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TNO report

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Geothermal energy – Scaling potential with cooling and CO$_2$ degassing

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Summary

The scaling potential of geothermal energy is assessed in the context of the project *TC waterbehandeling geothermie*. This project includes the majority of Dutch geothermal doublets in the exploration and production phase. Scaling is already observed in some of these doublets, indicating its relevance to geothermal operations in the Netherlands. Geochemical simulations can help identifying the processes involved in scaling. Insight in the process of scaling may point to possible preventive or remediation measures. The performed simulations are part of a theoretical model study to assess the scaling potential. Model verification is required – with measurements of scaling – for calibration of the model and making more accurate predictions of scaling.

This study is focussed on the possibilities of additional cooling of the produced water and on the desirability of degassing. Additional cooling of the produced water is beneficial for subsequent water injection since practical experience indicates that injection of colder water requires less energy which would increase the doublets efficiency. To improve the doublets economics the dissolved natural gas can be used as fuel. However both increased cooling and degassing may include a risk of scaling.

Geochemical simulations are performed with PHREEQC to assess the scaling potential. The simulations show that the predicted precipitation increases with cooling. This indicates that further cooling than done at present is not advisable without a scaling prevention strategy. Moreover, the simulations indicate that the scaling potential of current operations is already significant. This may suggest present or future reduced flow in reservoir. Depressurization and degassing of CO_2 predict the largest amount of scaling. This indicates that doublets containing dissolved CO_2 have high scaling risks and that it is advisable to take measures to keep the CO_2 in solution or re-introduce CO_2 or another pH decreasing agent during degassing.

Contents

1 Introduction

This report describes geochemical simulations performed in the project *TC waterbehandeling geothermie*. The aim of this project is to investigate the effect of additional cooling of the produced water and the effect of degassing. Both cooling and depressurizing/degassing of the produced water disturb the chemical equilibrium and can cause precipitation reactions. Mineral precipitation or scaling within the wellbore, surface installations and the reservoir can cause serious problems by reducing flow and hence energy efficiency. These risks are assed especially because increased cooling of the produced water is in itself beneficial for water injection since practical experience indicates that injection of colder water requires less energy. The energy or pressure required for water injection is a major issue in geothermal energy since the injection pressures required to achieve sufficient flow rates are often high. Insight in the possible adverse effect of chemical precipitation due to cooling can help optimize geothermal doublets. Data of seven doublets is used for this study.

Simulations are performed with PHREEQC to model the equilibrium chemical reactions with cooling for all doublets (chapter 2). For the doublets that degas the water or plan a degassing practice, the effect of CO_2 degassing is assessed. Simulated are performed with the maximum CO_2 solubility (chapter 3) and with reduced CH_4 controlled solubility (chapter 4). The model details including the assumptions adopted are described in Appendix A. Important assumptions in the simulations are equilibrium reactions (neglecting reaction rates) and chemical equilibrium in the reservoir and hence of the formation water. Specific redox processes are not defined in the model. This means that default values were used to calculate redox equilibrium. Any interaction with installation materials (including corrosion) is not included in the model.

2   Scaling potential with cooling

2.1   Scaling minerals

The scaling minerals are selected based on the oversaturation calculated by PHREEQC for the different model steps (see model details in Appendix A). Oversaturation means that minerals should precipitate. These calculations are done using the Thermoddem database (http://thermoddem.brgm.fr). This database contains all elements in the formation water but is not adapted for high salinities such as a (more limited) Pitzer database. The potentially precipitating minerals are screened to select minerals that are considered possible to precipitate within the relevant pressure and temperature domain. Initially oversaturated minerals are simulated with this oversaturation, which means that we assume initial equilibrium in the reservoir. Minerals are excluded from the simulation if they require different conditions for precipitation or take a long time to precipitate (relative to production time scales). Slow reacting minerals that are not included in this simulation are clays and zeolites. The minerals that are considered possible precipitating phases in the simulations are listed in Table 2. Note that iron is modelled as oxide or carbonate but may form sulphates depending on the redox conditions. Specific redox processes were not included in the model.

Table 1 Minerals used in the simulations.

