The H2020 project REFLECT - Redefining fluid properties at extreme conditions to optimise future geothermal energy extraction

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The efficiency and feasibility of geothermal utilisation depends strongly on the characteristics and behaviour of the fluids that transfer heat between the geosphere and the engineered components of a power plant. Chemical and physical processes such as precipitation, corrosion, or degassing are induced by pressure and temperature changes, with potentially serious consequences for power plant operation and project economics. The EU Horizon 2020-funded project REFLECT aims to avoid such problems by collecting high-quality chemical, physical, and microbiological data at extreme salinities, pressures or temperatures and improving the understanding of kinetic processes through laboratory experiments. These data are presented in a European geothermal fluid atlas and implemented in predictive models in order to provide recommendations on how to best operate geothermal systems for a sustainable future.

L'efficacité et la faisabilité de l'utilisation de la géothermie dépendent fortement des caractéristiques et du comportement des fluides qui transfèrent la chaleur entre la géosphère et les composants techniques d'une centrale électrique. Les processus chimiques et physiques tels que les précipitations, la corrosion ou le dégazage sont induits par les changements de pression et de température, avec des conséquences potentiellement graves pour le fonctionnement de la centrale électrique et l'économie du projet. Le projet REFLECT, financé par l'UE Horizon 2020, vise à éviter de tels problèmes en collectant des données chimiques, physiques et microbiologiques de haute qualité à des salinités, pressions ou températures extrêmes et en améliorant la compréhension des processus cinétiques grâce à des expériences en laboratoire. Ces données sont présentées dans un atlas européen des fluides géothermiques et mises en œuvre dans des modèles prédictifs afin de fournir des recommandations sur la meilleure façon d'exploiter les systèmes géothermiques pour un avenir durable.

La eficiencia y viabilidad de la utilización geotérmica dependen en gran medida de las características y el comportamiento de los fluidos que transfieren calor entre la geosfera y los componentes de ingeniería de una planta de energía. Los cambios de presión y temperatura inducen procesos químicos y físicos como la precipitación, la corrosión o la desgasificación, con consecuencias potencialmente graves para el funcionamiento de la planta de energía y la economía del proyecto. El proyecto REFLECT, financiado por la UE Horizonte 2020, tiene como objetivo evitar tales problemas mediante la recopilación de datos químicos, físicos y microbiológicos de alta calidad a salinidades, presiones o temperaturas extremas y mejorando la comprensión de los procesos cinéticos a través de experimentos de laboratorio. Estos datos se presentan en un atlas de fluidos geotérmicos europeo y se implementan en modelos predictivos para brindar recomendaciones sobre cómo operar mejor los sistemas geotérmicos para un futuro sostenible.

1. Introduction

The one problem plaguing almost all deep geothermal operations in the world is the in-situ chemistry of the geothermal fluids. In order to maximise the technical feasibility, operational efficiency and economic returns of geothermal power plants, it is vital that these systems work well for long periods without requiring significant maintenance. Key to this is preventing deleterious physical and chemical reactions such as degassing and mineral precipitation (see ***Figure 1***). Currently, accurate prediction of those reactions is difficult, due to poorly defined fluid properties, largely as a consequence of the difficulty in determining these properties at in-situ geothermal conditions (i.e., extremely hot or extremely saline fluids). The European project REFLECT - Redefining fluid properties at extreme conditions to optimise future geothermal energy extraction, funded by the European Commission in the research and innovation programme Horizon 2020, addresses these challenges and extends the presently limited experimental data on the thermodynamic and thermophysical properties of high temperature brines for various salt contents. Using the knowledge on fluid properties generated in REFLECT, the range of application for geothermal energy conversion can be significantly expanded to

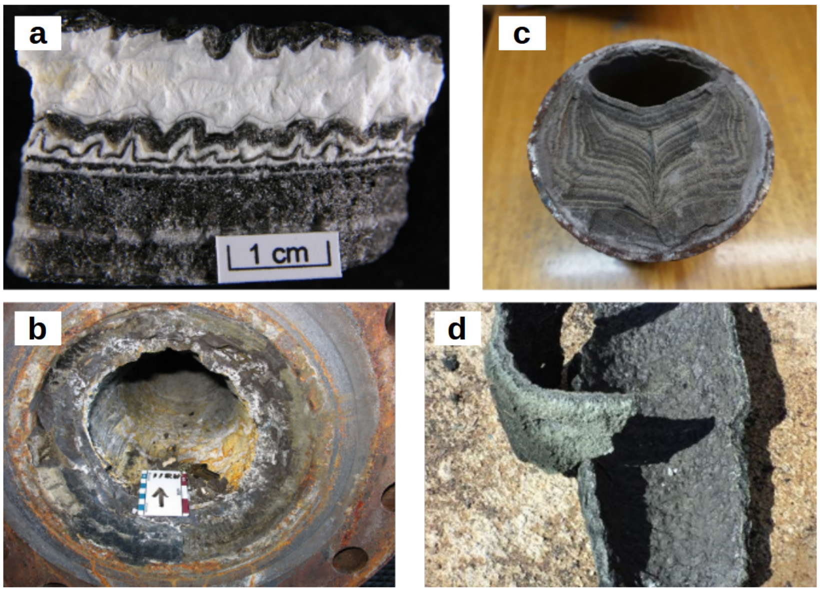

Figure 1: Examples of scaling, one of the most common problems in geothermal operations. (a) silica scale, Reykjanes, Iceland; (b) sulfide scale, Iceland (both © V. Hardardottir); (c) calcite scale, Hungary (© Z. Istfan); (d) Fe, Mg scale, Tuzla, Turkey (© A. Baba).

hotter and more saline conditions.

