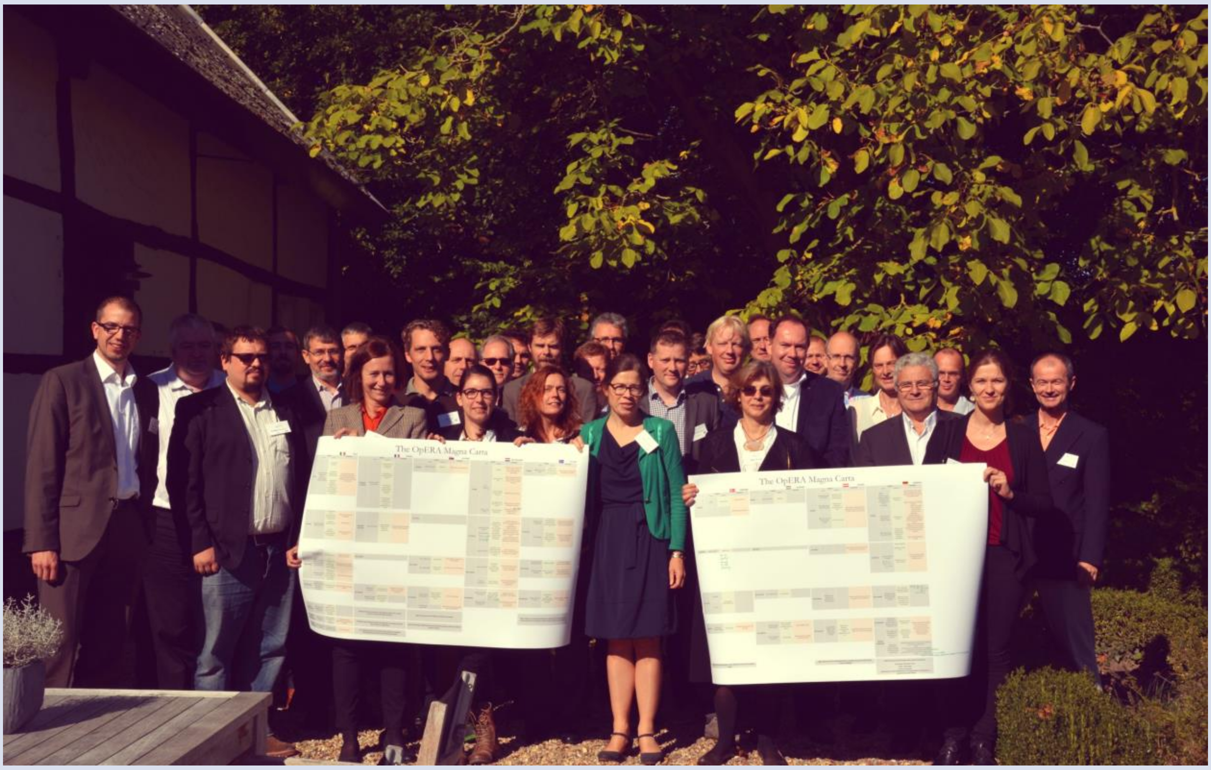
Geothermal ERA-NET

Operational issues in Geothermal Energy in Europe

Status and overview



October 2016

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Operational issues in Geothermal Energy in Europe: Status and Overview

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Executive Summary

Based on the results of the Geothermal ERA-NET work package (WP) 2 „Information exchange on national incentives and status of geothermal energy“, and WP4 “Development of joint activities”, the topical field of operational issues of geothermal energy installations was identified as one of the main barriers for the development of geothermal energy and as an urgent RD&D need mentioned by most of the participating countries in a ranking process.

As a first step towards a European knowledge exchange on this topic, the Geothermal ERANET organized a workshop on operational issues on the 1st & 2nd of October 2015 in Vaals (NL). The theme was baptized OpERA – **Op**erational issues in geothermal energy installations – by the Geothermal **ERA**-NET. 37 experts from 11 countries participated in the workshop. Country overviews, and four topical sessions on scaling, scaling & gas content, corrosion and re-injection issues were the issues that were discussed. These issues were documented in the “OpERA-Magna Carta”, Appendix 1 to this report.

At the workshop, the “OpERA-Expert Group” was founded, to collaborate further and to create the current joint publication on operational issues in Europe. Some twenty experts from around Europe have contributed to this publication. It is structured in the same way as the workshop, presenting country overviews, and four topical chapters on scaling, gas content, corrosion and re-injection issues. The presentations at the workshop are Appendix 2 to this report.

After the OpERA workshop, the Geothermal ERA-NET has decided to keep on working on operational issues. This will be done in two ways, firstly by implementing the “OpERApedia”, a wiki-style knowledge platform on operational issues, and secondly by stimulating innovations through further collaboration in the ERANET Cofund GEOTHERMICA. Further work on operational issues is will be important for optimal growth of geothermal energy in Europe.

Introduction

This report is a publication of the working group OpERA (**OP**erational issues in geothermal energy installations) within the Geothermal **ERA**-NET project. Besides general information, the topics "scaling", "corrosion", "gas content" and "reinjection issues" are addressed in detail. The report is the result of the voluntary input of many European specialists and brings together a wealth of information. The report moreover shows the relevance of European collaboration.

The basic idea of addressing operational issues of geothermal energy installations as a topic for transnational knowledge exchange was born in the framework of the EU funded project "Geothermal ERA-NET". The Geothermal ERA-NET is a network of Ministries, National Funding Agencies and Project management bodies from 11 European Countries responsible for the RD&D research funding on geothermal energy. The project is supported by the European Commission under the 7th Framework Program. The aim is to boost the development and implementation of Geothermal Energy in Europe by deepening European cooperation on geothermal energy at national and administrative levels and by enabling the integration of national RD&D programs. Led by Iceland, The Netherlands, France, Switzerland, Germany, Italy, Hungary, Turkey, Slovakia, Portugal and Slovenia are working together to propel Geothermal Energy in Europe to a higher level.

Based on the results of the Geothermal ERA-NET work package (WP) 2 „Information exchange on national incentives and status of geothermal energy", and WP4 "Development of joint activities", the topical field of operational issues of geothermal energy installations was identified as one of the main barriers for the development of geothermal energy and as an urgent RD&D need mentioned by most of the participating countries in a ranking process.

The major advantage of geothermal energy over other renewable energy sources is the time and weather independent availability of the geothermal resource. To use this advantage, the operational availability of geothermal energy installations has to be stable on a high level. Scalings and material corrosion for instance, are issues in many geothermal areas in Europe. Both lead to breakdown times due to necessary repair or service works. Also other issues like high gas content of the thermal brine or pressure related issues have to be controlled for continuous availability of the resource.

To create a platform for this discussion the OpERA working group was founded within the Geothermal ERA-NET. OpERA aimed on bringing together the national experts (Plant owners, project developers, researchers etc.) to provide an overview of potential solutions, like adapted materials in the geothermal installation, the use of inhibitors or optimized pipe geometries or well design. In this way, OpERA wants to foster the technical knowledge exchange to solve operational issues on a European level.

As a first step towards this European knowledge exchange, OpERA organized a workshop on operational issues on the 1st & 2nd of October 2015 in Vaals (NL). 37 experts from 11 countries participated in the workshop. On the first day country overviews from Hungary, Italy, the Netherlands, Slovenia, Germany, Iceland, Switzerland, France, Denmark and Austria were presented to create a summary of the most urgent operational issues in Europe. These issues were documented in the "OpERA-Magna Carta"[i] which shows solved and unsolved issues on scaling, gas content, corrosion and reinjection by country (see appendix).

The second day was structured with four topical sessions on scaling, scaling & gas content, corrosion and re-injection issues. In these sessions 13 presentations on specific issues, possible solutions and examples from different locations were held.

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[i] The name was chosen to honor the 800th anniversary of the original **Magna Carta Libertatum**, which was signed on the 15th of June 1215 in Runnymede, England.

Both days were enveloped by discussion & summary sessions moderated by a specialist for operational issues from the oil & gas industry. The experts participated very actively in the fruitful discussions and solutions for several issues were adressed on a European base.

In the last session of the workshop, the "OpERA-Expert Group" was founded, to create a joint publication on operational issues in Europe; the publication you are reading right now.

This publication is a kind of enhanced "Proceedings of the 1st OpERA workshop on operational issues of geothermal installations", including county overviews of ten countries, overviews on the general, solved and unsolved issues in the different topical fields and several excurses on specific topics as e.g. pressure retention or material science. The authors of the various contributions are responsible for their own content. The country statuses are summarized in the mentioned "OpERA-Magna Carta" which can be found in the appendix.

The OpERA Joint Activity revealed the necessity of a trans-european knowledge exchange on specific topics and showed, that the community appreciates a neutral plattform to discuss urgent issues on an open level without any country or company based restrictions. During the whole workshop the focus was on topics and solutions and not on competition. Therefore "OpERA" was a showcase, how a European geothermal community can work together in the future to support the further development of geothermal energy. Following the impressions from the workshop and the joint work related to this paper, the workshop and the publication won´t be the last activities on the field of operational issues of geothermal energy installations. Within the framework of the Geothermal ERA-NET, the planning for a web-based knowledge transfer system, the "OpERApedia", has been started.

An interactive information platform, filled with information from (in the beginning) five European countries, edited by a specialist from the oil & gas industry will go online in the first half of 2017 (planned) and will enhance the knowledge transfer, will provide information on specific issues and on the people who can provide solutions (registered users).

Details on this project will be published continously over the Geothermal ERA-NET project website www.geothermaleranet.is.

For now, we wish you an interesting reading with the present publication. We want to thank all authors for their voluntary contributions. If you have any further questions on specific topics, don´t hesitate to contact the authors (when contact data is available) or in more general cases the OpERA Steering Committee:

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1 Status of operational issues in Europe

1.1 Austria

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1.1.1 Status of hydrogeothermal use in Austria

The use of natural occurring thermal water in Austria has quite a long tradition. The first balneological applications can be traced back to Roman times (e.g. Baden near Vienna). Until the 1990's hydrogeothermal use was limited to naturally outflowing thermal springs and abandoned hydrocarbon wells (e.g. Bad Blumau). Since then, the systematic exploration and development of hydrogeothermal springs lead to the installation of a total capacity around 52 MW_{th} (Goldbrunner & Goetzl, 2013). The production of electric power based on ORC processes is currently still limited to two locations (Bad Blumau and Altheim) obtaining a total installed capacity of below 1 MW_e. Since 2005, a stagnation of the further development of hydrogeothermal applications can be observed. The reasons for that are given by (1) a saturation of the balneological market in most areas of Austria and (2) an increase of failed or only partly successful exploration wells. In addition, the current legal and financial framework in Austria does not support a significant increase of hydrogeothermal applications. Feed-in tariffs as well as sound insurance procedures are lacking. In addition, the exploration of hydrogeothermal resources is still governed by the Austrian Water Act, because the heat in the subsurface is not recognized as a source of energy by the Austrian government.

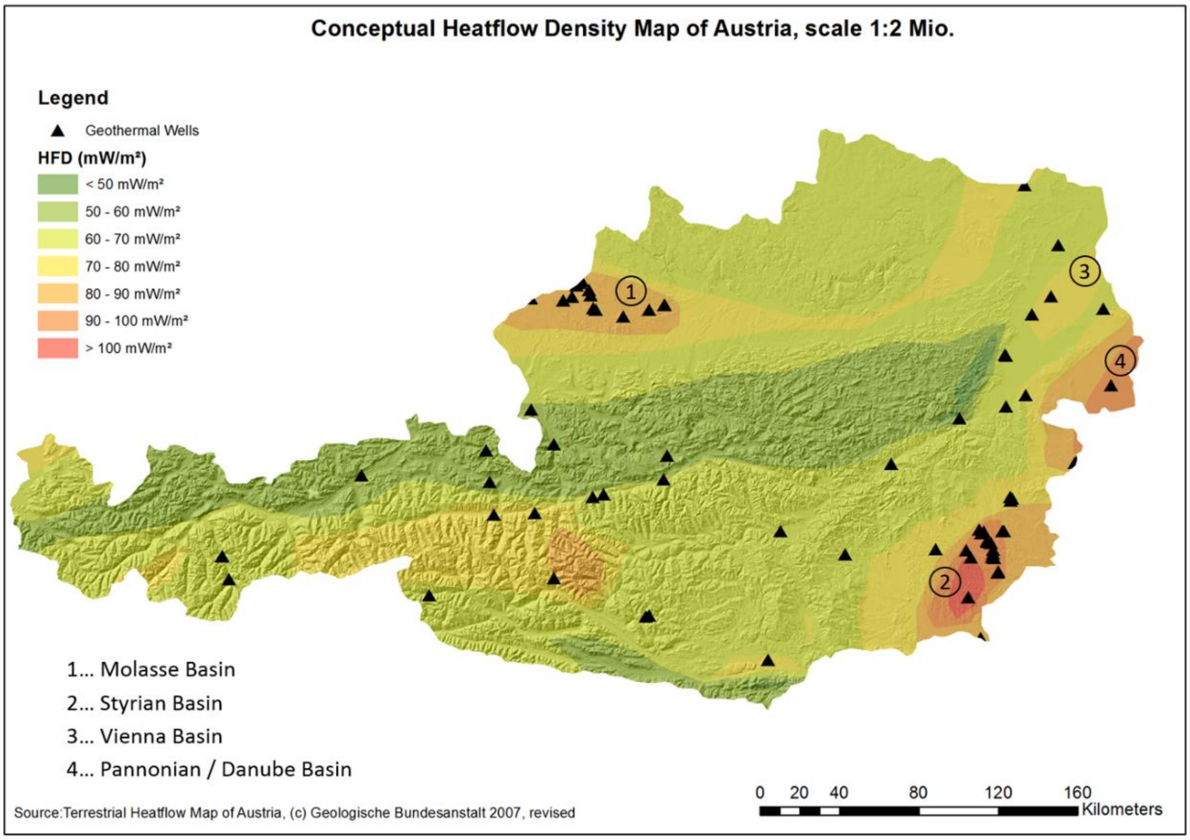

Figure 1 Heat-flow density map of Austria, scale (1: 2 million) combined with an overview of hydrogeothermal regions. Taken from Goldbrunner & Goetzl, 2016

1.1.2 Hydrogeothermal regions in Austria

Austria can be divided in different hydrogeothermal regions (

Figure 1):

(I) The Molasse Basin (MB) situated in the north-western part of Austria with low-mineralized thermal water located at the main reservoir, the so-called Malm Karst aquifer (Jurassic basement of the Molasse Basin).

(II) The Vienna Basin (VB), located in the Northeast of Austria is divided into two structural units divided by a significant reverse fault system. The structural deep zones (depocenters) bear highly saline, connate aquifers, which have been partly used for the exploitation of hydrocarbons. In contrast, the high zones, located at the margin of the Vienna Basin, obtain meteoric water linked to active recharge. These so-called hydrodynamic systems produce significant thermal anomalies linked to the descent and ascent paths of the circulating water.

(III) The Styrian Basin (SB), located in the Southwest part of Austria, is linked to the Pannonian Basin and shows, besides elevated heat-flow, significant occurrence of CO_2 (

(IV) Figure 1).

1.1.3 Scaling in hydrogeothermal plants in Austria

Currently, hydrogeothermal use for district heating and production of electricity is only realized in the Molasse Basin in Upper Austria as well as in the Styrian Basin with a total of eight installations. Only one of these eight installations faces significant operational problems related to scaling of carbonates due to the high content of CO_2. Similar problems occur in balneological uses of water from aquifers containing CO_2 and bicarbonate in the Styrian Basin (e.g. Bad Radkersburg). In the first stage of operation at Bad Blumau, scaling problems have been treated by the application of inhibitors (polyphosphates) and periodical acidic cleaning of the wells. Since some years, the existing CO_2 is separated and sold to the nutrition industry, which significantly enhanced the economic performance of the site.

Table 1 at the end of Chapter summarizes existing and possible operational issues of hydrogeothermal plants in Austria. It has to be pointed out, that there are still no hydrogeothermal uses in the Vienna Basin, although there is a great technical potential. All operational experiences gained at the Vienna Basin result from hydrocarbon exploitation.

In the recent national research project NoScale (Characterisation of thermal water for the prevention of scaling and corrosion in geothermal plants), which was led by the second author of this manuscript, different deep groundwater bodies in Austria were characterised for their scaling and corrosion potential (Figure 2). The aim of the project was to show the potential impact of the use of the thermal waters on the technical components of hydrogeothermal systems. The work is based on comprehensive and complex chemical and mineralogical experiments accompanied by hydrochemical modelling. 15 hydrogeothermal plants in Austria and Bavaria were sampled, whereas in 8 of them scaling on pipes and/or heat exchangers, but no corrosion phenomena occurred. The water and scaling samples were analysed for their hydro- and isotope chemical and mineralogical composition. The analyses were accompanied by the simulation of the relevant hydrochemical processes with PHREEQC as well as the numerical simulation of flow processes in plate heat exchangers with FLUENT and ASPEN. Finally, mineralogical experiments with technical components in different synthetic thermal waters at different temperature levels were carried out. Currently, the results of all the work packages (analysis, experiments, modelling) are subject to a comprehensive interpretation and the final results of the project are available from autumn 2016 onwards.

Material	Geographical location	Location in plant	Photos	Solution
Carbonates	Molasse basin (Upper Austria), Styrian Basin	Pipes, heat exchangers, stripper	 	Stripper, regular cleaning with acid, inhibitors
Fe-oxides/-hydroxides	Molasse basin (Lower and Upper Austria)	Well head		Regular cleaning, precipitation
Sulfur, Sulfates	Molasse basin (Upper Austria)	Heat exchangers		Regular cleaning
Fe-sulfides	Molasse basin (Upper Austria)	Heat exchangers, pipes, valve flaps	 	Regular cleaning, Exchange of parts

Figure 2 Scalings occurring in different deep groundwater bodies in Austria

1.1.4 Summary and conclusion

In Austria, currently existing operational problems of hydrogeothermal use are predominately associated to scaling of carbonates in CO_2-rich aquifers, especially in the Styrian Basin. Scaling problems are mostly tackled by insertion of inhibitors and / or frequent acidic cleaning of wells and plate heat exchangers. At the location Bad Blumau the CO_2 is separated and sold to the nutrition industry.

The major share of existing hydrogeothermal plants used for energetic purposes (district heating) is located at the Molasse Basin in Upper Austria. The most relevant aquifer in the Molasse Basin are Jurassic carbonates (predominately limestones) summarized as the so-called “Malm Karst” reservoir, which is also present in southern Germany. The occurring thermal water is of low mineralization and initially of hydrostatic pressure level. Production and reinjection of thermal water is not affected by significant operational problems.

Despite the high technical potential, there are no hydrogeothermal applications for energetic purposes in the Vienna Basin yet. Based on experiences from hydrocarbon exploitation, possible operational problems are associated with high salinity and organic material in connate aquifers in the deep zones of the Vienna Basin. Both structural units of the Vienna Basin are affected by significant content of H2S in aquifers, which are in contact with evaporites at the stratigraphic basement of the Vienna Basin.

Table 1 Summary of operational problems in Austria

	SOLVED		UNSOLVED
	Issue	*Solution*	*Issue*
Scaling	*Carbonate precipitation in pipes, heat exchangers, stripper (MB, SB)*	*Stripper, regular cleaning with acids, use of inhibitors*	
	Fe-oxides/hydroxides at well head (MB)	*Regular cleaning, precipitation*	
	Sulfur, Sulfates at heat exchangers (MB)	*Regular cleaning*	
	Fe-sulfides at heat exchangers, pipes, valve flaps (MB)	*Regular cleaning, exchange of parts*	
Corrosion			*High NaCl content (VB)*
Gas content			*High concentration of CH_4 and H_2S (VB)*
Reinjection			*Clogging of well because of skin effects (SB)*

1.1.5 References

Goldbrunner J. & Goetzl G., 2013: Geothermal Energy Use, Country Update for Austria; *Proceedings European Geothermal Congress 2013*, Pisa, Italy, 3-7 June 2013.

Goldbrunner J. & Goetzl G., 2016: Geothermal Energy Use, Country Update for Austria; *Proceedings European Geothermal Congress 2016,* Strasbourg, France, 19-23 September 2016.

Goetzl G., 2007: Heatflow density map of Austria, scale 1:2.000.000; in Hofmann T. & Schönlaub H.P.: *Geoatlas Österreich*, Geological Survey of Austria, Vienna.

1.2 Denmark

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1.2.1 Status of geothermal energy in Denmark

The Danish subsurface is mainly made up of thick sedimentary layers (up to 8-9 km thick). The only exception is the island of Bornholm, where the basement is exposed at surface.

From south to north the subsurface is in very general terms made up of the Northern German Basin, the Ringkøbing-Funen High, the Danish Basin and finally the Skagerrak-Kattegat Platform extending up into Norway and Sweden. Of these general structures it is primarily the sandstone layers of the Northern German Basin and the Danish Basin that are relevant as potential reservoirs for geothermal energy. These can be found in most parts of the country.

The geothermal gradient is approximately 25-30 °C pr. km with some local variations, and the permeability is as a very general rule halved for every 300 m of depth with huge local variations. This makes sandstone reservoirs in the depth range between 1,000 and 3,000 meters relevant as geothermal reservoirs. The geothermal brines are generally very saline with low to moderate contents of dissolved gasses.

So far, only three geothermal district heating plants are in operation: Thisted (commissioned 1984), Amager/Copenhagen (2005) and Sønderborg (2013). A number of projects have been under development for the last 5 years, but all of these are currently stopped or on hold as the future of the national guarantee fund for geothermal energy is being considered by the Danish government.

About 63% of all Danish households are supplied with district heating, and there are more than 400 district heating companies. This, in combination with the favourable geological conditions in many parts of the country, means that it should be technically and economically possible for geothermal energy to cover up to 20-25% of the current Danish district heating demand.

1.2.2 Operational issues in Denmark

The geothermal district heating plant in Thisted, Denmark's first, has been in operation since 1984 without any major operational issues. There is a small amount of CH_4 gas dissolved in the geothermal brine but this can be kept in solution by operating the plant at a sufficiently high surface pressure.

At the geothermal district heating plant in Amager/Copenhagen there has been issues with scaling right from the start in 2005. It is assumed that a relatively high content of Calcium in the geothermal brine leads to calcite precipitations if the geothermal brine is not cooled to below 20 °C. This leads to a build-up of calcite particles in the perforations of the injection well, making it necessary to increase the injection pressure over time in order to maintain flow. When the injection pressure becomes too high, the calcite particles can be removed efficiently by soft acidizing the injection well using 15% by weight HCl acid, injected as l/h in m3/h of geothermal brine.

As the geothermal brines found in Denmark generally have a very high salinity (15-26% by weight), corrosion of iron casing, piping, valves and other components in the geothermal loop is a potential problem. All three existing plants are therefore equipped with nitrogen protection in order to prevent air/oxygen ingress in case the pressure in the geothermal loop drops (e.g. due to planned or unplanned stops). At the

[iv] Due to the difficult framework of geothermal energy in Denmark and the lack of political support in Denmark, Danish Geothermal District Heating was closed in early 2016 (press release 29 November 2015).

same time, the conductivity of the treated water in the district heating loop is constantly monitored to avoid leaks of geothermal brine into the district heating loop.

Degassing is generally prevented by operating the plants at pressures above the bubble point (typically below 15 bar). If this is for some reason not possible, degassing of CH_4 (Thisted) and CO_2 (Amager/Copenhagen) has been seen.

Currently the plants in Amager/Copenhagen and Sønderborg are experiencing injection problems which cannot be solved by soft acidizing. The problems have been studied carefully, several camera inspections have been done, samples of bottom hole material have been collected, and the injection well at both plants have been cleaned up. Based on this the current theory is that the problems are caused by lead precipitation as has also been seen in similar plants in Northern Germany and the Netherlands. If this is the root cause, it is expected that further lead precipitations can be prevented by down- hole or surface injection of a suitable inhibitor. In any new plants the use of other materials (e.g. composite casings) can be considered.

Integration with heat pumps gives a more efficient but also more complex system

Table 2 Summary of operational problems in Denmark

	SOLVED		UNSOLVED
	Issue	**Solution**	**Issue**
Scaling	Carbonate scaling	Soft acidizing	
			Lead precipitation Other precipitations?
Corosion	Base corrosion	Keep air out	
Gas content	Methane and CO_2	Keep pressure above bubble point	Use in the closed system
Reinjection	Clogging with calcite and products of corrosion	Soft acidizing	Particles clog up screens with base pipe

1.3 France

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1.3.1 Status of geothermal energy in France

Geothermal energy sector is divided in three operational domains, following the "Code Minier" which individualizes: High temperature above 150 °C, low temperature below 150 °C and "géothermie de minime importance" maximum of 200 m drilling depth and 500 W of geothermal thermal power.

High temperature

Two operating plants in Soultz-sous-Forêts and Guadeloupe Island for 17 MW_e installed. More than 20 permits for high temperature cogeneration plants are issued with expected end of drilling operations in the end of 2016. Four permits are issued in the Caribbean islands. The developers are Electricité de Strasbourg Géothermie, Fonroche Géothermie, Electerre de France and Teranov. The expected installed power is planned at 80 MW_e in 2030. The successful doublet of Rittershoffen (25 MWth) started production in first quarter of the year 2016 and has proved that the EGS concept with adapted reservoir stimulations avoiding hydraulic fracking works.

A fund to cover geological risks in the initial phases (exploration wells and resources assessment…) of the EGS projects will be operational in the end of 2016. The fund with 100 M€ is created on a private-public participation 50/50 for EGS projects in France and geothermal volcanic projects in French overseas and French projects abroad.

GEODEEP, a French multi-disciplinary Cluster has been created in 2014 to gather large worldwide corporations and specialized companies in geothermal engineering and power plant EPC (EDF, Clemessy, Actemium, CEGELEC, Cryostar, COFOR, CFG Services, Fonroche, Electerre….). The cluster is aiming at offering, in geothermal electricity production, packages which are tailor-made to better suit the local ecosystems with a full respect of the environment. The offer is covering all the geothermal activities from preliminary studies down to exploitation and maintenance of the power plants when completed.

Low temperature

Direct use of geothermal energy was born in 1969 in Melun-l'Almont (Ile de France). At the moment, more than 60 geothermal doublets with a total installed power of 500 MW_{th} are in operation. Two third of them are tapping the famous Dogger reservoir made of Jurassic limestones in the depths between 1,500 and 2,000 m in the Paris region while the others are mainly located in the SW of the country.

The development restarts in 2009 following the establishment of a new "heating fund" managed by ADEME and providing subsidies for the construction of both deep drilling and heating networks at the surface. Between 2007 and 2015, 20 new doublets have been installed and 16 plants have been revamped in order to prolong the duration of each doublet by 30 years. The master plan for geothermal district heating anticipates a doubling of the installed power until 2030.

"Géothermie de minime importance"

New law adapted in July 2015 has replaced the old "Code Minier" in order to facilitate the construction of GSHP systems. These systems provide heating and cooling for of more than 600,000 inhabitants. Customers' size is from individual housing to small low temperature loops using heat pumps addressing new districts or office buildings representing 10.000 to 150.000 m^2 of heated place The development of GSHP for individual housing decreased in term of installation from 20,000 units in 2010 to 4,000 in 2015 due to the hard competition with air-air systems, nevertheless the total annual production is of 300,000 TOE and AFPG (French Geothermal Association for Professionals) anticipate that this number well be tripled in 2030.

1.3.2 Relevant operational issues

For high temperature cogeneration geothermal plants, the numerous ongoing projects face with negative public acceptance which remains a strong obstacle in some regions, due the fear of induced seismicity related to cold water injection using too high pressures during reservoir development as in Basel. The last doublet realized north of Strasbourg has solved most of these technological problems experimenting successfully with soft development methods.

Low temperature doublet drilled for district heating network are now utilizing mature technologies and the constant improvement of drilling and exploitation procedures have strongly improved the duration of the plants which are expected to be exploited up to 60 to 75 years. Some new frontiers are possible to attain, utilizing directional sub-horizontal drains in the geothermal aquifers and use of composite casings to avoid the high investment for down-hole inhibitors lines installation and OPEX in relation with chemical products used during the exploitation period.

Shallow geothermal schemes are bigger and bigger, two recent installations: one in Airbus factory in Toulouse with more than 25,000 m of vertical closed loop and the second with a geothermal doublet (800m depth in Albian sands) in Issy Les Moulineaux (Ile de France) with flow of 150 m^3/h at 30 °C using a cold loop with decentralized heat pumps and a cascade use; show that this technology is well adapted to small district heating systems which can be developed in more than 90% of the French territory. The “Heat Fund” managed by ADEME is in force with more than 250 million € per year and geothermal plants as small as 30 kW can benefit.

