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Sustainable Geothermal Production of the Seltjarnarnes Geothermal Field, SW-Iceland

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ABSTRACT

The Seltjarnarnes geothermal field has been actively utilized for a local heating system over the last 40 years. The field is located in a peninsula within the town of Seltjarnarnes, a suburb of Reykjavík, the capital city of Iceland. The maximum thermal gradient in shallow research wells within the field is 380 °C/km. About 50 L/s of 95–120 °C hot water is produced from three main feed zones. The fourth feed zone of temperature exceeding 150 °C is probably situated below 2500 m depth. Part of the return water is collected and mixed with the produced water to keep an appropriate temperature for distribution purposes. The geothermal field is possibly associated with a NNE-SSW trending fault zone with the highest permeability and upflow zone, located outside the northern shoreline and the main area of production. The first produced water from the field was found to be saline (1‰ salinity), and the salinity increased with time and production rate, causing severe corrosion problems. The best production well yields the most saline water, probably due to increased circulation in the middle of the upflow zone. In spite of the calcite supersaturation, scaling has been insignificant so far. There are no indications of reservoir cooling due to seawater inflow, but the production characteristics of the water have changed for the 40 years of production. The regional drawdown in the field has not increased for the last 20 years even though the production rate has increased slightly. As a result of new building plans in the town, the demand of energy for domestic heating will increase in the near future. Several options for future production are being considered, along with drilling of a new production well. A tracer test has been run in the field during the last two years in the order to estimate the possible rate of reinjection of effluent water into the field. Preliminary results are promising; indicating that up to 10 L/s of return water can be reinjected on a long time basis with nominal cooling of the production water. As the geothermal field is far from being fully exploited, the future possibilities are manifold, even though sustainable goals would be continuously retained.

1. INTRODUCTION

The Seltjarnarnes geothermal field is located within the borders of Seltjarnarnes town (figure 1), a suburb of the capital city Reykjavík with about 4300 inhabitants (Kristmannsdóttir, 1986; Kristmannsdóttir and Tulinius, 2000).

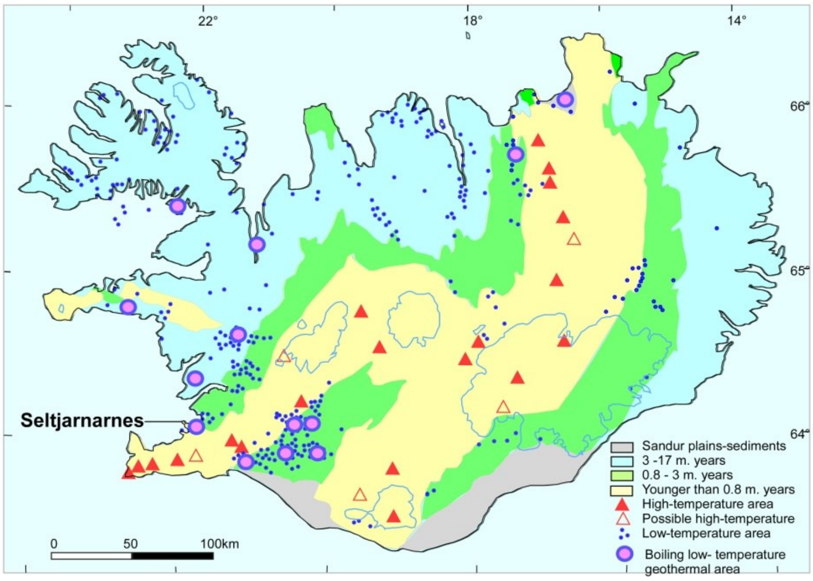

Figure 1. A simplified geological map of Iceland showing the location of the geothermal fields in Iceland. The location of the Seltjarnarnes field is pointed out. The figure is based on data from Saemundsson, (1979) and Björnsson et al., (1990).