In the project, 14 partners from geothermal research, industry, and geoscience associations work together to redefine fluid properties for future geothermal energy extraction. They combine expertise from geochemistry, material science, geothermal, geology, microbiology and engineering in order to narrow the knowledge gap in this field, leading to more reliable predictions of geothermal performance.

By addressing the main problems of geothermal operations (scaling, degassing, and corrosion), REFLECT results will offer solutions to avoid those problems. These solutions decrease operation and maintenance costs, minimise downtimes, and increase the overall reliability and efficiency of operations. REFLECT will, therefore, have a significant influence on the development of geothermal systems and on the overall electricity and heat supply generated from renewable energy sources. The project's main impact will thus be improved EU energy security: by encouraging an increase of the share of geothermal energy within the European energy market, REFLECT can help to reduce the consumption of fossil fuels, reduce dependence on non-EU suppliers and approach the aims of the Paris agreement.

The key objectives of the REFLECT project can be summarised as to:

1. Extend databases (solubility, activity, reaction kinetics) to higher temperatures and higher salinities through lab experiments and modelling approaches;
2. Determine the extent and location of the degasification front of geothermal fluids during production (field, lab, and modelling approaches);
3. Determine types of organic matter and microorganisms in various geothermal fluids and their effect on scaling and biofilm formation via laboratory studies;
4. Determine heat capacity, density, electrical and thermal conductivity, sonic velocity, and viscosity at various pressures, temperatures and salinities (p, T, X) through lab experiments and modelling approaches;
5. Develop a down-hole sampling technique suitable for collecting fluid at a chosen depth in hot and super-hot systems;
6. Verify and implement the improved dataset by application in reactive transport modelling;
7. Set up a Geothermal Fluid Atlas that collates information on geothermal fluid properties across Europe together with their geological setting.

In the following, we will briefly describe how each of the objectives is addressed in the project and which methods are applied.

2. Objectives and Methods

2.1. Extend databases (solubility, activity, reaction kinetics) to higher temperatures and higher salinities

Relevant fluid properties have been measured on samples from 13 geothermal sites across Europe (***Figure 2***). The sampling campaign has been severely impacted by border closures and lack

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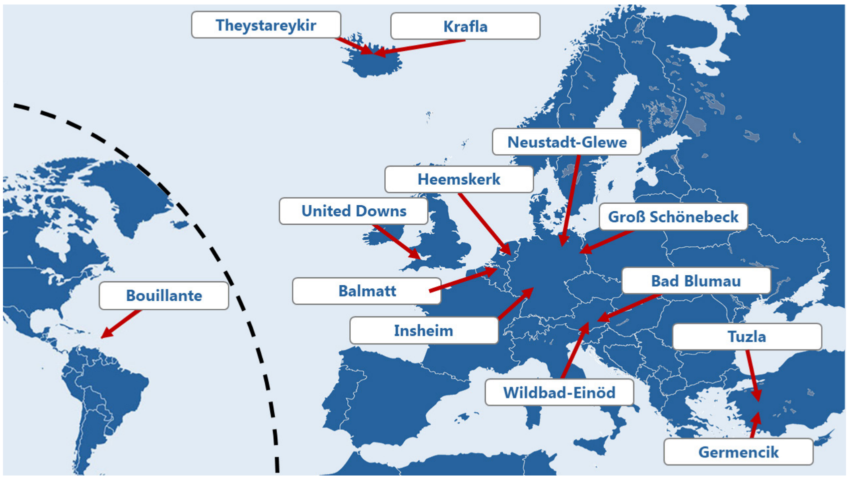

Figure 2: Geothermal sites from which samples were obtained for the analysis of organic and inorganic chemistry, and partly for microbiological analysis.

of access to geothermal sites due to the Covid-19 pandemic. Nonetheless, fluid samples were acquired from Insheim (DE), Bad Blumau (AT), Heemskerk (NL), Neustadt-Glewe (DE), Groß Schönebeck (DE), Wildbad-Einöd (AT), United Downs (UK) and additionally from high enthalpy sites Bouillante (FR), Krafla (IS), Theistareykir (IS), Tuzla (TR), and Germencik (TR). Additional fluid samples were obtained from Balmatt (BE) through SKC-CEN (member of the project's advisory board). Sampling protocols were shared among the participants to avoid contamination and ensure equal treatment of samples before transport and subsequent analysis in the labs. Partners of the consortium characterised the sample properties by measuring the main and minor cations and anions (HI, ÍSOR), bacteria and spores (UNINE), organic components (GFZ), dissolved gases (HI), silica (BGS/UKRI, IZTECH, LVK), NORM (GFZ), and selected isotopes (HI). Sample collection was usually above ground at the wellhead, where the average fluid was sampled. At some sites, several samples were taken in different locations in the circulation system (at the production well, shortly before or after the heat exchanger, and before injection) in order to analyse changes in chemistry and microbiology due to the changing conditions (i.e. reduced temperature and pressure).

