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Composition of Reservoir Fluids in Well IDDP-2

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ABSTRACT

As part of the Horizon 2020 project DEEPEGS (Deployment of deep enhanced geothermal systems for sustainable energy business), well IDDP-2 was drilled into the Reykjanes geothermal field to a depth of about 4.5 km by deepening the 3 km deep vertical well RN-15. The well has aquifers at 2.3, 3.4 and 4.5 km depth, the deepest of which is expected to yield supercritical fluids. Following injection testing, and a subsequent period of heating up, a discharge test of the well is planned in autumn 2019.

In this contribution, an attempt is made to estimate the chemical composition of the well fluids upon production. This was carried out by estimating the chemical composition at each depth by analogies with fluid from the currently produced Reykjanes geothermal system and by reported composition of fluids from hydrothermal vents on the ocean floor, followed by mixing calculations and calculations of depressurisation boiling from the mixing temperature (350°C) to an estimated wellhead pressure of 70 bar-a. This was carried out using the SOLVEQ-XPT and CHIM-XPT geochemical codes.

The reconstructed Reykjanes reservoir fluid at 350°C has seawater salinity and a pH of about 5.5. The sulphide concentration is somewhat higher and copper, iron, zinc and lead concentrations substantially higher, compared to the conventional Reykjanes fluid at 295°C. Mixing of this heated conventional fluid with dilute and concentrated supercritical seawater yields fluids with slightly lower pH, higher silica and substantially higher sulphide concentrations. During boiling to 286°C (70 bar-a), the fluid mixtures precipitate 1–6 mg per kg of produced fluid, mainly anhydrite, haematite, bornite and phyllosilicates. The boiled fluid has pH ranging from 3.8 to 4.5, and high sulphide concentrations. It is somewhat undersaturated with respect to amorphous silica. Upon further boiling of the fluid, to 210°C (19 bar-a) further deposits are formed, mainly amorphous silica (20–70 mg per kg) although the mixtures containing dilute vent fluid are also predicted to precipitate chalcopyrite, chalcocite and galena. After boiling to 210°C, the in situ pH of the fluid ranges from 3.4 to 4.1.

1. INTRODUCTION

Well IDDP-2 was drilled into the Reykjanes geothermal field to a depth of about 4.5 km by deepening the 3 km deep vertical well RN-15 (Friðleifsson et al., 2017; Friðleifsson et al., 2020). The well has three feed zones, at approximate depths of 2.3 km, 3.4 km and 4.5 km. The temperature and pressure logs collected during drilling and partial thermal recovery of the well after drilling suggest that during discharge, only the lower two feed zones will contribute to the flow, with an estimated 90–95% coming from the 3.4 km feed zone and the rest from the feed zone at 4.5 km.

The purpose of this contribution is to estimate the chemical composition of the fluid produced during a planned discharge test of the well in autumn 2019. As no well fluids have been sampled and information on the temperature and pressure at the feed zones are not well defined, this work is highly hypothetical, but an effort is made to constrain the chemistry of the fluids. Temperature and pressure logs suggest that the fluid produced from the 3.4 km feed zone will be vapour-saturated liquid at approximately 350°C and 1600 kJ/kg whereas the fluid from the 4.5 km feed zone will have a temperature of about 530°C and pressure 280–310 bar. Comparison with the fluid scenarios proposed by Friðriksson et al. (2015) suggests that the deeper fluid will either be a superheated vapour-phase in equilibrium with NaCl(s) or a two-liquid-phase super-critical fluid. Hypersaline fluid inclusions in cores collected near the bottom of the well suggest the latter scenario (Zierenberg et al., 2017; Bali et al., 2020) – which will be considered here.

The approach to this task is as follows:

a) Estimation of the well fluids at 3.4 km, by analogy with the conventional reservoir fluid.
b) Estimation of the well fluids at 4.5 km, by analogy with hydrothermal vents on the ocean floor (black smokers).
c) Mixing of the two in proportions of 90% : 10% to 95% : 5%.
d) Simulation of fluid composition and mineral deposition during depressurisation boiling of the deep fluid to an estimated well-head pressure of 70 bar.