The field is a boiling low-temperature geothermal field as many geothermal fields are located at the flanks of the zones of active rifting and volcanism in Iceland (Sæmundsson, 1979). Six low-temperature geothermal fields are located within and just outside the capital city region (Kristmannsdóttir and Tulinius, 2000). All those geothermal fields are located in the same Quaternary rock section within the Kjalarnes caldera (Fridleifsson, 1990). The subsurface rock section is built of eight formations of basaltic lavas and hyaloclastites interbedded with thin sedimentary beds and also intrusives of increasing density by increasing depth. A typical formation consisting of acid and andesitic rocks can be traced through the entire rock section, dipping from less than 1 km depth below Seltjarnarnes to about 2 km below the Elliðaár geothermal field in SE (Fridleifsson, 1990). In the geothermal fields faults and displacement of the rock formations have been observed (Fridleifsson, 1990). The heat source of the fields has high geothermal gradient in the young rocks and their location is due to active fracturing of the rock section at the site (Björnsson et al., 1990). The fields within the capital city area appear to have a transient pressure connection, but their water recharge is separate and chemical properties of the water are quite different (Kristmannsdóttir and Tulinius, 2000). No geothermal activity was known in the Seltjarnarnes area before drilling. The field was detected by drilling of two gradient wells in the years 1965-1967. The geothermal gradient was then found to be up to about 300 °C/km. The main upflow zone of the field was assumed to be located towards west and probably connected with the Álftanes geothermal field to the south (Tulinius et al, 1987). Later development of the field and drilling of further gradient wells have changed previous knowledge considerably. It appeared that the area is elongated along a NNW-SSE fault zone across the peninsula, which was surprising as the main fracture directions in the SW of Iceland are NE-SW and N-S trending. The salinity of the production water was found to be higher than in previously developed fields in the region and increased further by time and production. The field has been continuously monitored and research has been ongoing through the production time in order to avoid any serious trouble (Kristmannsdóttir and Ármannsson, 1996; Kristmannsdóttir, 2014). Reservoir models of the field have been made and updated several times (Tulinius et al., 1987, Vatnaskil, 1994, 2002). Due to the high production temperature, return water is needed to cool down through the water circulating in the system. As the town is mostly a residential area with few multistory buildings, it is rather costly to gather enough return water for this purpose. The water temperature from the wells is also changeable so the need for return water is subject to change by seasons and demand. As it is also quite costly to dispose of any auxiliary return water, it would be economical and environmentally beneficial to be able to reinject it. The heating system was established in 1972 and was almost fully outbuilt in 1996, when the last production well was connected. Since then the energy demand has not increased substantially, but now there are plans to build new resident quarters requiring more energy for heating. Therefore the possibilities to increase the energy production in the most sustainable and beneficial way have been considered recently (Kristmannsdóttir and Björnsson, 2014). All available data have been revaluated, a tracer test has been run to prepare injection of return water and three gradient wells are being drilled for a successful location of a new production well. Also possibilities have been considered and made plans for increased harnessing and use of return water and possibilities of binary electricity generation on a small scale (Kristmannsdóttir and Björnsson, 2014).

2. PROPERTIES AND DEVELOPMENT OF THE GEOTHERMAL FIELD

The geothermal field is defined as a boiling low-temperature geothermal field according to Icelandic terminology or a medium enthalpy geothermal field (Pálmason, 2005). Similar to other low-temperature geothermal fields, it draws the heat from the regional geothermal gradient, which is about 100 °C/km in this part of the active zone of rifting and volcanism. Where there are active fault zones, the circulation of water mines heat from the rocks and brings heated waters to higher elevation, thus heating up the upper part of the crust and subsequently cooling the lower parts (Björnsson et al, 1990). These result in very high geothermal gradients acquired from drilling of shallow gradient wells above the geothermal fields.

2.1 Drilling and exploration

Due to high salinity of the groundwater and the area being densely populated, little or no geophysical surveying could be done during the development of the Seltjarnarnes geothermal field. Cost of drilling was very high in those days so the drilling of many exploration wells was not a feasible choice. As the first two exploration wells gave very positive results, it was decided to continue with the drilling of production wells. The location of the first production wells, SN-03 and SN-04 (table 1) was based mainly on the results from the two gradient wells. Both, especially SN-04, were successful and yielded respectively about 15 L/s of 100-105 °C and 35 L/s of 110-118 °C hot water. The casings in both wells were shallow. Several aquifers were encountered in both wells and the temperature of the produced water changed with different pumping rates. Subsequent drilling of the next two wells, SN-05 and SN-06, was mainly based on results from earlier wells, both giving reasonably good results (table 1). Well SN-5 was drilled in 1981 and yielded up to 25 l/s of 95-105 °C hot water. In 1985, well SN-6 was drilled to the depth of 2701 m and cased to 414 m, which was believed to be enough to exclude the upper most saline part of the reservoir. According to testing, it yielded maximum 25 L/s of about 118 °C hot water.

Table 1. Wells drilled in the Seltjarnarnes geothermal field.

Well no.	Drilled	Depth in m	Depth of prod. casing m	Width (") of casing/well	Type of well	Maximum yield in L/s
SN-01	1967	1282	18.5	7 "	Monitoring	
SN-02	1965	856	81.5	8 "	Monitoring	
SN-03	1970	1715	99	$9^{5/8}$ "	Monitoring (prev.prod)	15
SN-04	1972	2025	172	$9^{5/8}$ "	Production	35
SN-05	1981	2207	168	$13^{5/8}$"	Production	25
SN-06	1985	2701	414	$13^{5/8}$ "	Production	25
SN-07	1993	154	none	3"	Exploration	
SN-08	1993	153	none	$6^{1/2}$"	Exploration	
SN-09	1994	132	none	$6^{1/2}$"	Exploration	
SN-10	1994	132	none	$6^{1/2}$"	Exploration	
SN-11	1994	145	none	3"	Exploration	
SN-12	1994	2714	791	$10^{3/4}$ "	Production	35
SN-13	2014	153	none	$6^{1/2}$"	Exploration	