The consortium of REFLECT operates and has expertise in instruments and equipment that resist the corrosive nature of brines and that allow the characterisation of a range of fluid properties. This also enables the collection of thermodynamic and kinetic data by enabling novel experiments at up to 400 °C and 400 bar. Solubility and speciation of silica and Si-metal species in 'superhot' fluid systems have been detected *in situ* via spectrometry, and *ex situ* via more traditional fluid sampling techniques. For example, Kummerow et al. [1] use electrical conductivity measurements to monitor the progress of calcite dissolution or precipitation from H_2O-NaCl-CO_2 solutions and to define equilibrium conditions.

2.2. Determine the extent and location of the degasification front of geothermal fluids during production

Decreasing pressures towards the production well can lead to the exsolution of gas from geothermal waters in the near-well region. This can cause problems like corrosion of the facilities or reduced water production. The degassing of CO_2 and N_2 saturated water has been studied using a visual cell and a high-speed camera at elevated pressures (up to 200 bar) and temperatures (up to 150 °C).

Colleagues from TU Delft also used a PEEK (polyether ether ketone) core holder in CT-assisted coreflood experiments, i.e. gas-brine flow experiments in rock cores (***Figure 3***). The experimental setup is designed for visualising the emergence of free gas bubbles during CO_2-brine coreflood experiments and determining to what extent the flow is affected by these bubbles. A model for CO_2 solubility in brine was created to assess whether the start of degassing (i.e. the bubble point) can be predicted accurately by comparing its results to that of the experiments.

2.3 Determine types of organic matter and microorganisms in geothermal fluids and their effect on scaling and biofilm formation

Microorganisms are present in most ecosystems on Earth, and despite the extreme environmental conditions in geothermal fluids, these systems are also home to microbial life. Inside power plant systems, microorganisms can be involved in microbially induced corrosion (MIC), form biofilms or induce mineral precipitation. One striking example of the impact of microorganisms on power plants is the induced precipitation of silica by bacteria, which strongly decreases the efficacy of a

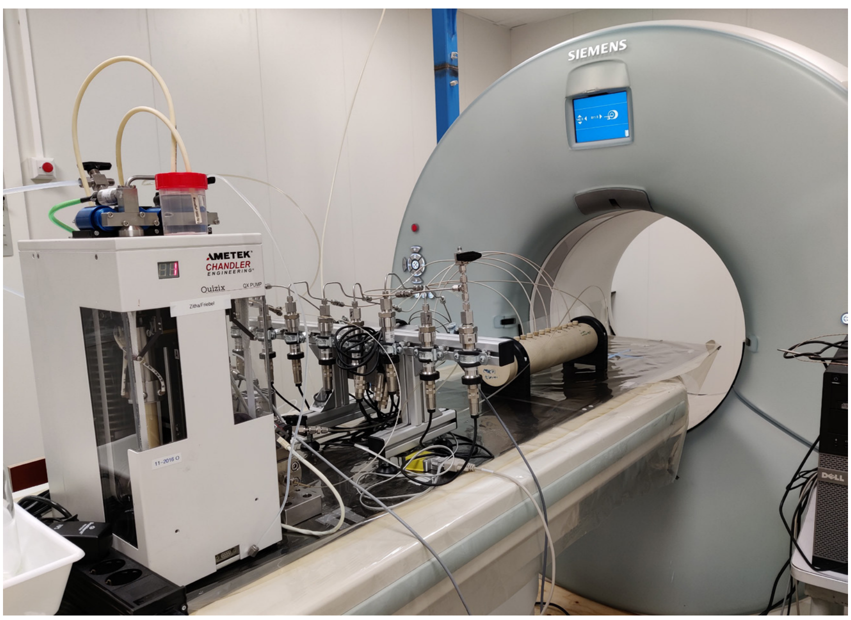

Figure 3: The core flooding setup using the PEEK core holder in the CT scanner. The setup at TU Delft is used to assess the extent to which free gas is limiting water flow inside rocks.

power plant [2].

However, other than in specific cases [2,3,4], knowledge of the diversity and prevalence of microbial life in deep geothermal reservoirs is still scarce. In order to fill in this knowledge gap, microbial life at extreme conditions has been studied by researchers of the University of Neuchatel by sampling 8 geothermal sites with a temperature range of 47–345 °C. During sampling large volumes of water (~40 l per sample) were filtered in order to concentrate the biomass in the filter product. From the concentrated biomass, DNA was isolated and used for sequencing, and microbes have been cultivated under laboratory conditions. This approach enables assessment of the diversity of microbial species present in different geothermal settings.

