European Geothermal Congress 2016
Strasbourg, France, 19-24 Sept 2016

Design, manufacturing and commissioning of the ECOGI's heat exchangers at Rittershoffen (France): a case study

Guillaume Ravier[1], Petra Huttenloch[2], Julia Scheiber[3], Vincent Perrot[4], Jean-Luc Sioly[5]

[1] ES-Géothermie, 3a chemin du gaz, 67500 Haguenau, France

[2] EIFER, I Emmy-Noether-Strasse, 11 76131 Karlsruhe, Germany

[3] GEIE « Exploitation Minière de la Chaleur », Route de Soultz – BP 40038, F-67250 Kutzenhausen, France

[4] Ateliers de chaudronnerie de Monplaisir, 101 rue du Dauphiné, 69800 Saint-Priest, France

[5] Roquette Frères, Route du Rhin, 67930 Beinheim, France

guillaume.ravier@es.fr

Keywords: Geothermal heat generation, EGS, shell and tube heat exchanger, corrosion, potentiodynamic polarisation, Eddy current testing, welding procedure

ABSTRACT

The purpose of this paper is to present the design, the manufacturing and the commissioning of the heat exchangers (HEX) of the Rittershoffen geothermal plant. This plant is located in the Rhine graben and is design to deliver a power of 25 MWth to the "Roquette Frères" bio-refinery at Beinheim. Operating conditions of these heat exchangers are particularly aggressive. Different types of heat exchangers (plate, tubular…) and also several material options were available on the geothermal equipment market. The choice of these units and that of the downhole production pump posed a technical challenge for this project.

1. INTRODUCTION

The Rittershoffen geothermal plant is a deep EGS geothermal project initiated in 2011 (Baujard, 2015). The drilling site is located in Rittershoffen, 6 km east of Soultz-sous-Forêts, in Northern Alsace, France. Shareholders are Electricité de Strasbourg (40%), the main energy supplier in Alsace, Roquette Frères (40%), a food processing industry, and the Caisse des dépôts et consignations (20%), a public group serving general interest and the economic development of the French country. This project comprises the first full and direct use of an EGS thermal plant. It has been designed to deliver a power of 25 MWth, which covers around 25% of the industrial heat demand of "Roquette Frères" bio-refinery at Beinheim, 10 km east of Rittershoffen. The project is supported by "ADEME" with the "Fond Chaleur", "Conseil Régional d'Alsace" and "SAF Environnement", as guarantor in case of unproductive well. Figure 1 is presenting a schematic sketch of the global heat use for this project.

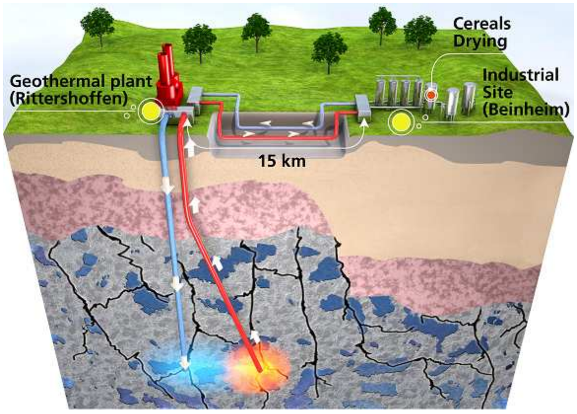


Figure 1: Sketch of the Rittershoffen geothermal project (source ECOGI)

Reservoir of the Rittershoffen geothermal plant is situated at the interface between the clastic Buntsandstein sandstone and the top of the crystalline Paleozoic basement. A geothermal doublet has been drilled to 2.6 km depth TVD, where the bottom temperature exceeds 160°C. The geothermal brine is very similar to that at Soultz: a Na-Cl-Ca dominated brine, with a salinity of 100 g/L and a gas-liquid-ratio of 1:1 (Sanjuan, 2010) and with a temperature higher than 165°C.

Thus, transporting the brine from Rittershoffen to Beinheim with a 15 km long pipeline, crossing a protected forest, fields and rivers, represented a real challenge. It was neither technically nor financially viable, because of the risks of corrosion, leakage and the consequent environmental issues. For this reason, a group of heat exchangers were designed to transfer the heat from the geothermal brine to a closed-cycle heat transport loop supplying industrial heat to the Roquette Frères bio-refinery.