Table 3 Summary of operational problems in France

	SOLVED		UNSOLVED
	Issue	***Solution***	***Issue***
Scaling and Corrosion	*Internal scaling and corrosion*	*Remediation by jetting executed while workover operation*	
		Remediation by smooth acidizing	
		Instalation of downhole chemical treatment at the bottom of the production well with continious inection (some ppm)	
		Re-lining old wells with iron or composite casing	
		Composite casing in new wells	
	External scaling and corrosion	*Composite casing in new wells (a first test carried out in 2015 for the re-vamping of old wells has been completed succesfully)*	
		New logging tools for measurement of casing thickness at the extrados (a new promissing tool has been tested in 2015 with promising results)	
Reinjection	*Reinjection in sandstones*	*Use of triplet scheme with one production and two injection wells*	
	Reinjection in poorly cemented sands or sand interbedded with clays	*Drilling of extra-large diameter in reservoir and setting pre-packed gravel screens (Johnson type)*	
General technological issues	*Lifetime of the geothermal doublet*	*Enlargeing the spacing between the doublet wells to over 1500 m*	
	Increase of well productivity	*Drilling large diameter wells Horizontal drilling in order to improve the production and injection flowrate*	
	Lifetime of down-hole pumping equipment		*Electro-submersible pumps with short duration in very hot geothermal water above 120 °C*

1.4 Germany

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1.4.1 Geothermal Energy in Germany

In Germany three preferential regions, i.e. the Bavarian Molasse Basin (BMB), the Upper Rhine Valley (URV) and the Northern German Basin (NGB) (Figure 3) exist, where thermal water is produced for energy production. In the moment (Status 2016) 34 hydrothermal plants are in operation, with a capacity of app. 300 MW thermic (MW_{th}) and app. 41 MW electric (MW_e) energy. Thereby thermal water with temperatures up to 165 °C and pumping rates up to 130 l/s is produced from depths down to 5,600 m below surface (b.s.). All geothermal plants are operated in a doublet system, where the cooled down thermal water, which circulates at the surface in a closed system, is re-injected in a second borehole to the same aquifer. The thermal waters and hence the operational issues and challenges differ in these three geothermal regions. Below the thermal waters produced in those three regions are briefly introduced:

Bavarian Molasse Basin

The Bavarian Molasse Basin is the region with the highest density of geothermal plants in the world. The intstalled capacity of 22 geothermal plants is app. 279 MW_{th} and app. 41 MW_e. Thermal Na-Ca-HCO_3-Cl type water with a mineralisation between 0.6 and 0.8 g/l is produced from an upper Jurassic carbonate dominated aquifer from depths between 800 and 5,600 m b.s. The water bears H_2S and hydrocarbons and has gas contents between 80 and 120 Nml/kgH_2O (~70 % CO_2, ~20 % CH_4, ~10 % N_2). The radioactivity is below 1 Bq/kg H_2O.

Upper Rhine Valley

In the Upper Rhine Valley, located in the SW of Germany, there are four geothermal plants with installed capacity of app. 11 MW_{th} and 6 MW_e. Saline thermal water of a Na-Ca-Cl type with mineralisation between 85 and 130 g/l is produced from lower and middle Triassic, as well as Tertiary carbonate and sandstone dominated aquifers from depths between 1100 and 3400 m b.s. The produced thermal waters are H_2S and hydrocarbon bearing and have gas volumes between 700 and 1500 Nml/kgH_2O (> 95% CO_2). The activities of radionuclides dissolved in thermal water vary between 20 and 100 Bq/kgH_2O.

Northern German Basin

In the Northern German Basin five geothermal plants have installed capacity of app. 9 MW_{th}. The highly saline Na-Ca-Cl type thermal water (TDS > 250 g/l) is produced from Triassic and Permian sandstone dominated aquifers from depths between 400 and 2,300 m b.s. The produced thermal waters are H_2S, hydrocarbon and heavy metal bearing and have strongly varying gas compositions and concentrations between 100 and 1000 Nml/kgH_2O. The activities of radionuclides dissolved vary between 20 and 100 Bq/kgH_2O.

Additionally, hydrothermal energy is produced in three plants in Upper Swabia (SW-Germany).

1.4.2 Operational Issues in German geothermal plants

The majority of the German geothermal plants are operating well, but nevertheless due to the handling with the “natural resource” thermal water operational problems and challenges exist, which are explained briefly below and summarized in Table 4.

Scaling

The formation of mineral precipitations (=scalings) in and on the electrical submergible pumps (ESP), rising and injection pipes, filters, surface pipes and heat exchangers can lead to problems in operating technical devices and cause hence substantial financial damage due to downtime of the plants. In several geothermal power plants in the Bavarian Molasse Basin with production rates > 100 l/s and water temperatures > 120 °C Ca-carbonate scalings associated with Fe-sulphide scalings occur in and on the ESP, rising pipes, filters and heat exchangers. The formation mechanisms of these scalings, which are formed despite of pressure maintenance, are not fully understood so far and are subject of recent investigations.

In geothermal plants located in the Upper Rhine Valley producing thermal water from the Triassic carbonates and sandstones Ba- and Sr-sulphate scalings occur in the rising-, injection and surface pipes and heat exchangers, which include high concentrations of radionuclides. To avoid such precipitations, inhibitors are used.

Dependent of the water chemistry, different scalings occur in geothermal plants of the Northern Garman Basin. In the plants, which produce water from the Triassic sediments, Ba- and Sr-sulphates and Pb-sulphides occur in the rising-, injection-, and surface pipes and heat exchangers, whereas in the plants producing from Permian layers Barite ($BaSO_4$), Laurionite (PbOHCl), Magnetite (Fe_3O_4) and Copper (Cu) are formed in the production well and aquifer areas behind the filter. The formation of Sulphates and Sulphides can be avoided by the application of inhibitors, whereas the avoidance of metallic scalings is still mater of ongoing investigations.

Induced seismicity

Due to the strong seismic activities of the Upper Rhine Valley, earthquakes can be triggered due to drilling and stimulation activities and by fluid injection during operation. Therefore a detailed seismic monitoring has to be installed and operated during the drilling and operation phase. In addition to avoid any induced seismicity a detailed characterisation of the tension regimes in the planning and exploration phase is conducted. During all phases a rapid adjustment of the seismic driving parameters has to be done.

Other disturbing processes like corrosion, gas contents and problems during reinjection do not mainly disturb the operation of geothermal plants in Germany. Nevertheless they are briefly mentioned in Table 4.

1.4.3 Summary and Perspective

The usage of geothermal energy, especially the production of heat is an absolute success story in Germany. Although the boom of the early 2000 is over, there are six power plants under construction and more than 25 planed. Nevertheless there are still open questions and unsolved problems, which are subject of ongoing investigations. The future of power producing projects depends on governmental subsidies, which are assured until the year 2020 and the solution of open questions, i.e. mainly the improvement of ESPs. A further challenge is to gain the acceptance of public for new geothermal energy projects.

1.4.4 Further information

Further information about geothermal energy in Germany can be gathered under www.geothermie.de and www.geotis.de and references therein.

Table 4 Summary of operational problems in Germany

	SOLVED		UNSOLVED
	Issue	Solution	Issue
Scaling	URV, NGB: Ba- and Sr-Sulphate scalings in rising pipes and surface pipes and devices	Application of inhibitors	
	URV, NGB: Enhanced radioactivity in sulphate scalings	Application of inhibitors	No inhibitors for radioactive Pb210
	NGB: NaCl scalings in production well	Pressure- and temperature keeping during drilling and borehole development	
	NGB: Formation of Pb and Cu bearing scalings in the rising pipe and borehole close area of the production well	Prevention of electrochemical corrosion by application of adequate materials (higher alloyed steels)	Removal of Cu above ground
			NGB, URV: Matalsulphide scalings
			BMB: Carbonate- and sulphide scalings - in and on the pumps - in the rising pipe - in filter systems - in entrance heat excanger Possible solutions: - Application of inhibitors - Problem: federal regulations - Development of new filter systems - Usage of coated rising pipes → Ongoing research projects and active discussions between the individual operating companies
Induced seismicity	URV: Induced seismicity due to fluid injection during operation	- Seismic monitoring - Graduated scheme, developed with mining authorities, to follow when microseismicity accumulates - Adjustment of reinjection volumes and pressures: run power plant as stable and smooth as possible	Still large debate about the main driving parameter (flow rate, injected volume, injection pressure?) of induced seismicity
	URV: Triggered and induced seismicity due to drilling and stimulation	- Detailed characterisation of the tension regimes in the planning and exploration phase (but hard to derive, in-situ only possible in and in the very vicinity of the borehole (HTPF, borehole break-outs …), Fault Plane Solution from microseismicity is unreliable - Seismicity monitoring before and during drilling, stimulation and borehole development phase - Rapid adjustment of the parameters during these phases (Reaction is necessary, but Careful! Example Soultz: experience from stimulation is that largest events accured during shut-in, therefore practise of "step wis shut-in")	
Corrosion	Corrosion induced by oxygen	- Pressure keeping - Application inert gas - Adjusted design of surface devices	
			Corrosion induced by H_2S → ongoing and planned research projects
Gas content	Formation of free gas phases during production (and injection)	- Adequate pressue maintainance in the production well, surface devices and injeciton well - URV: Controlled degassing and application of inhibitors	NGB: potentially high amounts of free gass (N_2 anc CH_4) and formation of gas bubbles reduce productivity
Reinjection	Formation of scalings due to pressure release in the upper meters of the injection well	Adequate pressure maintenance	
			Potential decrease of injectivity due to a decrease of the permeability of water-coducting fractures by the formuation of scalings → ongoing and planned research projects

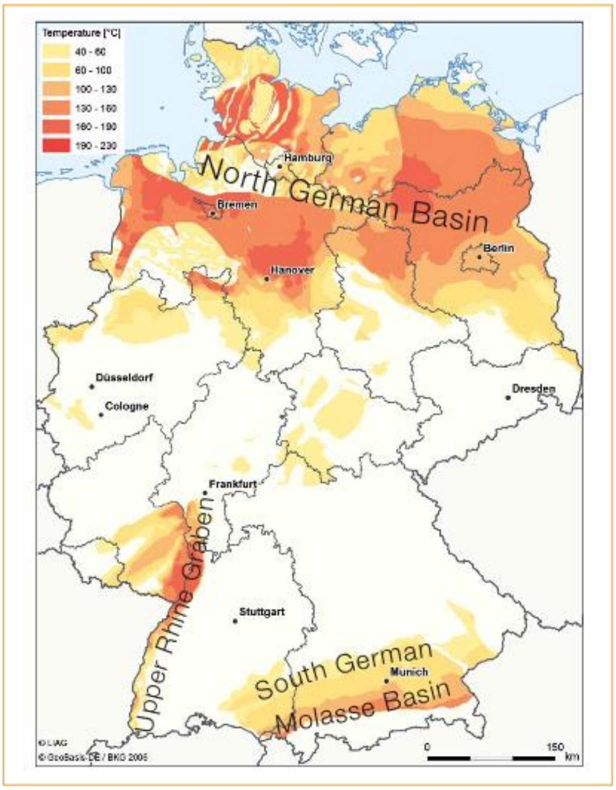

Figure 3 Overview of the most important geothermal regions in Germany and expected temperature ranges in deep aquifers (from Suchi et al., 2014)

1.4.5 References

Suchi, E., Dittmann, J., Knopf, S., Müller, C, Schulz, R., 2014: Geothermal Atlas to visualise potential conflicts of interest Between CO2 storage (CCS) and deep geothermal energy in Germany. *Z.Dt. Ges.Geowiss.*, 165(3)439-453.

1.5 Hungary

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1.5.1 Introduction

The geothermal potential of the Pannonian basin is outstanding, as it lies on a characteristic positive geothermal anomaly, with heat flow density ranging from 50 to 130 mW/m^2 (mean value of 90-100 mW/m^2) and geothermal gradient of about 45 °C/km (Dövényi and Horváth, 1988). This increased heat flux is related to the Early-Middle Miocene formation of the Pannonian Basin, when the lithosphere stretched and thinned (thus the crust is "only" 22-26 km thick) and the hot astenosphere got closer to the surface (Horváth and Royden, 1981).

There are two main types of geothermal reservoirs in Hungary:

(1) Integranular aquifers associated with the several thousand meter thick Upper Miocene-Pliocene "Pannonian" multi-layered basin fill sediments composed of successively clayey and sandy deposits. The best sandy aquifers at a depth interval of ca. 700-1,800 m in the interior parts of the basin have a temperature between 60-90 °C and are widely used for direct heat purposes (mainly agriculture - heating of greenhouses) as well as for balneology.

(2) The karstified zones of the Palaeozoic-Mesozoic carbonates, as well as fractured zones in the crystalline rocks in the basement with high secondary porosity. At this depth (on average 2000 m or more) temperature can exceed 100-120 °C, and are the target reservoirs for larger geothermal district heating systems.

In 2011 595 active thermal water wells produced 68,5 million m^3 of thermal water in Hungary representing 697,48 MW_{th} / 10,255TJ/y (Nádor et al., 2013). The majority of the abstracted water was used for balneology (249 wells, 36,8 million $m^3$of water, capacity of 265 MW_{th} and production of 5,285 TJ/year). In direct heat utilization the main sector was agriculture, where 9,34 million m^3 of thermal water was abstracted by altogether 154 wells, representing an installed capacity of 241,84 MW_t and an estimated use of 2,800 TJ/y. Of this about 75% was used for heating of greenhouses and plastic tents, and the rest for animal husbandries. As of 2011, geothermal energy contributed to the heating of 19 settlements. At an additional 16 locations individual buildings were heated by thermal water. This altogether used 6,76 million m^3 of thermal water, which represent an estimated installed capacity of 132,97 MW_t and use of 1,350 TJ/y. The reported industrial use was relatively low (8,3 MW_t / 170 TJ/y). In the "other" category (including public water supply – mainly for drinking water, sanitary water and some undefined utilization schemes) altogether 14,1 million m^3 of abstracted thermal water represents an installed capacity of 49,37 MW_t and an estimated use of 650 TJ/y.

Since 2011 altogether 58 new thermal water wells have been drilled in Hungary. The steady increase of new wells in each year demonstrates the developing geothermal sector in Hungary, partly related to the expansion of previous projects, partly related to new district heating projects and a moderate development in the agriculture sector. The increase of new reinjection wells is a positive progress, altogether 13 reinjection well were drilled, mostly into porous aquifers.

The 3 major operational issues in Hungary are reinjection, gas-content and scaling.

1.5.2 Reinjection

Reinjection is relatively simple into fractured-karstified carbonate reservoirs (as some successful examples exist in Hungary, mostly related to district-heating projects), however it is a more complex procedure to reinject water into the Upper Miocene (Pannonian) integranular reservoirs, as the necessary injection pressure can substantially increase within a relatively short time. The highly heterogeneous lithology (silt, clay intercalations) and high clay content often cause the plugging of screens (perforation) in the well and pore throats of the reservoir formation, which leads to the decrease of permeability due to clay swelling, pore-space blocking by fine particles, or precipitation of dissolved solids due to the mixing of injected and formation water. The precise mechanisms which determine injectivity are site specific and processes are not entirely understood yet, although several local experiments including theoretical analyses, numerical simulations, laboratory and in-situ experiments were carried out in SE –Hungary (Hódmezővásárhely, Szeged and Szentes areas - Szanyi and Kovács, 2010; Bálint et al., 2010; Barcza et al., 2011). The main lessons learned from these studies are that long-term sustainable injection is possible, but instead of ad hoc approaches, scientifically sound solutions must be found were the right selection of the injection well (location and depth), specially designed and completed well in technical terms, good hydraulic performance, very slow transient performance process (pressure, temperature, flow rate) are needed. Special investigations are needed as early as the drilling phase to determine permeability, conductivity, rock-mechanical, pressure, geothermal properties of the reservoir as well as hydrogeochemistry of the formation fluids. It was also revealed that the main reason for the initial failure was that early projects tried to transform existing abstraction wells into re-injection wells, not paying attention to micro-filtration prior to reinjection. As most of the agricultural utilization (heating of greenhouses) and some of the district heating projects are targeting these intergranular aquifers, there is a growing demand to increase the number of reinjection wells, which is shown by their growing number since 2011. Nevertheless the pressure and water level drop on the largest part of the Great Hungarian Plain is a significant issue, as the majority of thermal water production from the Upper Miocene (Pannonian) integranular reservoirs is still based on single-well configuration.

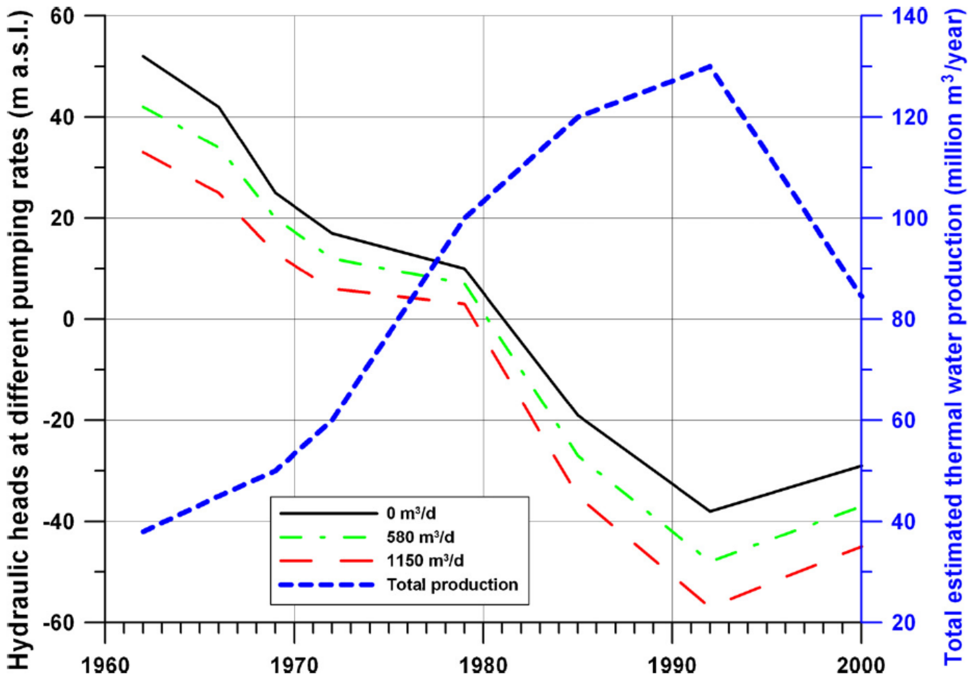

Figure 4 Changes in measured hydraulic head for pumping test of the Székelysor well with time for different well flow-rates, and estimated overall thermal water production in Hungary (Szanyi and Kovács, 2010)

1.5.3 Dissolved gas content

Many Hungarian wells produce thermal water with significant dissolved gas content (methane, nitrogen, CO_2, H_2S). Degasification units are often installed next to the production wells and in some cases the separated gas (methane) is used in auxiliary equipment, however often the gas is just released to the atmosphere.

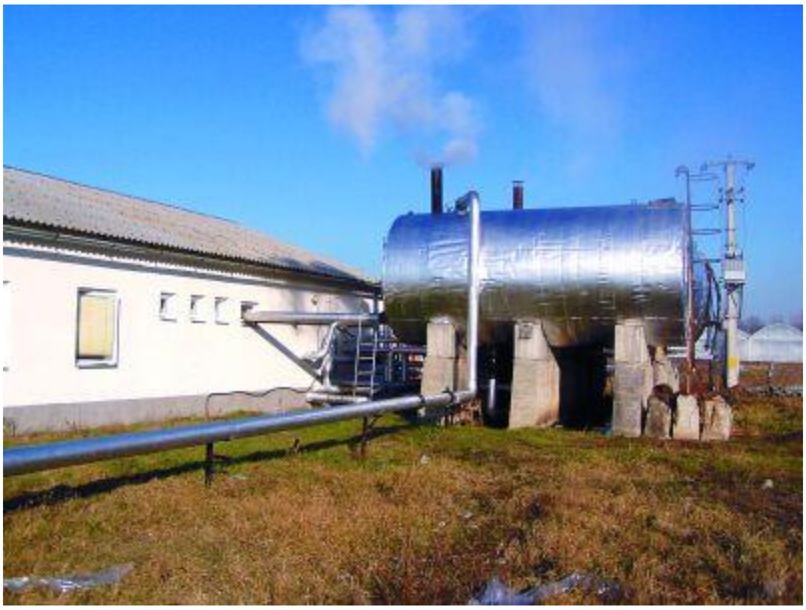

Figure 5 Degasification unit at Kunszentmárton, Hungary

1.5.4 Scaling

Scaling is a typical operational problem when producing thermal waters with high dissolved content. Precipitation of hard scales can radically reduce the effective flow diameter of geothermal wells. The most common scale type is calcite. In some cases (e.g. Egerszalók) the precipitating carbonates form tuff deposits which serve as a tourist attraction, however more often the solution to prevent scalings is use of inhibitors (acids). A special form of scaling is barite precipitation, which thermal decomposition by laser is an ongoing RD activity in Hungary (Bajcsi et al., 2015).

Table 5 Summary of operational problems in Hungary

	SOLVED		UNSOLVED
	Issue	Solution	Issue
Scaling	Carbonate scaling	Inhibitors (acids)	
			Barite scale removal
Corosion	No major issues reported		
Gas content	CH_4 - safety	Gas separator	Separated gas treatment or utilisation
Reinjection	Reinjection in poorly cemented sands or sand interbedded with clays	Proper well design, microfiltration, backwashing	Further RD&D needed
	Surface disposal of thermal waste water	Thermal lakes	High temperature and high TDS of thermal waste water

1.5.5 References

Bajcsi, P., Bozsó, P., Bozsó, R., Molnár, G., Tábor, V., Czinkota, I., Tóth, T.M., Kovács, B., Schubert, F., Bozsó, G., Szanyi, J., 2015: New geothermal well-completion and rework technology by laser. *Central European Geology*, Vol. 58/1–2, 88–99, DOI: 10.1556/24.58.2015.1–2.6

Barcza, M., Bálint, A., Kiss, S., Szanyi, J., Kovács, B., 2011: A Szentes térségi hévíztározó épződmények hidrodinamikai viszonyai szivattyú tesztek kiértékelése alapján. *A Miskolci Egyetem Közleménye, A sorozat, Bányászat*, vol. 81, p. 245-254

Bálint, A., Barcza, M., Szanyi, J., Kovács, B., Kóbor, B., Medgyes, T., 2010: Investigation of thermal water injection into porous aquifers. *Abstracts of 1st Knowbridge Conference on Renewables.* September 27-28, 2010. Miskolc, Hungary.

Dövényi, P., Horváth, F., 1988: A review of temperature, thermal conductivity and heat flow data form the Pannonian Basin. In: Royden, L.H., Horváth, F. (Eds): *The Pannonian Basin a Study in Basin Evolution.* American Association of Petroleum Geologist memoirs, Tulsa, Oklahoma, 45, 195-233.

Horváth, F., Royden, L.H., 1981: Mechanism for formation of the intra-Carpathian basins: A review. *Earth Evolutionary Sciences,* 1, (1981), 307-316.

Nádor, A., Tóth, A.N., Kujbus, A., Ádám, B., 2013: Geothermal energy use, country update for Hungary. *Abstracts, European Geothermal Conference*, June 3-7, Pisa, Italy, ISBN 978-2-8052-0226-1

Szanyi, J., Kovács, B., 2010: Utilization of geothermal systems in South-East Hungary. *Geothermics*, vol. 39, p. 357-364.

1.6 Iceland

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1.6.1 Geothermal Energy in Iceland

Iceland is a pioneer in the use of geothermal energy for space heating and generation of electricity with geothermal energy has increased significantly in recent years. Geothermal power facilities currently generate 25% of the country's total electricity production.

During the course of the 20th century, Iceland went from what was one of Europe's poorest countries, dependent upon peat and imported coal for its energy, to a country with a high standard of living where practically all stationary energy is derived from renewable resources. In 2014, roughly 85% of primary energy use in Iceland came from indigenous renewable resources. Thereof 66% was from geothermal.

Iceland is a geologically young country. It lies astride one of the earth's major fault lines, the Mid-Atlantic ridge. This is the boundary between the North American and Eurasian tectonic plates. The two plates are moving apart at a rate of about 2 cm per year. Iceland is an anomalous part of the ridge where deep mantle material wells up and creates a hot spot of unusually great volcanic productivity. This makes Iceland one of the few places on earth where one can see an active spreading ridge above sea level.

As a result of its location, Iceland is one of the most tectonically active places on earth, resulting in a large number of volcanoes and hot springs. Earthquakes are frequent, but rarely cause serious damage. More than 200 volcanoes are located within the active volcanic zone stretching through the country from the southwest to the northeast, and at least 30 of them have erupted since the country was settled. In this volcanic zone there are at least 20 high-temperature areas containing steam fields with underground temperatures reaching 250 °C within 1,000 m depth. These areas are directly linked to the active volcanic systems.

About 250 separate low-temperature areas with temperatures not exceeding 150 °C in the uppermost 1,000 m are found mostly in the areas flanking the active zone. To date, over 600 hot springs (temperature over 20 °C) have been located (

Figure 6).

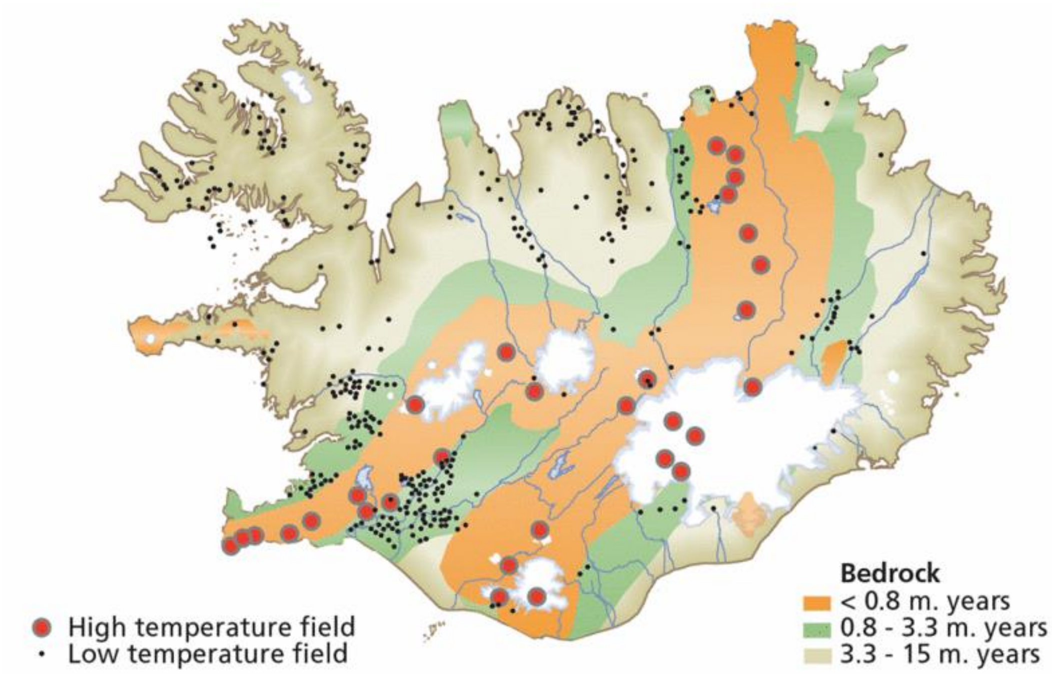

Figure 6 The geothermal resources in Iceland.

1.6.2 Direct Use of Geothermal Resources

Iceland is well known to be a world leader in the use of geothermal district heating. After the second World War, Orkustofnun (National Energy Authority of Iceland) carried out research and development, which has led to the use of geothermal resources for heating of households. Today, about 9/10 households are heated with geothermal energy.