When drilling of the last production well, SN-12, was planned, the cost of drilling shallow wells had gone considerably down due to increased competition in the drilling business. Thus it was decided to drill first five exploration wells to have a better basis for the location of the production well (Sæmundsson et al, 1993, 1994). The results of the drilling of those gradient wells indicated that the geothermal area was not connected to the Álftanes geothermal field to the south as previously believed (Kristmannsdóttir and Tulinius, 2000). This was demonstrated by the westernmost gradient well showing no indication of the geothermal area with a gradient of about 95 °C (figure 2), very near to the normal gradient of the crust in this region (Björnsson et al, 1990). The results from the southernmost wells also indicated termination of the geothermal area towards south (Sæmundsson et al., 1994). The results strongly pointed to a main upflow zone of the field located at the extreme north shore of the Seltjarnarnes peninsula and even in the sea to the north. The highest geothermal gradients obtained in those gradient wells ranged as high as 380°C/km at the shallowest indicated depth down to the geothermal area.

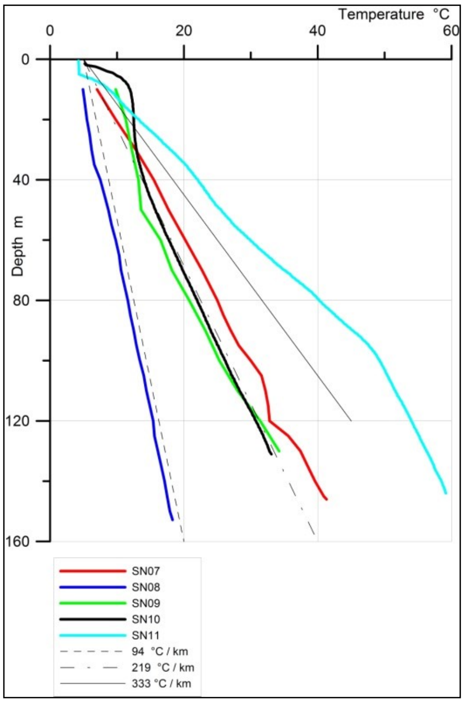

Figure 2. Temperature logs of all the gradient wells drilled in 1993-1994. Geothermal gradients of 94 °C/km, 219°C/km and 333°C/km are also shown for comparison.

Figure 3. Aerial view of the Seltjarnarnes peninsula. Location of production and exploration (monitoring) wells is shown.

Well SN-12 was subsequently drilled in the supposed main upflow zone, but no loss of circulation was observed during drilling and it yielded almost nothing in tests made after the drilling and before stimulation (Kristmannsdóttir, 1995). However it opened up tremendously by pressure stimulation by injection packer (Tulinius et al, 1996) and is now the best yielding production well. Well SN-12 was found to be much more productive than the forecast given from the production tests. The drawdown for a given production is much less than forecasted and the water level is quick to recover after high and long lasting production. In total, thirteen wells were drilled in the area and at least two more exploration wells will be drilled in the nearest future (table 1, figure 3).

2.2 Reservoir temperature

The maximum measured temperature in the field is 142 °C, but the calculated chalcedony geothermometer temperature of a downhole water sample in well SN-06, one of the deepest wells, indicates a reservoir temperature of about 150 °C.

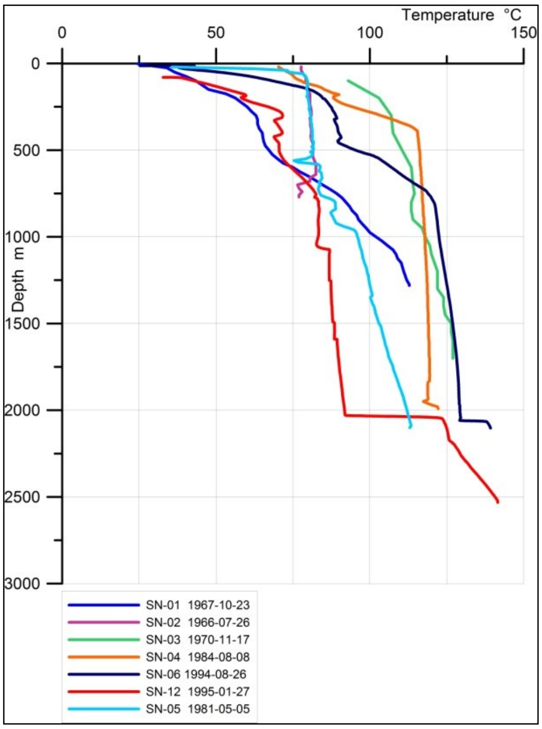

Figure 4. Selected temperature logs from all deep wells in the Seltjarnarnes field.