Mineral	Formula
Gibbsite	$Al(OH)_3$
Barite	$BaSO_4$
Quartz	SiO_2
Ferrihydrite6L	$Fe(OH)_3$
SiO_2glass	SiO_2
$ZnSiO_3$glass	$ZnSiO_3$
Siderite	$FeCO_3$
Calcite	$CaCO_3$
Vaterite	$CaCO_3$
Aragonite	$CaCO_3$
Dolomite	$CaMg(CO_3)_2$
Cerussite	$PbCO_3$
Strontianite	$SrCO_3$
Magnesite	$MgCO_3$
Halite	$NaCl$

2.2 Simulation results of cooling

The simulation details are described in Appendix A. The simulations predict that the main precipitating minerals are the same for all doublets (Figure 1). These are ferrihydrite, barite, gibbsite and silica (modelled as quartz). Precipitation generally increases with cooling. Note that GD 6 and GD 7 do not predict gibbsite scaling because the aluminium content was not (precisely) measured and included in the model. The same goes for GD 6, GD 7 and GD 4 with regard to silica scaling. Simulations were run for these doublets assuming an average aluminium and silica content (results not shown). Including silica and aluminium causes gibbsite and silica scaling similar to the other doublets and does not influence the behaviour of the other scaling minerals.

The predicted amount of ferrihydrite scaling varies between the different doublets, with the highest amounts for GD 5 and GD 8 and the lowest for GD 6B (Figure 1). Even though GD 2 and GD 1 have similar iron contents as GD 8, their predicted iron scaling is much less. For GD 5, GD 8 and GD 2A, ferrihydrite precipitation shows a strong increase for the first 20 °C of cooling with a smaller increase with further cooling. GD 3a even shows a decrease in predicted precipitation with cooling of more than 40 °C. The predicted gibbsite precipitation shows large differences between the Reservoir A and reservoir B doublets. The latter yielding far more precipitation (Figure 1). For all doublets, gibbsite precipitation increases strongly until cooling down to 50 °C. With further cooling, precipitation increases only slightly or even decreases. For both gibbsite and ferrihydrite additional cooling over the present ~30 °C appears to cause little additional risk of scaling. However, precipitation is already significant.

Barite precipitation increases with cooling for al doublets (Figure 1). The increase is roughly linear and hence further cooling largely increases the amount of predicted scaling. Quartz also shows a near linear increase of predicted precipitation with cooling. But in contrast to barite, gibbsite and ferrihydrite, quartz precipitation is not predicted from the onset of cooling but from a certain cooling temperature. The temperature from which quartz precipitates differs for the different doublets and lies between 65 °C and 25 °C. This means that by reducing the cooling temperature, quartz precipitation can be prevented. At temperatures below 25 °C quartz scaling is predicted for all doublets.

Carbonates are only predicted for GD 6A, not for GD 6B. This is due to the higher pH, 7.7 compared to 5.7. The high initial oversaturation of carbonates in the GD 6A simulation shows that the measured water out of equilibrium with respect to carbonates, a highly unlikely situation. Therefore, the results of high carbonate precipitation should be interpreted with caution. Note that carbonate solubility usually increases with cooling whereas the simulation shows increased carbonate precipitation. This is probably due to the pH increase with cooling.
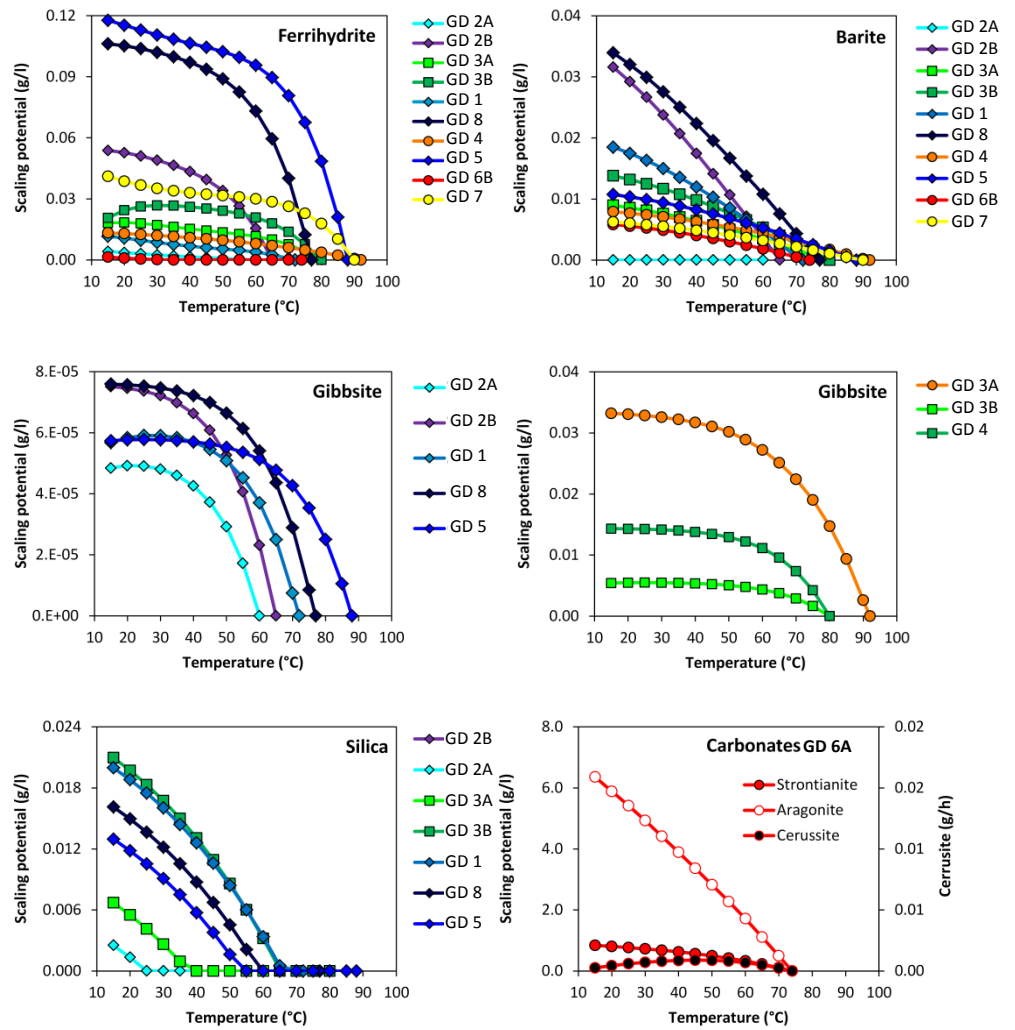
Figure 1 The scaling potential in gr/l for the different minerals with cooling. At each temperature the total amount of precipitation up to that temperature is plotted.