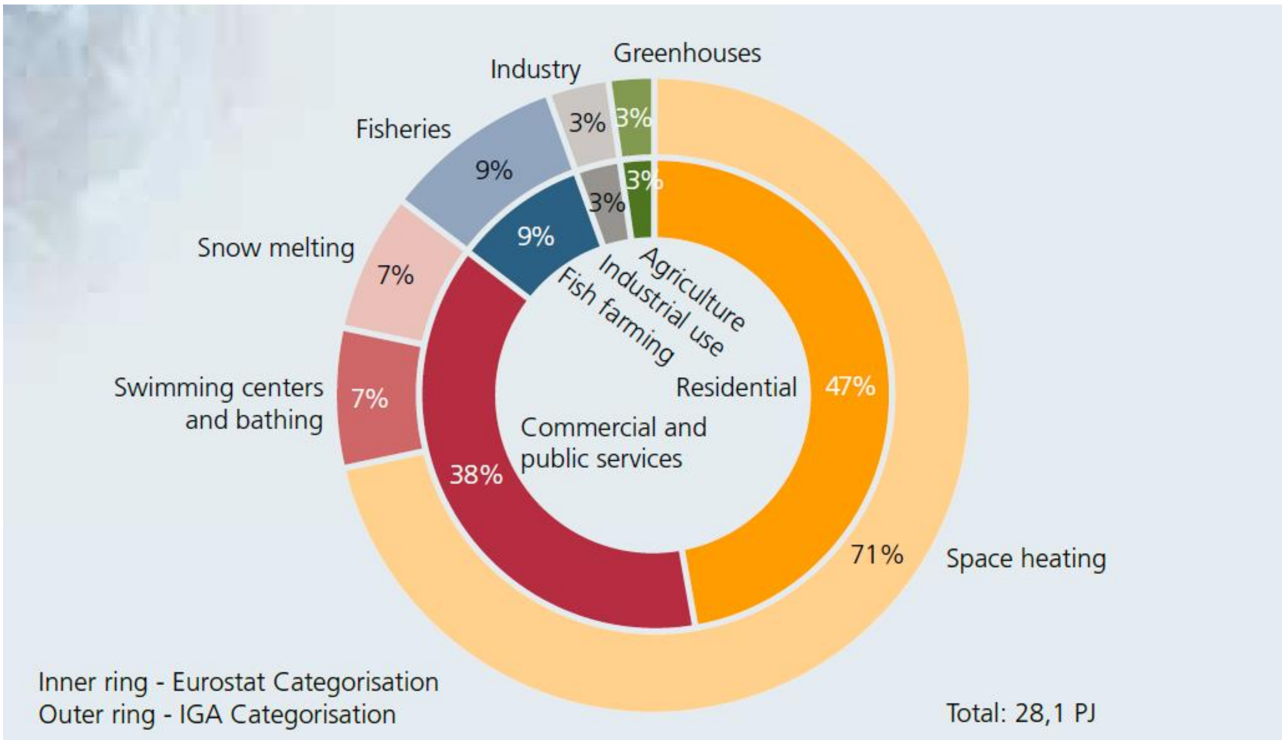

Figure 7 Utilisation of geothermal energy 2014 (Source: Orkustofnun)

Space heating is the largest component in the direct use of geothermal energy in Iceland.

Figure 7 gives a breakdown of the utilization of geothermal heat for 2014. In the year 2014, the total heat use by geothermal energy was 28,1 PJ, with space heating accounting for 71%.

1.6.3 Generation of Electricity using geothermal energy

Generating electricity with geothermal energy has increased significantly in recent years. As a result of a rapid expansion in Iceland's energy intensive industry, the demand for electricity has increased considerably.

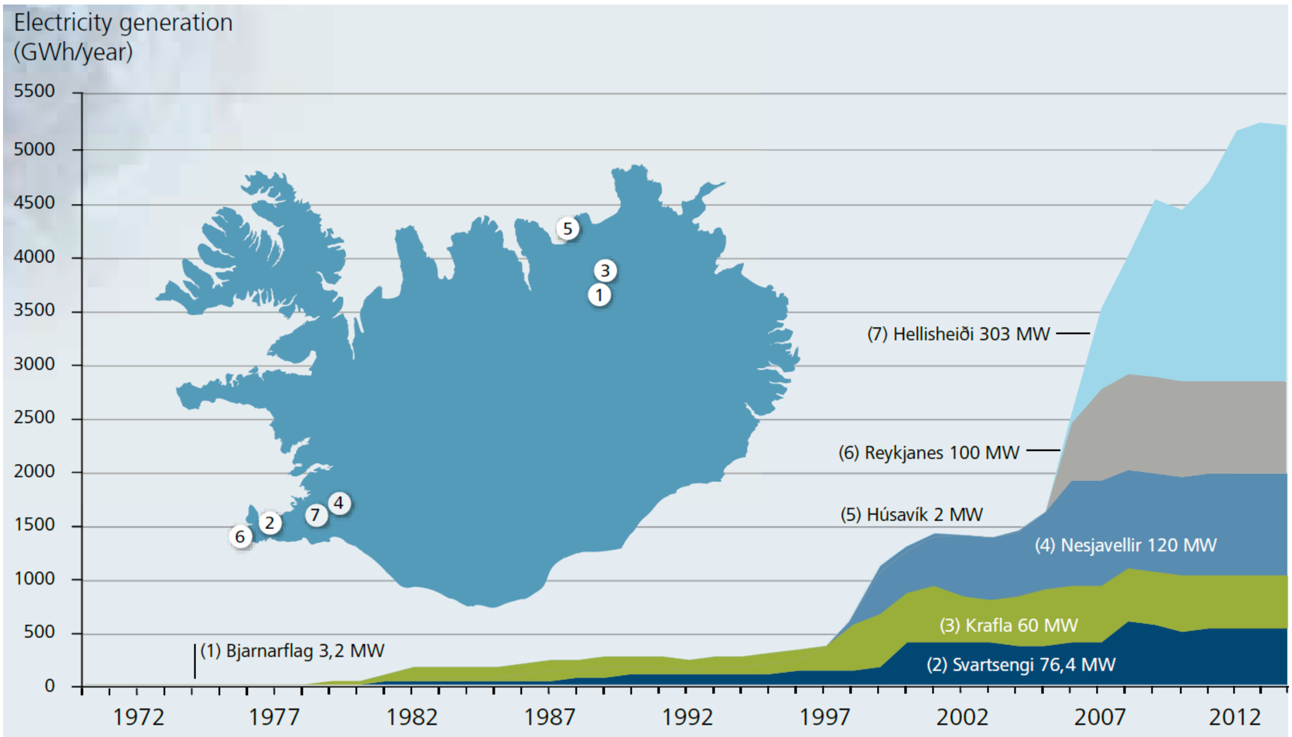

Figure 8 Generation of electricity from Geothermal resources (Source: Orkustofnun)

Figure 8 shows the development from 1970-2014. The installed generation capacity of geothermal power plants totalled 665 MW_e in 2013 and the production was 5,245 GWh, or 29% of the country's total electricity production. (Source: Orkustofnun)

1.6.4 Example of operational issues in utilizing geothermal energy in Iceland

The geothermal utilization in Iceland spans over 100 years and in this time huge amount of knowledge has been accumulated regarding operation of geothermal systems, possible problems and solutions. The utilization spectrum changed drastically when technology to produce electricity from geothermal steam became available and various direct uses of geothermal were developed i.e. for space heating and greenhouse heating, in aquaculture and industry and in snow and ice melting in addition to the balneology uses. The utilization of geothermal energy increased steadily during the last century and the most rapid development during the last decades has been the dramatic increase in use of geothermal heat pumps for space heating and cooling.

On the technical side, the most common operational problems are related to the chemistry of the geothermal fluids which sometimes contain quite considerable concentrations of minerals and gases, causing scaling and corrosion in wells and surface installation. Many of those technical problems have been solved, or minimized at least, by improved well design and well operation, proper material selection and chemical treatment of the geothermal fluids, including use of chemical inhibitors

This report will try to cast a light to some of the problems Iceland has faced and its solutions.

1.6.5 Scaling

Two of the most common geothermal scales are silica (SiO_2) and calcite ($CaCO_3$). Both these scales are white colored and not easy to tell apart visually. The silica scales often appear grey or black due to small amounts of iron sulphide, a corrosion product found inside all geothermal pipelines. A quick method to distinguish these is to put a drop of hydrochloric acid on a piece and if bubbles are formed it is calcite.

Types of scaling occurring in geothermal waters

Silica scales:

- Found to some extent in all high temp installations but by maintaining the temperature above the solubility level for amorphous silica the scaling should not occur

- In geothermal CHP plants silica scaling can occur in heat exchangers and pipes

- In the dilute high temperature fields where the chloride concentration is low the precipitation of amorphous silica can be postponed by low flow rate through heat exchangers allowing the aqueous silica to form polymers in the solution

- A problem in flash turbines and when reinjecting low pressure geothermal fluids

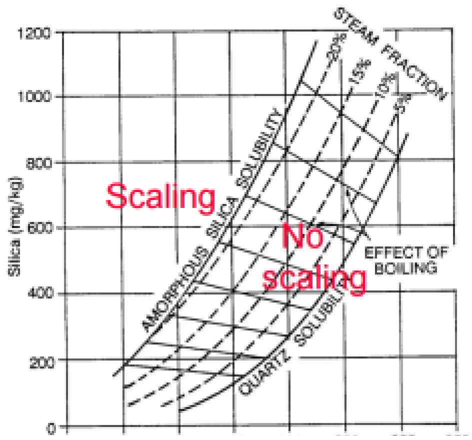

Figure 9 Solubility of silica in water, scaling occurs above the amorphous silica solubility curve

Iron silicate scales

- Occur in saline geothermal fluids or in fluids disturbed by the effects of volcanic gas
- Normally do not form at higher pressures than 16-18 bar

Sulphide scales

- In saline geothermal fluids or in fluids disturbed by the effects of volcanic gas sulphide deposits are prone to form by reaction of metal(s) with H2S.

Calcium carbonate scales

- Common in wells with reservoir temperatures of 140-240 °C, and are primarily found at the depth where the water starts to boil in the well
- Inhibitors have been used to prevent calcite deposition in geothermal wells.

Magnesium silicate scaling

- Magnesium silicates are formed upon heating of silica containing ground water or mixing of cold ground water and geothermal water.

1.6.5.1 *Corrosion*

Materials used in high temperature/pressure geothermal steam can be subjected to corrosion due to the aggressiveness of the geothermal fluid and non-condensable gasses such as hydrogen sulfide (H_2S) and carbon dioxide (CO_2), chloride ions (Cl^-) and hydrogen fluoride (HF).

The main species causing corrosion in geothermal waters:

Hydrogen Ion

- The corrosions rate of most materials increases as the pH of the fluid decrease

Chloride

- The chloride ion accelerates corrosion of metallic surfaces.
- “pitting” as well as uniform corrosion.
- Stress corrosion cracking in some types of stainless steel

Hydrogen Sulphide

- Copper and its alloys are attacked by hydrogen sulphide.
- Sulphide stress cracking in high strength steels
- Mild steel more suitable

Carbon Dioxide

- Mild oxidizing agent that causes increased corrosion of plain carbon steels

Ammonia

- Ammonia causes increased corrosion of copper-based alloys, and is especially important in

Sulphate

- Sulphate is the primary aggressive ion in some geothermal fluids.

Oxygen

- Usually not present in geothermal fluids except in fluids at low temperature and in heated ground waters for residential use
- Hydrogen sulphide reacts with the oxygen and prevents corrosion

1.6.5.2 *Lagnaval.is*

A lot of the knowledge and solutions to different operational issues within the Icelandic district heating system has been accumulated in a guideline website called Lagnaval.is (e. pipe selection) available only in Islandic language.

Lagnaval.is is designed to advise on pipe selection for Icelandic households taking into account the different properties of the geothermal water in question and piping system needed. The recommendations are based on two databases. One database lists up the chemical resistance of piping materials for the temperature range 0 to 80 °C and various installation systems. It is based on knowledge and experience of the owners of the site of the piping materials mainly used and is being used. The other database lists up the chemical properties of the geothermal waters based on analysis made by Orkustofnun, Reykjavik Energy and others. It covers almost all the heating and water supply systems of the country.

This site makes it also possible download data on technical properties of pipes, research on them and links to other sites that provided information on pipe systems.

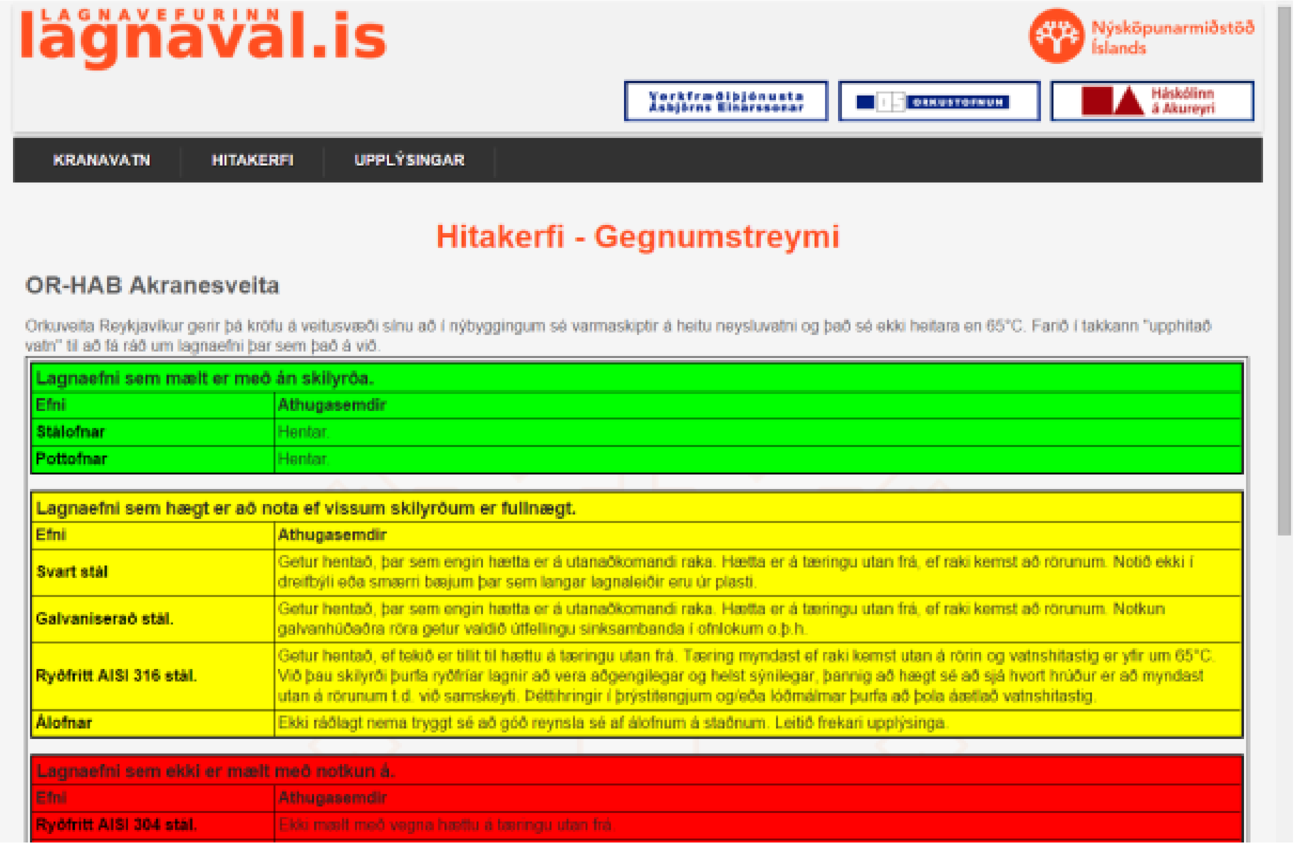

Figure 10 Screenshot of the Icelandic website www.lagnaval.is.

1.6.6 High enthalpy - Scaling and Corrosion

Silica and Sulfide scaling are very common in Icelandic High temperature fields.

Dissolved silica (SiO2) is the main component of geothermal fluids from volcanic rock reservoirs with concentrations typically in range between 400 and 600 ppm with increasing concentration at increasing reservoir temperature. Since precipitation of quartz is kinetically hindered, precipitation of amorphous silica is likely and monomers and polymers may deposit on available surfaces, such as pipes or equipment or solid particles in the geothermal fluid. Methods have been developed to control silica scaling in geothermal power plants, based on for example; pH control, rapid cooling of the geothermal fluid, or addition of inhibitors.

Sulfide scaling in wells down hole and in surface pipelines is more pronounced in high than low enthalpy geothermal areas were the liquid is of seawater or brine composition. Extensive research been carried out on saline’s areas for the last decades.

Figure 11 Silica scaling occurring inside geothermal pipes after 14 days of use. Samples for corrosion testing can be seen totally sealed by the scale.

Figure 12 Sulphides scales precipitated in one year. To the left the scales (mainly ZnS covered by Cu-sulphide) coats the fluid-flow control valve (14 cm long). To the right the scales (mainly ZnS) coats the inner surface of the pipe (7 cm thick).

1.6.7 Gas content of Icelandic Geothermal Waters

1.6.7.1 *Low temp fields*

Figure 13 Hæðarendi at Grimsnes; The product is used in greenhouses, for manufacturing carbonated beverages, and in other food industries

Since 1986, a facility at Hædarendi in Grímsnes, South Iceland, has produced commercially liquid carbon dioxide (CO_2) from geothermal fluid. The Hædarendi geothermal field temperature is intermediate (160 °C) and gas content of the fluid very high (1.4% by weight). The gas discharged by the wells is nearly pure carbon dioxide with a hydrogen sulfide concentration of only about 300 ppm. Upon flashing, the fluid from the Hædarendi wells produces large amounts of calcium carbonate scaling. Scaling in the wells is avoided by a 250 m long downhole heat exchanger made of two coaxial steel pipes. Cold water is pumped through the inner pipe and back up on the outside. Through this process, the geothermal fluid is cooled and the solubility of calcium carbonate increased sufficiently to prevent scaling. The plant uses approximately 6 l/sec of fluid and produces some 2,000 tons annually. The product is used in greenhouses, for manufacturing carbonated beverages, and in other food industries. The production is sufficient for the Icelandic market.

1.6.7.2 *High temperature fields*

Figure 14 Gas laboratory at Hellisheiði Power Plant, (photo: Orkuveita Reykjavíkur)

Although geothermal power plants produce renewable energy with very little emissions compared to their fossil fuel counterparts, emission of non-condensable gases is an inevitable part of high temperature geothermal power production. The major gases in geothermal fluids are CO_2, H_2S, H_2, N_2, CH_4 and Ar. Concentration of these gases varies from one geothermal field to another and depends on temperature, composition of fluid and geological setting.

Table 6 A summary of noncondensable gases from power plants in Iceland.

Location	MW	CO_2 (t/year)	CO_2/ MW	H_2S (t/year)	H_2S/ MW
Hellisheiði	303	43.158	142	12.370	56
Nesjavellir	90	18.612	207	8.700	126
Krafla*	60	44.300	667	6.810	83
Reykjanes	100	25.090	251	860	9
Svartsengi**	55	53.840	979	1020	19

*2011

**Installed capacity 75 MW

1.6.7.3 *The carbfix project* (source: https://www.or.is/en/projects/carbfix)

Reducing industrial CO_2 emissions is considered one of the main challenges of this century. By capturing CO_2 from variable sources and injecting it into suitable deep rock formations, the carbon released is returned back where it was extracted instead of freeing it to the atmosphere. This technology might help to mitigate climate change as injecting CO_2 at carefully selected geological sites with large potential storage capacity can be a long lasting and environmentally benign storage solution.

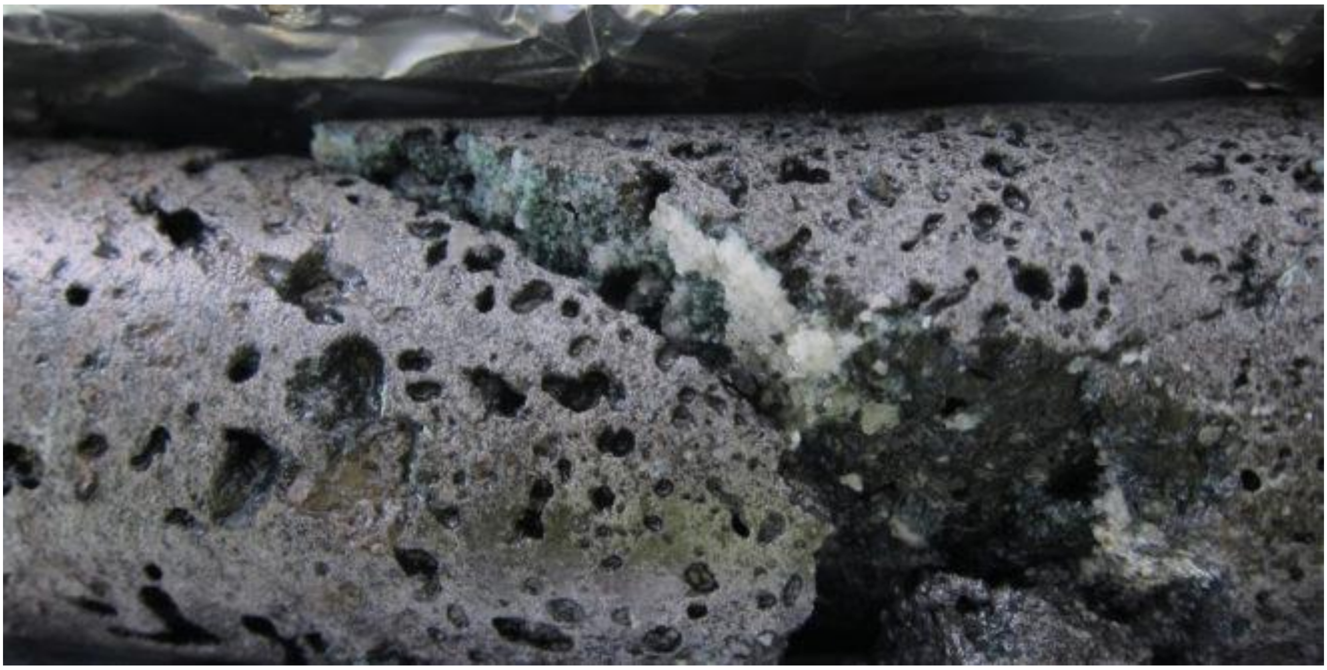

Figure 15 Core from Carbfix site. (Image: Carbfix project)

To address this challenge, the CarbFix project is designed to optimize industrial methods for storing CO_2 in basaltic rocks through a combined program consisting of, field scale injection of CO_2 charged waters into basaltic rocks, laboratory based experiments, study of natural analogues and state of the art geochemical modeling. A second and equally important goal of this research project is to generate the human capital and expertise to apply the advances made in this project in the future.

This research program includes:

- Field scale injection of CO_2 charged waters into basaltic rocks at the Hellisheidi natural laboratory. The Hellisheidi natural laboratory, situated in the Hengill area, SW Iceland, comprises ideal conditions for studying the feasibility of permanent CO_2 storage as minerals in basaltic rocks due to availability of CO_2 and water, the presence of fresh basalts, suitable geological structures, and an extensive infrastructure.

- Laboratory experiments research program. The emphasis of this experimental program is to quantify basalt dissolution and carbonate precipitation rates stemming from CO_2 injection.

- Studies of natural CO_2–rich water reactivity as natural analogues to the behavior of injected CO_2. A significant number of natural sites have experienced basalt interaction with CO_2 charges waters. Studies of these systems provide insight into the long-term stability of basalt hosted CO_2 storage.

- Geochemical modeling will be performed to interpret laboratory experiments and field work as well as to predict/optimize the long-term behavior of CO_2injection sites.

The Carbfix team recently submitted an article in Sciense that demonstrates it is possible to permanently store carbon dioxide as minerals in basaltic rocks and that over 95% of CO2 injected is mineralized within two years, instead of centuries or millennia as previously thought. Here is a link to the article http://science.sciencemag.org/content/352/6291/1312.full.

1.6.7.4 *Sulfix project (source: http://georg.hi.is/node/201)*

Hydrogen sulphide (H2S) is among the major components in geothermal fluids, with concentrations ranging from a few ppb to levels of hundreds of ppm (Arnórsson 1995a, 1995b). Hydrogen sulphide is volatile and is commonly emitted into the atmosphere from geothermal power plants, causing potential environmental problems.

Several methods are employed in cleaning H2S emissions including oxidation to form elemental sulphur or sulphuric acid (Sanopoulos and Karabelas, 1997). One method includes injection of H2S into geothermal systems where it may be mineralized into sulphides including pyrite. Reykjavík Energy and Landsvirkjun Iceland, are currently considering such an injection into the geothermal system at Hellisheidi, Námafjall and Krafla, where geothermal gas (CO2, H2S, N2 and H2) will be separated in a gas abatement station and the H2S (+CO2) stream mixed at the surface with water prior to injection into the geothermal aquifer.

1.6.8 Reinjection

With increased geothermal utilization the demand for reinjection of geothermal fluid has increased substantially. The largest impact of reinjection was associated with the Hellisheiði power plant reinjection at Húsmúli.

Commissioning of the Húsmúli reinjection area for the Hellisheiði power plant in late 2011 caused significant induced seismicity that was felt in nearby communities. Seismicity risk and risk mitigation were not taken sufficiently into account when planning the commissioning. Reinjection into the Húsmúli area has now been ongoing for almost three years. The startup and operation of the reinjection has resulted in several lessons learned regarding stakeholder engagement and better work procedures for future projects and operation of the reinjection areas.

The commissioning of the large scale reinjection area at Húsmúli would have benefitted from much better preparation with regard to seismic risk and communication with nearby communities and other stakeholders before the start of injection. Mistakes are often the most valuable experience, and so it can be said of this project. Since 2011 the operator has reviewed and revised its work procedures and processes regarding reinjection, increased monitoring in the geothermal field and increased engagement with local communities and public authorities regarding seismic risk.

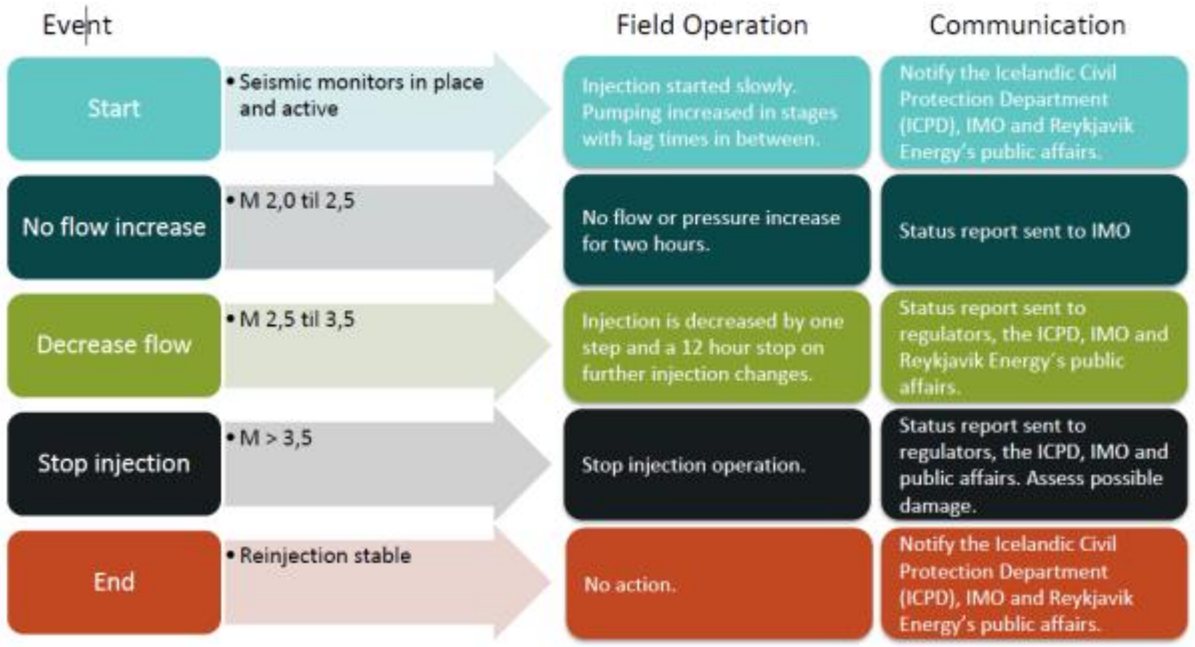

Figure 16 Reykjavik Energy's work procedure for large scale reinjection after a temporary shutdown or when significant changes are made in reinjection from the power plant. The procedure is modeled after AltaRock Energy's decision tree for triggers and mitigation actions from its Newberry EGS demonstration project Reykjavik Energy's work procedure for large scale reinjection after a temporary shutdown or when significant

Table 7 Summary of operational problems in Iceland

	SOLVED		UNSOLVED
	Issue	***Solution***	***Issue***
Scaling	*Scaling in low temp fields*	*Various ways, depending on the site and situation http://www.lagnaval.is*	*Silica precipitation in ultra high temp fields - IDDP wells*
Corosion	*Corrosion in low temp fields*	*Various ways, depending on the site and situation http://www.lagnaval.is*	*Silica precipitation in ultra high temp fields - IDDP wells*
	Acid scrubbing	*Wet scrubbing, low cost and rebust, but reduces energy output of plant*	*Find more energy efficient ways to remove acid components from the geothermal steam*
Gas content	*Gas emissions from geothermal plants*	*Carbfix and Sulfix (see www.or.is)*	*Cost reduction on gas separation and reinjection*
	CO2 content in low temp field	*Harness it and sell it*	*Value creation from the separated gases (an alternative to reinjection)*
Reinjection	*Triggered seismic events*	*- Start injection slowly - Keep flow steady - Inform and educate the public*	*Clogging of injeciton wells due to scaling*

1.6.9 References

Axelsson, G., and Gunnlaugsson, E. (ed.), 2000: Long-term monitoring of high- and low-enthalpy fields under exploitation. *World Geothermal Congress 2000 Short Course, Kokonoe, Kyushu District, Japan*. International Geothermal Association, 226 p.

Gunnlaugsson, E., Ármannsson, H,. Sverrir Thorhallsson, S., Steingrímsson, B. PROBLEMS IN GEOTHERMAL OPERATION – SCALING AND CORROSION, Presented at "Short Course VI on Utilization of Low- and Medium-Enthalpy Geothermal Resources and Financial Aspects of Utilization", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 23-29, 2014.