2. FLUID MODELLING

2.1 Modelling of the Fluid at 3.4 km Depth

The 3.4 km feed zone is assumed to yield a vapour-saturated single liquid with similar properties as the currently produced reservoir fluids at Reykjanes, but at a higher temperature. The composition of this fluid may be estimated by simulating the heating of the "regular" Reykjanes reservoir fluid to 350°C, allowing it to react with the host rock as needed to maintain equilibrium with alteration minerals. This was carried out using a sample collected from well RN-12 before injection into the reservoir started (sample 20060387 from the database of Iceland GeoSurvey; Friðriksson and Giroud, 2008). Well RN-12 was selected as it has liquid enthalpy, relatively stable fluid chemistry and may be regarded as a good average for the field.

First of all, the reservoir fluid was reconstructed from the two-phase samples collected at surface using the speciation program WATCH, version 2.4 (Arnórsson et al., 1982; Bjarnason, 2010), assuming a reservoir temperature of 295°C, determined from temperature logs and silica concentrations of the fluids (Friðriksson and Giroud, 2008). The chemical composition of this fluid is given in Table 1.

As the Reykjanes fluid is known to deposit sulphide minerals during its ascent to surface, the fluid was then allowed to equilibrate with the three sulphides that are most commonly observed in Reykjanes scale samples; chalcopyrite, galena, and sphalerite (Harðardóttir, 2011). This was done to account for the losses of sulphide containing elements deposited within the well or at surface. Finally, 0.1 g of basalt (Jakobsson et al., 1978) were added to 1 kg of the fluid, in order to reach equilibrium with alteration minerals known to be present in the Reykjanes system, including anhydrite, chlorite, epidote and quartz. These calculations were carried out using the geochemical codes SOLVEQ-XPT and CHIM-XPT, version 2.3 (Reed et al., 2010a, 2010b).

The reconstructed reservoir fluid after simulating sulphide and basalt dissolution had a pH of 5.46 and the following minerals were found to have precipitated: anhydrite, bornite, clinochlore, daphnite, Mn-chlorite, epidote, clinozoisite, galena, millerite, quartz, sphalerite and wairakite. The composition of this fluid is given in Table 1.

This reconstructed reservoir fluid was then heated in 1°C steps from 295°C to 350°C, again using CHIM-XPT, allowing the precipitation and dissolution of minerals as dictated by their solubilities. After every 5–10 steps, the saturation index of relevant hydrothermal minerals (including anhydrite, epidote, quartz and metal sulphides) was calculated and basalt and/or metal sulphides were added to the mixture to maintain equilibrium with these minerals. By the end of the simulation 400 mg of sulphides and 100 mg of basalt had been dissolved in 1 kg of the fluid. The final fluid at 350°C has a pH of 5.54 and is in equilibrium with anhydrite, andradite, grossular, epidote, clinozoisite, bornite, galena, millerite, sphalerite, haematite, quartz, tremolite and ferroactinolite. The composition of this fluid is given in Table 1.

A few things must be pointed out when comparing the three fluid compositions given in Table 1. First of all, the low pH of fluid (1) is at least partly due to the fact that the neutral HCl^0 species is missing from the database of WATCH, leading to an overestimate of the activity of H^+ – i.e. a too low pH. Secondly, little changes are observed in the carbonate concentration. This is due to the fact that the basalt that is titrated into the fluid contains very little CO_2 (Table 2), and that equilibrium between the fluid and carbonate minerals has not been forced. Many other component concentrations show little changes, including the predominantly conservative Cl and B, but also As, Ba, Mo, Sr, F and K. The greatest changes are observed in the concentrations of H_2S which increases by about 50%. Similarly, concentrations of the sulphide forming metals (Cu, Fe, Pb and Zn) increase by orders of magnitude, both in the initial equilibration step at 295°C and during heating of the fluid to 350°C. The former is in good agreement with the results of Friðriksson (2014), but the latter is only supported by the thermodynamic calculations.