Figure 4 shows selected temperature logs from all deep wells drilled into the geothermal field. In most wells, there are aquifers at about 400-600 m, 850-1100 m and 1900-2100 m depth. Aquifers are commonly encountered at about 200 m depth, but in most of the wells they are closed off by casing. At about 1350-1500, there are small aquifers in some of the wells. By interpreting all existing temperature logs, three main feed zones have been detected in the geothermal field. The uppermost is 60-80 °C hot and extends to about 400-600 m depth. A 90-110 °C hot reservoir extends down to 1500 m depth and below where a reservoir with 120-140 °C hot water is encountered. Only in one well, SN-06, a small aquifer with the temperature of 140 °C is encountered at 2500 m depth. The highest aquifer temperature in other wells is 126 °C. In Well SN-12, the bottom temperature is 140 °C, but no aquifers are found. No reservoir cooling has been observed in the reservoir over 40 years of production.

2.3 Chemical properties

It was anticipated in the beginning that the water could be somewhat saline due to the location of the field being close to the coast. The production water also turned out to be more saline than that of the other geothermal fields and became increasingly more saline by time and increased production (Kristmannsdóttir and Tulinius, 2000). At present, the production water has about 2.5-4 ‰ salinity (table 2), but the increase in salinity has slowed considerably down. When the wells were first produced, the water had about 1‰ salinity and chloride concentration was less than 550 mg/l. The salinity decreased sharply when the billing system was changed and production from the field dropped consequently (Kristmannsdóttir et al., 1995). Those changes were observed in all the wells, but they behaved very differently depending on the relative production from each feed zone. The uppermost reservoir is the most saline, with probably up to 3000 mg/l of chloride content. The produced water is a mixture of aquifers from two or three different reservoirs, depending on the depth of production casing. The deepest producing reservoir sampled in both wells SN-4 and SN-6, however, appeared to contain of about 1000 mg/l of chloride. Well SN-5, which is located outside the main upflow zone, has the least saline production water. Well SN-12, which produces from the middle and upper part of the deepest production zones, has production water of the highest salinity of all the wells in spite of the production casing reaching down to almost 800 m depth. This is probably due to more rapid circulation near the main upflow zone of the geothermal field. Sampling of deep water from the bottom of well SN-06 revealed that the water has much lower salinity and yielded silica geotemperature of about 150 °C. There is no dissolved oxygen in the production water and the water is not considered to be corrosive for steel pipes and radiators if no oxygen is absorbed into it. Unfortunately there is always some minor intake of air in the house inlets causing rapid corrosion in the saline water. The use of heat exchangers was made mandatory in 1984, solving most of the corrosion problems. The water is, as most Icelandic geothermal waters, in equilibrium with the silica mineral chalcedony (Arnórsson et al, 1983), as well as several aluminium-, alkali-, iron- and magnesium silicates. The water is occasionally supersaturated with respect to calcium carbonate, which is probably due to the mixture of aquifers of different temperature and salinity. Icelandic geothermal water is normally found to be in equilibrium with calcium carbonate at reservoir temperatures. The concentration of heavy metals is low. The stable isotope composition (δ^2H and $\delta^{18}O$) is similar to precipitation in the mountains located some tens of km to the north and northeast. No significant changes have been noted in the stable isotope composition in spite of the increased salinity of the water, indicating diffusion of elements rather than a direct inflow of seawater.

Table 2. Chemical composition of the production water from all production wells in the field. Samples collected in 2013.

	Well SN-4	Well SN-5	Well SN-6	Well SN-12
Temp. °C	108	100	118	108
pH/°C	8.34/19	8.44/19	8.39/20	8.38/22
Conduct. µS/cm	5945	5000	5210	6530
TDS mg/L	3430	2730	3200	3720
Tot. carb. as CO_2	4.9	6.2	4.5	4.4
H_2S mg/L	0.21	0.22	0.26	0.13
B mg/L	0.25	0.22	0.25	0.25
SiO_2 mg/L	125	116	147	103
Na mg/L	683	578	577	704
K mg/L	16.0	12.9	14.2	14.8
Mg mg/L	0.505	0.311	0.485	0.38
Ca mg/L	480	363	486	552
F mg/L	0.6	0.7	1.1	0.6
Cl mg/L	1800	1410	1650	2010
SO_4 mg/L	316	244	320	332
Al mg/L	0.015	0.022	0.036	0.015
Fe mg/L	0.003	0.013	0.006	0.006
Mn mg/L	0.011	0.008	0.010	0.013
Salinity ‰	3.2	2.5	3.0	3.6
δ^2H ‰	-73.59	-71.55	-72.48	-70.18
$\delta^{18}O$‰	-10.47	-10.56	-10.39	-10.56

Due to the saline character of the water and lower pH than common Icelandic geothermal water, it is found to be relieving for the skin diseases as psoriasis and appropriate for treatment of rheumatism. The water is used directly in the town's swimming pool, which is frequently visited by people for therapeutic purposes.