The origin, composition, and fate of dissolved organic matter (DOM) within deep geothermal reservoirs is relatively unknown. Natural DOM as well as artificial DOM (e.g. from chemical scaling inhibitors), might serve as nutrients for microorganisms or affect chemical properties of the fluids by complexation. The organic compounds in natural geothermal fluids were investigated by GFZ at 10 sampling sites. The thermal stability of organic components has been monitored by Fourier Transform IR spectroscopy (instrument with integrated high p-, T cell) and liquid chromatography organic carbon detection (LC-OCD).

TNO investigated the effect of organic complexes and colloids on flow properties and precipitation. The effect of several common carboxylic acids on the formation of homogeneous calcium carbonate scale was investigated and a novel method (dynamic light scattering) has been developed.

2.4 Determine heat capacity, density, electrical and thermal conductivity, sonic velocity, and viscosity at various pressures, temperatures and salinities

Thermophysical data (density, viscosity, thermal- and electrical conductivity, heat capacity, sonic velocity) are required for reliable geothermal site assessment and development (e.g. for exploration, reservoir engineering, well and pump design and power plant layout). While the database for binary solutions with water and one salt (usually NaCl) is good, information for more complex and high salinity fluids (e.g. ternary solutions) is scarce.

GFZ researchers performed laboratory scale measurements of fluid density and heat capacity on synthetic NaCl and $CaCl_2$ aqueous mixtures. Different cation ratios were explored for total molalities up to 6 $mol{\cdot}kg^{-1}$. Pressure and temperature ranged between 0.1 and 40 MPa, and 20 and 80 °C, respectively. An Anton Paar DMA4500M was used for density measurements at ambient pressure, whereas the DMA HP external density measuring cell measured density up to 700 bar and 200 °C. Approximately 700 new experimental measurement and data points were generated [5].

In a second experimental approach, electrical conductivities of carbonate solutions at different concentrations were measured at up to 450 °C to determine limiting conductivities and association constants [1]. In the first set of experiments the electrical conductivity of multi-component brines, representing the composition of natural geothermal fluids and consisting of variable mole fractions of NaCl, $CaCl_2$, KCl, $NaHCO_3$, Na_2SO_4, K_2SO_4 was measured in a high-temperature flow-through cell up to 450 °C. In the second set of experiments, binary carbonate solutions at various concentrations were measured in the flow-through cell to determine the limiting electrical conductivity up to 450 °C and to extract information on the molar association constants for the ions in solution.

Finally, Lassin and André [6] developed a new thermodynamic model for the H-Li-Na-K-Ca-Mg-Cl-H_2O chemical system, from dilute solutions up to salt solubility, and for temperatures up to 250 °C. This model relies on the Helgeson-Kirkham-Flowers (HKF) and the Pitzer equations, and considers the partial dissociation of the $CaCl_2$ electrolyte. It has been implemented in the PhreeSCALE geochemical calculation software [7] to compute properties such as heat capacity, enthalpy, and density of chloride-bearing multi-electrolyte solutions in conditions relevant for the production of geothermal energy.

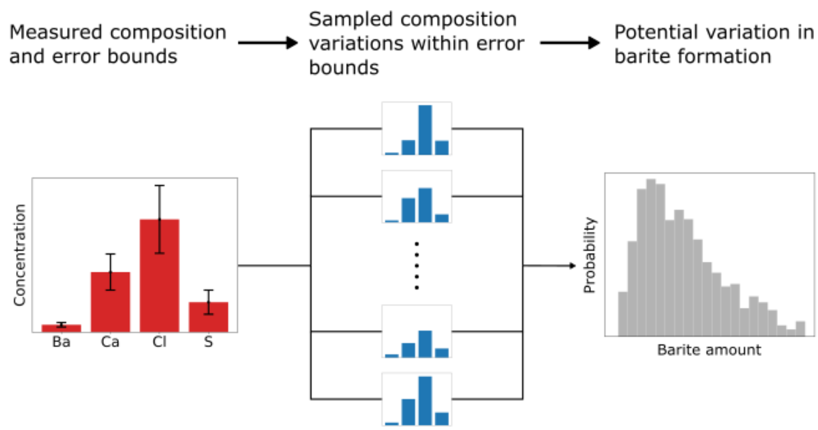

Figure 4: Graphical depiction of the uncertainty quantification approach (from [11]).

2.5 Develop a down-hole sampling technique suitable for collecting fluid at a chosen depth in hot and super-hot systems

Sample collection usually occurs at the wellhead, where the average fluid is sampled (i.e. a mixture of fluids from any inflows feeding the productive section(s) of the well). However, when multiple feed zones of deep wells blend, the local fluid conditions can cause corrosion and/or scaling in the perforated liner and production casing. Consequently, the lack of knowledge about fluid properties of distinct aquifers leads to long-term and high-cost geothermal utilisation problems. Downhole sampling of the fluid at depth provides information on the fluid composition that enables optimal design of downhole and surface installations to prevent operational problems.