Metal sulphides, garnet, amphibole and epidote, among others, have been observed in the cores collected during the drilling of the deeper parts of IDDP-2 as well as in mineral rubble brought to the surface by the core sampler (Zierenberg et al., 2017). The fact that the hypothetical Reykjanes fluid at 350°C is predicted to be in equilibrium with these minerals lends some support to the modelling results

2.2 Estimating the Fluid at 4.5 km Depth

It has been predicted and observed that supercritical seawater can separate into two different phases; a dilute “vapour-like” phase and a concentrated brine (cf. James et al., 2014), sometimes even coming from the same ocean floor hydrothermal vent (von Damm et al., 1997). While the measured temperatures of these vents generally do not exceed the critical point of seawater (407°C / 298 bar; Bischoff and Rosenbauer, 1988) the chemical composition of the discharged fluids suggests higher temperatures (cf. McDermott et al., 2018). The reported chemical composition of fluids from such hydro-thermal vents varies significantly, with pH (at 25°C) ranging from 2 to 7, the chloride concentration of the brines as high as 30,000 mg/kg, silica concentrations up to 1200 mg/kg and hydrogen sulphide concentrations up to 600 mg/kg. Concentrations of metals such as Fe and Mn are also often high, especially in the concentrated phase. Here, the two seawater phases will be represented by samples collected from the ‘F’ vent at East Pacific Rise in 1991 and 1994, as reported by von Damm et al. (1997).

The SOLVEQ-XPT code (Reed et al., 2010a) was used to calculate heating of the vent fluid to 350°C, without simulating any dissolution reactions, yielding pH values of 4.14 and 4.13 for the dilute and concentrated phases. The resulting fluids are found to be saturated with anhydrite and pyrite, and the brine is also slightly supersaturated with respect to quartz. It is likely that at the time of sampling, metal sulphides have already been lost from the fluids – and indeed analyses of Pb, Zn and Cu are rare for such fluids.

2.3 Mixing of the Fluids

Speciation was calculated for four different mixtures of the 3.4 km and 4.5 km fluids: 95% : 5% and 90% : 10% mixtures of the heated Reykjanes fluid and the dilute hydrothermal vent fluid, and same proportion mixtures of the heated Reykjanes fluid and the concentrated hydrothermal vent fluid. The calculations were carried out at 350°C. The speciation of all four mixtures was calculated by means of the SOLVEQ-XPT code (Reed et al., 2010a). The results of the calculations are given in Table 2.

The concentrations of most major components in the calculated mixtures are within the ranges observed for the same components in the Reykjanes reservoir fluid (cf. Óskarsson and Gałeczka, 2017). In particular, this applies to Cl, Na, SO_4, Ca and CO_2 – as well as pH. The silica concentration are somewhat higher than in the current reservoir fluids, as is to be expected. The greatest concentration differences are observed for H_2S, and the sulphide forming metals, all of which have higher concentrations in the mixed fluids than in the Reykjanes fluid. H_2S has higher concentration in mixtures of Reykjanes fluid and the dilute vent fluid whereas metals – particularly Fe and Mn – have higher concentration in mixtures of Reykjanes fluid and the concentrated vent fluid. This reflects the concentrations assumed in the initial fluids. The calculated fluids are supersaturated with respect to some minerals at 350°C, particularly sulphides (bornite, chalcopyrite, pyrite) and iron oxides (goehtite, haematite, magnetie, franklinite). All fluid mixtures are slightly supersaturated with anhydrite.

It should be noted that the analyses of the samples from the EPR hydrothermal vent are incomplete compared with the Reykjanes fluid sample, in particular metals such as Al, Cu, Zn and Pb are missing. This does of course affect the final chemical composition and speciation of the mixtures. It should also be noted that Zierenberg et al. (2017) reported evidence for a hypersaline, iron-rich brine in fluid inclusions from the IDDP-2 well, probably of even higher salinity than the brine sampled from EPR which was used in the simulation. However, no chemical analyses of such a fluid were found for this study.