2.4 Yield and permeability

The wells in the northern part of the geothermal field were previously thought to have higher yield than the ones in the south. As pointed out in table 1, wells SN-04 and SN-12 gave the highest yield in production testings. Well SN-12 shows the quickest recovery regarding drawdown and seems to be located in the most permeable part of the field. However, there are no wells being drilled in the middle part of the peninsula so no information exist on gradient and permeability in that part of the area. All the production wells are connected and production of each one of them affects the others. The drilling of well SN-06 and especially SN-12 had a great effect on well SN-04, it was both cooled and its production declined. Despite the recovery over time, it has never regained its former yield and temperature of production water. The highest possible total production from all wells is considerably lower than the sum of the yields listed in table 1, about 100L/s with the present installation of pumps. By change of pumps and their deeper sitting, it could be possible to produce more than at present from the existing wells.

2.5 Reevaluation of older data-new exploration wells

As it will eventually be necessary in the near future to drill a new production well, all existing data have recently been reevaluated (Kristmannsdóttir and Björnsson, 2014). On the basis of the reevaluation, it was suggested to drill at least three new exploration wells, which are now being drilled. From the existing data, there had been drawn up a gradient map of the area indicating that the fields lies along a NNW-SSE fault zone across the peninsula, with the highest gradient at the north site. From production experience through the years, the highest permeability is also observed in the northern part. The NNW-SSE direction is a rather uncommon trend for the faults in S and SW Iceland where NE-SW and N-S trending faults are dominant. From reevaluation of the data from the gradient wells, it is obvious that they give poor basis for the drawing of a good gradient map and it is hardly justifiable to close the temperature gradient lines towards south. Figure 5 shows the new gradient map made after the reevaluation of the temperature logs from all gradient wells and also partly from the production wells. Looking at the data, it seems that the gradients could also indicate more than one parallel faults with different directions. The drilling of the new gradient wells will probably clarify this better. After they have been measured and analyzed, the final location of a new production well will be determined.

2.6 Tracer test 2011-2013

A tracer test has just been run in the field with the aim of mapping the flow of the geothermal water, of the main flow channels, and groundwater flow velocity to be able to forecast possible cooling effects of reinjection of effluent return water. The test started in August 2011 and was terminated in December 2013, when the concentration of the tracer in the production water was getting rather low. Sodium fluorescein was chosen as a tracer due to its low detection limits, strong color at low concentration and easy analysis. It is resistant to the biodegradation, unaffected by the variation in water chemistry, but is subject to thermal decay at high temperatures (Adams and Davis, 1991). It is also cheap, relatively easy to handle and has negligible toxicity. At the reservoir temperatures in the Seltjarnarnes field, the thermal degradation is relatively slow. After thorough evaluation of the amount necessary for suitable return and negligibly danger of visibility in the water, there were injected 10 kg of sodium fluorescein. It was dissolved in 4 L of alcohol and 50 L of water and put into well SN-03 in the southern part of the field (figure 3). For several months after that about 1.5 L/s of return water was reinjected into the well. Due to shortage of return water, the amount had to be reduced to about 0.7 L/s after eight months of the test start. To save cost, the employees of the heating system were trained to analyze the samples themselves and did the job with little help. The tracer was first detected after 22 days in well SN-04, located at ~650 m distance from the reinjection well (figure 5). In well SN-06 at a distance of 580 m, it appeared after 36 days. It took the tracer over two months to reach the well SN-12 in 840 m distance. As shown in figure 6, the tracer reached maximum concentration of about 9 µg/L (900 ng/L) and was still detectable when the test was terminated in December 2013.

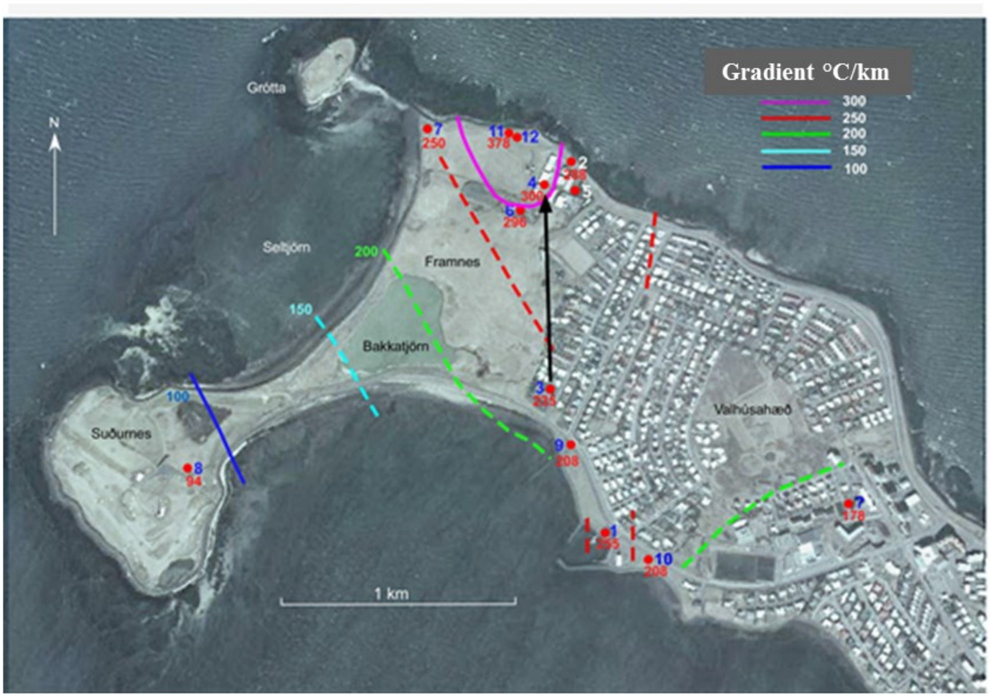

Figure 5. Reevaluated gradient map of the area. Also shown is a black arrow indicating the most direct flow path from the reinjection well SN-03 during the tracer test.