3 Scaling potential with CO_2 degassing – dominant CO_2 system

3.1 Pressure decrease and degassing

Several geothermal doublets produce natural gas and oil together with the formation water. At high pressure – in the reservoir – the gas is dissolved in water. During water production the pressure decreases which causes a decrease of gas solubility the produced water and consequently degassing. The released gas can be removed with an oil gas separator and utilised as fuel. However, the removal of oil and gas from the water disturbs the chemical equilibrium and can therefore cause chemical reactions. These reactions may involve harmful mineral scaling within the doublets. Methane has a low solubility and a negligible effect on the mineral reactions. A possible effect of organic compounds and other hydrocarbons on mineral reactivity is out of scope for this project but could be of influence.

In this study we focus on the effect of CO_2 degassing since the CO_2 content of natural gas has considerable influence on the chemistry of the water. Dissolved carbon dioxide in the water affects the pH and therefore chemical reactions. Since CO_2 degassing occurs when water depressurizes during production and/or sampling and analysis, the measured dissolved CO_2 content is most likely lower than the actual dissolved CO_2 in the reservoir. This also means that the measured pH is probably higher than in the reservoir since CO_2 dissolution reduces the pH. To implement the pH and dissolved CO_2 in the model, the maximum amount of dissolved CO_2 is calculated at reservoir temperature, salinity and pressure. A maximum solubility of CO_2 is most probable for systems that contain CO_2 as dominant gas so that the CO_2 solubility controls the total gas solubility.

3.2 Simulation results of degassing

Degassing of the water results in significant scaling potential of a number of minerals (Table 2). The carbonates – including dolomite, calcite and siderite – are the dominant scaling phase. Only the GD 4 formation water gives no carbonates due to the low final pH at which carbonates are not stable. Carbonates precipitate relatively fast compared to the other minerals and therefore have the highest risk of scaling within surface facilities. The lack of carbonate precipitation for GD 4 indicates the positive effect of a low pH in inhibiting carbonate scaling. A CO_2 containing water will have a low pH and this low pH can be retained by not degassing the water or by later addition of acid or CO_2.

It is important to consider that the amount of carbonate precipitation depends on the amount of CO_2 dissolved in water. We used the maximum solubility of CO_2 which gives the maximum amount of carbonates. The pH used is also of large influence to the predicted carbonate scaling. We compensated for the final pH since this pH was modelled lower than measured. This could indicate a numerical issue in for example the implementation of CO_2 solubility. These uncertainties indicate that the results presented in Table 2 should be taken as a qualitative scaling potential. To further investigate these uncertainties, simulations are performed with the measured amount of CO_2 degassed. These results are presented in the next chapter.

Table 2. Precipitation upon degassing in g/l.