The first stage of heat recovery at the bio-refinery is for vapour generation at low pressure (2.5 bars and 129 °C). In order to maximize the vapour generation, very small temperature pinches have been introduced in the design of the heat exchangers at Rittershoffen and of those in the plant at Beinheim. Then, after a cascaded succession of uses of the heat in the bio-refinery, the temperature of the fluid entering the cross-country return line is around 70°C. Thus heat exchangers have to reheat the returning fluid in the heat transport loop from approximately 68°C to the required production temperature.

2. OVERVIEW OF THE TECHNICAL CHOICES

2.1. Heat exchangers technology

Different technologies of heat exchangers are available on the market and proposed by a crowd of worldwide manufacturer. Main technologies are: shell and tube, gasket plate heat exchanger, welded plate heat exchanger and shell and plate. All those technologies have benefits and drawbacks. For example, when small pinch between the two thermal circuits is required, the most adapted technology is plate heat exchanger. Indeed, to get small pinch, high exchange surfaces are required and this technology is the most compact one. In case of high pressure service condition, shell and plate heat exchanger is the most adapted technology because tubes are more resistant to high pressure than plates. For the Rittershoffen geothermal plant, technological choice was mainly driven by three parameters:

- High pressure and high temperature resistance because of the nominal well head pressure about 25 bars and temperature over 165°C;
- Easy cleaning operation because of scales resulting to the temperature decrease in the heat exchangers oversaturating some minerals, such as strontium rich strontium rich barite ($Ba_{0.6}Sr_{0.4}SO_4$) (Scheiber et al., 2015);
- Small pinch between the two thermal loops in order to maximize the vapor production at the bio-refinery plant.

Last one was in favour of the heat and plates technology. However, the first parameter prevents the selection of gasket heat exchangers because gaskets can't resist to the service conditions of the geothermal loop. Welded plates heat exchangers could be an appropriated technology, however welded plates can't be easily cleaned, or need very important plates spacing, which significantly reduce the benefit in terms of pinch. Shell and plates technology was not retained because cleaning operating are easier than welded plate heat exchangers. Nevertheless, selected metallurgy, resistant to the brine chemistry, is not available on the market for corrugated plates.

Finally, the Rittershoffen geothermal plant was designed with shell and tubes heat exchangers which can resist to high service condition and be cleaned very easily by water jetting. Their drawback in terms of pinch was compensated by extra-CAPEX to increase the heat exchange.

2.2. Metallurgy

Corrosion and scaling phenomena on construction materials in aggressive geothermal brine may play a major role in long-term operation of geothermal power plants. Especially a high chloride content in the brine, as found at the Rittershofen site, can lead to pitting corrosion resulting in short time failure. Therefore corrosion and scaling investigations were performed on post exposure tube and coupon samples of different chemical composition and geometry. High performance materials like titanium (gr. 2: different geometries: normal, corrugated, welded, welded and corrugated), nickel-based alloys (2.4602, 2.4675), super and hyper duplex (1.4410 and 1.4658: normal and welded), duplex stainless steel (1.4462, twisted form) and austenitic stainless steel (1.4539, 1.4571) were tested. The samples were previously exposed by the operating team at the Soultz power plant in a corrosion by-pass (Scheiber, 2013) at production conditions over a time period of 83 days. The samples were investigated by stereomicroscopy and SEM/EDX analytics. Furthermore electrochemical polarization tests (PP) were performed on selected samples.

All exposed samples exhibited a black scaling of low adherence. However, the amount of deposits decreased with increasing steel quality (1.4571 >1.4539 > 1.4462 > 2.4602/2.4675 > Ti gr. 2). In the present case no relationship between the formation of scaling and the steel microstructure or geometry could be found. In general the composition of the deposits was consistent with the brine chemistry. The main chemical compounds of the most deposits were As, Pb and S. Minor compounds were Sb, Cu, Al, Mg, Ca, Cl or Ag. Parts of the deposits were covered by a Si-O-rich film.