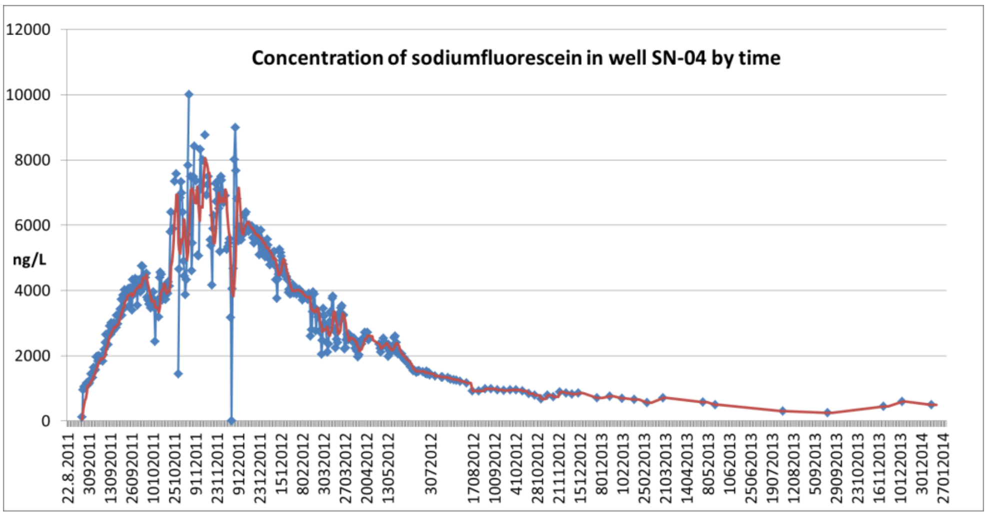

Figure 6. Concentration of sodium fluorescein by time measured in production water from well SN-04.

When the test was terminated, about 30 % of the tracer was assumed to be recovered. Possible thermal decay of the tracer may have influenced this assumption. Temperature logging of the reinjection well, SN-03, after the test, shows that most of the tracer was discharged out into the formation above 410 m depth. However, correlation of tracer concentration, conductivity and temperature of the water shows that the tracer has mixed with and dispersed into the deeper parts of the geothermal field (Axelsson and Sigurðsson, 2013). The first interpretation of the results from the test indicate that the maximum cooling in well SN-04 by 10 L/s reinjection into well SN-03 could be about 6 °C after 20 years, but insignificant in all other production wells (Axelsson and Sigurðsson, 2013). Well SN-01, which is further away from the main production field (figure 5), could also be a viable choice as a reinjection well, but only 3-4 L/s could probably be injected into it.

3. PRODUCTION HISTORY

The production from the field started in the late sixties from wells SN-1 and SN-2. Well SN-3 was drilled in 1970 and well SN-4 in 1972, after which the heating system was founded. After that, the production increased from a few liters per second to over 30 L/s. After well SN-5 was drilled and put in production in 1981 and subsequently well SN-6 in 1985, the production increased steadily until 1988, when it reached its maximum at over 56 l/s on average (figure 7). In 1989-1990, the billing system for the hot water was changed from maximum flow restriction method to a metering system. As a consequence, the production decreased considerably until 1993. The production increased again after the sharp drop, but has grown very little since 1998. The production has not yet reached the level before the changing of the billing system (figure 7).

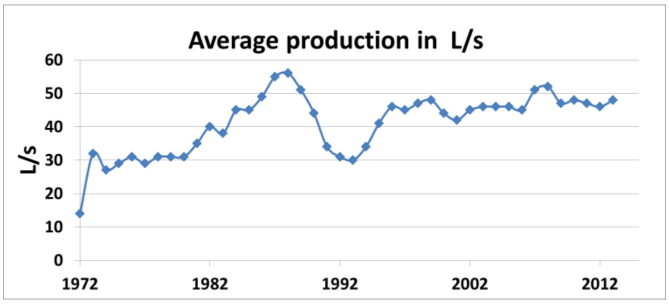

Figure 7. Average production from the Seltjarnarnes geothermal field from 1972 to present.

During all this time, the regional water level has changed in rhythm with the production, first it went steadily down, then rose and finally levelled off and has been almost unchanged during the last ~20 years. Figure 8 shows the changes in water level in well SN-01 and figure 9 shows the changes in well SN-02.