2.4 Production of the Mixed Fluids

In order to estimate the scaling potential of the mixed fluids and their composition at the wellhead, the fluids were allow to boil, following the P-T boiling curve from the mixing temperature of 350°C (165 bar-a) to the estimated wellhead pressure 70 bar-a (286°C), with a temperature step of 2°C. This was done using the CHIM-XPT software (Reed et al,. 2010b), assuming that the mixed fluid is a single liquid after mixing. This assumption may not hold; The presence of a two phase fluid after mixing would result in a higher vapour fraction after boiling to 70 bar, but it should not substantially affect the composition of the boiled liquid phase.

The chemical composition of the four mixtures after boiling are given in Table 3. During the boiling calculations, minerals were allowed to precipitate at local equilibrium and then fluid constituent concentrations were corrected for their removal due to solid formation, corresponding to mineral deposition at different depth in the producing well.

The resulting fluids vary somewhat in composition. The mixtures formed from the dilute vent fluid have higher pH and higher sulphide concentrations whereas the mixtures formed from the concentrated vent fluid have higher salinity and much higher concentrations of Fe and Mn. The vapour phase has relatively low gas concentrations; less than 0.7%-wt in all cases, although only CO_2 and H_2S are considered here.

All four mixtures are predicted to deposit some minerals during boiling, from 1 to 6 mg per kg of produced fluid. The minerals predicted to precipitate for the dilute fluid mixtures are anhydrite, haematite, bornite and some phyllosilicates, whereas the concentrated brine mixtures will mainly precipitate haematite and phyllosilicates. All the boiled mixtures are undersaturated with amorphous silica (with saturation indices close to -0.2), so silica deposits are not to be expected at 70 bar wellhead pressure.

On the other hand, it should be noted that all the boiled liquids at 70 bar still have high concentrations of Cu, Fe, Mn, Pb and Zn, as well as H_2S, and therefore have the potential to form sulphide scaling when the fluid boils to lower pressures. Harðardóttir (2011) observed that over 50% of metal sulphides precipitated from the Reykjanes fluids form in the pressure interval 20–40 bar-g, and thermodynamic modelling by Friðriksson (2014) suggests that 90% of metal sulphides precipitates at pressures higher than 25 bar-g. It is therefore likely that significant metal sulphide precipitation may occur during further boiling or at surface. However, the low pH of the liquids lowers the activity of the S^{2-} ion and thereby the saturation states of the metal sulphides.

For this reason, further boiling calculations were carried out and the fluid allowed to boil adiabatically in steps of 2°C to 210°C, corresponding to the 19 bar-a inlet pressure at the Reykjanes power plant. The results are given in Table 4. The results show a further decrease in pH, from 3.4 to 4.1 and more precipitation; from 22 to 66 mg per kg of produced fluid. The calculated mass of deposits of each 2°C step is plotted in Figure 2. In all cases, the bulk of the additional precipitates is amorphous silica, which starts precipitating at about 220-235°C depending on the fluid mixture. For the dilute vent fluid mixtures, metal sulphide precipitation is also predicted; mainly chalcopyrite, chalcocite and galena. No sulphide mineral precipitation is predicted for the mixtures containing concentrated vent fluid, as those fluids have the lowest pH.

3. CONCLUSIONS

The reconstructed Reykjanes reservoir fluid at 350°C has seawater salinity and a pH of about 5.5. The H_2S concentration is somewhat higher and Cu, Fe, Zn and Pb substantially higher, compared to the 295°C fluid in RN-12. The fluid is in equilibrium with anhydrite, quartz, garnet, epidote, actinolite, bornite, galena, millerite, sphalerite, and haematite.

Mixing of this heated Reykjanes fluid and two supercritical seawater fluids (dilute and concentrated) yields fluids with slightly lower pH, higher SiO_2 and substantially higher H_2S.