No corrosion attack could be detected in all cases. All steel qualities, including the weld seams and deformed areas in case of the special designed material (twisted, corrugated), remained stable during an exposure time of 83 days at production conditions.

Some construction materials, mainly nickel alloys like 2.4675 and 2.4602 were ruled due to their very high cost. Remaining materials were tested with electrochemical measurements, which are a useful tool to rank materials with regard to their corrosion resistance. Electrochemical tests as measuring the open circuit potential (OCP, 24h) and potentiodynamic polarization (PP) were performed as described at Mundhenk et al. (2014). The corrosion resistance was evaluated by the determination of the critical potentials like pitting corrosion potential E_P and the repassivation potential E_R (see Figure 2). A high corrosion resistance is characterized by an extended passive range, low passive current densities, E_P at high potentials and a small or no hysteresis loop. In this study the materials stability was determined by the conservative consideration of the safety margin (E_R-OCP_{max}).

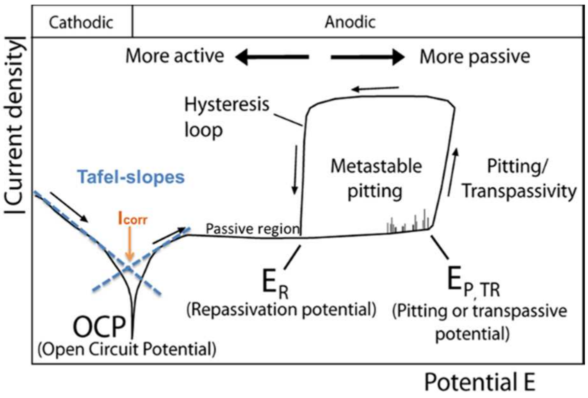


Figure 2: Schematic current density-potential diagram from potentiodynamic polarization.

The general corrosion rates CR, measured at the OCP, of the tested materials are very low (< 1.5•10-3 mm/y). All materials were spontaneously passive in the brine and show low passive current densities of < 10 µA/cm^2. The main statements of the results are summarized in Table 1.

Super duplex steel 1.4410 was stable under experimental conditions (80 °C). Very high corrosion resistance exhibits Titanium gr.2 (all geometries, welded form) and 1.4658. At higher overpotentials the welded form of 1.4658 showed a significantly decreased corrosion resistance compared to the not welded one. The formation of a stable passive film for the welded sample is not given. 1.4658 is available on the market on tubes form but not on plate. This was a major problem because 1.4658 tubes would have been welded on super duplex 1.4410 plate and the experience with the welded 1.4658 was not really successful. That's why this material was not selected.

Titanium gr.2 was also a good candidate for corrosion resistance, but this material is susceptible of cracking in presence of H_2, present in minor concentration in brine. Moreover, repairing Titanium heat exchanger require special atmosphere condition and welding procedure. Super duplex 1.4410 material was finally selected for tubes and tubesheets, because of its corrosion resistance, availability on tubes and plates and its easier welding procedure. This choice was also comforted by good operating performances of other plants using similar stainless steel grade on same brine condition.

Table 1: Main statements of the electrochemical test performed in Soultz brine (80 °C, pH 4.8, CO_2 gas)

Criterion / material	Safety margin (E_R-OCP)	Hysteresis (repassivation)	Type of corrosion
1.4571	41	extend: 180 mV able to repassivate	Pitting (at potential: -70 mV)
1.4539*	25	extend: 65 mV able to repassivate	pitting/crevice (at potential: + 115 mV)
1.4410	217 mV	extent: 144 mV able to repassivate	pitting (at potential: 160 mV)
1.4658	≈ 690 mV	small good repassivation	crevice along gasket (potential > 600 mV)
1.4658 welded	Not existent	extent: 415 mV no repassivation	crevice along gasket (at potential: 350 mV)
Ti gr. 2, welded and corrugated	≈ 625 mV	small good repassivation	general

*Mundhenk et al. (2014)

2.3. Criteria to select the supplier

Many manufacturers can propose shell and tube heat exchangers. Thus, the technical team in charge of the design of the Rittershoffen geothermal heat plant has defined some specific criteria for the supplier process selection. Supplier of the heat exchangers was selected according to the following criteria:

- Experience with Duplex and Super-Duplex: Welding of these special stainless steel alloy require specific welding procedure to avoid mechanical or corrosion problem. Experience in Duplex and Super-Duplex welding was considered as one of the key point of lifetime of the heat exchangers; To assess this experience, each supplier was asked to present its offer with a welding model; Figure 3 is showing a view of a welding model of one supplier presenting a lack of fusion; This model was rejected by the technical team of the Rittershoffen geothermal plant.