In course of the project, a downhole sampler was designed that is capable of collecting fluids at higher temperatures and pressures than the existing ones (together with an appropriate extraction line). High-temperature sampling scenarios in liquid phase, two-phase, saturated steam and superheated/supercritical conditions were defined. The fluid sampler developed [8] will be able to sample high-temperature geothermal wells of 200–300 °C, but the more ambitious aim is to adapt the design for even higher temperatures (up to 400 °C) and supercritical pressures.

A first proof-of-principle sampling test will be performed by the REFLECT team at a low-temperature well in early 2023.

2.6 Verification and implementation of the improved dataset by application in reactive transport modelling

Two modelling tools were further developed to predict scaling behaviour and flow properties of geothermal fluids during energy generation.

First, the numerical code porousMedia4Foam was developed in order to predict scaling risks on the geothermal fluid's path towards the surface, when its chemical equilibrium is disturbed. It is an open-source, multi-scale and multiphase package, where OpenFOAM® is coupled with the PHREEQC code (a geochemical model which is used to simulate the precipitation amount and kinetics of different geothermal minerals, see [9]) to investigate hydro-geochemical interactions. The flow, transport of chemical species, evolution of porous media properties, and temperature are handled by solving equations implemented in OpenFOAM®, whereas the chemistry is exclusively handled by PHREEQC.

Second, a workflow was developed to enable a better estimation of the location and amount of precipitated minerals in different locations of a geothermal system, focusing on processes in the surface installations [10]. A multiphase flow solver was coupled to thermodynamics libraries and PHREEQC. A detailed roughness model was developed to simulate the impact of mineral deposition on the fluid flow. In addition, an uncertainty quantification workflow was combined with the modelling framework to estimate the uncertainty bounds of the scaling and precipitation resulting from uncertainties in the fluid composition characterisation and operational settings (***Figure 4***).

2.7 Set up a Geothermal Fluid Atlas that collates information on geothermal fluid properties across Europe

The last objective of REFLECT was to set up the European Geothermal Fluid Atlas (EFA, ***https://reflect.uni-miskolc.hu/efa***) to provide a comprehensive data collection of properties of geothermal fluids used for electricity production (T>100 °C) along with information of the well, reservoir, and host rock. The first step was to create an exhaustive template for data collection. Existing fluid data from all over Europe was collated in cooperation with 20 EU countries (national geological associations that are members of the European Federation of Geologists) to generate a consistent and accessible database [12]. Together with properties of natural fluids analysed in REFLECT [13] these data form the basis for the European atlas on fluid properties, which is set up by the University of Miskolc. Furthermore, an approach will be developed to transfer the available fluid data into risk estimations for different operational issues by incorporating the data in numerical modelling.

3. Results and Discussion

Due to the complex nature of the project and the multitude of results, only a selection of results is described here. The reader is kindly asked to refer to project deliverables and further publications to find details on the results obtained. As for the methodology, the following section is structured in subsections that are aligned with the seven key project objectives.

3.1. Extend databases (solubility, activity, reaction kinetics) to higher temperatures and higher salinities

Data of the samples collected from 13 geothermal sites were published in two Deliverables: Iannotta and Hehn [14] for the eight high-saline geothermal sites and Baba et al. [15] for the five high-temperature sites. Analysis of major and minor cations and anions was limited to the elements that are usually abundant in geothermal systems. In the future, however, it would be desirable to extend the analysis to elements that are considered critical raw materials. Detailed analysis of the geochemistry of fluids, rock samples, and precipitates was performed at the two Turkish sites, Germencik [16] and Tuzla [17]. Knowledge from this analysis was also included in the investigation on Antimony (Sb)-rich geothermal deposits and their solubility in presence of different antiscalants with various functional groups. Karaburun et al. [18] found that macromolecules containing sulfonic acid groups and poly (vinyl sulfonic acid) derivatives could potentially act as antiscalants for the formation of antimony sulphide.

Solubility experiments for calcite solutions [1] showed that the solubility of calcite in all tested solvents decreases exponentially with increasing temperature at constant pressure, while the solubility increases with increasing pCO_2 at isothermal conditions.

Further studies on the kinetics, solubility, and Pitzer activities of silica and metal-silica precipitates are ongoing. Results from these experiments will be published in deliverable D1.4 and D2.3. Still, these studies are just a first step towards a better understanding of precipitation. In the future, it would be desirable to repeat the experiments with more complex fluids (i.e. containing multiple anions/cations) that mimic the chemistry of natural fluids.