Mineral	GD 1	GD 8	GD 4	GD 5	GD 6A	GD 6B	GD 7
Gibbsite	5.8E-05	3.2E-05	3.8E-02	2.3E-05	-	-	-
Barite	2.7E-04	1.1E-03	2.8E-04	3.0E-04	1.1E-05	0	2.1E-04
Ferrihydrite6L	4.3E-02	1.6E-01	1.5E-02	2.3E-01	2.2E-01	2.9E-02	1.2E-01
SiO2glass	7.6E-03	7.6E-03	-	8.0E-03	-	-	-
ZnSiO3glass	1.2E-03	9.4E-04	3.3E-02	1.0E-03	0	0	0
Siderite	1.5E-02	0	0	0	0	0	1.4E-02
Calcite	5.9E-03	0	0	0	9.9E-01	5.3E-01	4.0E-01
Dolomite	5.8E-01	8.8E-01	0	6.7E-01	0	0	0

3.3　Simulation results of cooling after degassing

After simulating degassing the water is cooled which yields additional mineral precipitation (Figure 2). Precitation due to cooling is generally lower than due to degassing (Compare Figure 2 and Table 2). Compared to cooling simulations with the measured composition, there is additional silica scaling occuring at the onset of cooling. The more abundant quartz pecipitation still starts after 40 to 60 °C of cooling. The occurrence of silica glass indicates the stability of a lower ordered phase with the first amount of cooling. Although the equilibrium simulations predict quartz precipitation with further cooling, kinetics may still favour a less crystalline amorphous form of silica (possibly forming a silica 'gel' more than a solid precipitate). Barite precipitation is little affected by degassing and its behaviour with cooling is unchanged compared to water cooling using the measured composition (Figure 1 and Figure 2). With cooling carbonate scaling is only predicted for GD 6A.
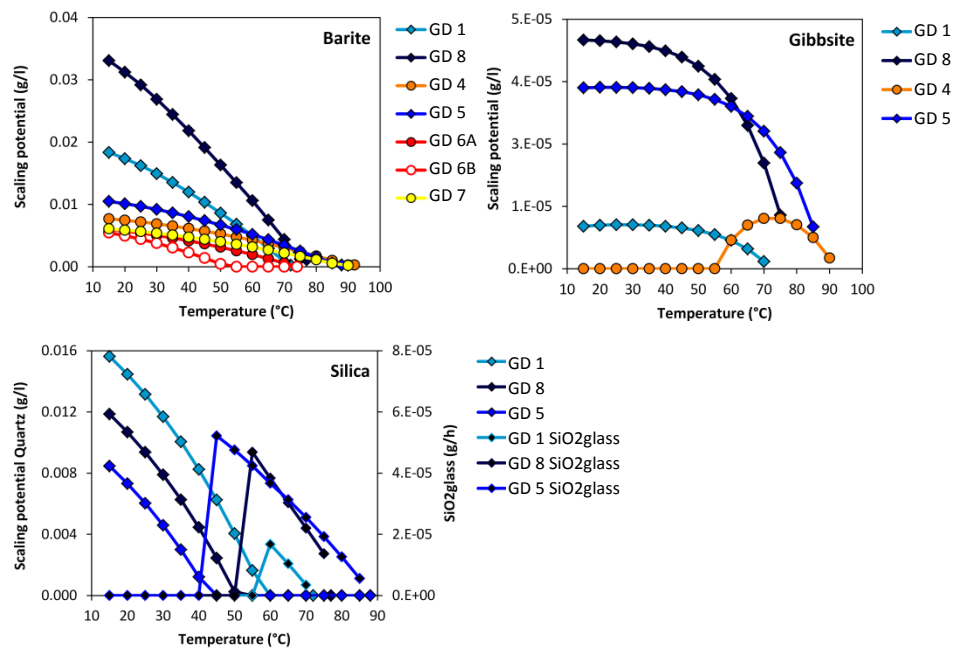

Figure 2. Predicted precipitation with cooling, precipitation in gr/l.