Figure 3: View of a welding model showing a lack of fusion

- Machining and welding of stainless steel in a special workshop dedicated to; This criteria was also an insurance for the lifetime of the heat exchangers by protecting stainless steel welding from carbon contamination due to machining of the carbon steel;

- Technical solutions insuring a long operating lifetime and a respect of the thermal heat exchange with the minimal thermal pinch between the geothermal loop and the transport loop;
- Financial aspect was also a criterion; nevertheless the supplier process selection was primarily driven by technical point of view.

Finally, a French pressure vessel manufacturer was selected according to its duplex and super duplex references, its ISO 3834-2 weld certification, its white workshop dedicated to stainless steel and the design proposed for the heat exchangers, which has convinced the technical team of the Rittershoffen project of a long operating lifetime.

3. HEAT EXCHANGERS DESIGN

3.1. Design according to TEMA

Heat exchangers of the Rittershoffen plant were design according to French code of construction CODAP 2010, transposing the European pressure equipment Directive 97/23/CE into national law, and the nomenclature of Tubular Exchanger Manufacturers Association standards. Double or multi pass heat exchangers were more economical. However, the project was researching a very small pinch between the primary and the secondary loop. Double or multi pass heat exchangers can suffer from heat transfer by-pass on the longitudinal sealing baffle. Single pass heat exchanger was preferred because this simple technology warranties the best counter-current flow heat exchange.

Due to possible scaling formation by decreasing the brine temperature, cleaning operation needed to be taken into account in the design. U-tubes, twisted or corrugated tubes are not compatible with cleaning issues, whereas straight tubes can be easily cleaned if the inner diameter is big enough. Direct access to the tubular plates is also preferable for cleaning operation. Moreover, for easier tubes and tubesheets inspection, removal covers were preferred to removal bonnets. As far filtered softened water is circulating in the shell, it was decided that shell cleaning was not an issue. That’s why heat exchangers could be designed with fixed tubesheet and shell side expansion joint.

Flowrate inside tubes and shell can induce vibration and all the software used for heat exchangers design are including vibration analysis. Vibration can be a source of stress, especially on baffle tubes supports, and prone to tubes failure. Some technical solutions are possible to minimize risk of failure due to vibration. Thus a baffle design with no tubes in windows is a simple technical solution and easy to implement. This solution is slightly more expansive than other solutions, like double segmental baffles, but it do not reduce the thermal heat transfer coefficient, warrant a better tubes support and it’s easier to implement.

Final Rittershoffen geothermal plant was designed with 10 000 x 660 AEL (TEMA, 2007) shell and tube heat exchangers, with straight tubes and no tubes in windows. .

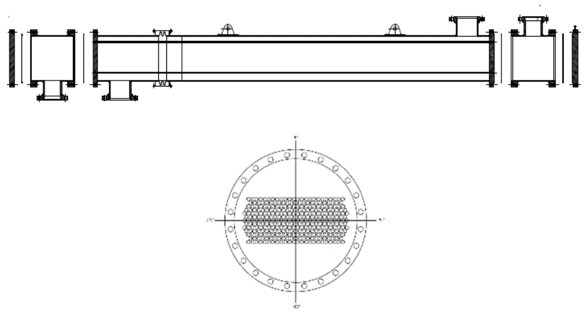


Figure 4: Draft of the AEL NTIW adopted for the heat exchangers of the Rittershoffen power plant

is presenting a draft of the selected TEMA design.