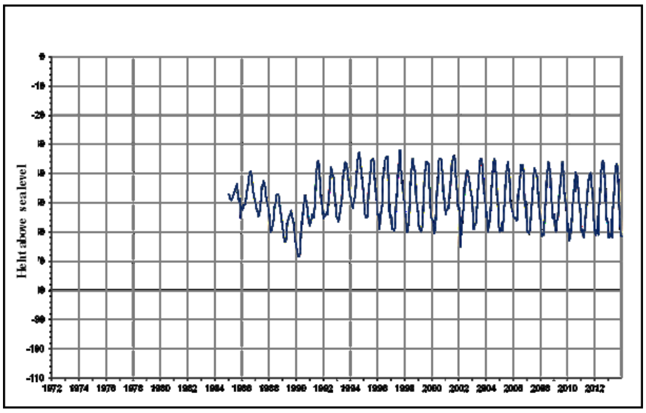

Figure 8. Water level measured in well SN-01.

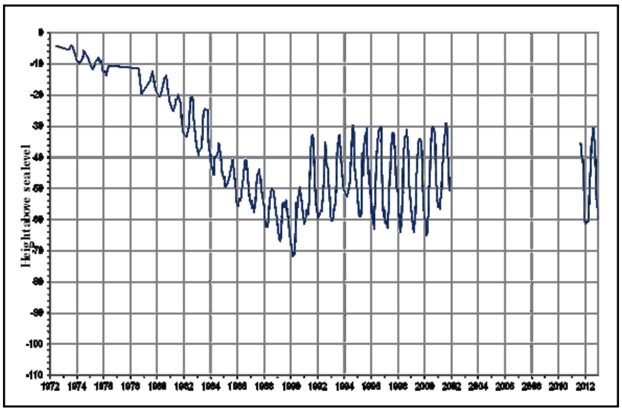

Figure 9. Water level measured in well SN-02.

Measurements were started in well SN-01 in 1985, whereas continuous measurements existed from 1972 to 2002 in SN-02 and again from 2011. The water level is at the same depth in both observation wells when measured at the same time, even though SN-02 is much nearer to the main production field.

No cooling of the reservoir has been detected through the 42 years of production, but there have been changes in production characteristics of the wells as well as in the production water. The pressure in the wells has declined by changed mixing rates of different aquifers, both temporarily and permanent. This has changed the temperature of the production water in some of the wells. Increased salinity has enhanced the danger of corrosion and scaling. Substantial supersaturation of calcium carbonate has been observed at times (Kristmannsdóttir and Vatnaskil, 2014) even though no scaling at wellhead has happened so far. The reason for supersaturation is probably mixing of water from different aquifers of different temperature and salinity. There may occur some scaling in the distribution net at unfortunate mixing condition, but mainly if accidental inflow of cold water occurs (Kristmannsdóttir, 2009). In the distribution net, some debris encountered occasionally, especially in the autumn when pumping is enhanced. It is partly originated from fine grained rock fragments in the wells, partly in layering from the walls of the distribution pipes and partly minor scales of calcite and magnesium silicates (Kristmannsdóttir, 2009, Kristmannsdóttir and Vatnaskil, 2014). Sedimentation traps that are recently installed in within the distribution net, have almost excluded that problem.

4. FUTURE POSSIBILITIES

Seltjarnarnes town has not grown much in the last few years. During the next five to ten years, the last building lots will be ready built and there will not be much increased energy demand in the years after that. Increase in energy will be required in connection with the building plans for the next few years and measures to meet the demand are being considered. The present production of the field can be greatly increased without putting much strain on the field and be maintained for decades without substantial increase in drawdown. As indicated by reinjection tests into Icelandic low temperature geothermal fields (Axelsson et al., 1995) and by the results of the recent tracer test in the Seltjarnarnes field, the exploitation of the field could be still optimized by reinjection of effluent return water. Only part of the town has double distribution system with gathering of return water. By increase of that manifold gain might be obtained, stabilizing of the temperature of the distributed water, the possibility of meeting crisis with lowered water temperature and optimizing the utilization of the field by reinjection of effluent return water. The increased use of return water would make the heating system still more sustainable and environmentally sound. As highest reservoir temperatures are 140-150 °C, one possibility for producing the field is to generate electricity by binary techniques. That would require drilling of deep wells with deep production casing to exclude the upper two aquifers in the field. The water would be cooled down to 75-80 °C by the electricity generation process before being distributed in the heating system. By utilizing colder water, the demand for the return water in the heating system would be much less. There would probably also be required more production from the field. On the other hand, there would be ample return water available for reinjection, increasing the pressure in the geothermal field counteracting the drawdown caused by increased production. Some cooling of the field might be expected in the wake of such change in the production. As the field is far from being fully exploited, the future possibilities are manifold, even though sustainable goals would be continuously retained.