During boiling to 286°C, the fluid mixtures precipitate 1–6 mg per kg of produced fluid, mainly anhydrite, haematite, bornite and phyllosilicates. The boiled fluid has pH ranging from 3.8 to 4.5, and high concentrations of H_2S and sulphide forming metals. It is somewhat undersaturated with respect to amorphous silica.

Upon further boiling to 210°C, the fluid is predicted to form further precipitates, increasing the amount of scales to 30–70 mg per kg of produced fluid. These precipitates are mainly amorphous silica (from about 235°C) but the fluid mixtures containing the dilute vent fluid are also predicted to deposit chalcopyrite, chalcocite and galena. The amount After boiling to 210°C, the pH of the fluid ranges from 3.4 to 4.1.

Table 1. Chemical composition of reconstructed Reykjanes fluid (1) based on surface samples, (2) after equilibration with metal sulphides and basalt and (3) after heating it up to 350°C. Concentrations are given as mg/kg solution.

Fluid	(1)	(2)	(3)
T_{ref} (°C)	295	295	350
pH at T_{ref}	4.72	5.46	5.53
CO_2	1690	1688	1688
H_2S	51.0	51.7	75.4
NH_3	1.25	1.25	1.25
SiO_2	649	516	633
B	7.82	7.82	7.82
F	0.216	0.229	0.229
Cl	18930	18910	18910
SO_4	16.1	16.5	6.7
Na	9526	10120	10120
K	1376	1375	1374
Mg	0.665	0.709	1.004
Ca	1162	1165	1142
Al	0.518	0.086	0.272
As	0.0459	0.0459	0.0459
Ba	9.14	9.14	9.14
Cu	0.00557	0.0653	1.33
Fe	0.449	0.192	2.284
Mn	1.66	1.78	1.78
Mo	0.00329	0.00328	0.00328
Ni	0.000590	0.000121	0.000523
Pb	0.000966	0.350	16.4
Sr	9.14	9.15	9.15
Zn	0.0160	0.621	14.8

Table 2. Chemical composition of mixtures between the proposed fluids at 3.4 km and 4.5 km depth in IDDP-2 calculated at 350°C. Concentrations are given as mg/kg.

Fluid	95% RN + 5% dilute	90% RN + 10% dilute	95% RN + 5% brine	90% RN + 10% brine
pH (at 350°C)	5.14	5.19	5.22	5.00
CO_2	1639	1589	1630	1571
H_2S	141	207	86.5	97.5
NH_3	1.18	1.12	1.18	1.12
B	7.43	7.04	7.43	7.04
SiO_2	619	605	661	690
F	0.216	0.205	0.216	0.205
Cl	18060	17200	19470	20030
SO_4	11.5	16.3	10.5	14.3
Na	9663	9201	10400	10680
K	1309	1242	1388	1400
Mg	0.955	0.904	0.955	0.904
Ca	1089	1036	1177	1211
Al	0.259	0.245	0.259	0.245
As	0.045	0.045	0.045	0.045
Ba	8.69	8.24	8.69	8.24
Cu	1.26	1.20	1.26	1.20
Fe	6.33	10.4	35.9	69.6
Mn	2.17	2.56	10.7	19.6
Pb	15.6	14.7	15.6	14.7
Sr	8.71	8.26	9.42	9.70
Zn	14.1	13.3	14.1	13.3

Table 3. Chemical composition (in mg/kg) of proposed mixed fluids from IDDP-2 after boiling to 70 bar-a (286°C).