3.4 Simulation results of cooling without degassing

If the dissolved CO_2 is not degassed the CO_2 is kept in solution and the pH remains low which results in reduced precipitation. There is no precipitation of gibbsite and ferrihydrite predicted, only of barite and silica (Figure 3). Barite precipitation is not affected by degassing or by the CO_2 content of the water and remains the same for the different cooling simulations (compare Figure 3 to Figure 1 and Figure 2). This means that changing the degassing practice or the pH of the injected water will not prevent barite precipitation. Quartz precipitation is also little affected by keeping CO_2 in solution. However, the silica precipitation at higher temperatures is enhanced. This might indicate a stronger tendency for silica (gel) scaling when the water is not degassed. But all in all cooling with no degassing predicts the lesser amount of precipitation compared to cooling using the measured or degassed water composition. The fewer number of minerals that are predicted to cause scaling also simplify a potential use of antiscalent.
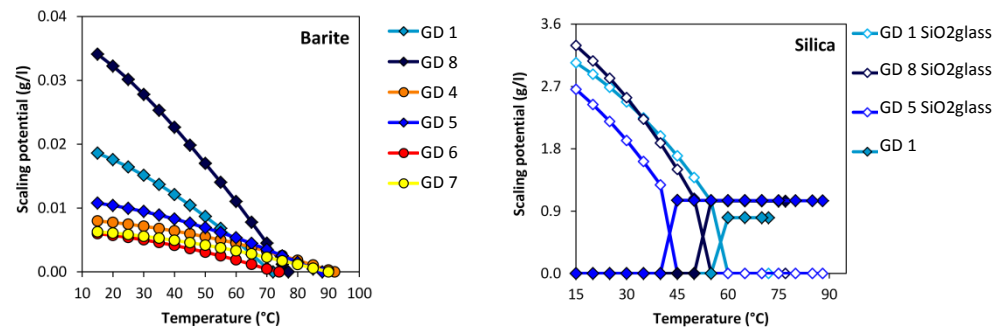

Figure 3. Predicted precipitation with cooling for different minerals. Scaling potential in gr/l.

4 Scaling potential with CO_2 degassing – dominant CH_4 system

4.1 CO_2 dissolution

As discussed in the previous chapter CO_2 is dissolved in the water at reservoir conditions and will degas upon production of the formation water. Assuming the maximum solubility of CO_2 in water results in high amounts of carbonate scaling. However, when CO_2 is a component of the natural gas dissolved and not the dominant phase, the dissolution of the CO_2 will be controlled by the solubility of CH_4 which is far less. A second set of calculations was performed with a lower amount of dissolved CO_2 based on the measured gas water ratio and the mol percentage of CO_2 in the gas at the reservoir pressure and temperature.

4.2 Simulation results of degassing

The results for the degassing simulations are presented in Table 3. There are clear differences between the predicted precipitations when assuming the maximum CO_2 content and when using the gas water ratio, CO_2 content and CO_2 partial pressure (compare Table 2 and Table 3). Gibbsite and barite precipitation is no longer predicted, except for GD 6A. Silica precipitation is comparable in amounts but is now predicted for all doublets. For GD 6B, GD 7, GD 4 and GD 3A no carbonates scaling is simulated. For GD 1, GD 5 and GD 8, the predicted carbonate precipitation is largely reduced, especially for dolomite. Differences are observed in the type of carbonate which could be strontianite, vaterite, siderite or dolomite. Note that calcite is no longer predicted to form but that including reaction rates could favour calcite over the other carbonates.

Table 3. Precipitation upon degassing in g/l.

	GD 1	GD 8	GD 4	GD 5	GD 6A	GD 6B	GD 7	GD 3A
Barite	0	0	0	0	7.7E-04	0	0	0
Ferrihydr.	1.8E-05	0	0	5.6E-05	0	9.5E-06	4.1E-06	0
SiO2	5.5E-03	5.0E-03	3.9E-03	4.9E-03	2.6E-04	2.8E-03	3.3E-03	5.8E-04
ZnSiO3	7.8E-04	4.4E-04	0	7.3E-04	0	0	0	0
Strontian.	0	0	0	0	2.4E-01	0	0	0
Vaterite	0	0	0	0	2.2	0	0	0
Siderite	4.0E-02	0	0	2.8E-02	0	0	0	0
Dolomite	1.0E-02	5.2E-02	0	0	1.7	0	0	0

