Towards an optimized operation of the EGS Soultz-sous-Forêts power plant (Upper Rhine Graben, France)

Guillaume Ravier[1], Olivier Seibel[1], Astu Sam Pratiwi[1], Justine Mouchot[1], Albert Genter[1], Kolbrún Ragna Ragnarsdóttir[2], Xavier Sengelen[3]

[1] Electricité de Strasbourg Géothermie, Bat Le Belem, rue de Lisbonne 5, 67300 Schiltigheim, France

[2] Innovation Center Iceland (ICI), Árleyni 2-8, Reykjavik 112, Iceland

[3] University of Cergy Pontoise, boulevard du port 33, Cergy-Pontoise 95011, France

guillaume.ravier@es.fr

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ABSTRACT

Increasing heat recovery is challenging for the geothermal projects in the Upper Rhine Graben (URG). In the framework of the H2020 project MEET, several studies about the thermal effect on the Soultz-sous-Forêts power plant and its deep wells are being conducted. The main goal is to improve the thermal power production and optimize the fractured granitic reservoir while minimising environmental issues. At the Soultz plant, the reinjection at 70°C leads to a well-known scaling formation in the heat exchanger due to the chemistry of the brine and the thermodynamic changes. Barium, sulphates and metal-rich sulphides precipitate in the surface installation.

Since early 2019, an operating heat exchanger system able to exploit reinjection temperature from 70°C to 40°C is tested in the power plant. This heat exchanger was designed to cool down about 10% of the nominal mass flow of the Soultz geothermal plant. Dissolved gases and high salinity of the Soultz brine have led to corrosion issues. The heat exchanger was designed with several tubes alloy in order to determine the best trade-off between corrosion resistance in Upper Rhine Graben conditions and economical aspect. This alloy selection will also assess the impact of metallurgy corrosion on scales. In case of successful results with the prototype, a small scale ORC will be designed and tested at Soultz-sous-Forêts to generate electricity with full flow and at low temperature.

1. INTRODUCTION

1.1 The Soultz-sous-Forêts plant

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

The current geothermal site is fed by one production well GPK-2, producing 30 kg/s of a geothermal fluid at 150°C on surface. Since the geothermal water is very saline with 100 g/L, the heat of the geothermal water is harnessed via heat exchangers by an ORC unit. The brine is reinjected in the reservoir at 70°C into two reinjection wells, GPK-3 and GPK-4. The geothermal plant is fully operational since mid-2016, right after a new ORC unit was erected. The installed ORC unit capacity reaches 1.7MWe for an annual electricity production of about 11 GWh/year. Figure 1 is presenting a view of the Soultz geothermal plant.

Figure 1: View of the Soultz geothermal plant

1.2 Main goals of the heat exchanger prototype

This extended abstract is presenting research carried out in the frame work of the H2020 project MEET. This project "Multidisciplinary and multi-context demonstration of EGS Exploration and Exploitation Techniques" applied to different geological conditions is presented for demonstrating the geothermal potential of Europe from real projects in relevant industrial environment for attracting investors. Thus, to enable the development and the market penetration of the EGS geothermal energy, there should be a demonstration of the feasibility and of the upscaling of EGS in different geological conditions in Europe by enhancing the heat use and/or by producing electricity in different geological contexts (Trullenque et al., 2018).

Currently the injection temperature of all geothermal plants in operation in the Upper Rhine Valley is limited to 60-70°C. The first goal of this test heat exchanger is to evaluate the feasibility of increasing the heat extraction from the brine and to bring the injection temperature down to 40°C. Information about scale formation at temperature lower than 70°C is determinant for this goal.

This prototype is also an opportunity to test several metallurgies. Corrosion investigations will be carried out in order to rank the different alloy tested in terms of resistance to general corrosion, pitting corrosion, as well as cost and availability on the market.

Finally, in case of successful results, a small scale 40 kW ORC unit will be designed in order to generate power from 70°C to 40°C at a nominal flow rate.