Fluid	**95% RN + 5% dilute**	**90% RN + 10% dilute**	**95% RN + 5% brine**	**90% RN + 10% brine**
Liquid phase				
pH (at 286°C)	4.54	4.27	4.00	3.79
CO_2	111	107	116	108
H_2S	20.4	30.4	12.8	14.2
NH_3	1.57	1.49	1.57	1.49
B	10.5	9.91	10.4	9.93
SiO_2	835	817	885	927
F	0.294	0.278	0.291	0.277
Cl	24380	23230	26080	26940
SO_4	10.3	11.8	12.3	17.0
Na	13049	12430	13930	14360
K	1767	1679	1858	1883
Mg	1.29	1.22	1.28	1.22
Ca	1468	1395	1576	1629
Al	0.0205	0.0208	0.0277	0.0282
As	0.0615	0.0582	0.0612	0.0584
Ba	11.7	11.1	11.6	11.1
Cu	1.10	1.53	1.70	1.61
Fe	8.24	14.0	39.8	83.2
Mn	2.93	3.46	14.4	26.4
Pb	21.0	19.9	20.8	19.8
Sr	11.8	11.2	12.6	13.0
Zn	19.0	18.0	18.8	17.9
Vapour phase				
CO_2	6071	5874	6165	5875
H_2S	493	721	310	347
Precipitates (g/kg)	0.004	0.006	0.001	0.001

Table 4. Chemical composition (in mg/kg) of proposed mixed fluids from IDDP-2 after boiling to 19 bar-a (210°C).

Fluid	**95% RN + 5% dilute**	**90% RN + 10% dilute**	**95% RN + 5% brine**	**90% RN + 10% brine**
Liquid phase				
pH (at 210°C)	4.08	3.86	3.65	3.44
CO_2	15.5	15.0	15.3	14.0
H_2S	1.95	3.51	0.733	0.945
NH_3	1.83	1.73	1.83	1.74
B	12.2	11.5	12.1	11.6
SiO_2	933	935	929	918
F	0.356	0.337	0.355	0.338
Cl	29551	28167	31817	32884
SO_4	12.4	14.1	15.0	20.7
Na	15814	15074	16994	17532
K	2142	2035	2267	2298
Mg	1.56	1.48	1.56	1.48
Ca	1779	1691	1922	1988
Al	0.00080	0.00169	0.00414	0.00964
As	0.0715	0.0678	0.0714	0.0680
Ba	14.2	13.5	14.2	13.5
Cu	0.893	0.980	2.07	1.97
Fe	9.57	16.1	48.5	102
Mn	3.55	4.19	17.5	32.2
Pb	23.3	24.1	25.4	24.2
Sr	14.2	13.5	15.4	15.9
Zn	23.0	21.8	23.0	21.9
Vapour phase				
CO_2	4219	4083	4207	3657
H_2S	361	528	225	251
Precipitates (g/kg)	0.029	0.029	0.052	0.071