Karlsdottir, K.R. & Thorbjornsson, I.O., 2009: High Temperature Geothermal Wells – Center of Excellence in Iceland – Phase I: Corrosion Testing of Steel in High Temperature Geothermal Wells in Iceland, Technical Report for RANNIS, The Icelandic Centre for Research, in Icelandic (2009).

Karlsdottir, K.R. & Thorbjornsson, I.O., 2013: Corrosion Testing Down-Hole in Sour High Temperature Geothermal Well in Iceland, Presented in NACE-Corrosion Conference and Expo 2013. March 17-21 2013. Orlando Florida.

Þorhallsson, S., 2003: Geothermal well operation and maintenance. IGC2003 - Short Course, The United Nation University, GEOTHERMAL TRAINING PROGRAMME, September 2003

Skulason, G. et al., 2015: „Structural modeling of the casings in high temperature geothermal wells" Geothermics Volume 55, Pages 126–137.

Karlsdottir, S.N., Ragnarsdottir, K.R., Thorbjornsson, I.O. & Einarsson, A., 2015: Corrosion Testing in Superheated Geothermal Steam in Iceland. Geothermics Volume 53, January 2015, Pages 281–290.

Juliusson, B.M., Gunnarsson, I., Matthiasdottir, K.V., Markusson, S.H., Bjarnason, B., Sveinsson, O.G., Gislason, Th., Thorsteinsson, H.H., 2015: Tackling the Challenge of H_2S Emissions, Proceedings World Geothermal Congress 2015 Melbourne, Australia, 19-25 April 2015.

Thorsteinsson, H.H., Gunnarsson, G., 2014: Induced Seismicity — Stakeholder Engagement in Iceland GRC Transactions, Vol. 38, 2014, 879 p.

Gunnarsson, G., Kristjánsson, B., R., Gunnarsson, I., Júlíusson, B., M., 2015: Reinjection into a Fractured Reservoir – Induced Seismicity and Other Challenges in Operating Reinjection Wells in the Hellisheiði Field, SW-Iceland, Proceedings World Geothermal Congress 2015 Melbourne, Australia, 19-25 April 2015.

Matter, Juerg M. et al., 2016: Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions, *Science*, 10 Jun 2016: Vol. 352, Issue 6291, pp. 1312-1314 DOI: 10.1126/science.aad8132

1.7 Italy

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1.7.1 Introduction

Italy is the sixth country in the world for power generation capacity from geothermal resources, and geothermal resources are mainly used for electricity generation. All of the power plants in operation are located in Tuscany, in the two "historical" areas of Larderello-Travale and Mt. Amiata, and are managed by Enel Green Power (Enel GP) (

Figure 17).

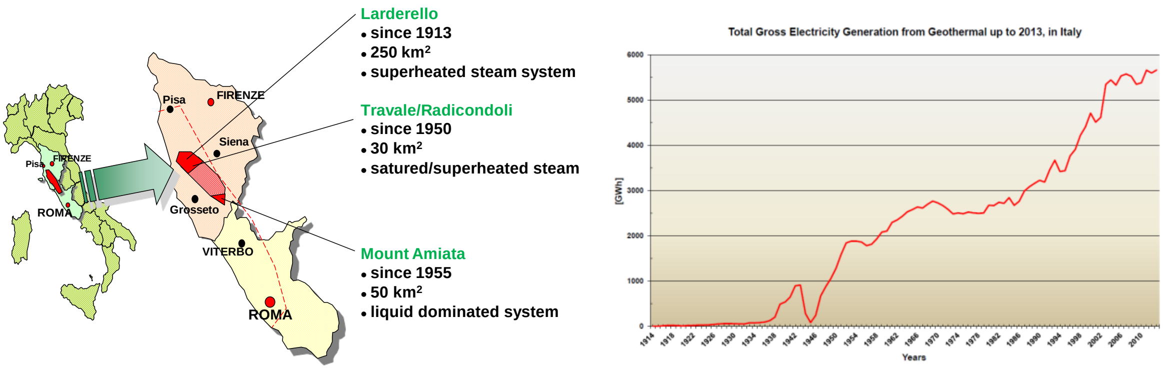

Figure 17 Location of the geothermal fields in Italy (left) and historical trend of electricity generation from geothermal resources (right).

After the Ministerial Decree of July 6, 2012 - Incentives for renewable sources and of the Law Decree 22/2010 the research and exploitation activity of geothermal resources has completely liberalized in Italy. Up to now, about 120 applications have been processed, mostly for new research permits in medium/high enthalpy geothermal resources suitable for power generation, cogeneration and district heating, and several new players entered into the market. Moreover, Research Permit Applications for experimental pilot projects, for a maximum of total 50 MW_e of installed capacity, will be authorized by the Ministry of Economic Development. These experimental projects have been introduced to help the entry of binary cycle technology (zero emissions) in the national geothermal framework. Although a pioneer binary plant was installed on 2001, it proved un-economical and only on 2013 an actually running binary power plant was installed in Mt. Amiata to use the liquid phase after the primary flash of geothermal fluid. All the other plants in operation are flash steam type.

In the year 2014, the gross electricity generation reached 5.8 billion kWh, with a capacity up to 914.5 MW_e. The first in the world Geothermal - Biomass combined power plant was installed in Larderello in 2015. The locally produced biomass feeds a boiler that superheats geothermal steam and increases the output power from 12 MW_e to 17.3 MW_e (Cei et al., 2015).

In the Larderello-Travale area the positive results of the deep drilling and a careful resource management with reinjection programs and chemical stimulation made it possible to continuously increase the steam production (

Figure 17), despite the prolonged and extensive exploitation history, and the Italian power production is an example of effective management. In the Mt. Amiata area, after many years in which all activities have been stopped due to pending engagement problems from local communities, on 2012 Enel GP resumed drilling, replace old units and installed three additional units with a total capacity of 60 MW_e.

All of the geothermal power plants are remotely controlled and operated from a Remote Control Station located in Larderello, where 12 people work in round the clock shifts (24/7), thus ensuring a continuous overseeing. In this way, every plant operating parameter can be monitored and analyzed and it is also possible to shut down and restart any unit from the Remote Station. This solution has allowed a better plant operation, at the same time dramatically reducing operating costs.

Since 1980, in order to increase the productivity of individual wells after drilling and to preserve it during their production life, some stimulation techniques have been developed and are currently being implemented. The aim of these techniques is to improve the permeability of fractured zones and to reduce or eliminate the formation damage (skin factor) by means of acid stimulation (Scali et al., 2013). With the experience gained during the operation and maintenance of the wells, different causes of well damage (formation or wellbore) have been identified and different techniques aimed to the recovery of the original productivity have been studied and implemented. Only in this way Enel GP experience in geothermal fields management, gained over decades, allowed obtaining positive results in a continuously increasing number of cases.

Direct utilization of geothermal heat in Italy showed a constant and stable increment with time, and the estimated total installed capacity is 1,350 MW_{th}, with an energy utilization of over 10,500 TJ/yr (Conti et al., 2015). Out of this total, space heating (DHs and individual systems) accounts for almost 42%, thermal balneology for over 32%, fish farming for about 18%, and the rest (less than 10 %) shared between agricultural and subordinate industrial process uses. Thermal balneology, by far the first use till 2010, delivering ~3,700 TJ/yr in 2014, was passed by space heating and cooling, with ~4,600 TJ/yr. The increase is mostly attributable to ground-source heat pump (GSHP) installations that have more than doubled their capacity: from ~250 MW_{th} to over 550 MW_{th}: an average annual growth rate of some 22%/yr.

Geothermal district heating (DH) networks are expanding thanks to GSHP technology, in particular open loop systems. Regarding deep geothermal resources, several new projects are currently under development, among which the new DH project of Grado (touristic town near Trieste) and the expansion of the DH system in Ferrara are worthy of mention. In addition, direct use projects have started operation during 2014, including the DH of the town of Montieri and a brewery in the Boraciferous region of Tuscany that uses geothermal steam to feed its industrial equipment.

1.7.2 General, solved and unsolved operational issues

The chemical composition of the geothermal fluid in high enthalpy fields (Larderello, Mt. Amiata) is the origin of the two major operational problems: Scaling and Corrosion.

Scaling Issues

It is the deposit from single flushing fluids, on reinjection wells, pipelines, separators of silica in solid phase.

This problem is usually tackled with:

- monitoring and diagnostic
- chemical (washing) and physical (pressure/temperature management) operations

Corrosion Issues

The steam produced by deep wells is often characterized by the presence of aggressive elements (O, H_2S, CO_2, NH_3, H, sulphates, Hg and Chlorine), which accelerates corrosion.

In general, the pressure decrease in-well or in pipes produces acid steam condensation, inducing localized corrosion on casing, pipes and turbine parts. This is a main issue.

Enel GP operates fields for electricity production having aggressive fluids that are considered unmanageable by most operators, adopting the following technical solutions:

- monitoring systems
- steam washing to break down the pH of the fluid
- temperature and pressure management
- special coatings and materials

According to the different location of the corrosion attack into the streamline of the fluid, washing systems could be installed inside the well, at well head or at power plant inlet.

Emission and Gas Content

Natural gases and associated minerals are emitted at power plant and, in minimal content, for production test of wells and power plant outage. This problem is relevant only when hydrothermal fluids are particularly rich of natural, incondensable gases and in steam flash plants. This problem is less relevant in binary or DH plants. Most of the problem is under control by monitoring, abatement systems and minimization of outage gas emission, although technology improvement would be beneficial, especially for improving economics. In order to control the environmental effect of the emissions, the following components are continuously monitored:

- Gas Phase: Hg, As, Sb, Se, NH_3, H_2O, CO_2, H_2S, CH_4, N_2, O_2+Ar
- Liquid Phase: Hg, As, Sb, Se, Al, Cd, Cr, Fe, Mn, Ni, Pb, Cu, V, Zn, NH_4, S, H_3BO_3

There are two different approaches for the reduction of the emissions:

Solution 1: Utilisation of an abatement systems

In Italy it is widely used the AMIS (Figure 18) abatement system: it is a system patented and developed by Enel GP to reduce SO_2 and Hg (Sabatelli et al., 2009). The abatement efficiency is very high (>90%), using a large amount of soda. The operational extra cost is in the range of 0.5k€/year and plant + equipment (3-4 M€).

Figure 18 AMIS system.

Solution 2: minimization of outage gas emission by networking the gathering system of different power plants

This approach is not always possible, and the costs are strongly site dependent.

Another important component of the gas emission is CO_2, which is naturally associated with exploitation of geothermal fluid. Large CO_2 content reduces production, due to the parasitic losses for gas extraction. The only possible solution could be the CO_2 capture and storage techniques (CO_2 can be also captured and used for industrial processes). The feasibility of total reinjection of fluids (liquid and gas) is still to be proved.

Reinjection Issues

On the reinjection stream the major operational issue is induced by scaling, due to cooling of separated fluid in liquid dominated reservoirs. In order to avoid scaling, the reinjected fluids should be kept at high temperature, with related loss of thermal energy. For example, in a typical 20 MW_e plant, the amount of liquid phase is about 300 t/h of hot fluid reinjected at T=180 °C. If it would be possible to reduce the reinjection temperature for 100 °C, reinjecting at 80 °C, it will allow to use the fluids for additional energy production of about 3-5 MW_e, with 20% of increasing in revenues.

Improved plant performance

An increase of the overall plant performances, i.e. increasing both availability and efficiency in energy conversion, is rather important in terms of increasing revenues. It can be achieved with advanced diagnostic, plant automation, by developing sensors and adapting industrial automation technology.

In case of utilization of submersible pumps, their failure can be considered as a major problem, with associated loss of production. The only possible solution is the replacement of pumps every 4 years, with an associated cost of about 3-5 k€/pump.

Geothermal system management: reservoir depletion mitigation

The loss of production due to the reservoir depletion is a major operative aspect of geothermal project life cycle. The only possible approach to mitigate it is through data acquisition and monitoring, resource evaluation and management, modeling. This is an urgent issue: new make-up wells are required to keep production at design level.

Table 8 Summary of operational problems in Italy

	SOLVED		UNSOLVED
	Issue	**Solution**	**Issue**
Scaling	Deposit from single flushing fluids, deposit on reinjection wells, pipelines, separators	Monitoring systems	Improvement of actual technology for chemical of physical treatment and for monitoring systems (including cost reduction)
		Chemical treatment (e.g., fluids washing)	
		Temperature dejection mangement (i.e. maintain the temperature above the scaling limit, linked to reinjection constraints)	
Corosion	Corrosin of casing, pipes and turbines	Monitoring systems	Improvement of actual technology
		Steam washing to break down the pH of the fluid	
		Special coating/material	New materials
		Avoid condensation by pressure/temperature management	Improvement of actual technology
Gas content	Natural gases and associated minerals	Abatement systems	Better economics of abatement systems
	- Large CO_2 content - Reduce production (parasitic loses for gas extraction)	CO_2 extraction/sequestration (it is economical only when used for chemical industry)	CO_2 sequestration and capture technology at economic price
	Power plant outage gas emission	Minimization of outage time, hamronitaziton of gathering system to avoid "island" power plant	Total reinjection technoogy
Reinjection	Scaling due to cooling of separated fluid and liquid dominated reservoirs	Reinjection at high temperature	Improved utilization of thermal energy
Plant performance	To increase plant performance and availability	Advanced diagnostic - plant automation with sensors, industrial technology	
Geothermal system management	Depletion of reservoir	Data acquisition and monitoring, resource management	Integrated model of geothermal system (from well to plant)
Auxiliary management	Submersible pump failure	Replacement of pumps every 4 years	Long-living pumps

1.7.3 References

Cei, M. & Razzano, F., 2015: Geothermal Power Generation in Italy 2010-2014 Update Report, *Proceedings of the World Geothermal Congress 2015*, Melbourne, Australia.

Conti, P., Grassi, W., Passaleva, G. & Cataldi, R., 2015: Geothermal Direct Uses In Italy: Country Update for WGC2015, *Proceedings of the World Geothermal Congress 2015*, Melbourne, Australia.

Sabatelli, F., Mannari, M., Parri, R., 2009: Hydrogen sulphide and mercury abatement: development and successful operation of AMIS technology, *Transactions* GRC.

Scali, M., Cei, M., Tarquini, S. & Romagnoli, P., 2013: The Larderello – Travale and Amiata Geothermal fields: case histories of engineered geothermal system since early 90's, *Proceedings* EGC, Pisa, Italy, June 3-7 2013.

1.8 The Netherlands

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1.8.1 Introduction

Geothermal energy in the Netherlands is high on the agenda for further sustainability, especially in heat production. The Dutch culture is the one of co-operation between industry and government, also known as the Rhineland model, or "polderen". This means that both are aware of the need for discussion and open knowledge exchange to come to progress in this era of energy transition.

In particularly for geothermal this co-operation is based in different bilateral agreements, but the main driver is the so called "Knowledge Agenda", in which the different stakeholders rank the priorities for initiatives and research.

In the last two year the initiative of DAGO (Dutch association geothermal operators) helped in the process to come to the first developments of specific industrial standards for geothermal. In 2016, main conclusion is that geothermal is a specific industry with specific needs, both for research, as well as for compliancy.

All doublets in the Netherlands produce well, but still some minor operational issues have to be solved. The used reservoirs are developing in a positive way, and the fit between the energy need and the subsoil is pretty good.

1.8.2 Near future

In 2016, the installations do mainly produce heat for the use in the horticultural industry, but first projects are coming to the point of execution, to produce heat for district heating. On the mid long term, it is expected that completions will be deeper, up to 4 km. On the longer term, 7 km might be also explored. This will also mean that other technical issues will occur, or conditions for the challenges will be more complex. Another challenge which is foreseen because of these deeper projects is the social impact. Drilling deeper than former projects in urban areas might have implications on the social acceptance.

1.8.3 General challenges

The discussions on social acceptance can develop very quickly, as it was seen in Germany. In the Netherlands, the social climate for geothermal energy is yet very positive. Major challenge is to keep it this way, and therefore it is important to communicate about the sustainable impact of the use of geothermal energy, and the way on how to keep it as sustainable as possible.

1.8.4 Operational challenges

The challenges of today are focussing on different research projects, mainly sponsored by the Knowledge Agenda. Three main projects are rolled out in 2016, motivated from a compliancy perspective, and fulfilling a practical need for the industry because the outcome will lead the industrial standards:

- Induced seismicity

Gas production in the Netherlands lead to induced seismicity and therefore, all other activities in the subsoil do have to follow a thorough methodology in a quantitative risk assessment. The methodology is directly derived from the oil- and gas industry, and also German experience is used to come to the best set up of the methodology.

- Well integrity

This project is set up with the objective to come to a standardized methodology for well integrity geothermal, based on the ISO 116530 for Oil & Gas. Output will be: maintenance programs, barrier monitoring plans for corrosion scaling and logging, HSE instructions, over the lifespan of a project and formalized in industrial standards.

- Production tests and water treatment

With a start of a new project, the test water needs to be handled with care. Different possibilities are studied to provide al long term solution for this water.

1.8.5 Operational issues

These topics are all complex and multi-dimensional caused. Relations to formation water and location are leading.

1.8.5.1 *Injection development*

Some projects suffer with a slow increase of the injection pressure. This is discussed on individual base. On the longer term, lower injection pressures are needed to come to higher COP's. This developing is closely related to the social climate, because acidizing or fracking are ways to lower the pressure, thus increase the overall COP in geothermal.

1.8.5.2 *Corrosion*

Corrosion is a very complex phenomenon and occurs by different causes. Parameters like temperature, pressure, pH, chemistry, gas and completion are needed to be taken into account. There are yet no corrosion models ready to be fit for geothermal. General opinion in the Netherlands is that these models can only be build up with proper empirical data. This might be a great value in co-operation with other reservoirs and technique, using multi based data to come the more intelligent modelling.

1.8.5.3 *Scaling and NORM*

NORM is seen as a result of scaling. Scaling is as complex as corrosion and both phenomena are related. The NORM working group of DAGO is coming to a set of standard on how to deal with NORM, related to EU and NL regulations. Input of oil and gas experts is used. These experts do agree that the comparison to oil and gas is very alike. More cooperation is needed on the longer term to come to proper ways on handling NORM and scaling.

1.8.6 Summary and perspective

Especially because of different phenomena, related to each other, with different disciplines, a total need for central conduct in research is needed. If a standardized way of collected data is developed on an open way, the link between empirical experiences and data to academic research and oil&gas know how can lead to further development in solid based solutions to this issues as above.

The challenge is:

- To convince operators to share data in an open and respectful way, assuring them that the data will not work against them
- To develop solution instead of develop more research questions
- To make solution open source, open access, to motivated new parties to develop in our industry
- To prevent any lock in, either from research institutes, contractors or any other services providers.
- To share ambitions to come to solutions in using geothermal in a general, socially acceptable, to help us into a realistic sustainable development.

1.9 Slovenia

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1.9.1 Introduction

Use of thermal waters is not fundamentally »green«. For a sustainable use of geothermal energy a proper technology of exploitation has to be applied in order to extract as much geothermal energy as sustainably possible along with the lowest impact to our environment. The practice differs much among the 32 utilisation sites in Slovenia, which produce thermal water through 53 wells and three thermal springs. The share of directly produced geothermal energy in the national primary energy consumption was 0.2% (15.5 ktoe or 647 TJ) in 2014, which was approximately 2.5% of RES. Almost half of the energy, 46%, is used for individual space heating at 18 sites, 26% for heating of four greenhouses, 21% for balneology and swimming pools in 18 spas and 8 wellnes centres, only 3% for district heating of settlements Lendava, Murska Sobota and Benedikt, the same share appertains to two sites with air-conditioning systems, and 1% for sanitary water heating at seven sites (Rajver et al., 2015). The Slovenian NREAP foresees an increase in direct use of geothermal energy until 2020 but not much is actually done to reach these goals.

The geological diversity of Slovenia, being positioned at the junction between the Southern and Central Alps, the Dinarides, and the Pannonian basin, results in three types of geothermal systems. Warm water geothermal systems occur in its central part and provide waters up to 48 °C. The basement aquifers produce up to 75 °C, while the sedimentary basin systems in north-east Slovenia are the most exploited, yielding waters of up to 65 °C. This region holds the vastest geothermal potential of the country, as shown by the measured temperature of 202 °C at 3,739 m depth in Murski Gozd, and the produced wet steam with 148 °C from a 4048 m deep well in Ljutomer, unfortunately already decades ago. Only three new wells were drilled in Slovenia in the last five years, having depths of 1.2–1.5 km, and therefore not much new information has been gained on deep geothermal potential lately (Figure 19).

1.9.2 Operational challenges

Thermal water users in Slovenia have to deal with two types of operational issues, hydrogeochemical and hydraulic ones, mostly dependant on the type of an exploited geothermal system. In four geothermal wells producing thermomineral waters with high gas content, degassing of CO_2 into the air has to be supplemented by injection of inhibitors into wells to prevent scaling of carbonates in the pipelines. Methane content is significant at nine wells, causing precaution measures to be taken to prevent possible explosion. Local groundwater level drawdowns caused that several thermal springs disappeared, but regional depletion in NE Slovenia caused by approximately 20 production wells poses greater challenges in preventing further depletion of the aquifers. Of course, use of obsolete technology further worsens the situation, but some users do apply a state–of–the art practice (high energy efficiency and reinjection).

Warm water systems produce mainly waters of Ca–Mg–HCO_3 type with mineralization up to 500 mg/l and no or little free gas. They outflow in natural springs or are tapped by up to 2000 m deep wells. They do not show much operational issues except for limited recharge which may cause either continuous drawdowns, ceasing of thermal springs and intrusion of fresh waters revealed by its tritium content. As a good example, we can point out Eco spa Snovik, which shows high thermal efficiency despite rather low temperature of the produced thermal water. Here, heat pumps are used to extract heat from thermal water with initial temperature of 30 °C so, that the waste water is cooled down to only 12 °C.

Thermal water from clastic aquifers in the Mura-Zala basin in NE Slovenia was mainly recharged in the Pleistocene. Water in the regional and transboundary Pliocene and Upper Pannonian sandy aquifers is abstracted from depths between 800 and 1,500 m. It evolved from Ca–Mg–HCO_3 to Na–HCO_3 type with moderate mineralisation. It contains little free gas and no chemical operational issues are reported. However, due to simultaneous water abstraction at multiple sites for several decades, the regional static groundwater level decreased for 16 to 24 m, and even more locally. Depletion has been observed since 1980's and the groundwater level in the Upper Pannonian aquifer continues to decrease with a rate of more than half meter per year.

Water of Na–Cl–HCO_3 type outflows with a yield of below 5 l/s in abandoned oil and gas fields. It contains up to 14,000 mg/l of total dissolved solids, has a high TOC and phenol index, and lots of methane and CO_2. Degassing of CO_2 causes high scaling potential of the fluid which is mitigated by injection of inhibitors a few hundred meters deep into the production wells, mostly phosphorous and polycarbon acids. Due to methane which is released in air, the production area is marked as an explosion hazard zone and used equipment has to be ATEX certified. When water rich in organic substances was disinfected with chloric acids, dangerous products caused skin burns. Consequently, the thermomineral water was no longer disinfected, but it is rather exchanged in pools more often. In pools, this thermomineral water is in contact with air which causes precipitation of FeS in form of black waddings.

The basement aquifers are various. In Krško–Brežice basin in SE Slovenia, thermal water is produced from the 180–700 m dolomite. It is neutral, of Ca–Mg–HCO_3 type, has mineralization of 400 mg/l and does not cause any operational issue due to chemistry. Its exploitation caused that a natural spring ceased, but not much is actually known on the current water balance of the aquifer. In Benedikt in NE Slovenia, as much as 10 l/s outflows by gaslift from a 1.8 km deep well tapping metamorphic basement (gneiss and dolomitic marble) in the Raba fault zone. It mineralization is 7,300 mg/l and degassing of lots of CO_2 causes severe scaling of carbonates (Figure 20) which is mitigated by injection of inhibitors.

1.9.3 Summary and perspective

The technology of exploitation in Slovenia is in general not sustainable. The only geothermal doublet in the country consists of wells open at depths of 700–1500 m, and is being used for a district heating system of the town of Lendava. All other users emit waste thermal water to surface waters or, more rarely, to sewage systems. While the average groundwater temperature in Slovenia is approximately 12 °C, the emitted waters may reach up to 30 °C, as it is permitted. It is estimated that more efficient heat abstraction could at least double the amount of produced geothermal energy at the same total production if the outlet temperature would be decreased to 12 °C.

Lack of reinjection practice results in chemical and thermal pollution of surface waters, but ecological aspects of thermal water production have yet not been investigated in details. Due to high economic burden of the investment, technological complexity and questionable success, it is not foreseen that thermomineral waters with high content of gases or organic substances will have to be reinjected to maintain the aquifers pressures. However, to enable further geothermal development of the most prosperous area, of NE Slovenia, it is necessary to immediately start with regional reinjection into the Upper Pannonian sandy aquifer. Pilot or demonstration projects are desperately needed if we want to increase the number of users as well as the produced geothermal energy. This issue is further elaborated in Chapter 5.2. *Solved and unsolved reinjection issues in the Slovenian part of the Pannonian Basin.*

Last but not least, it is worth reminding the readers that many parts of Slovenia are poorly investigated in depth (Figure 19). Therefore, exploration of geothermal potential with new research boreholes in target depths of 3–6 km is necessary to find resources with sufficient temperature for cogeneration of electricity and heat.

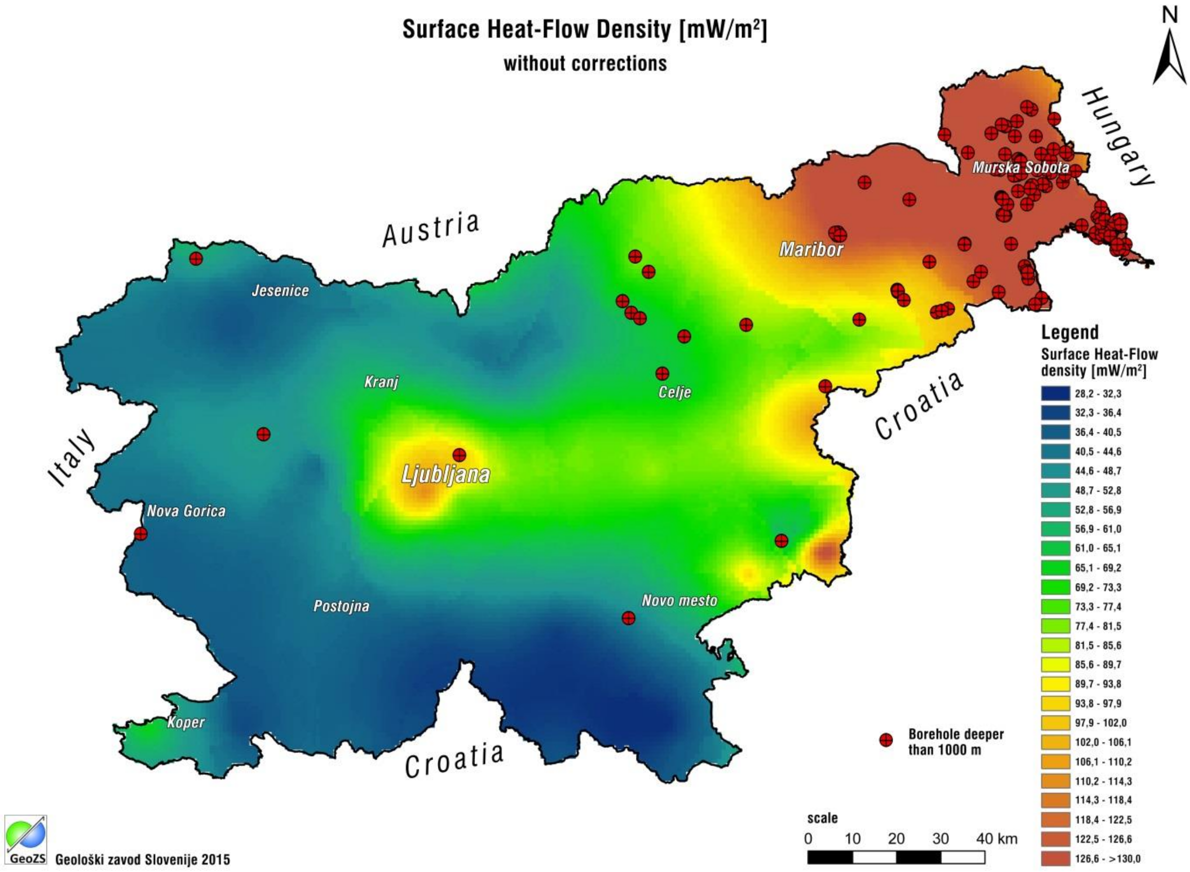

Figure 19 Surface heat flow density map indicating favourable geothermal areas with points standing for sites of existing research boreholes deeper than 1000 m

Figure 20 Carbonate scaling in Benedikt as occurred during testing of the well

Table 9 Summary of operational problems in Slovenia

	SOLVED		UNSOLVED
	Issue	*Solution*	*Issue*
Scaling	Carbonate scaling	Inhibitors	Improvement of treatment or use in the closed system
Corosion	Casing corrosion	Re-lining of old wells	
Gas content	CO_2 - safety	Gas separator	Use in the closed system
	CH_4 - safety	Ex hazard zones, Gas separator	
Reinjection	Reinjection in poorly cemented sands or sand interbedded with clays	Proper well design, microfiltration, backwashing	Further RD&D needed
	High temperature or injected water		Lower injectibility due to lack of end user

1.9.4 References

Rajver, D., Lapanje, A., Rman, N., Prestor, J. 2015: Geothermal development in Slovenia: country update report 2010-2014. In: R., Horne, T., Boyd (eds.). Views from down under - geotermal in perspective : proceedings, World Geothermal Congress, 19-24 April 2015, Melbourne. pp14.