4.3 Simulation results of degassing at different pressures

The amount of carbonate scaling largely depends on the amount of CO_2 degassing as was shown by comparison with the CO_2 saturated system. The amount of CO_2 degassing is in turn controlled by the CO_2 partial pressure and hence depends on the pressure release. Many geothermal installations have the possibility of keeping the doublet under a certain amount of pressure. Therefore insight in the change in precipitation with pressure could help determining an optimal installation pressure. Figure 4 shows that scaling increases at lower pressures with maximum scaling potential at the total pressure release to 1 bar. For some minerals it appears that a slight pressurization can prevent their formation.
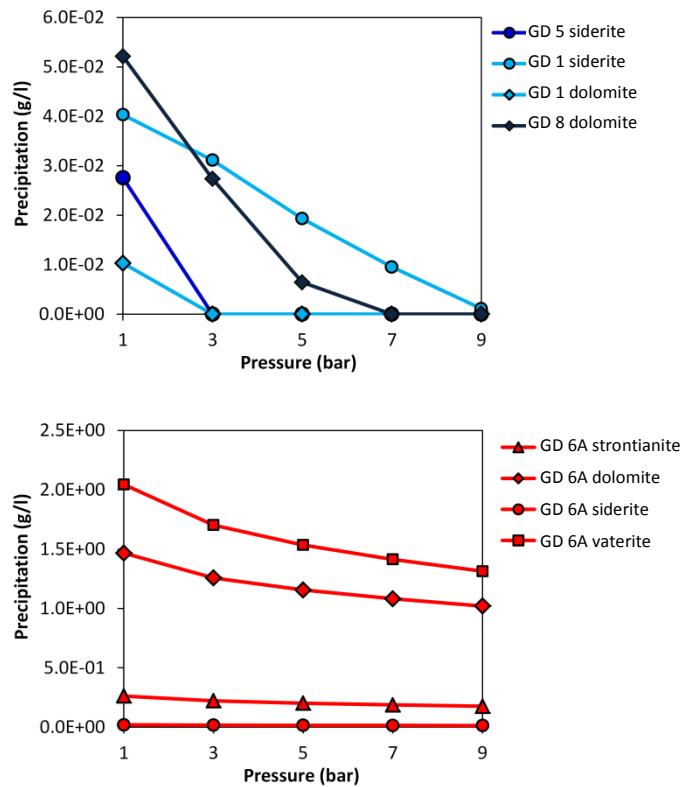

Figure 4. Carbonate scaling due to degassing, given for different pressures.

5   Discussion and Conclusions

5.1   Model verification

The presented model results are obtained with a theoretical model that is not yet validated by experiments or field data of scaling. To validate the model, mineralogical measurements of precipitates are required. Validation can also be done with experiments. For example by taking a down hole water sample and keeping it closed for a certain time at low temperature in order to measure which precipitates form with time.

5.2   Sampling, analysis and uncertainties

The accuracy of the model is directly linked to the quality of the data used. Sample analysis always has an uncertainty which translates to uncertainties in the model. To better evaluate these uncertainties, duplicate measurements of samples should be taken. Ideally a water sample is taken down hole or at least before degassing occurs and then measured for water chemical composition, gas water ratio and gas composition. Pressurization of the sample is required to prevent oxygenation as long as possible. Additional information required includes the sample depth, pressure, temperature, salinity (total dissolved solids) and density. The water chemistry measurement should include pH, Na, Cl, Mg, Ca, Fe, Pb, Al, K, Sr, Ba, C, S, Si (Ni, Cu, Zn). The used laboratory should be asked for uncertainties in their analysis techniques for the different elements. Information on precipitates that formed before sample analyses are also beneficial. If samples of actual scales are available they should be analysed with XRD to determine the mineralogy. Performing only a chemical analysis of a scale will give limited information on the nature of the scale.

5.3   Scaling potential with cooling

This study showed that all simulated doublets have a significant scaling potential due to cooling. A save cooling temperature, at which there is no scaling potential, was not found. Only in a few cases precipitation starts after a certain temperature. Most minerals show a precipitation tendency from the onset of cooling. The major scaling minerals are ferrihydrite (iron hydroxide), gibbsite (aluminium hydroxide), barite and silica. In general, the predicted precipitation of minerals increases with cooling for al doublets. Barite and quartz precipitation show a strong increase with cooling. For both gibbsite and ferrihydrite, additional cooling below the currently used cooling temperature of around 30 °C appears to cause little to no additional risk of scaling. However, precipitation is in general already significant and additional cooling appears not advisable without remediation measures. In addition, further study is required to assess whether scaling has already caused formation damage and how corrective measures can be taken.

5.4   Scaling potential with CO_2 degassing

Degassing simulations are performed using the calculated amount of originally dissolved CO_2 in the reservoir. This approach gives the *maximum* CO_2 dissolved and hence a worst case scenario in terms of disequilibrium of the water. Using only the measured composition – neglecting the fact that CO_2 may have been lost from the solution – leads to an underestimation. When CO_2 is present in the reservoir and is degassed, the scaling potential is the largest since degassing induces carbonate formation. When CO_2 is kept in solution this risk will be largely reduced. This could be done by not degassing the water or alternatively CO_2 or an acid can be used to re-acidify the water. If degassing can be prevented depends on the bubble point of the gas, the temperature decrease and the pressure that can be contained within the doublet system. An interesting possibility could be to find a pressure at which most of the CH_4 degasses and can be utilized while CO_2 remains largely in solution. This method uses the lower solubility of CH_4, which means that it will come out of solution in relatively larger amounts than CO_2 at the beginning of depressurization. The possibilities of this method are very case specific.