1.3 Scaling and corrosion context in the URG

Cooling the geothermal brine of a very high salinity changes the geochemical stability and some scaling could be formed. In the URG geochemical context, barium sulphate and metal-rich sulphides precipitation is triggered by thermal exchanges, this process being enhanced with decreasing temperatures (Scheiber, 2013). Scaling and corrosion inhibitors are currently injected into geothermal fluid at Soultz plant to protect the surface installations from fouling and generalized corrosion issues.

While the nature of these scales is under investigation for a temperature down to 70°C, they are not yet really known below this temperature. As geothermal Soultz brine contains about 180 mg/l of dissolved silica (Sanjuan et al., 2010), a new issue is expected to arise with regards to new amorphous scaling formation by cooling the brine down to 40°C (Figure 2). Based on Soultz brine silica's concentration and on the curve of solubility of amorphous silica and quartz, scale containing silica can be expected in the test heat exchanger below 50°C.

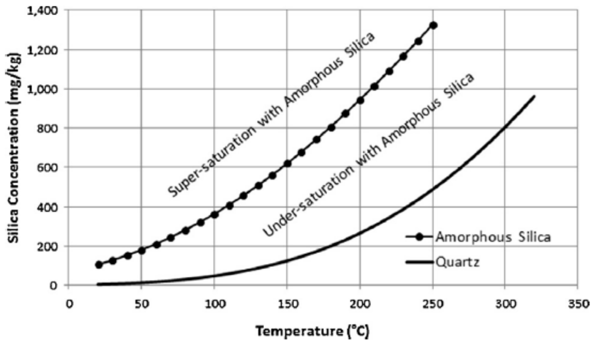

Figure 2: Temperature dependence of the solubility of quartz and amorphous forms of silica (Fournier and Rowe, 1977).

As reported in several papers (Mouchot et al., 2018), particular scales formed in the Upper Rhine Graben are related to electrochemical processes driven by corrosion. Different alloys were already tested at Soultz in 2013 on a hot temperature skid. During this test, pipes were only exposed to temperature up to 150°C. After 83 days of exposure, the pipes were removed from the skid and cut along their lengths. An initial visual inspection revealed that in the same operating conditions, the lower the resistance of an alloy to general and localized corrosion, the higher the quantity of scales (Figure 3). This visual inspection was completed with a Scanning Electronic Microscope analysis performed on scales by EIFER. Interestingly, chemistry of scales was also different depending on the alloy.

The test heat exchanger with several materials will also give an understanding of the relation between the scales, corrosion and metallurgy.

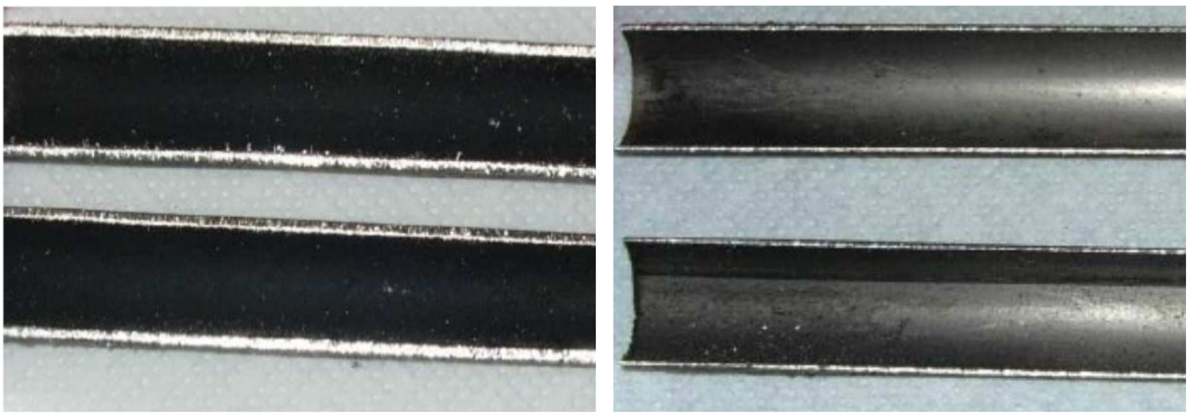

Figure 3: Visual inspection of scales in 1.4571 (316Ti, left) and Ti Gr.2 (right) after 83 days of exposure in the hot temperature skid at Soultz-sous-Forêts.