1.10 Turkey

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1.10.1 Geothermal Energy in Turkey

Turkey is located in a tectonic region with a high activity which is the Alpine-Himalayan orogenic belt. The number of geothermal prospects is nearly 200 and they are mostly in the scope of low-temperature applications. Unlike the low-temperature resources, Büyük Menderes Graben, lies in western Anatolia, has high-temperature resources (DiPippo, 2012).

At the eastern end of the Büyük Menderes Graben, there exist three distinct production zones, determined by well drilling. The shallowest one is the Sazak Formation between Pliocene units. The zone is extended to 706 meters with a temperature of 190 - 200 °C. The deeper second zone is the Igdecik Formation of Menderes metamorphics, with a depth of 1261 meters and a temperature of 200 – 212 °C. The deepest one consists of gneiss and quartzite under the micaschists. There may even be a fourth, very deep (B3000 m) reservoir with a possible temperature in the 250- 260 °C range (Kaya, 2009). The upper layer, the cap rock, is comprised of Pliocene-aged clay, marl, and altered sandstones (DiPippo, 2012).

1.10.2 Operational Issues in Turkish geothermal plants

The scaling and induced seismicity are the two main issues in the operation level of Turkish geothermal plants. The challenges on these problems are being solved by some methods briefly defined under the subheadings (DiPippo, 2012).

Scaling and Noncondensable Gas Content

The main challenges to be eliminated were wellbore scaling from calcium carbonate with a high potential and the high percentage of noncondensable gas (NCG) existed in geofluid, which are both common problems for all Turkish geothermal power plants.

Many calcite inhibitors were studied, one was selected for injection downhole below the flash point. The anti-scalant used is called Geosperse (PowerChem Technology, Minden, Nevada).

The second challenge, the handling of the NCG, is overcome by a hybrid extraction system with first stage steam-jet ejectors followed by liquid-ring vacuum pumps. The steam-jet ejectors are composed of three ejectors in parallel, having capacities of 25%, 40%, and 60%, to allow flexibility in dealing with variations in NCG over time. As another alternative, turbocompressors were considered but were not cost-effective either in capital or operating costs for the aspect of these geofluid conditions (DiPippo, 2012).

Induced Seismicity

The Germencik area of Büyük Menderes Graben is experienced to earthquake activity with many quakes in the 3 – 5 magnitude range and a less number in the range 5-6 (Kumsar, 2010). This results in keeping the fault zones alive and changing frequently and promoting the permeability in the reservoir. It is important that the levels of earthquake activity are concentrated on the west and east ends of Büyük Menderes Graben which are the most productive Turkish fields (DiPippo, 2012).

Environmental Impact

As the impact of one of the plants located in Büyük Menderes Graben, the Kızıldere plant centers on the disposal of the waste brine. Since in its early days, the plant did not reinject any brine, all of it was sent to the Menderes River via drainage channels. As of 2005, roughly 278 kg/s was being discharged with no treatment (Şimşek and coworkers).

The brine temperature is about 140 °C and the main problem constituent is boron with a concentration of 25 ppm. Since this amount of boron is excessive relative to its use in agricultural irrigation, three possible solutions have been considered: (1) reinjection, (2) removal of boron, and (3) disposal of brine into the Aegean Sea (DiPippo, 2012).

The only realistic solution is the first one, reinjection. The last one was ruled out on the basis of cost, practicality, and effectiveness. The second option is promising but as yet unproven on the scale needed for Kızıldere (DiPippo, 2012).

1.10.3 Summary and Perspective

There is a significant geothermal resource base in Turkey. With respect to the lower limits of potentials and the currently installed power generation and direct use capacities, there is a considerable development potential for geothermal energy in Turkey; proper investment climate and attractive geothermal energy policy can increase the currently installed capacities by a factor of 10, only to reach to the lower limits of potentials (Korkmaz, 2014).

Table 10 Summary of operational problems in Turkey

	SOLVED		UNSOLVED
	Issue	*Solution*	*Issue*
Scaling	*Calcite Scaling*	*Use of anti-scalants*	
Non-condensable gas content	*Handling of non-condensable gas content*	*Use of hybrid extraction system with first stage steam-jet ejectors followed by liquid-ring vacuum pumps*	*Develop materials that can withstand superheated and supercritical conditions*
Induced seismicity	*Active fault zones*		*Main parameter of induced seismicity should be found out*
Environmental Impact	*Disposal of Waste Brine*	*Reinjection, removal of boron, and disposal of brine into the Aegean Sea are the possible ways*	*Reinjection is chosen as the realistic option whereas removal of boron is most promising*

References

DiPippo, R., 2012: Geothermal Power Plants, Principles, Applications, Case Studies and Environmental Impact, Third Edition, Elsevier.

Korkmaz, E.D., Serpen, U., Satman, A., 2014: Geothermal boom in Turkey: Growth in identified capacities and Potentials. *Renewable Energy* 68, pp.314-325.

Kumsar, H., Aydan, O., Tano, H., Ulusay, R., Celik, S. B.,Kaya, M. and Karaman, M., 2010: An On-Line Monitoring System of Multi-Parameter Changes of Geothermal Systems Related to Earthquake Activity in Western Anatolia in Turkey. *Proc. World Geothermal Congress 2010*, *Paper 1389*, Bali, Indonesia, April 25-29.

Şimşek, Ş., Yıldırım N., Gülgör, A., 2005: Developmental and environmental effects of the Kızıldere geothermal power project, Turkey. *Geothermics* 34, pp. 239–256.

2 Scaling issues

2.1 General, solved and unsolved issues

Scaling is the precipitation from aqueous solution of a solid and its deposition onto a surface, thus forming a solid layer. Geothermal fluids will contain dissolved ions and gases, in equilibrium with the surrounding reservoir rock. When these fluids are brought to the surface, solids may form if the solubility limits of specific species are exceeded, e.g. through changes in temperature, pressure, gas-liquid transport or galvanic effects.

Scaling is a very common challenge in geothermal operations, and all countries involved in OPERA reported solved and unsolved issues. The table below presents an overview of the many of the scaling types and issues mentioned in the country reports in Chapter 2.

Table 11 Scaling issues from country reports

Scaling type	Geographical location	Location in plant	Solution
Carbonates	(Bavarian) Molasse Basin Styrian Basin Northern German Basin/ Danish Basin Pannonian Basin	ESP, pipes, filters, heat exchangers, stripper	Regular cleaning with acid Soft acidizing Inhibitors Coated rising pipes?
Iron oxides/hydroxides	Molasse Basin	Well head	Regular cleaning Precipitation
Sulfur/ Sulfates Ba- and Sr-Sulfates	Molasse Basin Upper Rhine Valley	Heat exchangers Pipes and heat exchangers	Regular cleaning Inhibitors
Fe-Sulfides	(Bavarian) Molasse Basin	ESP, pipes, filters, heat exchangers, valve flaps	Regular cleaning, Exchange of parts
Lead precipitation Pb-Sulfides	Northern German Basin/ Danish Basin Triassic Northern German Basin	Pipes and heat exchangers	Danish projects still looking for solution, inhibitors in Germany. No inhibitors for radioactive Pb^{210}.
Barite ($BaSO_4$), Laurionite ($PbOHCl$), Magnetite (Fe_3O_4) and copper (Cu)	Permian Nothern German Basin	Production well and aquifer areas behind the filter	Inhibitors for sulfates, Metallic scaling to be solved.
Barite	Pannonian Basin		As yet unsolved
Various types of internal scaling	France	n.a.	Jetting during workovers Smooth acidizing Downhole chemical treatment Relining old wells Composite casing

At the OPERA Workshop, we saw a range of approaches to understand and handle scaling, both robust technologies that have proven their value again and again, and technologies in very early stages of development. These presentations can be found in Appendix 2 to this report “Workshop presentations”.

Section 2.2 in this Chapter goes into some detail on carbonate scaling, a very common issue in geothermal projects. Why this scale forms is the first question. Then, experiences with carbonate scales in the Pannonian

Basin, the Bavarian Molasse Basin and the Dutch low-enthalpy geothermal systems are presented. The right approach to control scaling can be scaling inhibitors, regular acid jobs, or CO_2 dosing. What is the right approach depends on the chemistry of the reservoir, the geothermal system conditions but also on local legislation?

Section 2.3 in this Chapter considers scaling of heavy metals. These metals precipitate as a salt or through an electrochemical reaction. A different choice of material (high alloy steel, cladded materials, composite casing) would prevent electrochemical reaction. Composite casing is under development; not a standard solution yet. The workshop contribution “Experience with scaling in geothermal wells, especially on lead scaling in Slochteren reservoirs in the Netherlands”, also showed a succesfull approach with a filming inhibitor. This presentation can be found in Appendix 2 to this report.

Section 2.4 in this Chapter takes it from another angle. “Thermal decomposition of Barite scale by laser” is an early stage of development of a unique and different approach to scale removal. The laser causes chemical decomposition and redissolves the barite, at an operating temperature of about 2000 °C. In the lab, the Barite decomposed into the soluble $Ba(OH)_{2, aq}$ and SO_2 (g).

The material in this section mainly concerns utilisation of geothermal for direct use, at temperatures around 70-120°C. High-enthalpy applications have additional issues such as silica precipitation, mentioned in Section 1.6 on Iceland as an unsolved issue.

A succesful strategy to handle scaling issues includes prediction, monitoring in an early stage, and remediation measures. Getting the right samples, using the right programme and taking the right decisions is what is needed; The right approach may include inhibitors, but also periodic removal. There is a lot of experience out there, and sharing information will be beneficial for the development of geothermal in Europe.

2.2 Carbonate scalings in deep geothermal systems

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2.2.1 Introduction

The chemistry of inorganic carbon in natural geothermal groundwaters is a complex system, which is influenced by various parameters. The solubility of carbonate species mainly depends on the factors temperature, pressure, pH and water composition/salinity. Deep groundwater is in equilibrium with the surrounding host rock and the existing gas regime. In the operation of a geothermal plant the temperature and pressure condition change by the production, heat extraction and reinjection of thermal water, which can lead to an over- or undersaturation with respect to carbonates and other mineral phases. If temperature and pH increase, the solubility of calcium and magnesium carbonates decreases (Figure 21a, b), whereas in case of a pressure increase, the solubility of carbonates also increases (Figure 21c). The solubility of carbonates as function of the water composition is complex and has to be determined by hydrochemical modelling (e.g. by PhreeqC). It is exemplary shown for a simple NaCl water in Figure 21d.

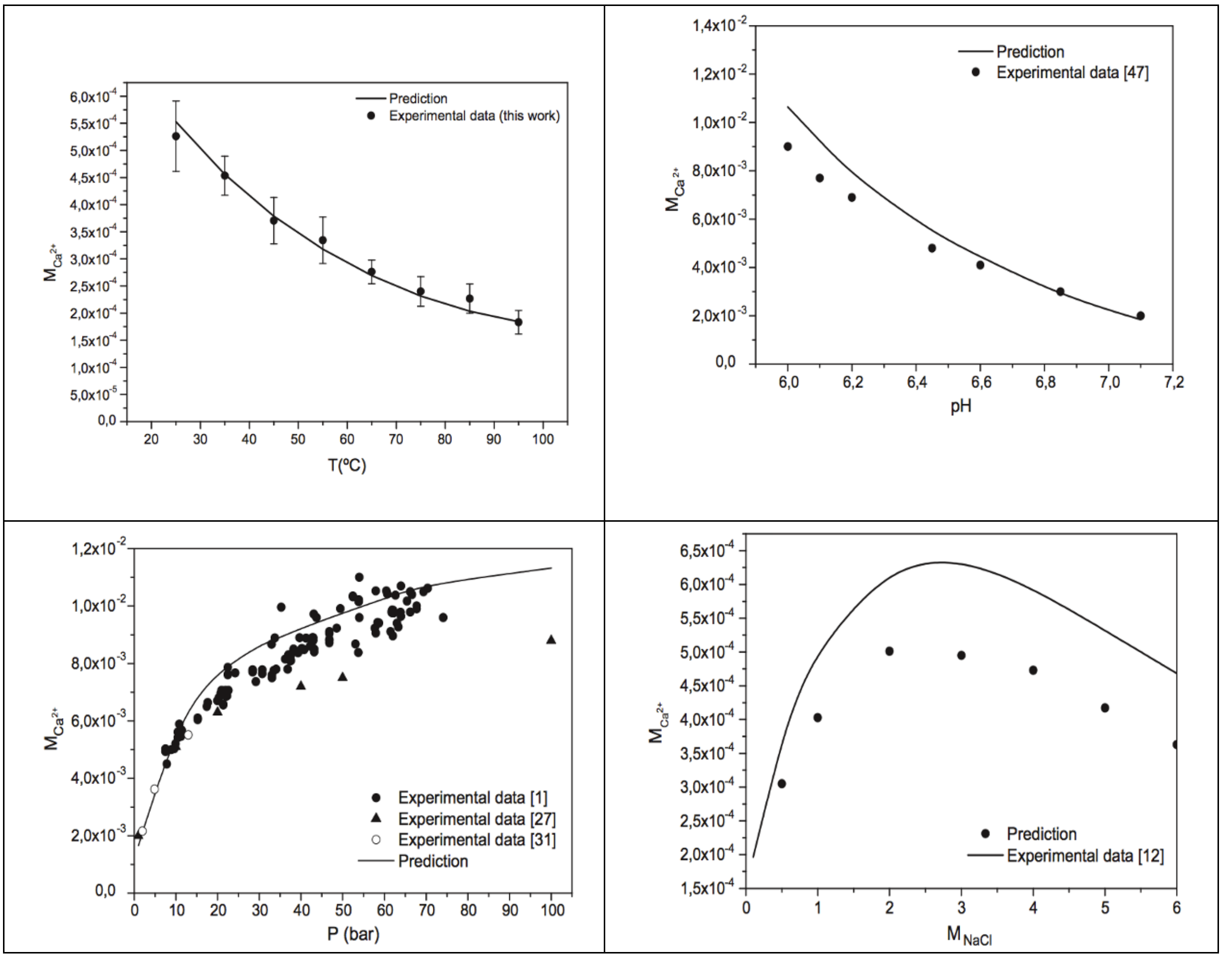

Figure 21 Influence on the solubility of carbonates (here Ca-carbonate) of a) temperature (P = 1 bar), b) pH (P = 1bar, T = 25 °C), c) pressure (T=100 °C) and salinity (T=25 °C, PCO_2 = 0.97 atm); modified after Coto et al., 2012.

Following the occurrence of carbonate scalings and applied or potential counteractions in geothermal plants from different European geothermal regions are presented.

2.2.2 Carbonate scalings in deep geothermal systems of the Pannonian basin

Geothermal water with temperatures of 75 °C to 108 °C and flow rates of 10 – 20 l/s are produced in depths from 1900 to 2800 below surface in four geothermal plants in the Austrian and Slovenian Pannonian basin. The thermal waters, which are produced by a natural CO_2 gaslift (operating without pump), are of a Na-HCO_3-(Cl) type with a mineralisation between 8 and 28 g/l and CO_2 concentrations between 8 and 20 NL/L water. In all boreholes, CO_2 makes 99.9 Vol.% of the total gas volume (Kralj et al., 2009; Eichinger et al., 2006). During ascend in the boreholes the thermal water degasses, consequently the pH of the water increases and carbonate minerals (mainly calcite) precipitates. The rising and surface pipes clog within few days (Figure 22). To avoid this, in two of the four geothermal plants carbonate inhibitors are injected in the producing well app. 200 m below the degassing depth. In the other two geothermal plants the pipe systems are frequently acidified.

Figure 22 Carbonate scalings in production wells of geothermal plants in the Pannonian basin; left: massive calcite precipitations caused by the ascent of thermal waters during a defect in the inhibitor injection hose; right: massive calcite precipitations formed by the ascent and degassing of thermal water, which are removed by periodic acidification

2.2.3 Carbonate scalings in deep geothermal systems of the Bavarian Molasse Basin

In the Bavarian Molasse Basin carbonate scalings occur in four deep geothermal plants, which produce thermal water from depths between 3,800 m and 5,500 m b.s. with temperatures between 124 and 138 °C and production rates between 100 and 130 l/s. There scalings, consisting mainly of Ca-carbonates, occur in and on the electric submergible pump (ESP), on the rising and surface pipes, in the filters and in the entrance of the heat exchanger (Figure 23). The formation of these scalings, which occur in spite of a theoretically sufficient pressure maintenance, avoid a regular operation of these geothermal plants. The thermal waters, which are produced in these plants are of a Na-Ca-HCO_3-Cl type with a total mineralisation between 0.6 and 0.8 g/L. The gas concentrations vary between 95 and 135 Nml/L, with CO_2 and N_2 as main gas phases.

The reasons for the formation of those Ca-carbonate scalings are not fully understood so far and are matter of recent investigations. Mass balance calculations showed that only < 1 wt.% of the dissolved Ca and HCO_3 precipitate during the ascend of the thermal water. However, due to the high pumping rates, the masses of precipitates cumulate rapidly. Reasons can be (a) degassing of the thermal water in the pump due to cavity effects (b) micro degassing due to roughness of the materials and existing flow conditions and/or (c) corrosion effects and entrance of iron ions (Wanner et al., 2015).

In the moment the surface devices (pipes and heat exchangers) are acidified periodically. In one of the four plants the pump and rising pipes are acidified every half of year. The application of inhibitors is not allowed according to Bavarian environmental laws.

Figure 23 Carbonate scalings in (a) a pumping stage of the ESP (b) rising pipe, (c) surface pipe and (d) heat exchanger of four geothermal power plants located in the Bavarian Molasse Basin.

2.2.4 Carbonate scalings in Dutch deep geothermal heat production plants

Carbonate precipitates occur in all current Dutch low-enthalpy geothermal systems. This precipitation may cause injectivity problems. In a recent study working on the geochemical aspects related to injectivity issues (Hartog, 2015), the degassing of CO_2 in the production well and degassing tanks is recognized as the main process for carbonates precipitation. The total gas pressure is however, unlike the German and Austrian systems described, mainly controlled by CH_4, with the CO_2 fraction typically smaller than 5-10% (Figure 24).

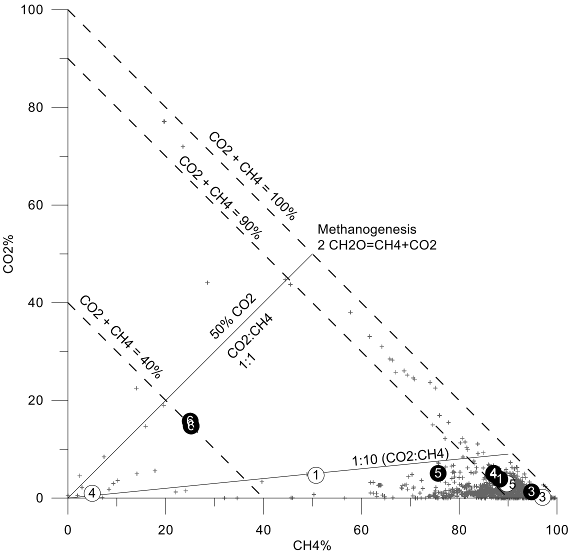

Figure 24 The relative proportions of methane (CH_4) versus carbon dioxide (CO_2) in the total amount of gas extracted from the geothermal waters. Numbers refer to the sites as studied in Hartog (2015). Black circles refer to the compositions in the produced water; white circles refer to the composition in the injected water. For reference, the grey plusses indicate gas compositions measured for Dutch oil and gas production sites (nlog.nl).

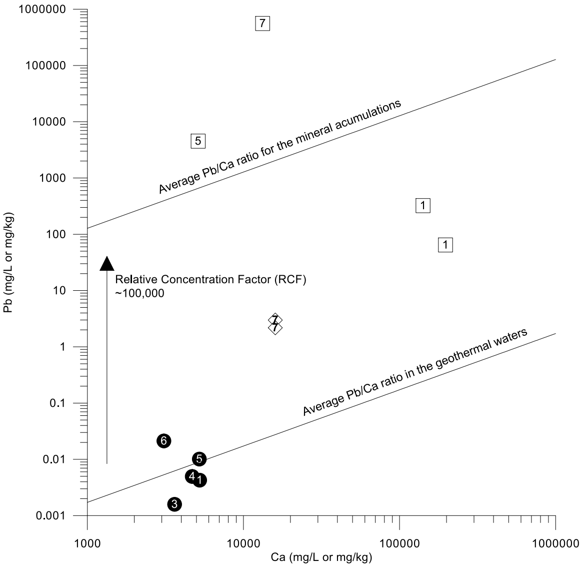

Figure 25 Calcium (Ca) and lead (Pb) concentrations the produced water and accumulates at the sites (numbers) studied by Hartog (2015). Black circles refer to the compositions in the produced water in mg/L. Squares indicate the concentrations in the accumulations in mg/kg. The lines are the through-the-origin fits, representing the average Pb/Ca ratios for the produced water and accumulates.

The carbonates as accumulated in filters and at the bottom of degassing tanks typically have a mixed composition, with typically varying contributions of Ca, Fe, Mg and in some reservoirs Pb. Particularly Fe and Pb are relatively concentrated in the carbonate precipitates relative to the bulk brine composition (Figure 25). Since the contribution of CO_2 to the native total gas pressure, the dosing of CO_2 is suggested after degassing.

2.2.5 Conclusions

Carbonate scaling is a common occurrence in geothermal systems in Europe, mainly induced by the degassing of CO_2. Consequences of carbonate scaling range from increased flow resistance in production wells, failure of pumps, filling and clogging of filters as well as injectivity problems. Managing carbonate scaling with scalant inhibitors, regular acid jobs, CO_2-dosing or other depends on local environmental legislation, chemistry reservoir and geothermal system conditions.

2.2.6 References

Coto, B., Martos, C., Pena, J.L., R. Rodriguez, Pastor, G., 2012: Effects in the solubility of CaCO3: Experimental study and model description. *Fluid Phase Equilibria* 324, 1-7.

Hartog, N., 2015: Geochemical Assessment of Injectivity Problems in Geothermal Wells - a Case Study for Several Greenhouse Geothermal Systems in the Netherlands. *KWR 2015.012*, KWR Watercycle Research Institute.

Wanner, C., Eichinger, F., Jahrfeld, T., Diamond, L., 2015: Assessing the formation of large amounts of calcite scaling in geothermal wells in southern Germany. *Proceedings to the 13th Swiss Geoscience Meeting*, Basel 2015.

2.3 Heavy metal scaling

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2.3.1 Introduction

Heavy metal-rich scales have often been observed to precipitate from geothermal brine. These precipitates are of significance for power plant operation, because they are often hardly soluble, of high density, and enrich other toxic (such as arsenic) and often radioactive components (such as ^{210}Pb).

2.3.2 General explanation of the issue

Due to their ability to form soluble complexes with chloride or organic components, heavy metals such as lead (Pb), copper (Cu), or mercury (Hg) are often enriched in saline formation water, thus occurring at concentrations of up to several hundred mg/L (Hanor, 1994). They precipitate upon disturbance of the chemical equilibrium of the reservoir brine, for example due to the temperature drop or when the fluid comes in contact with other materials. These materials might either react directly with the heavy metals, or indirectly, when fluid -material interaction change the pH- or redox value of the water. In these cases, they precipitate either due to salt oversaturation or as consequence of an electrochemical reaction. The latter occurs, for example, when the dissolved component (such as Cu^{2+}) reacts with the iron (Fe_0) of the less noble carbon steel casing of the production well. In that case, the Cu^{2+} would be reduced to Cu_0 (solid native copper) and iron oxidizes to either dissolved Fe^{2+}or to solid Fe(II) or Fe(II) phases such as magnetite (Fe_3O_4), which was observed together with the heavy metal scaling.

2.3.3 Examples

The most prominent example for that type of scaling that clogged the production well at the geothermal research platform Groß Schönebeck (North Germany) for nearly 200 m, is a mixture of native copper, laurionite, barite, and magnetite (Figure 26; Reinsch et al., 2015; Regenspurg et al., 2015).

Figure 26 Heavy metal scaling (predominantly native copper, barite, and laurionite) removed from the production well at the geothermal site Groß Schönebeck (2013).

This well produced water from a Permian Rotliegend sedimentary - and Carboniferous volcanic rock reservoir. Similar geological formations (Rotliegend sandstones) were encountered in wells of the Altmark gas field, about 200 km West of Groß Schönebeck, where scales, observed in the well, were enriched with the highly toxic lead mercury mineral Altmarkit (Read et al., 2004). Similarly, Pb scales were found in many geothermal wells, drilled into Dutch Rotliegend sandstone or in scales formed from geothermal fluids of the Upper Rhine valley, where the radioactive ^{210}Pb is highly enriched in those scales that were removed by filtration, representing an immense challenge for power plant operators with respect to solid waste disposal (Scheiber et al., 2012).

Heavy metal scales, were also identified in wells of the Molasse basin, where pyrite and magnetite frequently occur on the casing or in filter residues. Here, the Fe derives most likely from the carbon steel casing that reacts with the H_2S that is dissolved in the fluid (H_2S corrosion).

2.3.4 Solutions

The most obvious solution to prevent the electrochemical reactions between the casing material and the metals of the brine is by utilizing a more noble material such as stainless steel or Ni-based alloys. However, these materials are usually very expensive and required in large amounts. Other options are the use of cladded materials (deposition of a thin layer of highly alloyed material on top of the cheaper carbon steel) or coated materials (such as polymer resins), or using non-metallic materials such as glass-fibre reinforced plastic (GRP). However, the problem is that these materials are often either not tested at field conditions or known to be not resistant at the given very high temperatures and pressures of reservoir conditions. Moreover these problems are typically not considered before drilling the wells and wellbore completion and thus occur, when it is already too late for inserting another casing material. The application of inhibitors might be another option, but so far, specific inhibitors for Cu, Pb, and Fe have not yet been developed/ applied for geothermal systems. In addition, the inhibitor would have to be injected permanently at the inflow of the formation water into the production well by installing an injection line. Moreover, it also would not prevent any reactions between the casing/liner and the fluid that occurs on the casing material facing the reservoir side of the well. There, the formed precipitates could cause even worse damage by clogging the reservoir rock pores thereby decreasing the permeability and well productivity, respectively.

2.3.5 Conclusions

Heavy metal- rich fluids represent a huge challenge for geothermal plants and research is still needed – mainly in the field of material science to prevent those reactions. However, due to the commercial value of some metals, such as Cu or rare earth elements, they could also be of advantage when occurring in high concentration in geothermal fluids, when separated above ground in sufficiently high quantities during fluid production.

2.3.6 References

Hanor, J. S., 1994: Origin of saline fluids in sedimentary basins. In Parnell, J. (ed.) 1994, Geofluids: Origin, Migration and evolution of Fluids in Sedimentary Basins, *Geological Society Special Publication No 78*, 151-174.

Read D., Black S., Ceccarello, S., Weiss, H., Schubert, M., Kunze, Ch., Grossmann J., 2004: Radioactive scales from a natural gas production facility in the Altmark region, Germany. *ICAM 2004, Int. Congress on Applied Mineralogy*, Águas de Lindóla, Brazil, September 19-22.

Reinsch, T., Regenspurg, S., Feldbusch, E., Saadat, A., Huenges, E., Erbas, K., Zimmermann, G., Henninges, J., Pfeil, S., 2015: Reverse clean-out in a geothermal well - Analysis of a failed coiled tubing operation. *SPE Production & Operations*.

Regenspurg, S., Feldbusch, E., Byrne, J., Deon, F., Driba, L.D., Henninges, J., Kappler, A., Naumann, R., Reinsch, T., Schubert, C., 2015: Mineral precipitation during production of geothermal fluid from a Permian Rotliegend reservoir. *Geothermics* 54, 122-135.

Scheiber, J., Nitschke, F., Seibt, A., Genter, A., 2012: Geochemical and mineralogical monitoring of the geothermal power plant in Soultz-sous-Forêts (France). *Proceedings, Thirty-Seventh Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, January 30 - February 1, 2012.

2.4 Thermal Decomposition of Barite Scale by Laser

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2.4.1 Introduction

Hard scales often precipitate in the production tubes of geothermal wells, which radically reduce the effective flow diameter of the tube. Scales may even totally block the effective cross section of the pipe. Typical examples of such scales include $CaCO_3$, $SrCO_3$, $BaCO_3$, $CaSO_4$, $SrSO_4$, $BaSO_4$ and their crystals, often mixed with various SiO_2 content substances (Bellarby, 2009). Carbonate salts will become soluble by acid treatment. Sulphate salts, however, will require very high temperatures and a reductive environment to become soluble.