3.2 Determine the extent and location of the degasification front of geothermal fluids during production

High speed imaging of degassing kinetics of CO_2-water mixtures revealed that when CO_2 is in a gaseous state, the formation of the first free gas bubbles is in reasonable agreement with the van 't Hoff equation, which dictates the solubility of gases at elevated temperatures. However, this is not the case for experiments at higher initial pressure (>73.8 bar), which start out with CO_2 in a supercritical state. Here the bubble point pressure is consistently lower than the expected bubble point based on the Van 't Hoff equation. Further information can be found in separate articles on these experiments [19,20,21].

The coreflood experiments showed that the formation of free gas can reduce the water relative permeability by up to 50% in a high permeability Bentheimer sandstone and up to 90% in a low permeability Berea sandstone (an Upper Devonian sandstone

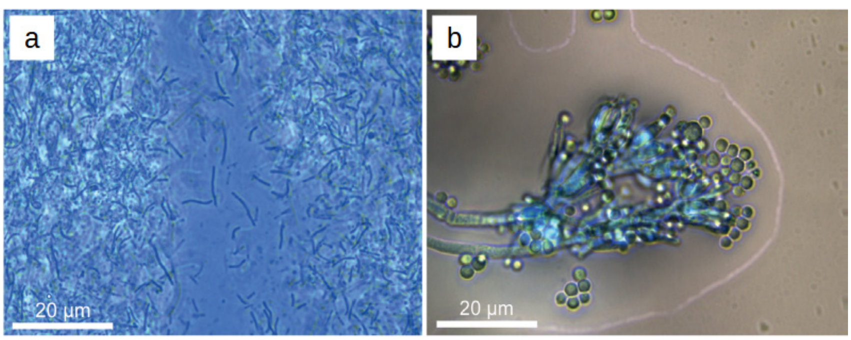

Figure 5: Microscopical (optical microscopy) images of two microbial strains isolated from geothermal power plants. (a) Bacteria (b) Fungus.

formation from north-east USA) [21]. The bubble point does not vary between the two different rocks. The CT-assisted corefloods show increasing gas saturation inside the core as the pressure is reduced. Gravity override due to a difference in density between the gas and liquid phase was also observed in these experiments.

3.3 Determine types of organic matter and microorganisms in geothermal fluids and their effect on scaling and biofilm formation

The review of Leins et al. [22] and the connected data publication [23] reviewed data on organic compounds in geothermal fluids of 143 fluid samples from 22 geothermal sites. The study observed lower dissolved organic carbon (DOC) concentrations in the lower temperature ranges (30–80 °C), which might be explained by microbial degradation of DOM in this temperature range. Thermal degradation of DOM accounts for the decreasing DOC concentrations in the temperature range of 80–200 °C. Higher salinity of the fluids might limit microbial activity, leading to higher possible DOM content in more saline brines. Hydraulic connections to organic-rich sediments or oil-bearing strata within the reservoir can be detected by investigating the DOM content and composition of the geothermal fluids.

The review of Bregnard et al. [24] investigated the information on microbiological diversity in geothermal fluids. The researchers also studied the microbiological diversity at six of the sampling sites investigated in REFLECT. In the analysis they found different bacterial signatures for each power stations. They were able to isolate specific bacteria, but also fungi, from geothermal systems (see ***Figure 5***). The temperature does not seem to be the dominating factor when it comes to diversity in general, since many microbes can form dormant, resistant spores that can survive unfavourable conditions and be reactivated as soon as the conditions are favourable again (e.g. when temperatures drop in the heat exchanger).

The effect of several common carboxylic acids on the formation of homogeneous calcium carbonate scale was investigated using dynamic light scattering [25], which has proven to be a new method to study important aspects of homogeneous nucleation like induction time and relative amounts of precipitate formed [26]. All carboxylic acids tested in this research had an inhibiting effect on the precipitation of calcium carbonate. Both the induction time and amount of precipitation were influenced by the carboxylic acids: an increase in concentration of acid groups results in an increase in induction time and a reduction in the total amount of scaling/precipitation.

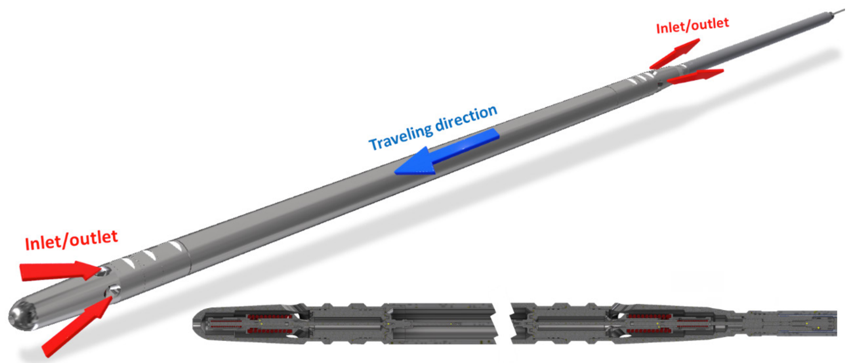

Figure 6: REFLECT downhole sampler developed to sample various phases (liquid, two-phase, steam) at low to high temperature/high pressure superheated/supercritical conditions in geothermal wells.