2. DESIGN OF THE HEAT EXCHANGER

2.1 Heat exchangers technology

Geothermal plants located in the Upper Rhine Graben are mostly designed for a maximal temperature and pressure service over 150°C and 25 bar, respectively. Due to this high condition service and a risk of scaling formation, all the geothermal plants in operation in this area are designed with shell and tube heat exchangers. Geothermal brine is always circulating in the tubes for cleaning purposes. Thus, the heat exchanger prototype tested at Soultz was also designed according to this technology.

2.2 Thermal design

The heat exchanger tested at Soultz was designed to cool down a brine flow of 3.0 l/s; around 10% of the nominal flow of the power plant, from 70°C to 40°C using a cooling loop at 15°C. The length of the tubes was limited to 3.0 m in order to limit the footprint of the equipment. External diameter of the tubes was set at 19.05 mm and thickness at 1.24 mm.

Following thermal calculation with HTFS software developed by ASPEN, the test heat exchanger was designed with 4 passes with 8 to 9 tubes of 3.0 m long and with a minimal brine velocity in the tubes of 1.0 m/s to reduce scales formation. The shell side was designed with 1 pass with 5 simple segmental baffles. Table 1 presents the expected temperature profile of the geothermal brine circulating in the 4 passes of the heat exchangers.

Table 1: Expected tubes side temperature drop of the prototype heat exchanger.

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

These temperatures will be monitored by 5 temperature sensors installed on the inlet brine pipe and directly on the heat exchanger bonnets. This temperature profile is particularly interesting for scaling studies. Scales are easily accessible for sampling on tubesheets. Analysis of these scales will be particularly helpful to compare results with chemical modelling.

2.3 Design according to TEMA nomenclature

The prototype was designed according to the French code of construction CODAP 2015 Div.2, transposing the European pressure equipment Directive 2014/68/UE into national law, and the nomenclature of Tubular Exchanger Manufacturers Association standards. Straight tubes were preferred to U tubes for cleaning and sampling reasons, like all the geothermal power plants in URG.

Following the thermal design with 4 passes on tubes side and 1 pass on the shell side, a very simple design was selected: 3 000 x 200 NEN (TEMA, 2007). tubesheets are welded to both Shell and Bonnets. Access to the tubes is only possible through covers on the bonnets and channels. Figure 3 presents a draft of the selected TEMA design.

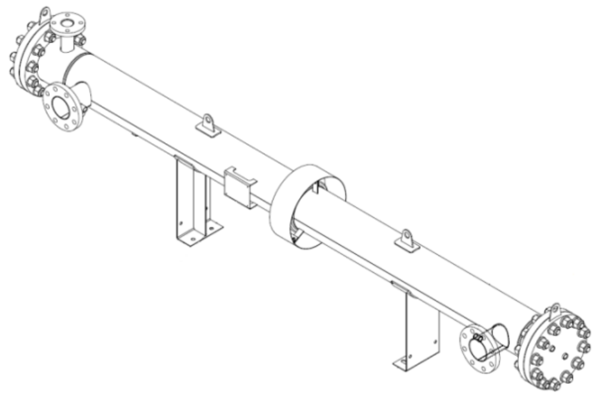

Figure 3: Draft of the NEN design adopted for prototype heat exchanger

2.4 Method used for metallurgy selection

As explained before, this prototype is an opportunity to test different metallurgies. As previously described, each pass of the prototype heat exchanger is designed with 8 to 9 tubes. For economical reasons, alloy selection was limited to 6 different alloys. Thus it means that each passes could be arranged with 2 or 3 alloys used twice for the pipes (Figure 4).

Selection of the different alloys was done according to Icelandic and Rhine Graben experiences, as well as different methods to rank alloys in terms of pitting susceptibility. Pitting Resistance Equivalent Number (PREN) is one of these methods and was established for stainless steels ranking, but unfortunately not for nickel or titanium alloys. That’s why PREN concept was completed with electrochemical studies of pitting corrosion in Soultz brine conditions (Mundhenk et al., 2014).