Barium-sulfate precipitates are an especially frequent occurrence in sulphate ion containing mineral waters (Quddus et Allam, 2000). In the oil industry barium scaling, caused by seawater injection in many parts of the world including the North Sea, is a serious issue (Hardy and Simm, 1996). In case of seawater breakthrough, the likelihood of barite scaling will rapidly increase and stay high whilst individual zones or perforations produce a contrast of seawater and formation water. Later in the field life, this likelihood will fall especially once formation water stops being produced. The scale will form where the fluids mix as the reaction is very rapid (Bellarby, 2009).

Barite scaling is also a problem during the operation of geothermal wells in the North German Basin, where various scales (e.g., Ba and Sr sulphates, Fe sulphides and Pb hydroxides) are typically observed (Bozau et al., 2014).

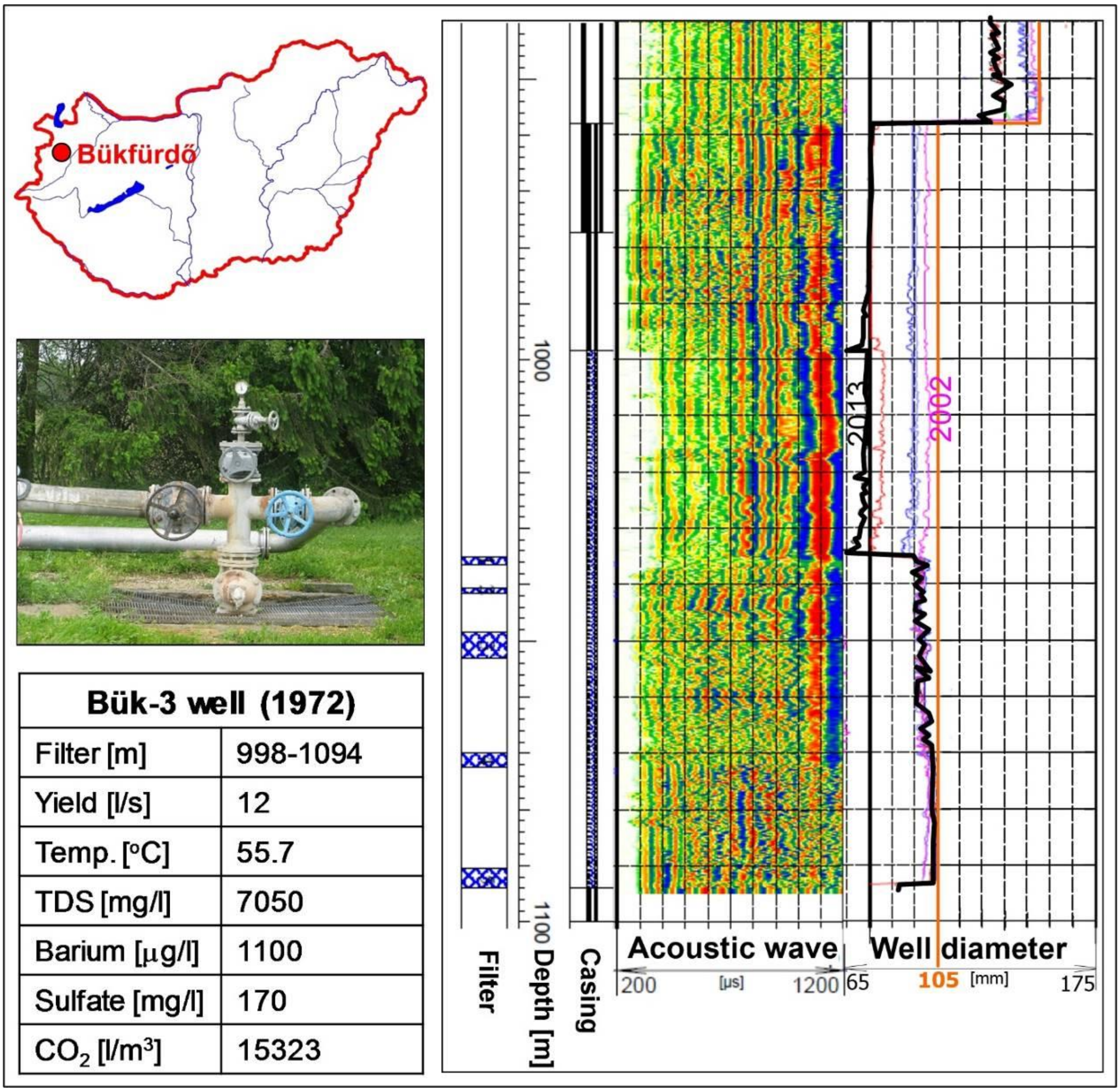
A Hungarian example in Bükfürdő Spa is in a 1,100 m deep well drilled into Devonian dolomite in which the original 105 mm caliber decreased to 70 mm due to barite scale buildup. It was removed by drilling in 2002, but the yield of this well decreased by more than 50% because of the caliper decreased to 65 mm above the screening as a result of barite scaling by 2013 (Figure 27). Production has been stopped, because re-drilling could damage well integrity and the risk was not taken. Therefore, a new production well was drilled in 2015.

The influence of different parameters on the velocity of barite precipitation in geothermal brines was investigated by Canic and her colleagues (Canic et al., 2015). According Canic barite precipitation rate increases with rising supersaturation, lower overall salt concentration, when barite particles as crystallization nuclei are provided and when sulphate is added in excess.

Several patented solutions were found to remove such scales, some with physical impact (Brown et al., 1991) and others with chemical treatments (Nasr-El-Din et al., 2004). These methods offer less, rather than more, chance to succeed. Thermal decomposition, however, is a possibility for every salt. Carbonates start to thermically decompose at a temperature range of approximately 1,000 K and in a solid phase. For sulphates this temperature range is close to the melting point or above.

The ZerLux Scale Removal Laser (SRL) technology allows the use of high power laser devices even in large depths via the standard high carrying capacity of optical fibres. ZerLux deploys a cutting-edge, underbalance laser well rework and completion technology in fluid mining. The tool is comprised of a surface located high power laser generator and a specially designed subsurface directional laser drilling head and uses nitrogen to displace all fluids during the drilling process.

The purpose of our effort is to analyze the solubility of various alkaline earth salt mixtures at a given energy laser treatment and draw conclusions on the melting efficiency of various mixtures.



Bük-3 well (1972)	
Filter [m]	998-1094
Yield [l/s]	12
Temp. [°C]	55.7
TDS [mg/l]	7050
Barium [µg/l]	1100
Sulfate [mg/l]	170
CO_2 [l/m³]	15323

Figure 27 The location and main parameters of Bükfürdő thermal well and geophysical logging regarding well diameter (orange line means the original caliper in 2002; black line means the barite scale progradation up to 2013)

2.4.2 Materials and Methodology

We were using the following mixed samples for experiments:

- 100% $BaSO_4$,
- 75 % $BaSO_4$ + 25% $CaSO_4$
- 50 % $BaSO_4$ + 25% $CaSO_4$ + 25% $CaCO_3$,
- 50 % $BaSO_4$ + 25% $CaSO_4$ + 25% SiO_2,

The powder mixture was inserted into an aluminum tube of a diameter of 25 mm and a length of 100 mm and was compacted. The samples were impinged by laser for duration of 1 minute with an SLD-B 850 infra-red laser of an electric capacity of 3 kW and light capacity of 850 W, wavelength: 915 nm (Figure 28). The solid lumps were removed after being melted and were cleaned of the original powder. We measured the mass of the molten substance and the mineralogical composition was determined immediately by X-ray diffractometry (XRD). To analyze the thermal decomposition of the molten substance we extracted samples of 5-5 g with 100 cm^3 0.1 mol/dm^3 KCl solution and 0.1 mol/dm^3 HNO_3 solution, respectively. The extracted Ba concentration was measured by flame emission spectrometry. The Ca concentration was measured by atomic absorption spectrometry. We replicated the tests three times.

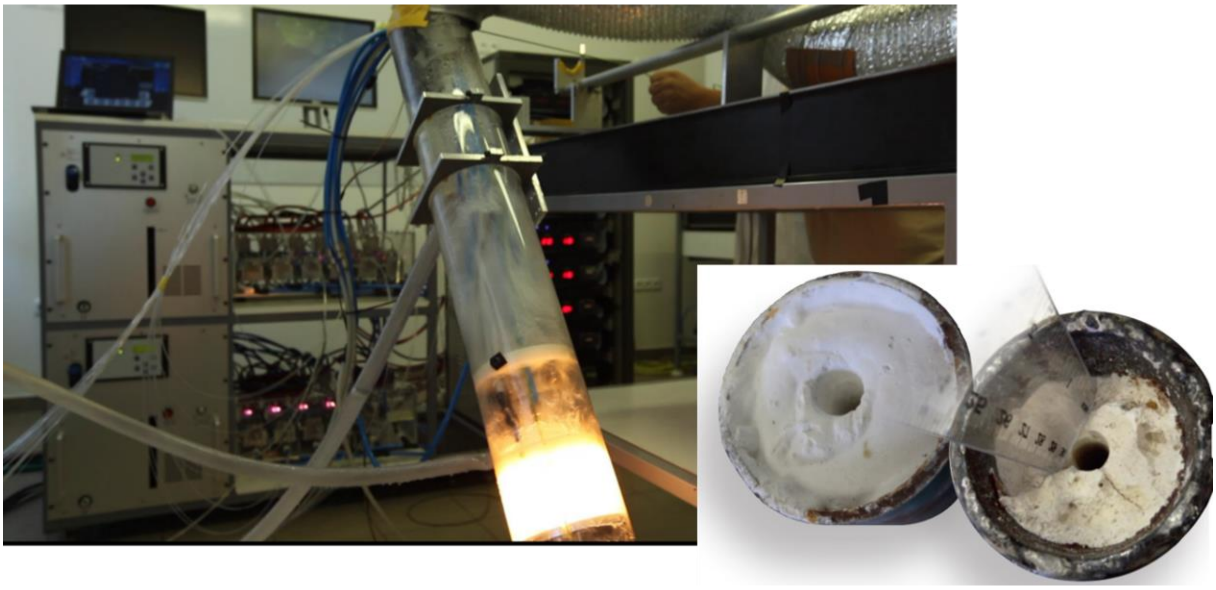


Figure 28 Laser equipment melted barite scale in wet condition without any damage to tubing

2.4.3 Summary

The largest amount of soluble barium ion concentration came from clean barite, whereas the smallest quantities were from carbonate samples. In the presence of calcium ions the largest amount of soluble barium ion concentration came from anhydrite containing samples and the smallest quantities were from the carbonate samples. The largest amount of barium ions was extractable from barite but all the other samples yielded roughly the same amounts. The titration measurement results, the higher alkalinity, confirmed that the clean barite samples produced the largest mass, whereas silicon oxide content of samples greatly reduced alkalinization. In all sample compounds it was clear that laser induced melting prompted the originally water insoluble alkaline earth sulfates to decompose to water soluble hydroxides and gas state water soluble sulphur dioxides. The results of the experiments indicate that if the appropriate mechanical solution is not available, laser induced heat treatment is a suitable alternative to effectively remove otherwise almost immovable deposits and scales from thermal water well pipes.

2.4.4 References

Bellarby, J., 2009: Well Completion Design. Elsevier, ISBN: 978-0-444-53210-7 pp. 378-390.

Brown, A. D. F., Merrett, S. J. and Putnam, J. S., 1991: Coil-Tubing Milling/Underreaming of Barium Sulphate Scale and Scale Control in the Forties Field. *SPE 23106*.

Bozau, H.E., Hausler, S., van Berk, W., 2014: Hydrogeochemical modelling of corrosion effects and barite scaling in deep geothermal wells of the North German Basin using PHREEQC and PHAST. *Geothermics*, Vol. 53, 540-547.

Canic, T., Baur, S., Bergfeldt, T., Kuhn, D., 2015: Influences on the Barite Precipitation from Geothermal Brines. *Proceedings World Geothermal Congress 2015*, Melbourne, Australia, 19-25 April 2015.

Hardy, J.A., Simm, I., 1996: Low sulphate seawater mitigates barite scale. *Oil & Gas Journal*, PennWell Publications.

Nasr-El-Din, H. A., Al-Mutairi, S. H., Al-Hajji, H. H., et al., 2004: Evaluation of a New Barite Dissolver: Lab Studies. *SPE 86501*.

Quddus, A., Allam, I.M., 2000: BaSO4 scale deposition on stainless steel, *Desalination* 127 (2000) 219-224.

3 Corrosion issues

3.1 Introduction

Corrosion is the deterioration of a metal as a result of chemical reactions with the surrounding environment and/or mechanical stress. The sections in this Chapter include the following:

- General, solved and unsolved issues gives an overview of the background of corrosion, and solved and unsolved issues.
- Materials sciences in corrosion
- CO_2 corrosion in low-enthalpy doublets
- This chapter highlights the main topics concerning corrosion in geothermal projects, but as geothermal fluids are different, so will corrosion issues be different. Most focus is on CO_2 corrosion, which is probably most frequent. However, also H_2S from the geothermal waters, and O_2 ingress from the air can be bad actors for corrosion in geothermal systems. Also:

There is no information on microbial growth as an issue in this chapter. It is seldom reported as problematic in geothermal energy. The information on materials science is in fact exclusively related to the different types of steel. Utilization of composites for geothermal in direct use applications gains a lot of interest, and can be included in the follow-on project Operapedia when it is becoming a proven technology

3.2 General, solved and unsolved issues

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3.2.1 Introduction

Massive failure of plant equipment, caused by corrosion was reported from many geothermal sites (e.g. Thoralfson, 2005; Bettke & Schröder, 2009). Corrosion is the destruction of a material due to chemical reactions with its surrounding environment and/or mechanical stress. In geothermal application, most components that are in contact with the formation fluid are made of steel because of its high stability at high pressures and temperatures. Some iron containing materials (stainless steels) can develop thin films of oxide on their surfaces (passivation films), which prevent them from general corrosion. Geothermal conditions, however, represent extremely harsh environments for most materials when even these passivation layers would not be resistant over time.

Different types of corrosion are frequently observed in geothermal facilities (Table 12). The underling chemical reactions are induced by certain characteristic properties of the geothermal fluids, such as high chloride concentration, low pH value, presence of corrosive gases, and high temperatures (Table 12).

Table 12 Summary of species and properties within the geothermal fluid responsible for corrosion, resulting corrosion type, and underlying chemical processes.

Species/ relevant property in the fluid	Corrosion-type	Process
High chloride	Pitting	Interference with an alloy's ability to re-form a passivation film[1]. Local fluctuations induced by high chloride concentrations would prevent the film

(Cl^-) content	corrosion	formation inasmuch the oxide film would be degraded at a few critical points which can then amplify and cause corrosion pits.
High Cl^- + high T		Enhances the reduction of hydrogen in water ($4 H_2O + 3Fe \rightarrow Fe_3O_4 + 4H_2$)
High proton (H^+) content	Acid corrosion	Low pH-values result in material dissolution (e.g. protonation). The decrease of the fluids pH-value can be induced, e.g., by formation of carbonic acid, precipitation of hydroxides, or artificially by fluid acidification.
CO_2	CO_2 corrosion	Formation of hydro carbonic acid (see acid corrosion) and carbonates as corrosion by-products.
H_2	Hydrogen embrittle-ment	Hydrogen atoms diffuse through the metal and by recombination to hydrogen molecules creating pressure from within the metal resulting in cracks.
H_2S	Sulfide stress corrosion (SSC)	Reaction of steel with H_2S: formation of metal sulfides and elementary hydrogen. The hydrogen diffuses into the metal matrix and continues damaging the material (see effects of H_2); SSC is enhanced by sulphate-reducing bacteria catalyzing sulphide production.
Oxidizing ions (e.g. O_2 or dissolved metals of more noble potential as steel)	Electro-chemical corrosion	Oxidation/dissolution of Fe_0 (steel) in an aqueous solution (anodic half reaction: $Fe \rightarrow Fe^{2+} + 2e^-$; cathodic half reaction: $H^+ + ¼ O_2 + e^- \rightarrow ½ H_2O$ or $H^+ + e^- \rightarrow ½ H_2$. Metals (e.g. dissolved Cu^{2+} or Pb^{2+}) could be reduced at contact with materials of the installations (e.g. carbon steel), thereby the dissolved species precipitates and iron dissolves.
Other metallic materials	Contact corrosion	Oxidation (=corrosion) of the less noble metal when two metals of different potential are in direct contact (e.g. in a geothermal brine).
High temperature	[2]	High T enhances all kind of reactions.[2]

[1] passivation film: thin and hard films occurring on steel and alloy surfaces that consist usually of metal oxide or nitride and would, due to their low reactivity, inhibit corrosion.

[2] the term "high temperature corrosion" reveals to more extreme temperatures (several hundred °C) resulting in partially melting of metal components (e.g. in gas turbines)

In high enthalpy geothermal systems (e.g. in Iceland or Italy), the extremely high temperatures represent the main challenge for the materials. These systems frequently also contain H_2S gas as corrosive ingredient that might cause sulfide stress corrosion (Table 12). H_2S gas was also found in fluids of some low enthalpy geothermal sites such as the South German Molasse Basin, representing there the main threat for material destruction (Wolfgramm et al., 2009). Due to the very high salinity (chloride concentration) of fluids from geothermal sites in the Middle European Basin and in the Upper Rhine Valley, materials there would suffer mostly of pitting corrosion (Klapper et al., 2012).

Besides material destruction, corrosion also provokes another challenge for power plant operators because the reaction of the corroding iron (from steel) typically results in its subsequent re-precipitation as Fe(II) and/or Fe(III) phase. This type of scaling, could be oxides (e.g. magnetite (Fe_3O_4) or hematite (Fe_2O_3)), hydroxides (e.g. ferrihydrite, or green rust ($Fe(OH)_2$), or iron carbonate ($FeCO_3$); Cornell & Schwertmann, 1996).

3.2.2 Overview of solved issues

Within the past years comprehensive corrosion- and material research was performed to identify materials resistant to the environment in geothermal facilities (e.g. Bäßler et al., 2009; Klapper et al., 2011; Iberl et al., 2015). Many materials have been tested under well-defined lab conditions that represent different brine properties at elevated temperatures and pressures in autoclaves. However, since the real geothermal fluids are much more complex than artificially produced brines, field testing allows more reliable prediction. In-situ corrosion test tracks investigating the material persistence and determining corrosion rates on-site were installed, for example, at the geothermal facilities Groß Schönebeck (Germany) or Soultz-sous-Forêts (France) (Klapper et al., 2011; Mundhenk et al., 2013). These field and lab tests showed that for less saline waters such as those from the South German Molasse basin, already simple carbon steels are sufficiently corrosion resistant, whereas materials in highly saline brines would need to be made either of stainless steel with high pitting corrosion equivalent number (PREN; representing the sum of alloying elements N, Cr, Mb, W; > 40-45), Ni-based alloys, or titanium to be sufficiently corrosion resistant (Iberl et al., 2015).

However, the use of those corrosion resistant materials is often not economic and power plant operators have to consider if corroded components should better be exchanged from time to time. Alas, replacement of equipment is not possible for all components (or at least very difficult/expensive; e.g. the casing or the pump). Therefore it is highly recommended to consider carefully, before wellbore completion, which material ideally should be used. Material databases that give resistivity for different environments such as Paradox3 (McIlhone & Lichti, 1991) need to be further extended for a large range of geothermal applications. There is also high need to develop cheaper materials with high corrosion resistivity that can be used everywhere in the geothermal circuit. The remaining most relevant issues are therefore, material research on cladding and coating, or on developing other materials that can be more cheaply produced at various geothermal conditions.

3.2.3 References

Bettke, D., Schröder, H. (Eds.), 2009: Langfristige Betriebssicherhit geethermischer Anlagen. Federal Institute for Materials Research and Testing, Hannover, Germany.

Bäßler, R., Burkert, A., Kirchheiner, R., Saadat, A., Finke, M., 2009: in Proc. of Corrosion 2009, Paper No. 09377, NACE International, Houston, Tx.

Cornell, R.M., Schwertmann, U., 1996: The iron oxides. VCH, New York.

Iberl, P., Alt, N.S.A., Schluecker, E., 2015: Evaluation of corrosion materials for application in geothermal systems I Central Europe. *Materials and Corrosion,* 66(8), 733-755.

Klapper, H.S., Bäßler, R., Saadat, A., Astemann, H., 2011: in Proc. of Corrosion 2011, Paper No. 11172, NACE International, Houston, TX 2011.

McIIlhone, P.G.H., Lichti, K.A., 1991: Database for Materials Performance in Geothermal Fluids. *Proc. 13th New Zealand Geothermal Workshop*, 233-238.

Klapper, H.S., Bäßler, R., Sobetzki, J., Weidauer, K., Stuerzbecher, D., 2012: *Mater.Coros.*, 64, 764.

Mundhenk, N., Huttenloch, P., Kohl, T., Steger, H., Zorn, R., 2013: Metal corrosion in geothermal brine environments of the Upper Rhine graben – Laboratory and on-site studies. *Geothermics*, 46, 14-21.

Wolframm, M., Rauppach, K., Thorwart, K., 2011: *Zeitschrift für geologische Wissenschaften*, 39, 213.

3.3 Excursus: Materials Science and Engineering for Corrosion Issues

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3.3.1 Introduction

Geothermal energy systems face different technical and practical challenges. Among these, corrosion represents a major hazard for the long-term and cost-effective operation of geothermal facilities. The first solution approach is to select appropriate materials based on the needed properties and on economic factors. However, materials selection is in some cases not sufficient for the prevention and control of corrosion phenomena, and breakthroughs in Materials Science and Engineering (MSE) might play an important role. The main objective is the improvement of existing materials or the design of new ones to increase their corrosion resistance while keeping costs at acceptable low levels.

3.3.2 General concepts of Corrosion and Materials Science and Engineering

The corrosion of a metallic material is basically the electrochemical reaction of the material with its environment, which leads to a measurable degradation of the material (Shreir et al., 1994). Since both material and environment are involved in the process, corrosion is considered a system property. As a result of the exchange of electrons and ions, corrosion products are formed; they can be soluble or may form as a deposit at the metal/electrolyte interface. The further dissolution of the metal might lead to more severe consequences, such as loss of mechanical strength and instability of the structure or component.

On the other hand, Materials Science and Engineering is an interdisciplinary field that establishes relationships between the properties of a material and its internal structure, chemical composition, and processing technique (Askeland et al., 2011). The terms shown in the outer ring represent the underlying concepts of this field. Both the chemical composition and the processing of the material determine its microstructure and, in consequence, its properties. They also influence the total performance-to-cost ratio. The principal aim is to control specific properties of the material (mainly chemical, mechanical, and thermal properties) to fulfil the operational requirements of different applications or product specifications.

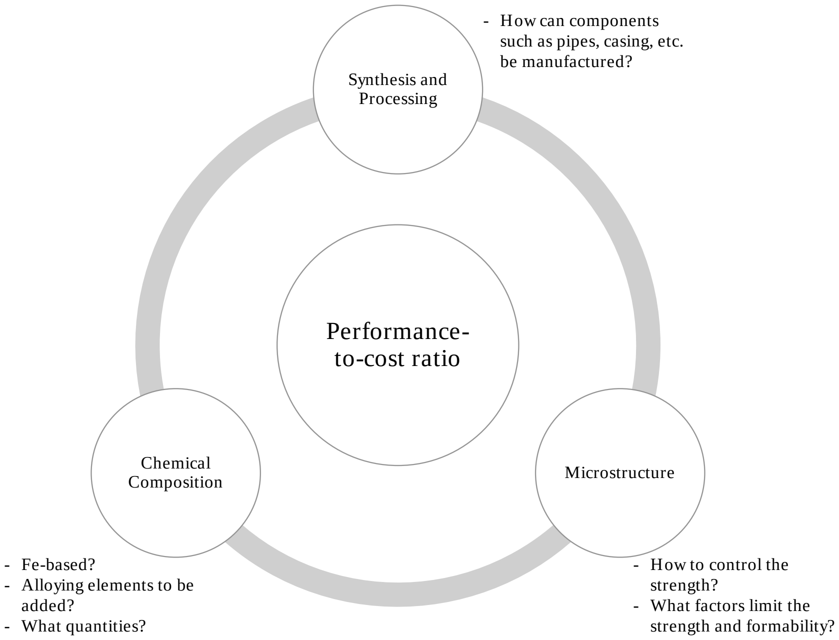

Figure 29 Summary of underlying concepts in Materials Science and Engineering whereby material's properties can be changed [adapted from Askeland et al. 2011]

3.3.3 Materials Science and Engineering for Geothermal Corrosion Prevention and Control

In geothermal applications, material scientists and engineers commonly require materials with outstanding properties such as corrosion resistance to highly saline fluids at high temperatures, mechanical strength, or formability. A wide variety of iron-based alloys (mainly carbon and low-alloy steels) are utilized in components such as the well casing and tubing, pumps, heat exchangers, or pipelines due to their excellent mechanical behaviour, ease of fabrication, and availability. Despite that these alloys present good combinations of properties compared to pure metals, they may suffer different forms of corrosion (e.g. uniform corrosion, pitting corrosion, or sulphide stress cracking). The corrosion phenomena along with other environmental factors (fluid composition, high temperature, mechanical stress, etc.) affect the overall performance of the system.

During the processing of materials, it is possible to modify mechanical or chemical properties, amongst others. To improve mechanical properties, steels can be subject to heat treatment processes (e.g. quenching) or strain hardening processes (e.g. casting, rolling, extrusion, or drawing). This improvement commonly refers to the increase of the yield or tensile strength, against a loss of ductility. In regard to chemical properties, the corrosion resistance of a material may be improved by applying metallic or organic coatings to its surface that might prevent electrochemical reactions and permit the operation in extreme geothermal environments. Heat treatments such as homogenization treatments or full recrystallization annealing might reduce the risk of localized galvanic or stress cells, respectively, and thus, can also improve the corrosion resistance.

The chemical composition also has a major impact on the properties of metallic materials. Mechanical properties such as the hardness or tensile strength can be enhanced in steels by increasing the content of carbon. This is known as solid solution hardening. On the other hand, by adding specific alloying elements, such as Cr and Mo, the passivation of the metal occurs spontaneously, and the corrosion resistance is markedly improved (stainless steels). In low-alloy steels, higher Cr contents in the matrix might reduce the corrosion rate as well as the susceptibility to localized corrosion in aqueous solutions containing CO_2. This occurs due to the formation of a protective layer at the surface enriched with Cr oxides (Chen et al., 2005; Guo et al., 2012; Ueda & Ikeda, 1996; Wu et al., 2013).

The microstructure of a metal is primarily determined by its chemical composition and the processing technique. Microstructural changes may lead to significant variations of many materials properties (strength, toughness, corrosion resistance, ductility, hardness), even if the chemical composition remains identical. Several authors have discussed the role of the microstructure on the corrosion behaviour of steels. A ferrite-pearlite structure shows a poorer performance against localized corrosion, in comparison to other microstructures, such as ferritic or tempered martensitic. This can be explained by the non-uniform distribution of the iron carbide phase cementite (Fe_3C) that results in a lower adhesion of the corrosion products and a higher risk of spallation of the scale layer (Al-Hassan et al., 1998; Clover et al., 2005; López et al., 2003).

3.3.4 Conclusions

Materials science and engineering is essential in avoiding functional impairment (damage) of a component part or the whole system in geothermal energy facilities. The main objective mostly refers to the improvement of existing materials or the development of novel corrosion-resistant alloys that do not present excessively high costs and that might be crucial for the long-term operation of geothermal power plants. The field of materials science and engineering aims at optimizing materials properties to reach an optimal performance in geothermal environments. These materials properties refer not only to corrosion resistance but also to mechanical properties. To obtain different properties, the main targets are to adjust the chemical composition of the metal and to select cost-effective processing methodologies, and this, in turn, will lead to further changes in the microstructure.

3.3.5 References

Al-Hassan, S., Mishra, B., Olson, D.L. & Salama, M.M., 1998: Effect of Microstructure on Corrosion of Steels in Aqueous Solutions Containing Carbon Dioxide. *Corrosion*, 54(6), pp. 480-491.

Askeland, D.R., Fulay, P.P. & Wright, W. J., 2011: The Science and Engineering of Materials. 6th Ed., Wadsworth Publishing Co. Inc..

Chen, C.F. et al., 2005: Effect of Chromium on the Pitting Resistance of Oil Tube Steel in a Carbon Dioxide Corrosion System. *Corrosion*, 61(6), pp. 594-601.

Clover, D., Kinsella, B., Pejcic, B. & De Marco, R., 2005: The influence of microstructure on the corrosion rate of various carbon steels. *Journal of Applied Electrochemistry*, Issue 35, pp. 139-149.