A good determination of the actual carbonate scaling relies on accurate measurements of the amount of dissolved carbon in the water at reservoir pressure and temperature and the amount of CO_2 degassed. A second set of simulations was performed with a lower amount of dissolved CO_2 based on the gas water ratio and the percentage of CO_2 in the natural gas. This showed reduced carbonate scaling compared to the maximum amount of CO_2 dissolved but still no scaling free degassing.

5.5   Comparison with observed scaling problems

Lead scaling is observed in one of the doublets. This corresponds with a high dissolved lead concentration. Cerussite (lead carbonate) is only predicted for GD 6A when no CO_2 is used in the model. This might indicate that lead scaling is more relevant for doublets containing no or little CO_2 and having a high pH. However, other possibly important processes such as redox reactions and related corrosion are not yet incorporated in the model and should be studied in future projects. Furthermore, the model predicts that the lead carbonate is scaling is small compared to the other precipitating carbonates.

Calcite has been observed as a scaling phase in certain doublets. The modelling generally indicates dolomite as the dominant scale. This can be explained by the reaction rates. Since calcite is a faster reacting mineral, it may form before dolomite can. The amount of carbonate scaling is difficult to simulate since their formation is very dependent on the CO_2 content of the water and the pH. The uncertainties in the controlling parameters for carbonate precipitation yield a significant uncertainty in the simulated precipitation of carbonates.

5.6   Location of scaling

The model used does not indicate the exact location of scaling. The heat exchanger has a high risk of scaling since the water is cooled. The oil/gas separator is another likely place for scaling since the water is degassed. However, the pressure already decreases in the well and hence scaling is possible before the oil/gas separator is reached. The location of mineral precipitation is also dependent on the rate of precipitation. The current model only considers equilibrium reactions assuming instantaneous reactions. The slowest reacting minerals are therefore not included in this study but the minerals used also react according to a mineral specific rate. For example fast reacting carbonates minerals may form in the heat exchanger and piping. The slower reacting phases may form (increasingly) in time down the injection well or in the reservoir. This could cause flow decrease in the reservoir with time. The occurrence and severity of formation damage in time should be assessed with more complex reactive transport modelling.

5.7   Formation water composition

The simulations show that the type of reservoir or formation is not always a good indicator for scaling potential as was beforehand expected. The water composition of a formation can be very variable over large distances, and therefore the scaling reactions can be quite different. Caution is therefore in order for geothermal exploration when using water composition data of wells far away. For exploration, the presented results can only be used to identify the likely scaling reactions for a certain reservoir. The results highlight the strong case specific nature and variability of scaling reactions. This calls for flexibility in a doublets design accounting for remediation measures in case of high scaling potential. Furthermore, it is clear that detailed analyses such as performed in the context of this project are required to give predictions on scaling potential to be used for scaling prevention.

5.8   Minor elements

The minor elements were not included in the simulation since they usually are not abundant enough to precipitate as minerals. However, it is known that they can be incorporated as impurities in the crystal lattice of other minerals. This is important when considering radioactive isotopes of these elements. For example radioactive strontium can replace barium in barite. Lead has radioactive isotopes which can be incorporated in lead scaling. It is important to consider that scales can be (lightly) radioactive and should be handled appropriately.

Especially metals can be included silica scaling as impurities. This was already indicated by modelling since a Zn containing silica glass was predicted to form. Incorporation of metals occurs probably in amorphous silica precipitate (silica gel). The occurrence of a scaling phase as crystalline or amorphous is difficult to predict by modelling since it depends highly on reaction rates leading to the formation of metastable phases. This is in particular likely for silica and Al/Fe hydroxide. Barite and carbonates usually precipitate in their crystalline forms.
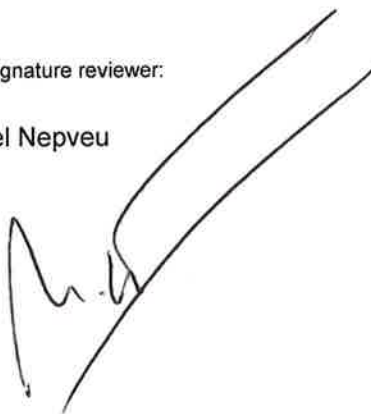
6 Authentication

Name and address of the principal
TC Waterbehandeling Geothermie

Date upon which, or period in which the research took place
January 1, 2013 – April 1, 2014

Name and signature reviewer:

Dr. Manuel Nepveu

Signature:

Wilfred Appelman, M.Sc. MBA
project leader

Release:

Monique Oldenburg, M.Sc.
Research Manager

Appendix A – Simulation details

Model steps

The model steps of the PHREEQC simulations are listed below. This is for the complete simulation including CO_2 degassing. For the simulations using the measured composition only step 2 to 5 were removed.