The susceptibility to local corrosion attack, related to the breakdown of the passive layer, can be evaluated by the determination of characteristic electrochemical potentials, as the pitting potential E_P, the repassivation potential E_R and the open-circuit potential OCP (Frankel 2003). The following relations are generally accepted:

OCP << E_P, no pitting corrosion

OCP ~ E_P, pitting may occur (metastable)

OCP > E_P, pitting corrosion.

Once experimentally determined, electrochemical potentials can be used to compare different materials and to rank them according to their pitting susceptibility (Table 2).

Table 2: Comparison of Pitting Resistance Equivalent Number (PREN) and data resulting from different corrosion investigations in Soultz brine (80°C, pH 4.8, CO_2 environment).

Material	PREN	OCP_{max} [mV]	$CR_{general}$ [mm/y]	E_P [mV]	E_R [mV]	I_{pass} [µA/cm^2]	ER-OCP_{max} [mV]	Type of corrosion
1.4571 [1]	23	-220	0.025	-70	-250	~ 30	-30	pitting, crevice
1.4539 [1]	35	25	0.015	115	50	~ 1	25	pitting, crevice
1.4462 [1]	34	-177	0.024	5	-135	< 2	42	pitting, crevice
1.4410 [2]	42	-198	$4.6\ 10^{-4}$	163	19	< 0.6	217	pitting
SAF 2707 [2]	48	-143	$4.7\ 10^{-4}$	970_{Crev}	550	To 160 mV: >1 590 mV: <10	693	crevice
2.4858 [1]	-	-127	$2.1\ 10^{-3}$	600	550	~ 1	677	general
3.7035 [1]	-	-115	$2.1\ 10^{-3}$	700	-	< 3	-	general

[1] Mundhenk et al. (2014)

[2] Results carried for the Rittershoffen geothermal plant by EIFER

2.5 Metallurgy selection

Hereafter is the drawing of the test heat exchanger Tubesheets (Figure 4) and a short presentation of the selected alloys.

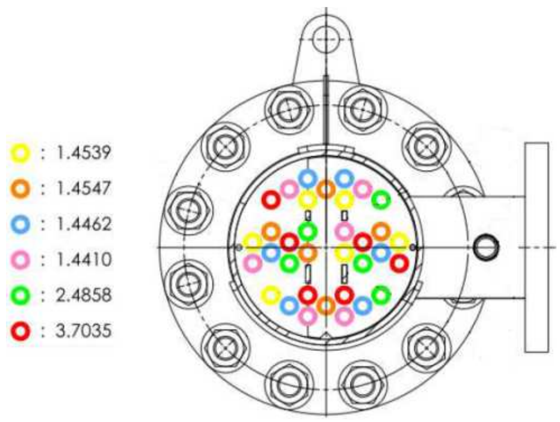

Figure 4: Drawing of a tubesheets with the different tubes metallurgy selected.

1.4539 (904L): Its molybdenum addition gives it superior resistance to pitting and crevice corrosion (PREN of 35) than lower grade austenitic stainless steel such 1.4571 (316Ti). This austenitic stainless steel had been tested at Soultz-sous-Forêts in a corrosion skid and in laboratory with Soultz brine conditions. Electrochemical tests, open circuit potential (OCP, 24h) and potentiodynamic polarization (PP) performed on this material showed good general corrosion resistance, but a susceptibility to pitting (Table 2).