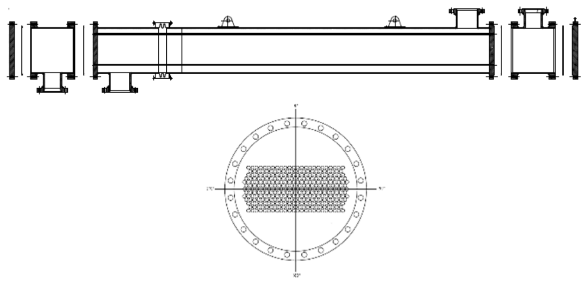


Figure 4: Draft of the AEL NTIW adopted for the heat exchangers of the Rittershoffen power plant

3.2. Thermal design

Due to scaling risk formation and fouling, heat exchangers of the Rittershoffen geothermal plant have been designed with some extra surface. Extra surface was easier to implement in heat exchanger software design than fouling coefficient. Indeed nature of scaling and its thermal conductivity were not easy to determine in advance.

Table 2 is presenting the thermal performances of the heat exchangers with fouling, a brine flow of 275 t/h, a secondary flow of 245 t/h and different number of heat exchangers in series. These results were modelling with software developed by Heat Transfer Research, Inc. (HTRI).

Table 2: Thermal performances with different number of heat exchangers in series

Nbr in series	6	8	10	12
Brine inlet temperature	165.0	165.0	165.0	165.0
°Brine outlet temperature	74.0	71.5	70.0	69.5
Brine pressure drop	0.71	0.95	1.19	1.43
Secondary inlet temperature	65.0	65.0	65.0	65.0
Secondary outlet temperature	156.0	158.7	160.0	160.6
Secondary pressure drop	2.1	2.8	3.5	4.0
Thermal power	26.2	27.0	27.5	27.6

Six heat exchangers were normally enough for a pinch of 10°C. However, in order to maximise the low pressure vapour generation at the bio-refinery, 5°C of temperature difference between the brine temperature and the secondary was the target. To succeed with this target, a minimum of 10 heat exchangers were required. Following the recommendation of the technical team of the Rittershoffen project, the investors finally agreed to design the geothermal plant with 12 heat exchangers in series, giving extra thermal power for future development.

3.3. Skid assembling

In order to maximize the operating time of the geothermal plant, it was decided to assemble the 12 heat exchanger on skid assembly of four equipment. Brine and secondary loop pipes were also designed to connect four by four the heat exchangers with intermediate by-passes. These by-passes can be used during cleaning operation of one heat exchangers skid, preventing to stop completely the Rittershoffen geothermal plant.

In case of four heat exchangers out of operation for cleaning operation, Table 2 is showing that Rittershoffen geothermal plant can still produce 27 MWth with 6.3°C of pinch. Figure 5 is presenting a view of the heat exchangers skid assembly before insulation.