3.4 Determine heat capacity, density, electrical and thermal conductivity, sonic velocity and viscosity at various pressures, temperatures and salinities

The 700 measured data points for fluid density and heat capacity of synthetic NaCl and $CaCl_2$ aqueous mixtures [5] were provided to the partners at BRGM for modelling. In a blind test, the model of [6] for the NaCl-$CaCl_2$-H_2O system was used to calculate density and heat capacities of the solutions experimentally investigated. The model produced a very good match for density and heat capacity in NaCl solutions, with errors lower than 2% (except when chloride concentration exceeds 9 mol·kg^{-1}). For calcium chloride system, a good match is observed up to 3 mol·kg^{-1}. The model will hence be able to produce valuable predictions for various salt concentrations.

Experimentally, limiting conductivities of the binary aqueous $NaHCO_3$ system were determined in the temperature range 24–450 °C from measured equivalence conductivities of solutions of four different concentrations (0.1 M, 0.05 M, 0.01 M, 0.001 M). The results for sodium-bicarbonate show that up to 200 °C limiting conductivities increase linearly with temperature, but decrease again for higher temperatures. The new data allow the calculation of electrical conductivities of aqueous $NaHCO_3$ solutions at any concentration. This may also allow us to develop numerical models that better describe the electrical conductivity of complex salt solutions for given temperature and pressure parameters than the established equations derived from measurements on binary solutions.

3.5 Develop a down-hole sampling technique suitable for collecting fluid at a chosen depth in hot and super-hot systems

For the downhole sampler developed by ÍSOR, a flow-through design (***Figure 6***) has been selected as the most reliable principle. A special emphasis was put on the selection of corrosion resistant and leak-tight materials and parts suitable for construction of the downhole sampler. Since the sealing of the sampler will be one of the most crucial mechanisms, different materials for seals have been chosen, which can be adapted to the temperature/pressure conditions aimed for during sampling (e.g. metal-to-metal seals for superheated, high-pressure wells, and high-temperature polymer seals for wells up to 300 °C). Samples will be collected at depth with sampling volume up to 1000 ml. The sampler's delayed clocking mechanism will close the sampler at sampling depth. The sample is then taken to the surface, allowing for isochoric temperature and pressure decline.

Another challenge that was addressed by project partner Hydroisotop is the transfer of gas-rich liquids or steam-water mixtures from the downhole sampling tool to adequate sampling containers that can be safely transported to a laboratory for further analysis. In order to transfer samples from the downhole sampling tool to sample cells without contamination, a structure is required that allows for vertical positioning of the sampling tool and all sample cells. Cooling of the sampling tool upon retrieval from the well results in pressure loss and can lead to degassing. To avoid or reverse degassing, the upper part of the sampling tool needs to be pressurised.

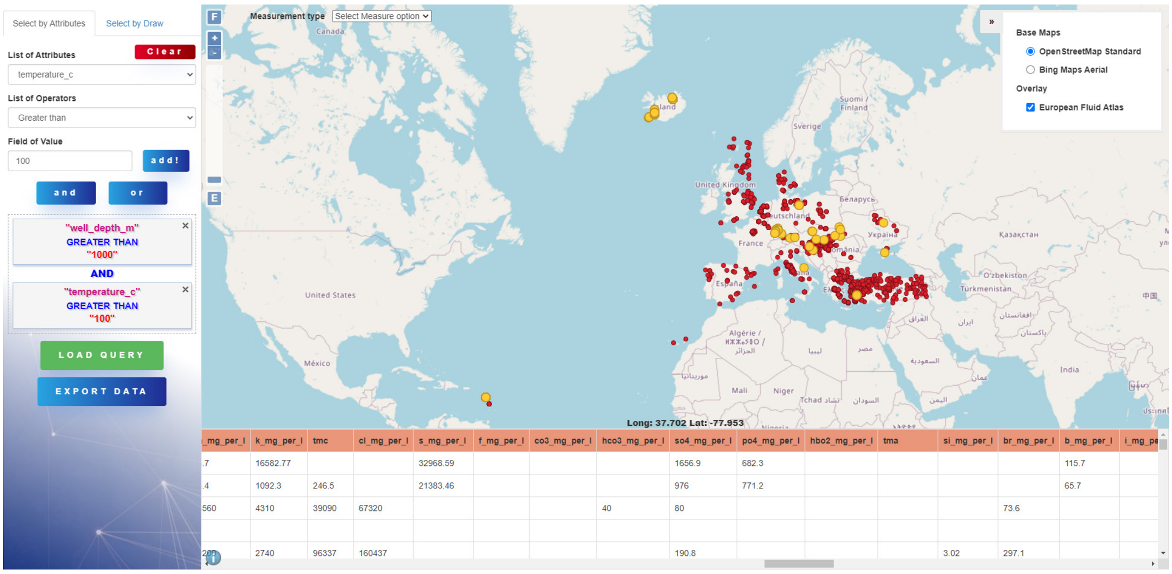

Figure 7: Screenshot of the European Geothermal Fluid Atlas with location of the 2,400 wells where already existing well, fluid, rock and reservoir data were collected. The example shows the query for wells with depth > 1,000 m and temperature > 100°C, resulting in the locations on the map marked with yellow dots.