1.4547 (254 SMO): This highly alloyed austenitic stainless steel is designed for maximum resistance to pitting and crevice corrosion (PREN of 46). It has higher strength than conventional austenitic stainless steels. 254 SMO has a high resistance to general corrosion and stress corrosion cracking, as well as a high ductility and impact strength. In both Italian and Icelandic plants, the 254 SMO alloy has shown good performance in corrosion tests in geothermal environments, for example from the wells KJ-39 and KG-12 in Krafla (Einarsson, 1980). The austenitic stainless steel 254 SMO was one of the most promising materials from the experiments done in the IDDP-1 well in Krafla. However there were indications of extensive cracking in the heat exchanger experiments for the IDDP-1 well in Krafla (Ragnarsdóttir, 2013; Karlsdóttir et al., 2014). Nevertheless, the tests at the IDDP-1 were performed under extreme conditions (supercritical geothermal steam), which would not exist at the Soultz-sous-Forêts geothermal power plant, especially on the reinjection line. Unfortunately, the steel is expensive and is therefore not commonly used.

1.4462 (DX 2205): This duplex (austenitic-ferritic) stainless steel is designed for high resistance against general corrosion, pitting (PREN of 34), crevice corrosion, erosion corrosion and corrosion fatigue. This alloy has been tested in a corrosion skid at Soultz and showed a good corrosion resistance (Table 2).

1.4410 (SDX 2507): This super duplex stainless steel is designed for service in highly corrosive conditions. It is more resistant against chloride compared to other duplex steels, and it has a much higher corrosion resistance against pitting (PREN of 42) than 1.4539 and 1.4462, even in Soultz brine conditions (Table 2). That's why heat exchangers of Soultz-sous-Forêts and Rittershoffen geothermal plants were designed with this metallurgy (Ravier et al., 2016). The super duplex stainless steel has also shown good results in very corrosive and acid environments such as from the wells KJ-39 in Krafla (Karlsdóttir et al., 2010) and also in the coupon test at the IDDP-1 test site in Kralfa (Karlsdóttir et al., 2015).

3.7035 (Ti Gr.2): This pure titanium grade has excellent cold formability and weldability with a moderate strength. It has excellent corrosion resistance and also excellent resistance to high oxidization. Ti Gr.2 was also tested at Soultz in a corrosion skid and in laboratory. A very wide range of passivity could be observed by PP measurement in Soultz brine condition (Table 2).

2.4858 (Alloy 625): High nickel alloys such as 2.4858 are commonly used where there is a risk of severe corrosion issues. It operates in temperatures reaching up to 1200°C. This nickel alloy has an excellent resistance to localized corrosion and against stress corrosion cracking in chloride solution. A very wide range of passivity could be observed by PP measurement in Soultz brine condition (Table 2).

Two other metallurgies were also discussed: Ti Gr.7 and hyper duplex SAF2707. In 2013, one coupon of Ti 35, a pure titanium alloy similar to Ti Gr.2 but designed for plates, and one coupon of Ti Gr.7 were tested in a high temperature corrosion skid at Soultz. If no scales were observed on the Ti 35 coupon after 101 days of exposure, a yellow layer of scales could be observed on the Ti Gr.7 coupon. This test revealed that the palladium used to increase corrosion resistance of the Ti Gr.7 had catalyzed some scales formation, composed with a matrix of Fe, Cu and S with enriched Pb and S particles (Figure 5). Therefore, Ti Gr.7 was not selected for the test.