Figure 5: Heat exchangers skid assembly

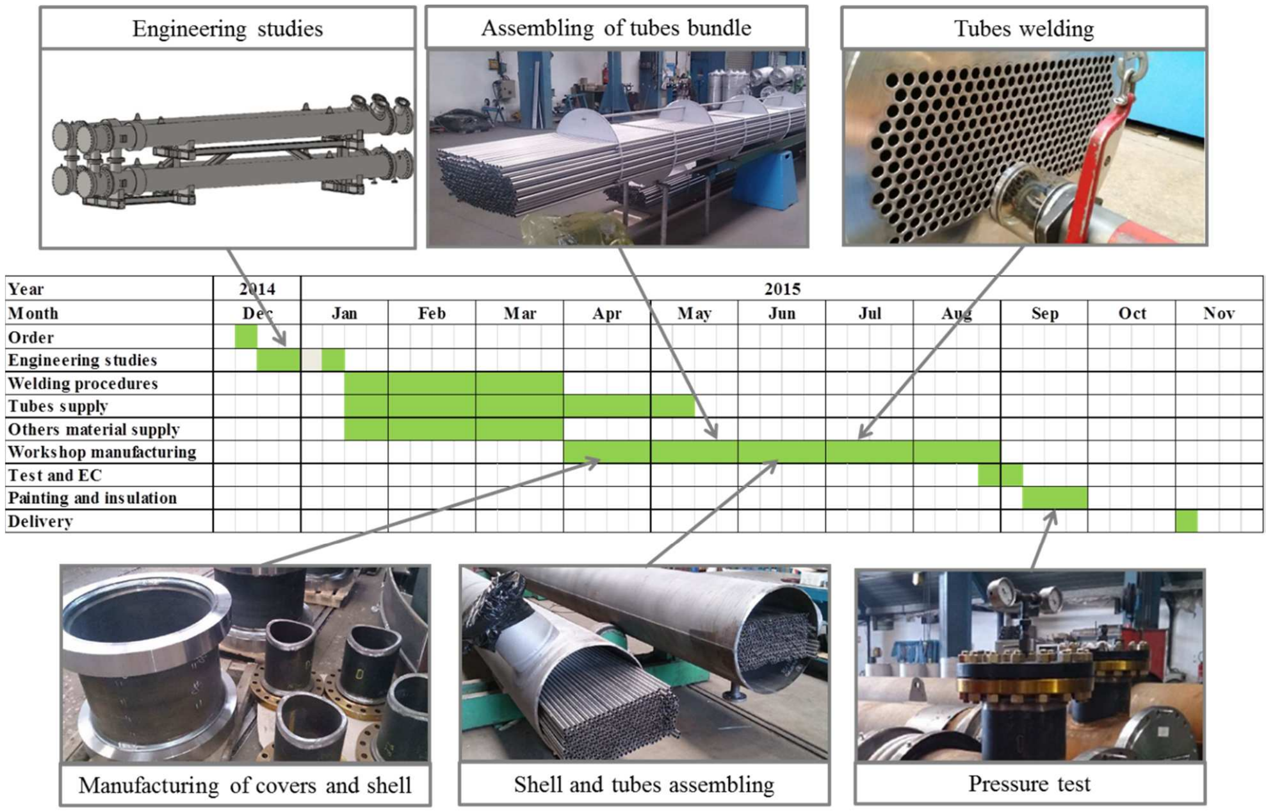
4. MANUFACTURING AND CONTROL

4.1. Manufacturing planning and cost

From the order in December 2014, manufacturing of the 12 heat exchangers lasted about 10 months. Manufacturing started with three weeks of engineering studies and design. After validation of the design, materials supply could be launched. This step was quite long, especially for the tubes, which delivery time was about 4 months. Delivery time of other parts, such flanges, plates or shell tubes was shorter, about 10 weeks. Workshop manufacturing first started with the removal covers and shell. As soon as tubes were delivered, assembling of the tubes bundle could start and follow up with shell assembling and tubes welding. Workshop manufacturing lasted about six month and was performed with hydraulic pressure test. Heats exchangers were delivered at the Rittershoffen geothermal plant few weeks after painting and insulating operation. Table 3 presents an illustrating planning of the manufacturing.

Cost of each heat exchanger was about 127 k€. Most expensive positions were manufacturing (welding, machining, assembling…) and tubes and sheetplates acquirement, representing respectively about 37.0 % and 30.0 % of the total cost. Other material acquirement (shell, flanges, bolts…) were representing about 20.0 % of the total cost, engineering 6.0 %, painting and insulation 5.5 %, control and EC certification 1.5 %.

Table 3: Illustrated planning of the heat exchangers manufacturing



4.2. Chemical and metallurgical control

As previously explained, corrosion and material quality was a big concern for the Rittershoffen geothermal plant. Material suppliers were asked to present accordingly to a quality management a detail chemical composition of the ladle material and of some random samples of tubes and plates. These chemical compositions were compared to the EN 10216-5:2013 for seamless stainless steel tubes and EN 10028-7:2007 for stainless steel flat product for pressure purposes, in order to assess quality of the 1.4410 material used in contact of the brine. **Table** 4 is presenting the norm and ladle chemical material of the tubes and tubesheets.

Table 4: Comparison between norm and ladle chemical composition of tubes and tubesheets

	C %	Mn %	Cr %	Ni %	Mo %	N %
EN 10216-5	≤0.030	≤1.2	24.0-26.0	6.0-8.0	3.0-5.0	0.24-0.32
Tubes	0.013	0.43	25.32	6.43	3.87	0.292
Tubes	0.013	0.42	25.35	6.44	3.85	0.291
EN 10028-7	≤0.030	≤2.00	24.0-26.0	6.0-8.0	3.0-4.5	0.20-0.35
Tubesheet	0.023	0.77	25.6	6.6	3.8	0.29

Table 4 shows that ladle chemical composition of tubes and tubesheet are in agreement with EN 10216-5 and EN 10028-7. A mechanical properties and a micrographic examination were also asked to the material supplier, especially to check the ferritic and austenitic structure of the Super Duplex. Figure 6 is presenting a view of a micrographic examination of the tubesheet, confirming the conformity of the metallurgical structure.