Guo, S. et al., 2012: Corrosion of alloy steels containing 2% chromium in CO2 environments. *Corrosion Science*, Issue 63, pp. 246-258.

López, D. A., Pérez, T. & Simison, S.N., 2003: The influence of microstructure and chemical composition of carbon and low alloy steels in CO2 corrosion. A state-of-the-art appraisal. *Materials & Design*, Issue 24, pp. 561-575.

Shreir, L.L., Jarman, R. A. & Burstein, G.T., 1994: Corrosion. 3rd ed., Butterworth-Heinemann, London.

Ueda, M. & Ikeda, A., 1996: Effect of Microstructure and Cr Content in Steel on CO2 Corrosion. NACE International.

Wu, Q., Zhang, Z., Dong, X. & Yang, J., 2013. Corrosion behavior of low-alloy steel containing 1% chromium in CO2 environments. *Corrosion Science*, Issue 75, pp. 400-408.

3.4 CO_2 corrosion in low-enthalpy doublets

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3.4.1 Introduction

One of the most prominent causes of steel corrosion is the presence of oxidizing, corrosive species in formation waters, such as CO_2 (Chilingar et al., 2008). Extensive areas in the Southern Permian Basin, stretching west-east from England to Lithuania, and north-south from Denmark to Belgium, have been gas charged with natural gas, mostly from Carboniferous source rocks (Doornenbal and Stephenson, 2010). Formation fluid that has been in the migration path still contains dissolved gas. The charged gas reservoirs, the majority being of Permian, Triassic, Jurassic and Cretaceous age, are often targeted for geothermal exploration too. The dominant components of the natural gas usually are methane (CH_4), CO_2, and nitrogen (N_2) with minor amounts of other components like ethane (C_2H_6). H_2S is not present in the Carboniferous sourced natural gas but is sometimes found in carbonate rocks like those of the Zechstein, Malm or Dogger and concentration of He is not measured in gas samples.

CO_2, when dissolved in water, forms partly carbonic acid, which dissociates to protons and bicarbonate (see equation 1) in the following way:

$$CO_2 + H_2O \rightarrow H^+ + HCO_3^- \qquad \text{Eq. 1}$$

As a consequence of this reaction, the pH of the formation water decreases. The production of hydrogen ions (H^+) can oxidize and mobilize iron (Fe) from the casing surface by reducing protons to hydrogen (H_2) gas (eq. 2). In total, a cathode reaction (eq. 3) takes place which reduces protons to form bicarbonate ions (HCO_3^-). Generally speaking, an increase in the amount of dissolved CO_2 increases the uniform corrosion rate in aqueous solutions by increasing the rate of hydrogen production (Nesic, 2007).

$$Fe^0\,(solid) + 2H^+ \rightarrow Fe^{2+} + H_2 \qquad \text{Eq. 2}$$

$$Fe^0\,(solid) + CO_2 + H_2O \rightarrow Fe^{2+} + 2HCO_3^- + H_2 \qquad \text{Eq. 3}$$

Siderite (iron carbonate $FeCO_3$) may precipitate forming a protective (passiviation) layer on the casing. An increase in the hydrogen concentration in the fluid can be considered to be an indicator of corrosion in the well (Alt-Epping et al. 2013).

CO_2 corrosion can occur in both the production and injection wells. If the brine is degassed, the risk of CO_2 corrosion in the injection well is minimal. The CO_2 corrosion risk in the surface installation is also considered to be limited due to the use of high grade steel types.

3.4.2 CO2 content of dissolved gas

CO_2 corrosion prediction software tools developed by the oil and gas industry all show that there is a correlation between the CO_2 content of the gas (often expressed as the CO_2 partial pressure) and the corrosion rate (Nyborg 2010). As a rough rule of thumb, NACE (1999) states that below 0.2 bar partial CO_2 pressure there is no risk of corrosion for carbon steel, and above 2.0 bar corrosion will certainly occur. Therefore it is important to be able to estimate or measure the CO_2 content of the gas.

Abundant *free* gas composition data are known from gas production wells in the oil and gas industry. Black dots on Figure 30 show the ratio CH4 to CO2 for a large number of Dutch gas fields. The vast majority of analysed samples contain less than about 5% CO2. The CH4 content usually exceeds 80% (in the gas phase).

In the Dutch geothermal systems, the gas is dissolved in water at reservoir conditions; its solubility depends on P, T, S and composition. Most analysis results from dissolved gas taken from geothermal brines apparently show much higher CO2 content, and considerable scatter (Figure 30, green dots). The former can partly be explained by the better solubility of CO_2 in water, when compared to CH_4.

A major problem for evaluating CO_2 corrosion in geothermal wells is the inappropriate sampling and measurements of the gas. Brine samples containing dissolved gas are rarely taken in situ and therefore poorly represent local conditions. An in situ sample should be taken after the well has been cleaned by circulating out the relatively cold drilling mud, and after a temperature equilibrium has been reached. Temperature, depth, and pressure during sampling should be noted and sampling performed under pressure in a pressure-tight sampling tool, but this is not yet standard practice. Use of a sampling standard, like for instance API Recommended Practice 45 (Sampling Oil Field Waters, if adapted for geothermal systems), or detailed description of the sampling procedures (e.g. Regenspurg et al., 2013) is recommended.

The CO_2 partial pressure can be calculated using Henry's law and the bubble point pressure. In practice, an accurate determination of the bubble point pressure in geothermal systems is found to be problematic, because measurements on different samples, taken from the same well, yield different values. The uncertainty is large, and therefore any estimate of the CO_2 corrosion rate.

3.4.3 Corrosion mitigation

Uniform CO_2 corrosion can be mitigated by applying inhibitors all along the trajectory where dissolved CO_2 is present. El-Lateef et al. (2012) provide a comprehensive overview of corrosion protection of steel pipelines against CO_2 corrosion. Another method of preventing CO2 corrosion is degassing, which decreases the CO_2 corrosion risk by removing CO_2 from the brine. As a consequence, the pH-value would increase, which may trigger scaling. Seibt et al. (2000), for instance, advised against CO_2 degassing in North German Basin geothermal wells. Correct determination of the CO_2 content of the dissolved gas, and the bubble point, as early as possible in the development of a geothermal well doublet, helps in estimating the CO_2 corrosion rate and thereby enables to take immediate mitigating measures.

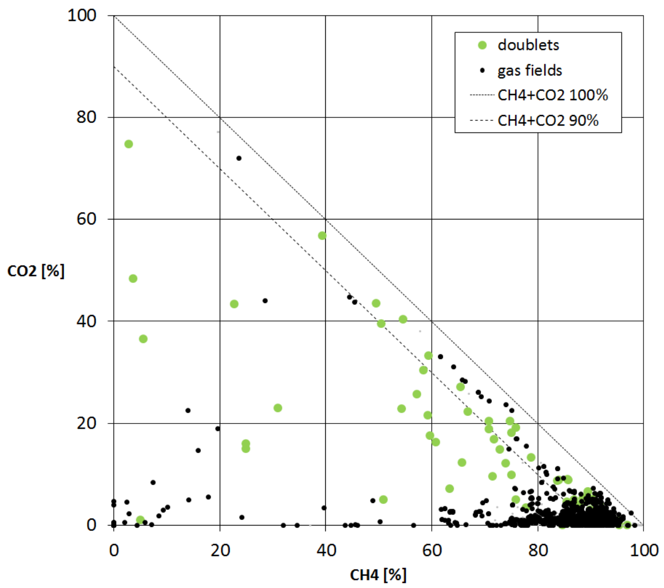

Figure 30 CO_2 – CH_4 ratios in Dutch gas fields (free gas) and geothermal systems (dissolved at depth). Source: www.NLOG.nl

3.4.4 References

Alt-Epping, P., Wabera, H.N., Diamonda, L.W. & Eichinger, L., 2013: Reactive transport modelling of the geothermal system at Bad Blumau, Austria: implications of the combined extraction of heat and CO2. *Geothermics*, 45(2013), p18-30.

American Petroleum Institute (API), 1998: Analysis of oilfield waters. *API recommend practice RP 45*. 3rd edition, august 1998, 72p.

Doornenbal, H., & Stevenson, A., 2010: Petroleum geological atlas of the Southern Permian Basin area. EAGE.

Chilingar, G.V., Mourhatch, R. & Al-Qahtani, G.D., 2008: The fundamentals of corrosion and scaling for petroleum and environmental engineers. 276p. Gulf publishing company, Houston, Texas.

El-Lateef, H.M., Abbasov, V.M., Aliyeva, L.I. & Ismayilov, T.A., 2012: Corrosion protection of steel pipelines against CO2 corrosion – a review. *Chemistry Journal*, 02(02), p52-63.

NACE, 1999: TPC5 Corrosion control in petroleum production. 350p.

Nesic, S., 2007: Key issues related to modelling of internal corrosion of oil and gas pipelines – A review. *Corrosion Science* 49, 4308–4338.

Nyborg, R., 2010: CO2 corrosion models for oil and gas production systems.

Regenspurg, S., Feldbusch Helmholtz, E. & Saadat, A., 2013: Corrosion Processes at the Geothermal Site Groß Schönebeck (North German Basin). *NACE Corrosion 2013 conference and expo paper 2606.* 15p.

Seibt, A., Hoth, P. & Naumann, D., 2000: Gas solubility in formation waters of the North German Basin – implications for geothermal energy recovery. Proceedings World Geothermal Congress 2000 Beppu - Morioka, Japan, May 28 - June 10, 2000, 6p.

4 Gas issues

4.1 Introduction

Geothermal fluids will always contain a certain amount of gases, and a two-phase flow may develop as a result of pressure drops and/or flashing. Gas issues are generally closely linked to scaling – because of changes in the composition of the liquid, the solubility of the minerals present in the liquid phase changes. Separating off non-condensable gases is a frequently applied strategy to avoid two-phase flow. For example in Hungary and the Netherlands, degasification units are often installed next to the production wells. In some cases the separated gas (methane) is used in auxiliary equipment in both of these countries.

Some important issues related to gas formation include:

- Dissolved CO_2 that separates out of the liquid flow will increase the pH of the liquid and can lead to scaling;

- H_2S may be present; this is a toxic gas that needs to be treated with care;

- CH_4 may be present in a gas phase; a flammable gas which should again be treated with care;

- Ingress of O_2 and resulting corrosion can also be regarded as a gas issue.

Chapter 5.2 presents a general introduction to gas issues. It looks into gases common in many low-enthalpy fields, in particular CO_2. After this, there is an excursus in Chapter 5.3 on a solution for pressure related issues, with a downhole pressure retention valve, contributed by the developer of the equipment.

The OPERA Workshop, Reykjavik Energy presented the 'Sulfix' project, which converts H_2S that is co-produced with the geothermal fluid through an underground reaction of H_2S, to form pyrite. The subsoil conditions in Iceland, cracked basaltic rock, make such a project possible. See Appendix 2 to this report "Workshop presentations".

Pressure maintenance works for CO_2 to prevent the formation of carbonates, but for more exotic scales, it does not. Separating off the non condensable gases is a valid strategy if there is a market for them (e.g. for CH_4). At the same time, there is also an environmental benefit in total reinjection. However, total reinjection costs energy as well (and might therefore cause CO_2 emissions somewhere else).

4.2 General, solved and unsolved issues / Gas aspects in geothermal systems

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The total amount and composition of gas dissolved in geothermal waters are important conditional aspects to consider in the operational and risk management of geothermal systems. The resulting total and partial gas pressures vary strongly between different geothermal areas. With respect to corrosion risks, particularly the height of partial gas pressures for H2S and CO2 determine the sensitivity. Therefore, material selection should be made with these conditions in mind.

With respect to scaling risks, the main gas related aspect is the extent to which CO2 degassing occurs as this triggers the precipitation of carbonate minerals (as described in the detail in the scaling chapter). Depending on the pressure difference between the total gas pressure and the pressure maintained in the above ground installation, degassing will occur. In the absence of over- or under pressured reservoir conditions, this total pressure is equal to the hydrostatic pressure exerted by the height of the overlying water column. With increasing depths, the hydrostatic pressure increases linearly and for reservoir depths over 2km, hydrostatic and associated maximum total gas pressures would be over 200 atm. Operating the surface part of the geothermal installation under excessive pressures to prevent degassing becomes unrealistic. However, whether or not the dissolved gas pressure equals the hydrostatic pressure depends on whether or not sufficient gas is available. In the presence of known near-by free gas occurrences, this might be possible. Bottom hole bubble point determinations therefore provide crucial information for pressure management in geothermal system.

Since typically, the above-ground geothermal system is operating under pressures that are at least multiple times lower (e.g. 15 atm) than the hydrostatic pressure in the aquifer from which the geothermal water is produced. In such cases, it is expected that degassing occurs as the produced geothermal water is pumped upward along the pressure gradient. This is in keeping with the observations for multiple geothermal systems in The Netherlands where the pressure in the production well had already dropped below the bubbling point (GPC/KWR, 2014), i.e. the gas pressure already exceeded the hydrostatic pressure in the upper part of the well and a free gas phase had already formed. Compositional analysis of the gas phase indicates that the for the largest part the gas is composed of methane (Figure 31), although with significant amounts of CO2 present (up to 20%) . For the highest CO2 fraction in produced geothermal water in this figure a partial pressure of over 10 bar is calculated (with 53 bar total gas pressure). However for other geothermal systems elsewhere in Europe (e.g. Austria) CO2 can be the dominant fraction (>90%).

Finally, the presence of free gas phase in geothermal systems can itself cause clogging problems, as reduction in water permeability occurs in the presence of free gas. To control the degree of degassing that is allowed, adequate system pressure control for the above and below ground parts of the installation is key. The most common control measure to get rid of excess gas is the use of a degasser, which will aid the prevention of gas clogging by removing the amount of free gas that is produced by the time the produced water reaches the surface operation. In the evaluation to what extent excess gas can be released to the atmosphere the composition of main and minor components (e.g. H2S, Hg) in the gas need to be considered.

Pressure keeping to avoid degassing is an economic factor. The coupled application of inhibitors and lower operation pressures can increase the rentability of geothermal systems and prevention of carbonate scalings.

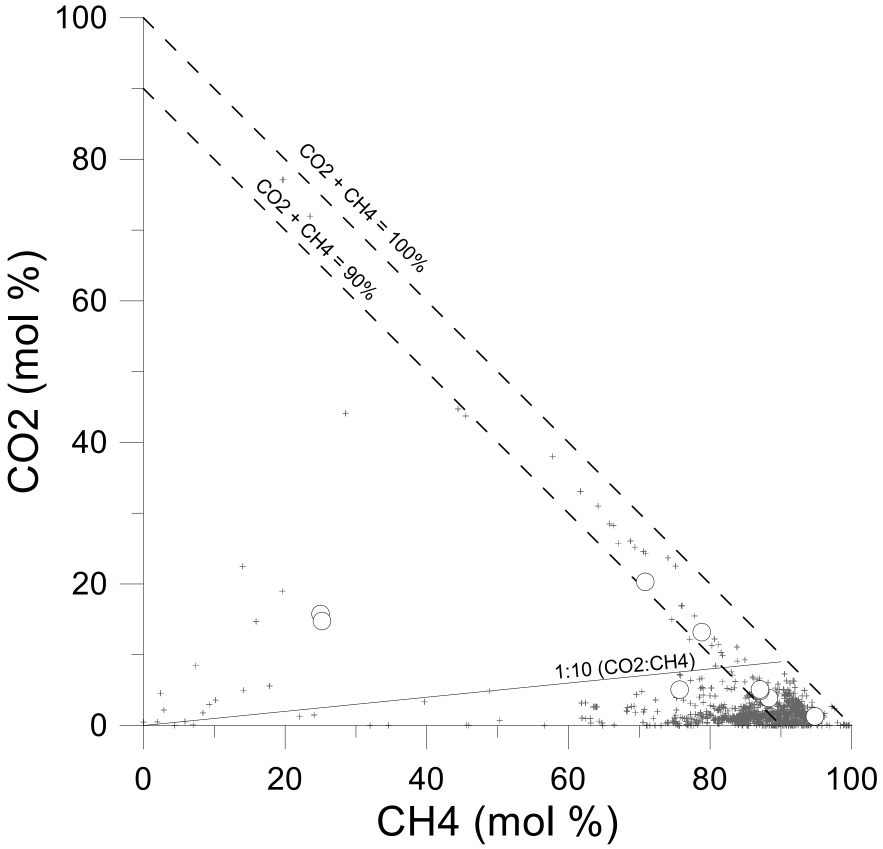

Figure 31 The relative proportions of methane (CH4) versus carbon dioxide (CO2) in the total amount of gas extracted in produced water from geothermal systems in The Netherlands (white circles) from various studies (e.g. (Hartog, 2015)). For reference, the grey plusses indicate gas compositions measured for Dutch oil and gas production sites (nlog.nl).

4.2.1 References

GPC/KWR, 2014: Assessment of Injectivity Problems in Geothermal Greenhouse Heating Wells.

Hartog, N., 2015: Geochemical Assessment of Injectivity Problems in Geothermal Wells - a Case Study for Several Greenhouse Geothermal Systems in the Netherlands. *KWR 2015.012*, KWR Watercycle Research Institute.

4.3 Excursus: Solution for Pressure related issues

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A lot of geothermal water circuits, e.g. a closed system with 1 production and 1 injection well, have to deal with reinjection issues. These issues may be different from area to area, and the operators have to deal with topics regarding the reservoir and the injectivity or with chemical issues and the properties of the geothermal water.

Issues regarding the reservoir can be less injectivity due to clogging, clogging can be initialized by filtration, which is not fine enough. A solution to free the clogged reservoir can be injection with higher pressure, to clean the structure in the reservoir. A further aspect for clogging can be scaling and new minerals formation as a result of degassing, where new particles form and grow and then clog the reservoir down hole. These particles, as a result of scaling and degassing, can mostly be removed by chemical injection. But chemical injection is not allowed in every single country.

The aim of the geothermal water to degas and start new minerals formation is often a pressure related issue and starts, when the local pressure is under the pressure of the fluid where degassing begins. Not all geothermal loops have to deal with low pressure; they often have to inject the water with higher pressure due to the reservoir behavior.

In closed geothermal loops the low pressure will have a huge effect. Scaling will occur on pipes, valves and heat exchanger and reduce the power of the whole equipment and plant and also reduce the diameter of injection well and finally clog the reservoir.

To prevent the fluid from degassing and scaling and all the negative effects a pressure maintenance system has to be installed. A lot of system on the market are installed at the surface and do not protect the cost intensive injection well from scaling.

To protect the whole geothermal loop, the pressure maintenance system hast to be installed down hole underneath the water level, to keep the whole circuit above the pressure, where degassing of the fluid starts, this is shown in Figure 32.

Advantages of the installation down hole are:

Prevention / reduction from pressure induced scaling

Protection of the whole geothermal loop

Protection of the equipment on the surface from pressure induced scaling

The invented system from gec-co global engineering & consulting company from Germany fulfills all the mention requirements. The pressure maintenance is installed down hole, the actuation is placed on the surface for easy maintenance and to get information from the direct linked system down hole.

A further advantage of the system is the prevention from cavitation inside the valve. Cavitation can destroy valves, pipes and other equipment. Figure 33 shows the physical principle of the valve.

To sum up, a solution for pressure related issues can be a down hole pressure maintenance to avoid or reduce scaling and degassing of the fluid and keep the whole geothermal loop in operation for longer time.

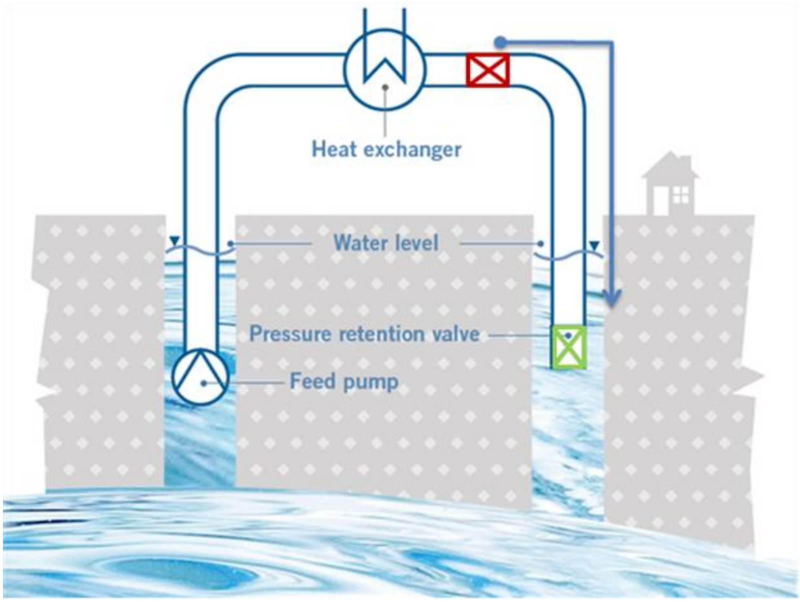

Figure 32 Closed geothermal loop, with replacement of a surface installed pressure maintenance through a down hole pressure retention valve PRV-GT

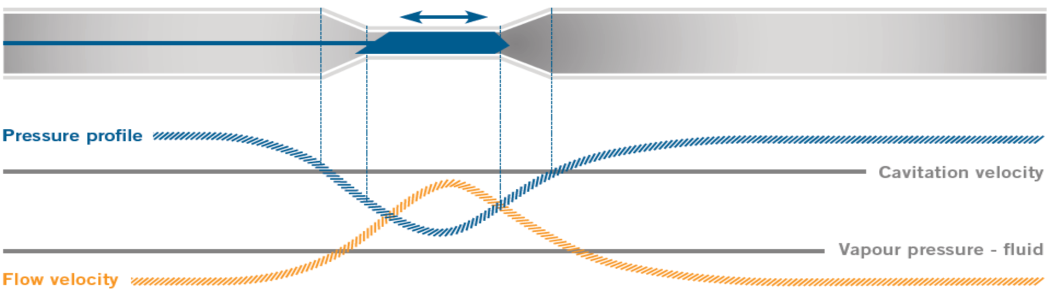

Figure 33 The physical principle of the pressure retention valve to avoid scaling and cavitation

5 Reinjection issues

5.1 General, solved and unsolved issues

Reinjection of geothermal fluid into the subsoil is an important operation which may be more of a challenge than the production – but also the other way around. In some countries, reinjection is required by law, while in others, single-well operation is much more common, e.g. in Iceland, Hungary and Slovenia. However, the abstraction of thermal waters may lead to a decrease of the ground water table, as seen today in the Pannonian Basin, and reinjection will have to be applied more frequently there to curb this trend.

As mentioned above, reinjection can be more difficult than production, especially in soft sandstones and detrital sedimentary rocks. Also, injection of cold water can give rise to induced seismicity. Problems that may occur in heterogeneous reservoirs include plugging of screens, and pore throats in the reservoir formation, clay swelling, or pore throats blockage by fine particles. Incidental backwashing may help. In France, there is experience with using a triplet scheme in detrital formations, or drilling extra-large diameters and setting pre-gravel packed screens (Johnson type) – which effectively creates additional surface area for the injection to proceed.

In high enthalpy fields, scaling and reinjection problems are of a different nature. The reinjection temperature is kept at 180°C, so that scaling (most probably silica) is prevented. This is in principle a huge energy loss.

Section 5.2 goes into details on reinjection in soft sandstones, in particular in the Pannonian Basin with examples from Slovenia.

Induced seismicity is mainly perceived in regions with a strong seismic activity, such as the Upper Rhine Valley in Germany. It can be both a result of fluid reinjection or due to drilling and stimulation. Induced seismicity can have a very detrimental effect on public support for geothermal operation, presumably more so in more densely populated areas. Also the background level of natural seismicity will play an important role.

Concerning induced seismicity during stimulation, German experts propose a detailed characterisation of the tension regimes, monitoring before and during drilling, and rapid but educated adjustment of operation once the situation deviates from expectations.

Section 5.3 presents mechanisms, considerations and examples related to induced seismicity during fluid reinjection. A smooth plant operation and temporal reduction of flow rate when higher frequencies of micro-events occur have proven a viable strategy for a geothermal site in the Upper Rhine Valley area. The research showed that microseismic events decreased with time, when flow paths are established.

5.2 Solved and unsolved reinjection issues in the Slovenian part of the Pannonian Basin

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5.2.1 Introduction

Sandy geothermal aquifers in the Pannonian basin are low temperature (<150 °C) geothermal resources. The transboundary Upper Pannonian sandy geothermal aquifer has a surface area of more than 22,000 km^2 and is widely exploited in Slovenia, Croatia, Austria, Hungary and Slovakia. Despite being tapped by over 225 geothermal wells, there is only one active reinjection well, situated in Lendava (SLO).

The success of reinjection in intergranular aquifers may be limited by several risk factors, such as: spatial distribution, depth and geotechnical quality of wells, pressure, temperature and quantity of reinjected water, reinjection return velocity and thermal breakthrough, particle migration and ground swelling around reinjection wells, chemical compatibility of reinjected water and thermal water in the aquifer, degassing, oxidation or corrosion of pipelines, bacterial activity and economic feasibility of setting the geothermal doublet. In Hungary at least 40 reinjection wells are present; 32 drilled into Neogene porous intergranular sandstone aquifers and 8 into basement carbonates. Of these abovementioned 32 wells not all are active (some of them are related to HC production), and most of them do not operate at 100% reinjection, only partial (Nador, personal communication). This is partly attributed to more difficult reinjection conditions in the areas of regional groundwater discharge in sedimentary basins, but also to migration of grains in heterogeneous aquifers and swelling of clay minerals.

The regional static groundwater level in the abovementioned Upper Pannonian loose sandstone aquifer in NE Slovenia has been declining at a rate of approximately -0.67 m per year recently. Besides, mineralization and some main ions were noticed to change over the years and cycling of pressure, temperature and chemical composition of thermal water was noticed in Murska Sobota. We believe that increased production of geothermal energy in the region will only be possible by establishing many more reinjection wells and geothermal doublets.

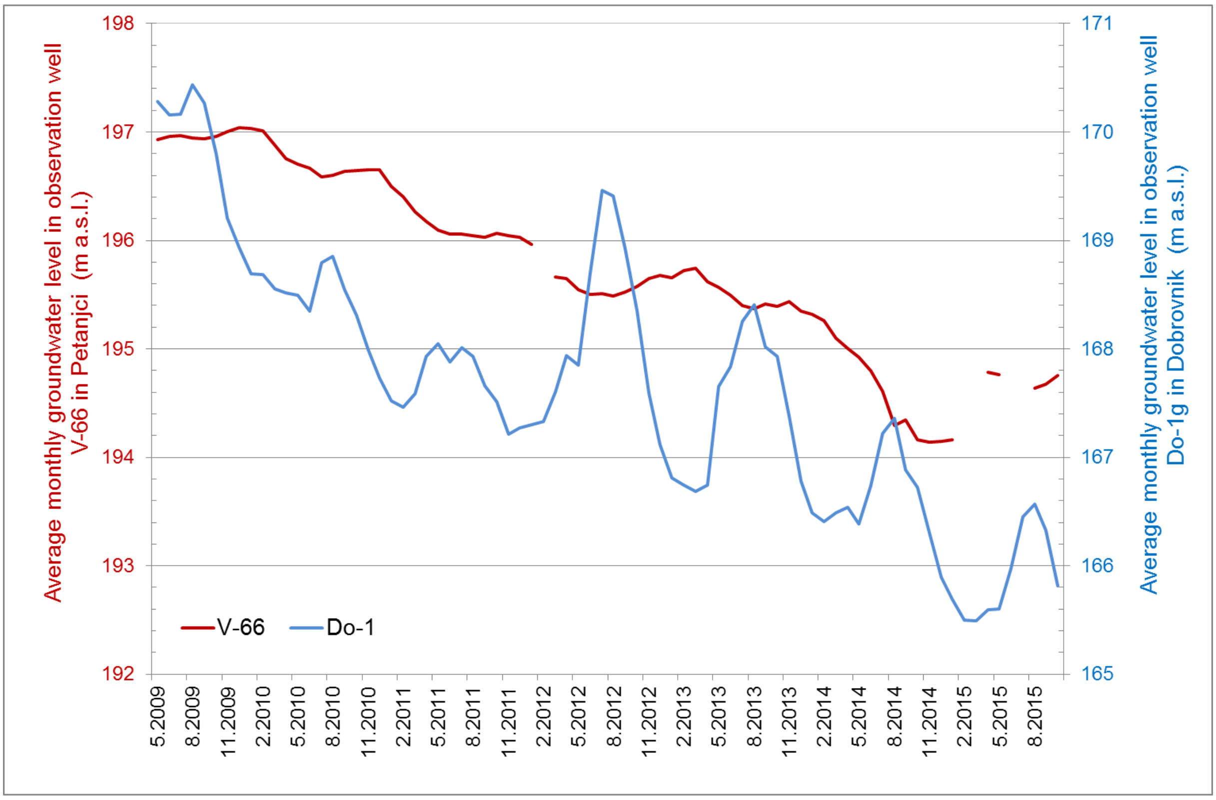

Figure 34 Regional static groundwater level trend Upper Pannonian loose sandstone aquifer in NE Slovenia

Up to now, three wells were planned to be used for reinjection into this aquifer in NE Slovenia but only one has been active since 2009. A one kilometre deep inclined reinjection well Mt-7 was active in the middle of 1990’s in Moravske Toplice. Approximately one third of the cooled thermal water with a temperature of 40–54 °C was injected at a rate from 1.0 to 5.4 l/s and at wellhead pressure between 1.8 and 2.7 bars. It was changed to a production well in 2000 due to increased need for hot water.