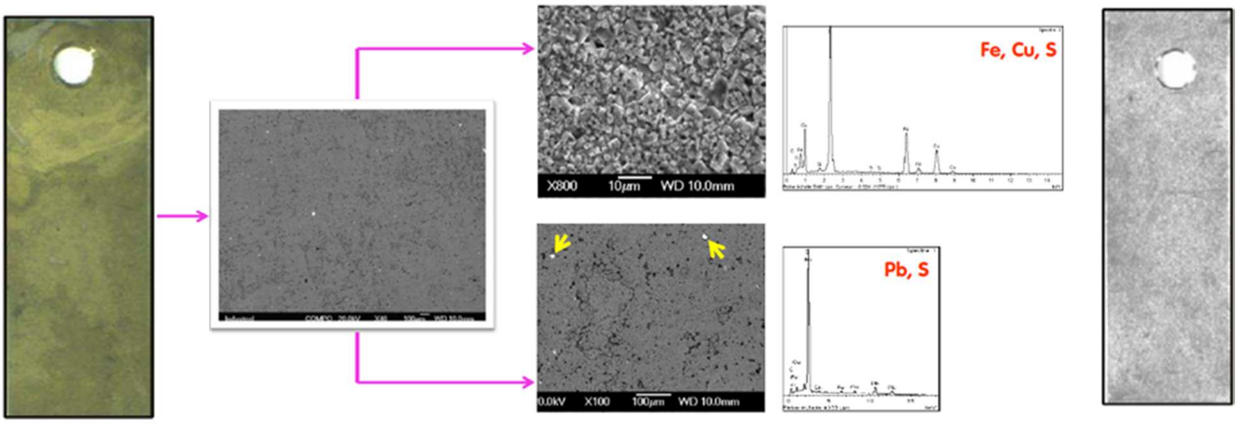

Figure 5: View of one TI 35 coupon (right) and one Ti Gr.7 coupon (left) after 101 days of exposure and the results of Scanning Electronic Microscope analysis performed on scales.

SAF 2707 was also tested at Soultz in laboratory with very promising results (Table 2). However, this alloy is unfortunately not available on the market for tubesheets. For this reason SAF 2707 was no selected for this test.

Shell, bonnets and tubesheets of the test heat exchanger were designed with lower alloy, stainless steel 1.4307 (304L), in order to reduce the cost of the equipment.

2.6 Connexion tubes-tubesheets

Welding 1.4307 austenitic stainless tubesheet with different stainless steel tubes or high nickel alloys can be possible with a very special welding procedure. However, heterogeneous weldings can be very tricky in corrosive environment and could be a source of galvanic corrosion. Moreover, welding titanium tubes on a stainless steel tubesheet is not feasible. For these reasons, the test heat exchanger was designed with grooves in the tubesheets and tube expansion to insure the sealing (Figure 6). Stainless steel and nickel alloy tubes were expanded in two square grooves; whereas titanium tubes were expanded in 3 triangular grooves.

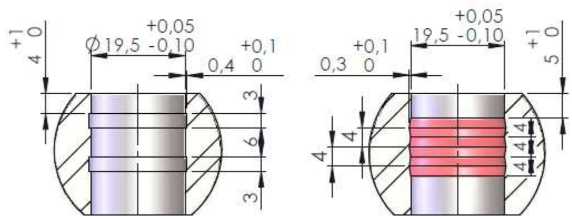

Figure 6: Draft of the 2 square grooves for stainless steel and nickel alloy tubes (left) and the 3 triangular groves for titanium tubes (right)

The shell was also designed with an expansion joint in order to cope with the differential expansion between the tubes and the shell. This expansion management is particularly important considering the use of several alloys with different expansion coefficients.

3. MANUFACTURING, INSTALLATION AND COMMISSIONNING

3.1 Manufacturing

Starting from the purchase in October 2018, manufacturing of the test heat exchanger lasted about 13 weeks (Figure 7). It started with several weeks of engineering studies and design. Different validation steps were necessary for the mechanical design, for example in order to add some temperature probes. In the meantime, the material supply was launched (Figure 7). Unfortunately, due to very small amount of tubes, 34 in total, it was not possible for the manufacturer to provide all the selected alloy tubes with uniform dimensions (external diameter of 19.05 mm and a thickness of 1.24 mm). The tubes of 1.4539, 1.4462 and 3.7035 are slightly thicker, with a thickness of 1.65 mm. This would slightly affect the thermal calculation.

Workshop manufacturing lasted three weeks and first started with Tubesheets machining. Then, the shell was prepared by adjusting length and welding an expansion joint and nozzles. The tubes bundle was assembled and inserted in the shell. Tubesheets were welded on the shell and tubes were expanded. Meanwhile Bonnets were prepared and then welded on the Tubesheets. Manufacturing ended with the hydraulic pressure test (Figure 7).