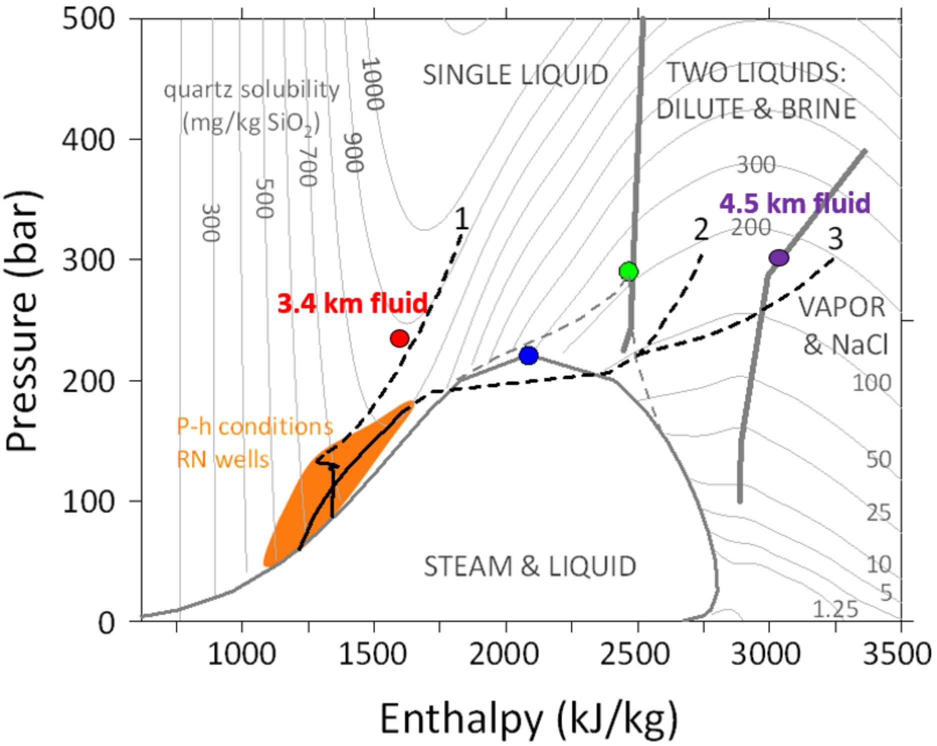

Figure 1: Phase diagram for H_2O in terms of pressure and enthalpy with superimposed quartz solubility (grey contour lines) and phase boundaries in a 3.5% NaCl-H_2O system (single liquid, dilute fluid/brine, and vapor/solid NaCl). The critical points for pure water and seawater are shown by blue and green symbols, respectively. The P-h conditions of the current Reykjanes production wells is indicated by an orange field. The estimated P-h conditions of fluid at 3.4 km and 4.5 km depth are indicated by red and purple symbols, respectively. Modified from Friðriksson et al. (2015).

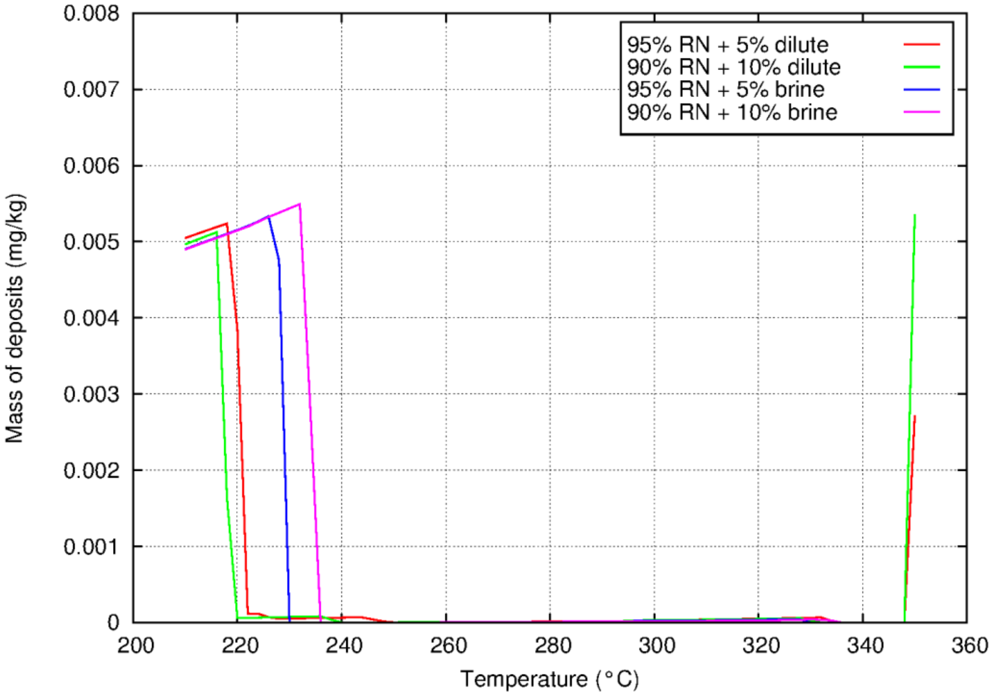

Figure 2: Calculated deposition for boiling of 1 kg of solution from 350°C to 210°C in steps of 2°C, for the four scenarios considered. Precipitation of amorphous silica is predicted to begin at 220-235°C, depending on the fluid mixture.

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