1) The formation water

The measured water composition is used as input for the geochemical simulator. This is excluding some minor phases that are not expected to form minerals. The measured composition is not completely charge balanced so the chloride content is adjusted to achieve charge balance. The simulations include the brine density which is calculated from the salinity when a density measurement was not available. The formation water is equilibrated and charge balanced at the relevant reservoir pressure and temperature. When pressure data was not available the pressure was estimated based on the formation depth.

2) Calculating CO_2 dissolved in the reservoir

The measured amount of dissolved carbon is the amount of dissolved carbon at 1 bar and room temperature. To determine the carbon content in the reservoir, the solubility of CO_2 in brine at reservoir conditions was calculated for the reservoir pressure, temperature and salinity. This gives the maximum amount of carbon that can be dissolved in the formation water.
A second set of simulations was done with a CO_2 content that was calculated from the gas water ratio, the CO_2 content in the natural gas and the CO_2 partial pressure.

3) Equilibrating the formation water with CO_2

The in step 2 calculated amount of CO_2 is added to the measured water composition (minus the measured amount of dissolved carbon) of step 1. The equilibration with CO_2 decreases the pH. The chemical equilibrium is calculated at reservoir temperature and pressure. PHREEQC gives a list of minerals that are oversaturated with respect to the formation water. Minerals for the simulation are selected from this list excluding minerals that do not form in sedimentary rocks or that take a long time to precipitate. Oversaturation could occur in the reservoir but could also be due to uncertainties in the measurements or used database. The formation water was assumed to be in equilibrium and hence minerals that are oversaturated during formation water equilibration are simulated respecting this oversaturation in the following model steps. The minerals that are initially oversaturated are usually barite and ferrihydrite. This assumption may not hold when oversaturation is allowed in the reservoir but will not be attained with a dynamic system of flow and depressurization.

4) CO_2 degassing

The pressure decrease and CO_2 degassing during production is simulated. CO_2 degassing is probably instantaneous so degassing is simulated first without allowing minerals to precipitate.

5) Water equilibration

Degassing causes the pH to increase again. However, the pH does not come up to the measured composition. This could be due to uncertainties in the measurements or due to a too high carbon content added compared to the actual value. Keeping the pH low would inhibit carbonate formation and would not respect the measured value so the pH is fixed to that value. The minerals then occur for the degassed composition and the measured pH. This results in precipitation of several minerals. Oversaturation of minerals is checked and minerals are selected that may precipitate as a consequence of CO_2 degassing.

Degassing using the measured amount of CO_2 in the gas leads to a pH that is close to the measured value so no corrections are required.

6) Cooling

The degassed and depressurized water is cooled in 5 °C increments. Oversaturation (precipitation potential) of minerals is checked and minerals are selected that may precipitate as a consequence of cooling. Precipitation is calculated after that.

Processes not included in the model

We included the processes that we assume most important for scaling in the model. Currently neglected processes that could be of influence are listed below.

1) Rate dependent precipitation

Reaction rates cause a delay in precipitation or preferential precipitation of fast reacting minerals. Delayed precipitation means that there is a time component influencing the location of scaling as well as impact of scaling during the doublets lifetime.

2) Wellbore processes

Possible wellbore processes such as corrosion are not included in the model. Corrosion might introduce additional iron in the system which may precipitate upon cooling.

3) Redox processes related to corrosion

Redox processes could be involved in the corrosion processes. In addition, redox potential controls the type of metal phases that precipitate. These could for example be either oxides or sulphides.

4) Organics

Possible effects of complex organic compounds that can affect mineral reactivity were not taken into account. Organics may act as natural inhibitors and when removed during oil separation, their reaction inhibiting function may be removed possibly causing precipitation.

5) Other gasses then CO_2

Natural gas may involve other impurities then CO_2 such as sulphur. Degassing of these gases may also have an effect on the chemical equilibrium.

6) Oxygen

Possible oxidation due to contact with the atmosphere was not taken into account. Equilibration with oxygen may occur during opening of the surface installation when for example filters are changed. Oxygen in the subsurface may trigger microbiological activity. Microbes have been reported to clog near-wellbore environments. However, the actual amount of oxygen that reaches the subsurface is very difficult to determine as it involves all the doublets operations from drilling up to now.