lowering the current limit for the low temperature of brine injection from 60°C to 47.5°C seems feasible, without changing neither the tube material from the heat exchangers already used so far in the URG, hence the SDX 2507, nor the corrosion and scaling inhibitors used to protect the installations from the production well to the injection well.

Since the variations in the geochemistry of the brine produced in the URG do not greatly differ from one site to another, it would seem that the conclusions drawn in Chapter 3.2 can be applied to all the existing and future geothermal plants operating in this area. Table 7 presents the potential thermal valorisation that could be achieved by applying these results and lowering the brine injection temperature to 50°C, in order to keep an operational margin with the point at which the deposition of new amorphous scaling containing silica theoretically occurs.

Site	Production flow	Production temperature	Injection temperature	Current thermal power used	Valorisation potential @ 50°C
Soultz-sous-Forêts - FR	30 L/s	150°C	65°C	11.3 MW	1.7 MW
Rittershoffen - FR	75 L/s	168°C	80°C	25 MW	8.55 MW
Insheim – DE	70 L/s	164°C	65°C	26 MW	4 MW
Landau – DE	70 L/s	155°C	65°C	24 MW	4 MW
Bruchsal – DE	24 L/s	123 °C	65°C	5.5 MW	1.4 MW

Table 7: Potential thermal valorisation in existing and future geothermal plants in the URG

Table 7 presents results based only on the three-month test and should be further analysed on each site due to local specificities of the brine harnessed by each plant. Moreover, the impact on the reservoir itself and the propagation of the cold plume should be simulated for each geothermal plant considered before installing and operating an additional heat exchanger harnessing the remaining thermal power contained in the geothermal brine considering this new hypothetical low limit for the brine reinjection temperature.

Finally, the future projects that will be developed in the URG will have to take this usable additional heat into account when designing the plants in order to identify and implement from the start processes able to use this heat without generating huge needs for investments to adapt an existing plant.

2.4 CONCLUSION

The geothermal plants in the URG currently do not have an optimised use of the heat extracted from the reservoirs they harness. The SDX 2507, already used so far for the heat exchangers in the geothermal plants of the URG, proved to be an excellent choice to further harness the heat from the heavily salted geothermal brine at temperatures lower than 60°C, down to 47.5°C. Below this limit, the deposition of new amorphous scaling potentially containing silica seems to be triggered. Setting an operational lower temperature limit at 50°C would allow keeping an operational margin for the protection of the surface installations. Detailed analyses of these scales and the corrosion of the pipes are being performed by UCP and ICI respectively in order to better identify the elements contained in these scales and to confirm the preliminary conclusions drawn so far. The results of these analyses will be presented within the deliverables D3.5 and D6.6.

Before implementing these results on the existing geothermal plants located in the URG, further investigations should be carried out, especially regarding the cold plume propagation within the reservoir, in order to ensure the liability of the colder reinjection. Such investigations are being carried out and will be presented within the deliverable D3.3. Moreover, the UCP scaling analyses to be performed will help identify whether the use of other scaling or corrosion inhibitors might allow the brine injection temperature to be further decreased, or if this seemingly new lower limit of 47.5°C represents the operationally acceptable lowest setting achievable to this day.

By applying these results to the existing geothermal plants in the URG, it would be possible to increase the heat use for each site by 15% to 35%, with a total potential thermal power valorisation of nearly 20 MW. For example, a small scale 40 kW ORC unit will be designed and tested in Soultz-sous-Forêts in order to valorise this remaining heat and generate power with the 60-70°C brine available at the outlet of the existing 1.7 MW ORC unit already in operation.

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