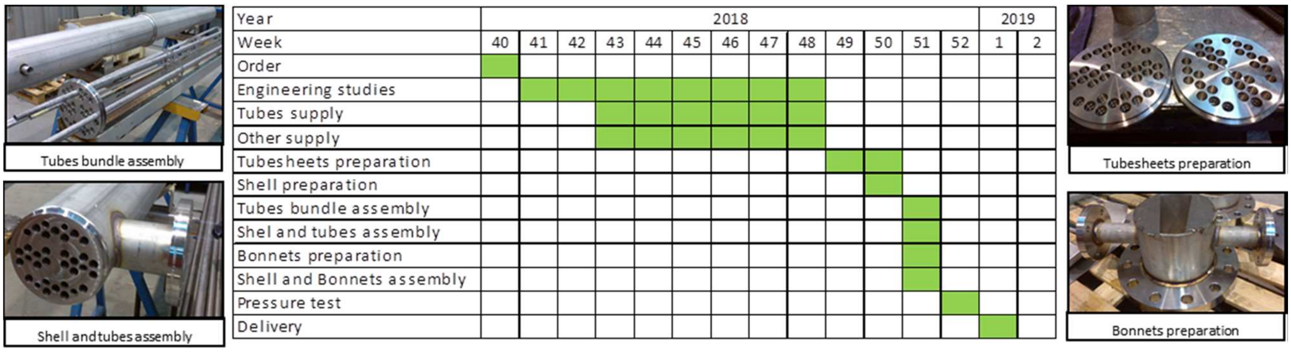

Figure 7: Illustrated planning of the test heat exchanger manufacturing

3.2 On site installation

Once delivered on the Soultz power plant early-January 2019, the test heat exchanger was inspected before the installation (Figure 8). This inspection was performed to check the conformity with the order and draft validated. It was also an opportunity to have initial condition of the tubes before the three months test for the scaling monitoring.

Figure 8: View of the test heat exchanger inspection before piping works.

Then the heat exchanger was connected to the existing injection pipes and to the cooling loop pipes (Figure 9). An additional pump was installed on the cooling loop for the project with total developed head and flow according to the thermal and pressure drop calculations.

Temperature sensors were also installed to monitor the thermal profile in the tubes and in the shell and have been controlled before the commissioning. Temperature sensors accuracy was between -0.4°C and +0.5°C. One flowmeter was also inserted in the brine pipes connexion. All these sensors have been included in the automation system of the geothermal power plant.

Heat exchanger inlet brine flow is controlled using the by-pass valve by partially opening or closing it. Inlet cooling flow will be controlled by the pump and a valve (Figure 9). All the parameters, such temperature and flow, will be closely monitored in order to respect the thermal design. If necessary, position of the valves will be adjusted during the three months of testing.

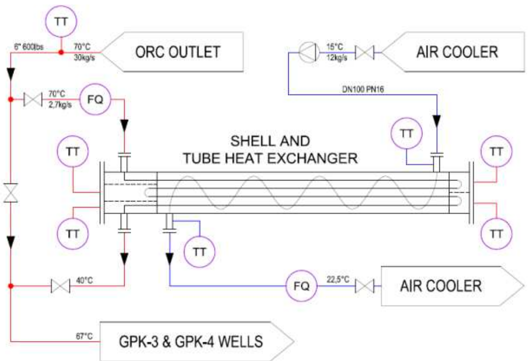

Figure 9: Simplified Pipping and Instrumentation Diagram of the test heat exchanger pipes (TT, temperature sensor, FQ, flowmeter).

3.3 Commissioning

The test heat exchanger is in operation since January 31st 2019, after three weeks of piping, electrical and automation works. Inlet brine flow and cooling flow were adjusted close to the nominal values, about 4.1 kg/s for the geothermal fluid and 21.3 kg/s for the cooling fluid.

The test heat exchanger was stopped a couple of hours on the 8th of February to replace a Bonnet gasket. Indeed, an internal leak was suspected because temperatures measured on pass 2 and 4 were slightly higher than expected. Since the 8th of February, temperatures of the different passes are relatively in accordance with HTFS thermal calculation (Table 3). Difference can be explained by temperature sensors and flowmeter accuracy.

Table 3: Comparison of temperature measurements and HTFS calculations of the test heat exchanger in operation.