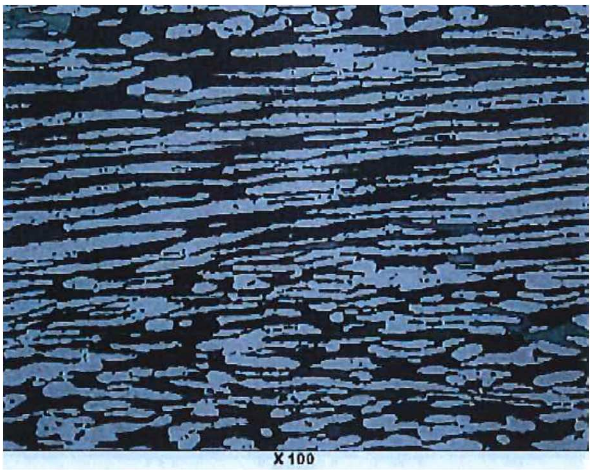


Figure 6: Micrographic examination of the tubesheet

Tubes surface and thickness were characterize by Eddy-current testing (ECT). This nondestructive testing method, using electromagnetic induction on conducting materials, can identify cracks and pits corrosion, material thickness, coating and scaling thickness. About 10% of the tubes of the heat exchangers were inspected with ECT. First purpose of ECT was checking tube thickness to be sure that thickness tolerance was respected by supplier. Moreover this ECT gives an initial status of the tubes for the corrosion and scaling monitoring. Figure 7 is presenting tubes inspected on 6 of the 12 heat exchangers before operating. Green color indicates that no default regarding thickness, crack, pitting or scaling was detected. During operation, these tubes will be further inspected for corrosion and scaling monitoring.

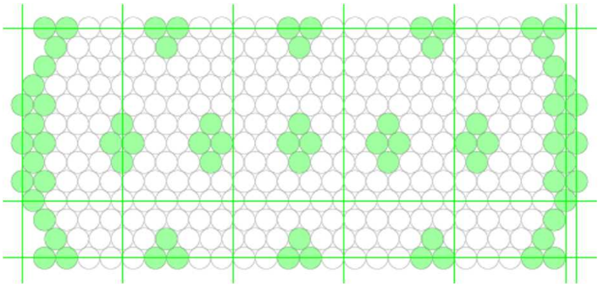


Figure 7: Tubes inspected by ECT before operation on 6 of the heat exchangers

4.3. Manufacturing control

Compliance of the heat exchangers with pressure equipment Directive 97/23/CE was evaluated with module B+F. Module B describes the part of the procedure by which a notified body ascertains and attests that a representative example of the production in question meets the provisions of the Directive that apply to it. Module F describes the procedure whereby a manufacturer ensures and declares that the pressure equipment is in conformity with the type examination certificate. Combination of modules B + F is usually suitable for manufacturers who only produce smaller quantities of equipment.

Manufacturing of heats exchangers was completed according to Welding Procedure Specifications (WPS). These WPS, developed for each alloy and for each welding type used, were supported by a welding Procedure Qualification Record (PQR) validated by an examining body. PQR is a record of a test weld performed to assess the essential safety requirement stated by the European pressure equipment Directive 97/23/EC and ensure that procedures give perfect weld.

Then, individual welders, involved in the manufacturing of these heat exchangers were certified by an examining body with a qualification test documented in a Welder Qualification Test Record (WQTR). WQTR is proving that involved welders on manufacturing demonstrated ability to work within the specified WPS.

Figure 8 is presenting a macrographic examination of the tubes welding on tubesheet performed for the PQR. Thus macropraphic examination is showing a very good melting of the weld on the sides and no lack of fusion.