The second one, drilled in 2007, is still used for its original purpose. In Lendava, the geothermal doublet consists of a 1.5 km deep production well Le-2g and a 1.2 km deep reinjection well Le-3g, both are vertical. Thermal water with outflow temperature 66 °C is first used in a district heating system of the town of Lendava, which is managed by the Petrol Geoterm Co. Cooled water of approximately 45 °C is injected back into the aquifer (with approximately 80–85 °C at reinjection depth) at a rate below 25 l/s and at wellhead pressure of approximately 4 bars. Three-stage mechanical filtering of suspended solids is performed prior to injection, using sand and two microfiber filters for removal of particles with a diameter of above 10 μm (E. Torhač, personal information). If the injection pressure increases, the flow through sand filters is reversed and the 20 and 10 μm microfiber filters are changed. Additionally, cleaning of the well is performed once or twice per year. The flow direction is reversed and the well is activated to produce thermal water by a 20-bars compressor (backwashing). Produced thermal water of the Na-HCO_3 type contains 1130 mg/l of total dissolved solids and 31 mg/l of silica, and has low calcium, magnesium and chloride concentrations. No major scaling or corrosion is observed and no additional geochemical treatment of water is known to be performed.

The third one was drilled as a part of a geothermal doublet in Murska Sobota in 2012–2013. It has yet not been tested as a doublet as only production characteristics of each well were investigated. The production well Sob-3g is 1.5 km deep and reached the Pre-Neogene gneiss at 1.1 km. The reinjection well Sob-4g reaches depth of 1.2 km. They both tap predominately Middle Miocene turbiditic sandstones while gneiss in the basement is not productive. The water of 50–58 °C is moderately mineralised and has high content of CO_2. Despite, current practice from two nearby wells indicates that scaling tendency is very low.

Figure 35 Core of the Upper Miocene loose sandstone formation into which reinjection of water has to be established

In order to support increased use of geothermal energy, and not of thermal water, it is necessary to support the design of new reinjection wells as fast as possible. Pilot or demonstration projects with strong dissemination activities are desperately needed if we want to increase the number of users within the same regional aquifer as well as the total produced geothermal energy. A transparent dissemination of all steps (preparation of project, all design characteristics, all costs including maintenance costs and all results of reinjection including monitoring) of the project is crucial for replicability of reinjection well projects.

The demonstration project should investigate site specific characteristics of the transboundary Upper Miocene sandy geothermal aquifer and address solutions for issues as:

- geotechnical and physical-chemical limiting factors for reinjection wells,
- spatial distribution, depth and geotechnical quality of wells,
- optimal injection pressure, temperature and quantity of reinjected water,
- rate of reinjection return,
- possibility of thermal breakthrough,
- possibility of particle migration and swelling,
- chemical compatibility of waters,
- degassing, oxidation or corrosion of pipelines, bacterial activity,
- economic feasibility of a geothermal doublet.

5.2.2 References

Prestor, J., Szőcs, T., Rman, N., Nádor, A., Černák, R., Lapanje, A., Schubert, G., Marcin, D., Benkova, K., Götzl, G., 2015: Benchmarking - Indicators of Sustainability of Thermal Groundwater Management. *Proceedings World Geothermal Congress 2015*, Melbourne, Australia, 19-25 april 2015.

Nádor, A., Lapanje, A., Tóth, G., Rman, N., Szőcs, T., Prestor, J., Uhrin, A., Rajver, D., Fodor, L., Muráti, J., Székely, E., 2012: Transboundary geothermal resources of the Mura-Zala basin: joint thermal aquifer management of Slovenia and Hungary. *Geologija* 55(2), 209-224. http://www.geologija-revija.si/dokument.aspx?id=1159

Rajver, D., Ravnik, D., Premru, U., Mioč, P., Kralj, P., 2002: Slovenia. V: S. Hurter & R. Haenel (ur.), Atlas of Geothermal Resources in Europe. - European Commission, *Research Directorate-General, Publ. No. 17811*, Luxembourg, 54-56.

Rajver, D., Lapanje, A., Rman, N., 2012: Možnosti proizvodnje elektrike iz geotermalne energije v Sloveniji v naslednjem desetletju. Ge*ologija* 55, 117-140.

Rman, N., 2014: Analysis of long-term thermal water abstraction and its impact on low-temperature intergranular geothermal aquifers in the Mura-Zala basin, NE Slovenia. Geothermics 51, 214-227.

Rman, N., Gál, N., Marcin, D., Weilbold, J., Schubert, G., Lapanje, A., Rajver, D., Benková, K., Nádor, A., 2015: Potentials of transboundary thermal water resources in the westernpart of the Pannonian basin. *Geothermics* 55, 88–98.

Rman, N., Lapanje, A., Rajver, D., 2012: Analiza uporabe termalne vode v severovzhodni Sloveniji. *Geologija* 55(2), 225-242.

Rman, N., Lapanje, A., Prestor, J., O'Sullivan, M.J., 2016: Mitigating depletion of a porous geothermal aquifer in the Pannonian sedimentary basin. *Environmental Earth Sciences* (accepted manuscript).

Simonič, M., Ozim V., 2000: Purification of a contaminated thermal well at an oil drilling site. *Environmental Toxicology* 14(2): 211-216.

5.3 Induced Seismicity

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5.3.1 Introduction

The first earthquakes to be identified as man-made are the Denver earthquakes of the 1960s (Evans, 1966; Ellsworth, 2013), where wastewater was disposed into wells at the Rocky Mountain Arsenal. Since then we know the following main activities that might cause fluid-injection induced earthquakes: wastewater disposal, hydraulic fracturing, enhanced oil recovery, and reservoir stimulation in oil, gas and geothermal fields. Wastewater disposal with its large fluid-injection volumes which cumulate over years or decades is by far the main contributor of felt induced earthquakes and responsible for the largest induced earthquakes in recent times with a M 5.3 earthquake at Trinidad, Colorado, and a M 5.6 earthquake at Prague, Oklahoma (Rubinstein & Mahani, 2015). Hydraulic fracturing usually causes no or only small seismicity. However, larger seismic events might be the result of the reactivation of pre-existing fractures that shear instead of just open during hydraulic fracturing activities (Rubinstein & Mahani, 2015). The largest events till now caused by hydraulic fracturing were M 4.4 earthquakes in central west Alberta and British Columbia due to injected fluid volumes exceeding 100.000 m³ (Rubinstein & Mahani, 2015). Enhanced oil recovery is applied to increase the amount of oil or gas to be produced from a reservoir by injection of water, steam or carbon dioxide in order to keep the fluid pressure close to its original level. There was an M 4.6 earthquake due to enhanced oil recovery in the Cogdell field near Snyder, Texas (Rubinstein & Mahani, 2015).

5.3.2 Mechanisms of induced Seismicity

In the framework of man-made seismicity, two kinds of seismic events are distinguished: triggered and induced seismic events. As the driving forces of earthquakes are stresses, the term triggered is used for earthquakes where the human-introduced stresses are small compared to the natural stresses, whereas the term induced is used for earthquakes where the human-introduced stresses are comparable in magnitude to the natural stresses (McGarr et al., 2001). Another, more recent nomenclature is that the size of triggered earthquakes is not controlled by the human-introduced stresses while induced earthquakes are completely controlled by the anthropogenic stresses (DGG-FKPE-Arbeitsgruppe, 2013). In practise it is usually not possible to differentiate between the two cases, as it might be a mixture of both and it might happen that an induced earthquake triggers later events, as it happens with natural occurring earthquakes where the main shock triggers after-shocks. In geothermal applications, the term induced seismicity is usually used for all types of the above mentioned seismicity.

The mechanism of fluid-induced seismicity is well known and there are three different ways how fluids might induce earthquakes: 1) increase of pore-fluid pressure in the fault, 2) fluid compression within pore spaces which causes deformation (poro-elasticity), and 3) thermoelastic deformation due to temperature differences between injected and attendant fluids and formation temperature. The main mechanism that induces earthquakes is the raise of pore-fluid pressure Rubinstein & Mahani, 2015; Ellsworth, 2013). As fluids are nearly incompressible, the pore fluids reduce the normal stress (the confining pressure) acting on a fault making it more likely to shear (see Figure 36).

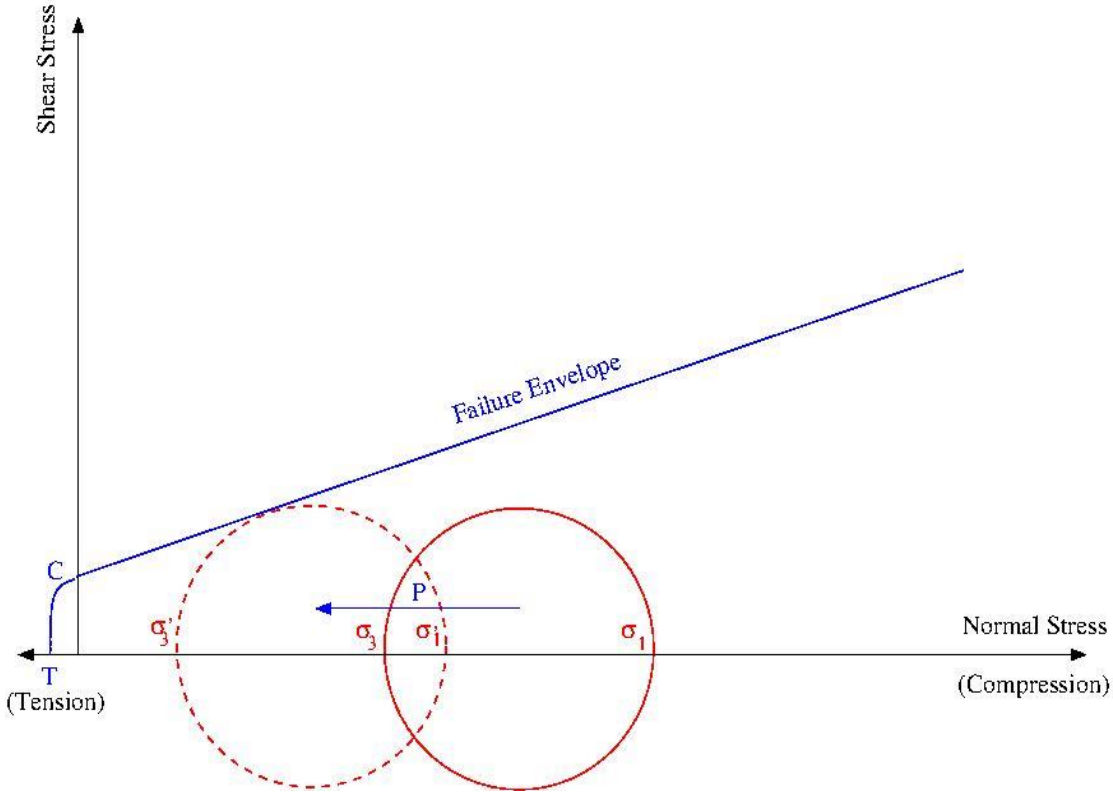

Figure 36 Mohr-circle diagram showing the effect of increased pore pressure on a fault. The increased pore pressure shifts the Mohr-circle to the left closer to the failure envelope and makes shear or tensile failure more likely. σ1 and σ3 are the maximum and least normal stresses acting on the fault, which are reduced due to pore pressure increase. C is the cohesion (intrinsic property of the rock) and T is the tensile strength of the rock. Negative normal stress is tension, positive normal stress is compression.

Usually, no high injection pressures are necessary to induce shearing. Experiments e.g. at the KTB (Kontinentale Tiefbohrung, Oberpfalz, Germany, e.g. Baisch et al., 2002; Zoback & Harjes, 1997) and Soultz-sous-Forêts (Elsass, France, e.g. Michelet et al., 2004; Baria et al., 2004) showed, that the crystalline basement is in a label state of equilibrium and even a small increase in pore pressure results in induced seismicity. If pre-existing faults are favourably oriented regarding to the main principle axes of the tectonic stress regime, they might be reactivated and remain open as the opposite fault planes no more fit together. This is called the self-propping effect (e.g. Baisch & Harjes, 2002; Evans et al., 1999). These two mechanisms make fluid-injection induced seismicity useful for reservoir management: on the one hand the locations of the induced seismic events mirror the fluid migration in the reservoir and thus the reservoir volume, and on the other hand the self-propping effect keeps new fluid paths open which increases the permeability of the reservoir and hence the injection or production index, and creates new heat exchanger surfaces. In geothermal reservoirs, both are desired tools in subsurface engineering and not failures in the system! Furthermore, without both tools the original Hot Dry Rock concept (HDR, later on called Enhanced Geothermal System, EGS) would not work (e.g. Evans et al., 1999). Of course it is desired to keep the size of the induced events limited, i.e. earthquakes should not be felt by the population (then called microseismicity, if the events are detectable only with sensitive instruments). Practise shows that only a very small portion of the induced seismic events is felt by the population.

5.3.3 Example: Geothermal power plant Insheim (Rheinland-Pfalz, Germany)

In the vicinity of geothermal plants the quantity and the size of the seismic events (i.e. the magnitude) is largest during stimulation activities and at the start-up of the geothermal power plant (Küperkoch, 2016). Figure 37 shows the temporal evolution of the seismic events with its magnitudes and corresponding maximum peak-ground velocities (if detected!) and the operational data injection pressure, injection temperature and injection flow rate of the geothermal power plant Insheim (Rheinland-Pfalz, Germany) which started operating in October 2012. It is based on a hydro-thermal reservoir, which is the most efficient geothermal reservoir in low-enthalpy areas, as the fluids are already in the formation and fluid paths already exist, making long and expensive stimulation activities needless (Baumgärtner et al., 2013). It is obvious especially from the cumulative number of seismic events that the vast majority of induced seismicity occurred during start-up of the power plant. After some time of flat-line operation, the number of seismic events drops down. The same behaviour can be seen from the maximum detected peak-ground velocities. The onsets of seismic active periods usually correspond to down- and up-times of the power plant which means that a new state of equilibrium in the formation has to be reached. Unfortunately, the relationship between power plant operation and induced seismicity is not unambiguous, as there are seismic active periods without obvious operational reasons. However, it turned out that a sensitive handling with the reservoir (i.e. soft starting and stopping, if possible) avoids larger events which might be felt by the population. Furthermore, the application of a traffic-light or graduated scheme shows good results in practise. Though flat-line operations are usually recommended, it might be necessary to reduce the flow-rate temporarily if a larger event has been induced. The successfully applied graduated scheme of Insheim is shown in Table 13.

Table 13 Graduated scheme at Insheim geothermal power plant

Seismicity	Activity
0.2 mm/s < PGV* < 0.5 mm/s	Information, documentation
0.5 mm/s < PGV < 1.0 mm/s or 5 induced events within 12 hours	Information, temporal reduction of flow rate
1.0 mm/s < PGV < 5 mm/s	Information, evaluation of seismicity, stepwise reduction of flow rate
5 mm/s < PGV < 10 mm/s or 1 induced event producing PGV > 5 mm/s or 3 induced events producing PGV > 3 mm/s	Information, operation at reduced flow rate
PGV > 10 mm/s	Shut down power plant

**PGV Peak-ground velocity*

5.3.4 Conclusions/Summary

Though the main physics of induced seismicity is well understood, it is yet not possible to predict entirely the behaviour of a reservoir, particularly when stimulating new boreholes or starting a new geothermal power plant. Nevertheless, induced seismicity is taken into account in the development phase of new geothermal projects in Germany to minimize seismicity related issues.

To estimate the quantity and size of a reservoir before stimulation activities it is inevitable to consider the natural background seismicity, the state of stress and recent active faults (e.g. Majer et al., 2012). However, it is yet not clear, if a reservoir in an active seismic area shows more or larger events than a reservoir in a seismically more inactive area. Furthermore, even knowledge of the regional stress field does not necessarily imply good estimates of quantity, size and mechanisms of induced seismic events, since microearthquakes mirror the very local stresses, which are impressed on the regional stress regime. Moreover, faults might be reactivated due to fluid-injection and were unmapped before seismic events reveal them. The complex interaction of various injection parameters (flow-rate, injection temperature, cumulative injected volume, injection pressure, reservoir depth) and reservoir conditions (pore pressure, temperature, stress field, rock strength, pre-existing faults and their orientation) results into a system difficult to predict, which needs careful preliminary geoscientific surveys and sensitive handling during stimulation and operation.

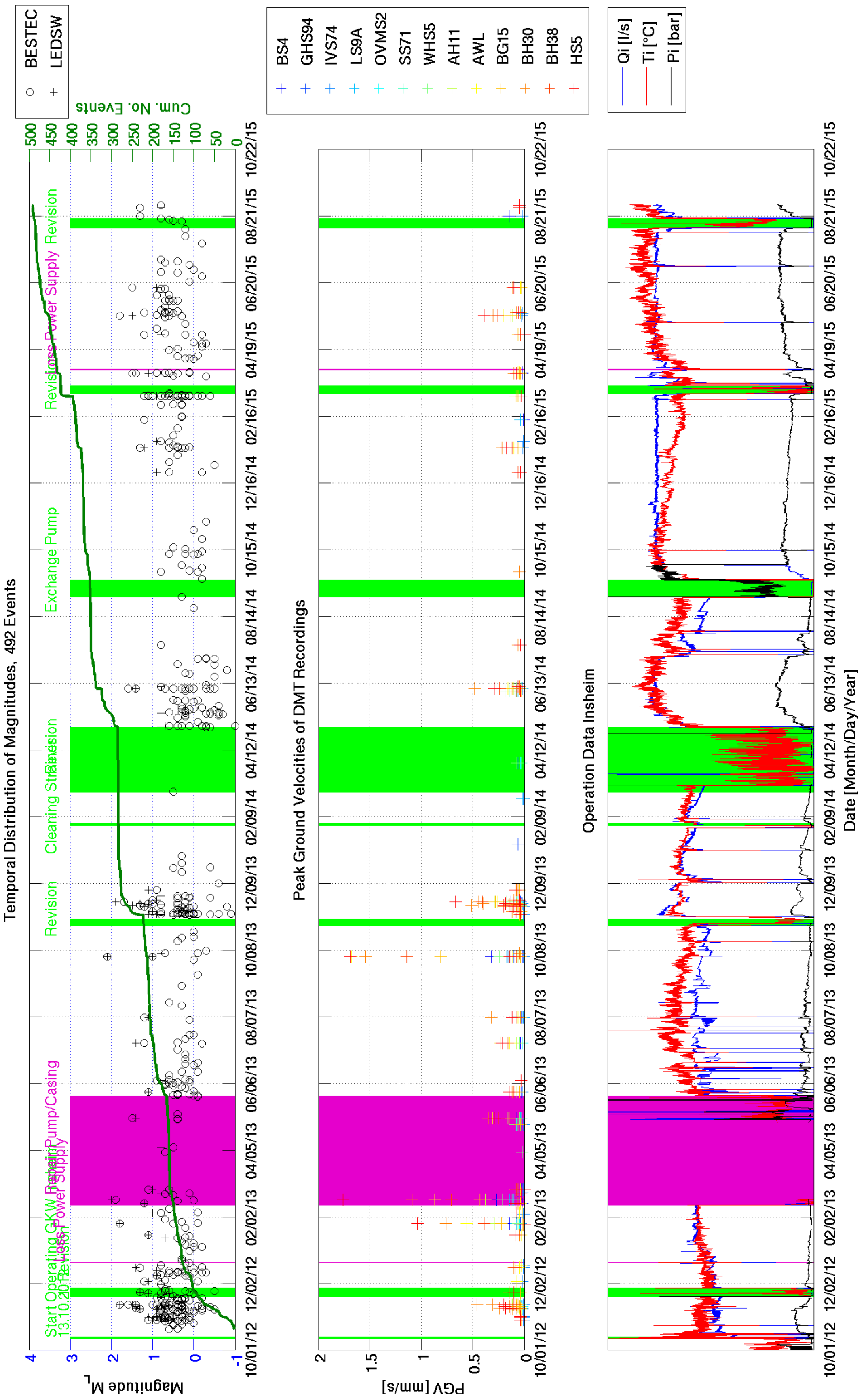

Figure 37 Temporal evolution of induced seismicity at Insheim geothermal power plant and corresponding peak-ground velocities and operational data. Green shaded areas indicate planed down-times and pink shaded areas unplanned down-times of the geothermal power plant, respectively.

5.3.5 References

Baumgärtner, J., Hettkamp, T., Teza, D., Kölbel, T., Mergner, H., Schlagermann, P. & Lerch, C., 2013: Betriebserfahrungen mit den Geothermiekraftwerken Landau, Insheim und Bruchsal. bbr 05-2013.

Baisch, S., & Harjes, H.-P., 2002: A model fpr fluid-injection-induced seismicity at the KTB, Germany, Geophys. J. Int., 152, pp 160-170.

Baisch, S., Bohnhoff, M., Ceranna, L., Tu, Y., & Harjes, H.-P., 2002: Probing the crust to 9 km depth: fluid injection experiments and induced seismicity at the KTB superdeep drilling, Germany, Bull. Seism. Soc. Am., 6, pp 2369-2380, DOI: 10.1785/0120010236.

Baria, R., Michelet, S., baumgärtner, J., Dyer, B., Gérard, A., Nicholls, J. Hettkamp, T., Teza, D., Soma, N., Asanuma, H., Garnish, J., & Megel, T., 2004: Microseismic monitoring of the world's largest potential HDR reservoir, in Twenty-Ninth Workshop on Gepthermal Reservoir Engeneering, Stanford University, Stanford, California, January 26-28.

DGG-FKPE-Arbeitsgruppe und externe Experten, 2013: Zur Diskriminierung induzierter Seismizität, in Mitteilungen der Deutschen Geophysikalischen Gesellschaft, 2/2013, Wissenschaftliche Beiträge.

Ellsworth, W.L., 2013: Injection-induced earthquakes, Science, 341, DOI: 10.1126/science.1225942.

Evans, D.M., 1966: The Denver area earthquakes and the Rocky Mountains arsenal disposal well, The Mountain Geologist, 3, pp 23-35.

Evans, K.F., Cornet, F.H., Hashida, T., Hayashi, K., Ito, T., Matsuki, K., & Wallroth, T., 1999: Stress and rock mechanics issues of relevance to HDR/HWR engineered geothermal systems: review of development during past 15 years, in Geothermics, Special Issue: Hot Dry Rock/Hot Wet Rock Academic Review.

Küperkoch, L., 2016: Bericht zur Überwachung der mikroseismischen Aktivität um Insheim im Dezember 2015, internal report.

Majer, E., Nelson, J., Robertson-Tait, A., Savy, J., & Wong, I., 2012: Protocol for addressing induced seismicity associated with Enhanced Geothermal Systems, Geothermal Technologies Program of the U.S. Department of Energy.

McGarr, A., Simpson, D., & Seeber, L., 2002: Case histories of induced and triggered seismicity, Int. Geophys., 81A, pp 647-661.

Michelet, S., Baria, R., Baumgärtner, J., Gérard, A., Oates, S., Hettkamp, T., and Teza, D.: Seismic source parameters evaluation and its importance in the development of an HDR/EGS system, in Twenty-Ninth Workshop on Gepthermal Reservoir Engeneering, Stanford University, Stanford, California, January 26-28.

Rubinstein, J.L., & Mahani, A.B., 2015: Myths and facts on wastewater injection, hydraulic fractering, enhanced oil recovery, and induced seismicity, in Seism. Res. Let., 86, 4.

Zoback, M.D., & Harjes, H.-P., 1997: Injection-induced earthquakes and crustal stress at 9 km depth at the KTB drilling site, Germany, J. Geophys. Res., 102(B8), pp 18477-18491.

6 Summary and outlook

This report, with contributions from the OpERA Expert Group and its Appendices from the OpERA workshop in Vaals, brings together a wealth of information on operational issues in geothermal energy. The workshop has been very successful in bringing the experts together. It has stimulated them to forge new collaborations on a European scale. This publication is more than just a collection of presentations. – it also includes contributions from the OPERA expert group on the various issues, which brings the publication to a higher level.

The "Magna Carta" that is published as Appendix 1 to this report helps to identify solved and unsolved issues in the various European countries. It makes it clear where we can learn from one another, and where joint activities are necessary to further the skills of the geothermal energy professionals.

The thematic approach that the workshop adopted has helped the focus of the workshop sessions and of the current report. However, there are of course evident interrelations, e.g. between scaling and gas content management. Figure 38 below illustrates this. The figure was made by our moderator Dario Frigo during the workshop to facilitate the discussion and draw the larger picture, where all operational issues need to be managed.

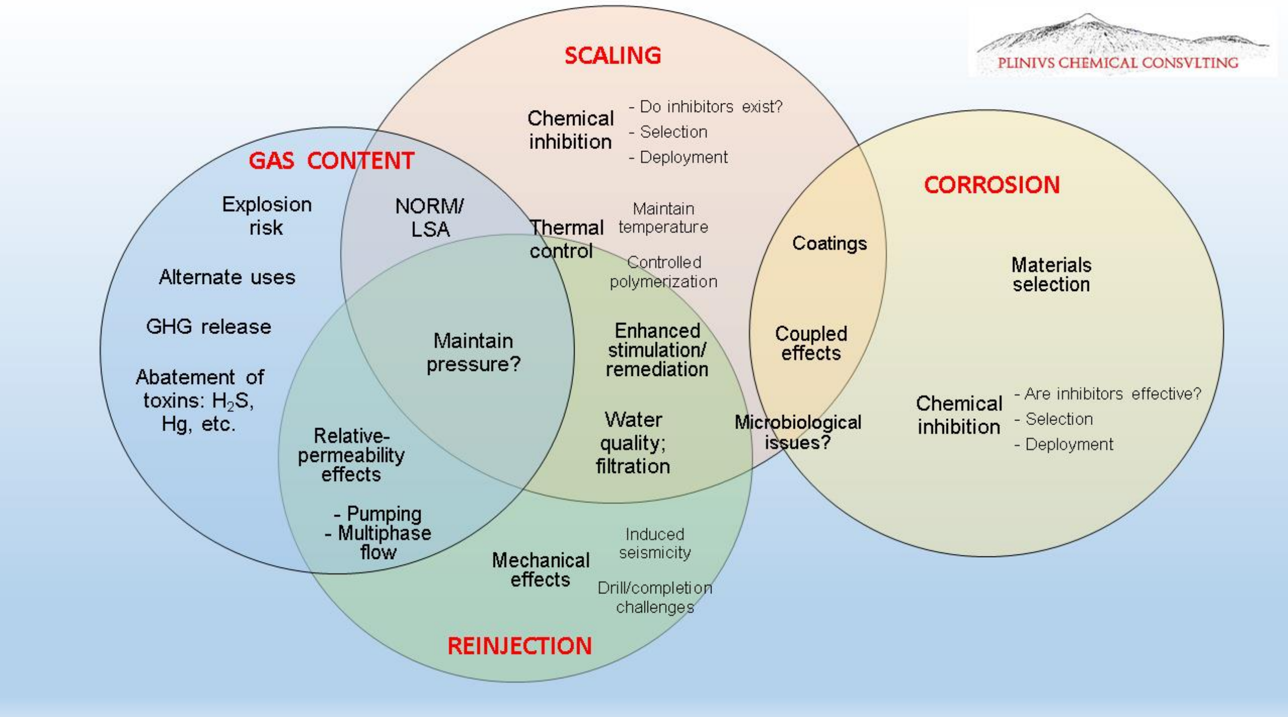

Figure 38 The interdependence of operational issues, drawn by moderator Dario Frigo, to facilitate discussion at the OPERA workshop in Vaals, the Netherlands.

Based on the success of the OpERA workshop, the Geothermal ERA-NET has decided to keep on working on operational issues. This will be done in two ways, firstly by implementing the "OpERApedia", and secondly by stimulating innovations through further collaboration in the ERANET Cofund GEOTHERMICA. The "OpERApedia" will be a web-based tool, which optimises European knowledge sharing on operational issues. The contents of OpERApedia will be thematic as well as country-specific. There will be two ways to search the information that we will bring together. The work in GEOTHERMICA will include joint calls on a broad range of geothermal topics, focussing on demonstration of innovations.

The organisers conclude that the OpERA is an important initiative at this stage of the application of geothermal energy in Europe. They invite everybody to help keep this ball rolling, because Europe and the world will need more use of geothermal energy, and that is only possible when the operational issues of these systems can be managed well.

Appendix 1 - The “Magna Carta”

Please find A0 pdf of the Magna Carta under the following link:

www.geothermaleranet.is/media/publications-2015/Geothermal-ERA-NET-JA-Report-OpERA_publication_def_MC_Update_20161010.pdf

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