Side	Pass	T_{inlet} (°C)	T_{outlet} (°C)	T_{inlet} (°C)	T_{outlet} (°C)
		Onsite measurement		HTFS thermal calculations	
Tube	1	62.4	52.9	62.4	54.6
	2	52.9	48.7	54.6	48.8
	3	48.7	45.0	48.8	44.2
	4	45.0	42.0	44.2	39.4
Shell	1	20.5	24.5	20.5	25.5

Temperature and flow monitoring is very important to follow the heat coefficient transfer of the heat exchanger. This coefficient gives a good indication of scales formation in the tubes. In clean operation, heat coefficient transfer of the test heat exchanger is 1843.2 W/m^2/K. Figure 10 presents a monitoring of the heat transfer coefficient during nearly 4 weeks of test.

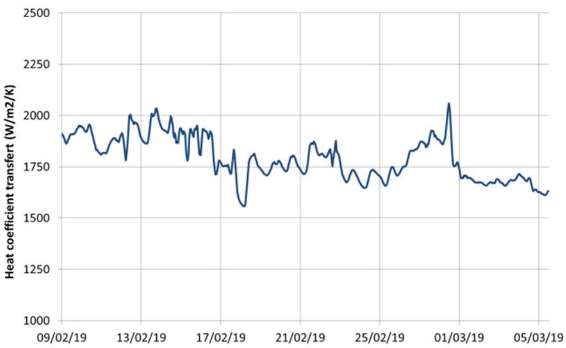

Figure 10: Evolution of the heat transfer coefficient during the first week of test.

At the start of the test, values of the heat transfer coefficient are about 1918 W/m^2/K, about 4% over the design coefficient. This error is in accordance with uncertainties on temperature and flow measurement, as well as uncertainties on physical properties like viscosity and specific heat estimation used for the thermal design. Figure 10 also shows that after two weeks of operation scaling are affecting the heat transfer coefficient; with a decrease from 1918 W/m^2/K to 1767 W/m^2/K. Trend of the heat transfer coefficient will be monitored until the end of the three-month test.

4. CONCLUSION AND PERSPECTIVES

Increasing the heat extraction from the brine is a challenge to enable the development and the market penetration of the EGS geothermal energy. Thus this ongoing test with a heat exchanger in the frame of the H2020 project MEET is a promising approach. This shell and tubes heat exchanger was carefully designed to cool down the brine to 40°C with 4 passes. Different alloys were selected according to URG and Icelandic experiences and know-how.

After three months of continuous geothermal fluid circulation, scaling samples will be analysed regarding their structure, mineral and chemical compositions, as well as quantity, for each temperature step and material. These analyses will be performed using X-Ray Diffraction and a Scanning Electronic Microscope. In parallel of these analyses, a chemical modelling with PhreeqC software (USGS) will investigate the saturation index of the minerals dissolved in the brine at different temperatures in order to confirm scaling formation. The results from the laboratory and predictive modelling will be compared.

This three-month test will also provide a better understanding of the efficiency at lower temperature of the chemical treatments used so far in Soultz. If silica scales are observed, two scenarios can be applied to increase the thermal capacity of the EGS power plant in the URG, depending on the temperature at which this phenomenon occurs. The first scenario is to limit the injection temperature to the amorphous silica solubility temperature, and the second is to use silica inhibitor to prevent formation of scales in the equipment and injection wells.

In addition, the heat exchanger will be dismantled in April 2019 to analyse the integrity of each tube material at different temperature levels. Corrosion analyses will be carried out in order to rank the different alloys tested in terms of resistance to general and pitting corrosion. The detection of severe localised corrosion would be a way to discard the use of certain tube materials in the detailed designs for future applications. The chemistry and quantity of scales will also be compared for each tubes alloy, enabling a better understanding of the relations between scaling formation, corrosion processes and tubes materials.

The expected outcome of this field test is to optimise the geothermal fluid injection temperature in the URG as a balance between scaling precipitation and corrosion processes with controlled costs, in order to allow harnessing up to 20-35% of additional heat.

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