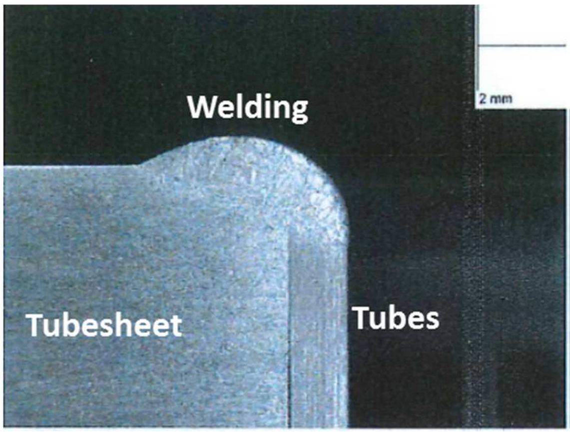


Figure 8: Macrographic examination of the tubes welding on tubesheet performed for the PQR

6. CONCLUSION AND PERSPECTIVES

Choice of the Rittershoffen geothermal plant’s heat exchangers posed a technical challenge for this project. Most important parameters of the design were resistance to temperature and pressure conditions, small pinch between the primary and secondary loops, maintenance aspect, specially cleaning operation and long lifetime. Selected design was finally single pass shell and tubes heat exchangers with removal covers, called AEL according to the Tubular Exchanger Manufacturers Association. Moreover, in order to resist to the aggressive brine condition, tubes and tubesheet were built with super duplex 1.4410 material. This alloy is adapted to chlorine environment and is available on tubes and plates.

Manufacturing of the heat exchangers lasted ten month and was led by many controls such chemical, macrographical, eddy current testing, welding procedure records and compliance with pressure equipment Directive 97/23/CE. As of the date of this extended abstract, what is missing is the control of the hydraulic and thermic performances of the heat exchangers. This control requires the commissioning of the project, which is plan at the end of May 2016. During this commissioning, flowrate, temperature and pressure will be measured at the inlet and outlet of each skid heat exchangers at primary and secondary loop. These measurements will be compared to the HTRI model in order to assess if the manufacturer has respected its performance commitments.

REFERENCES

Baujard C., Genter A., Graff J.J., Maurer V., Dalmais E., ECOGI a new deep EGS project in Alsace, Rhine graben, France. *Proceedings World Geothermal Congress 2015*, Melbourne, Australia, 19-25 April 2015, (2015).

Mundhenk, N., Huttenloch, P., Bäßler R., Kohl, T., Steger, H., Zorn, R.: Electrochemical study of the corrosion of different alloys exposed to deaerated 80 °C geothermal brines containing CO2, Corrosion Science, 84, 2014: 180 – 188.

Sanjuan, B., Millot, R., Dezayes, Ch. and Brach, M. : Main characteristics of the deep geothermal brine (5 km) at Soultz-sous-Forêts determined using geochemical and tracer test data, Comptes Rendus Geoscience, 342, (2010), 546-559.

Scheiber, J., Ravier, G., Sontot, O., Hensch, C., Genter, A., In situ material studies at the high temperature skid (HTS) bypass system of the geothermal power plant in Soultz-sous-Forêts, France, *Proceedings Thirty-Eighth Workshop on Geothermal Reservoir Engineering 2013*, Stanford University, Stanford, California, (2013), SGP-TR-198.

Scheiber J, Seibt, A., Birner, J., Genter, A., Cuenot, N., & Moeckes, Scale Inhibition at the Soultz-sous-Forêts (France) EGS site: Laboratory and On-Site Studies, *Proceedings World Geothermal Congress 2015*, Melbourne, Australia, (2015)

TEMA, Ninth Edition of the Standards of the Tubular Exchanger Manufacturers Association, 2007

EN 10216-5:2013, Seamless steel tubes for pressure purposes. Technical delivery conditions. Stainless steel tubes

EN 10028-7:2007, Flat products made of steels for pressure purposes. Stainless steels

ISO 3834-2: Quality requirements for fusion welding of metallic materials -- Part 2: Comprehensive quality requirements

European pressure equipment Directive 97/E3/EC

Acknowledgements

The authors are grateful to ECOGI for using data from the Rittershoffen geothermal site. The authors are grateful to Ademe support.