First results from an initial test of the downhole sampler and the extractions system at a low-temperature well are expected towards the end of the REFLECT project.

3.6 Verification and implementation of the improved dataset by application in reactive transport modelling

Soulaine et al. [27] described the developed coupled hydro-thermal-chemical software porousMedia4Foam and made the source code as well as some tutorials available on GitHub: ***https://github.com/csoulain/porousMedia4Foam*** [28]. A User's Guide to the software is available as REFLECT Deliverable 4.1 [29]. The software porousMedia4Foam has been extensively validated for single phase flows at different scales, i.e. at the pore-scale and continuum-scale, for which reference solutions exist. For example, Soulaine et al. [27] demonstrated the ability to simulate dissolution and precipitation processes in fractured porous media at the pore-scale using the hybrid-scale approach. In their study, the reactive medium consisted of celestite grains that reacted with a barium chloride solution injected into the system, leading to the dissolution of celestite and the growth of barite. The model can also be used to simulate the reactivity of the fluid in the geothermal well, especially the potential re-circulation of fluid developing at the corners of the expanding well cross-sections that could modify chemical concentrations in the fluid and potentially impact the saturation indices of precipitating minerals [30].

The modelling and uncertainty quantification workflow was demonstrated on a barite precipitation case study in a heat exchanger [11]. Initially, the impact of geochemical uncertainties (in the fluid composition) on the mineral precipitation was assessed. Afterwards, the coupled fluid flow and precipitation model with the developed roughness model was tested. Finally, the coupled uncertainty quantification workflow with the coupled model was simulated to assess the impact of fluid composition uncertainties on mineral deposition. As an outcome of the simulation, the impact of uncertainties in the mineral deposition on reduction in the production rate and heat transfer (within the heat exchanger) was calculated. The sample code to perform uncertainty quantification with geochemical modelling using PHREEQC and instructions on using the code are available on Github: ***https://github.com/poortjp/REFLECT_D4-3_example***. Using the presented workflows, it is possible to predict the occurrence and severity of various scaling types within a geothermal system, its effects on the decrease in flow rate over time, and the expected potential variation of these results based on the uncertainty in brine composition.

3.7 Set up a Geothermal Fluid Atlas that collates information on geothermal fluid properties across Europe

The European Geothermal Fluid Atlas collates information from pre-existing geothermal fluid data and data analysed during the project (see Section 3.1). For the atlas, a free and open-source cross-platform is used in which the geographic information system provides the environment to view and analyse geospatial data. The entire dataset is available for query and download through the website ***https://www.reflect-h2020.eu/efa***. The interface includes query and filtering tools to explore the database with map-based visualisation (***Figure 7***). Since many fluid data were submitted with additional comments or complementary information, an additional data sheet or report containing this additional information is available for each fluid sample.

With the Fluid Atlas, we aim to provide a tool to rapidly access known geothermal fluid properties all over Europe, and proxy correlation with host rocks and reservoir formations. The compositional maps are used for estimations of risk for the different operational issues, in combination with numerical modelling. The Fluid Atlas can be later integrated into other databases; thus, it can be an addition to existing initiatives of geological data collection. The aim of the REFLECT project is to provide a living database that can be updated with more data after the end of the project.`

4. Conclusions

The presented approach, methodologies, and results established in the REFLECT project are contributing to the closing of knowledge gaps related to geothermal fluids properties. With the downhole sampling approach, a technological challenge to assess superhot geothermal wells will be solved. This will extend the existing dataset to even higher temperature systems. REFLECT has brought together newly collected and analysed samples from geothermal sites with previously existing data to form the database for the European Geothermal Fluid Atlas, but also for a first database of organic compounds and microbes in geothermal fluids. These datasets can be used to rapidly assess the kind of fluids at a certain location, and thus permit an improved view of the associated risks when installing a geothermal power plant. They may also be used for predictive modelling to optimise plant layout and operations. However, predictive modelling may benefit not only from the improved datasets on natural geothermal fluids, but also from the data on physical and chemical fluid properties that resulted from the experimental investigations of synthetic fluids concerning degassing, precipitation, dissolution and biofilm formation. Finally, the improved and combined modelling approaches that have been developed in REFLECT allow the consideration of more parameters of the complex (geo-) chemical and engineering system of geothermal operations and improve the informative value of predictive models by including uncertainty propagation.

In conclusion, the knowledge and methods generated by the REFLECT project will enable solutions to improve the overall performance of geothermal energy production and reduce maintenance costs, and therefore to increase the economic viability and environmental sustainability of geothermal plant operations. Results of the project are published via scientific publications, but also factsheets, brochures, project deliverables and public presentations at scientific conferences and events of the geothermal community. All public material is available via the project website: ***www.reflect-h2020.eu***.

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