5. CONCLUSIONS

The Seltjarnarnes geothermal field has been produced over 40 years and for the last 20 years. The production has been sustainable and environmentally benign. The production has never put much strain on the system, even though the production characteristics have been showed changes over the years. Individual wells have changed during the development and the production of the field. The main change of the field was the increased salinity of the produced water, mainly in the uppermost reservoir. No general cooling of the field has been observed so far. The present production of the field can be largely increased and be maintained for decades without increasing the drawdown substantially. The future possibilities for production of the field are manifold and much care has been taken to study the possibilities for a future environmentally beneficial exploitation of the resource. A tracer test has been performed to map the flow of the geothermal water and forecast the possible cooling effects of effluent reinjection of return water. Up to 10 L/s can probably be reinjected on average into the field for 20 years causing a maximal cooling of 6°C in the most affected well and nominal cooling in the main production well. At present, new exploration wells are being drilled to map the outlines of the geothermal area in more detail and secure the most successful location of a new production well. Possibilities for the electricity generation in a moderate scale are also being considered. The aim of all this effort is to maintain a sustainable and environmentally sound production of the field for the future generations.

REFERENCES

Adams, M.C. and Davis, J. (1991). Kinetics of fluorescein decay and its application as a geothermal tracer. *Geothermics*, 1/2, 53-66.

Arnórsson S., Gunnlaugsson, E. and Svavarsson, H. (1983). The chemistry of geothermal waters in Iceland. II Mineral equilibria and independent variables controling water compositions. *Geochim. Cosmochim. Acta* 47, 547-566.

Axelsson, G. and Sigurðsson, P. (2013). „*Interpretation of the results of a tracer test in the Seltjarnarnes geothermal area 2011-2013*" (In Icelandic). Ísor-2013/065, 22pp.

Axelsson, G., Björnsson, G., Flóvenz, Ó, Kristmannsdóttir, K. and Sverrisdóttir, G., (1995). Injection Experiments in Low-Temperature Geothermal Areas in Iceland. *Proceedings of the World Geothermal Congress 1995, Florence, Italy, 1995*, 1991-1996.

Björnsson. A. Axelsson G. and Flóvenz Ó. G. „The origin and nature of geothermal fields in Iceland" (In Icelandic) *Náttúrufræðingurinn* 60. (1990) 15-38.

Fridleifsson, G.Ó. (1990). *The geology of the Laugarnes geothermal area in Reykjavík* (in Icelandic) Orkustofnun, OS-90035/JHD-07, 63pp.

Kristmannsdóttir, H. (1986). Exploitation-Induced Infiltration of Seawater into the Seltjarnarnes Geothermal Field, Iceland Geothermal Resources Council, *Transactions* 19, 389-393.

Kristmannsdóttir, H. (1995*)." Pump tests of well 12 on Seltjarnarnes"(*In Icelandic*).* Orkustofnun, HK-9510, 15 pp.

Kristmannsdóttir, H. (2009). "*Analysis of possible scales in the distribution net of Seltjarnarnes heating company*" (In Icelandic). University of Akureyri, Department of science, TS09:03, 23pp.

Kristmannsdóttir, H. and Ármannsson, H. (1996). Chemical Monitoring of Icelandic Geothermal Fields during Production. *Geothermics*, 25, 349-364.

Kristmannsdóttir, H. and Björnsson, A. (2014). "*Energy acquisition for Seltjarnarnes heating system. Increased production of water and improved utilization*" (In Icelandic). Geological consulting company of HK/AB, technical report 14:01, 49pp.

Kristmannsdóttir, H. and Tulinius, H.. The development of the Seltjarnarnes geothermal field, SW Iceland during thirty years production. *Proceedings World Geothermal Congress 2000*, Japan (2000) 3465-3470.

Kristmannsdóttir, H. and Vatnaskil (2014) „*Seltjarnarnes heating system. Production monitoring 2012-2013*" (In Icelandic). Vatnaskil enineering company, report 14/06, 50pp.

Kristmannsdóttir, H., Ármannsson, H., Axelsson, G., Ólafsson, M., Hákonarson, S. and Thórhallsson, S. (1995). Monitoring of Iceland Geothermal Fields During Production. *Proceedings of the Geothermal Congress 1995, Florence, Italy 1995*, 1813-1817.

Pálmason, G.. (2005). „*Geothermal book: Nature and utilization of a resource"* (In Icelandic).Hið íslenska bókmenntafélag, 298pp.

Saemundsson. K. (1979). Outline of the geology of Iceland. *Jökull* 29, 11-28.

Sæmundsson, K., Kristmannsdóttir, H., Tómasson, J. and Sigvaldason, H. (1993). "*Gradient well drilling in Seltjarnarnes, in the autumn 1993 and testing and proposed repair of wells SN-2 and SN-3"* (In Icelandic). Orkustofnun, OS-93079/JHD-40 B, 17pp.

Sæmundsson, K., Gudmundsson, A. and Kristmannsdóttir, H. (1994). "*Gradient well drilling in Seltjarnarnes and the location of well number 12"* (In Icelandic). Orkustofnun, KS/AG/HK-94-15, 9 pp.

Tulinius, H.,. Spencer, A.L, Böðvarsson, G. S., Kristmannsdóttir, H., Thorsteinsson, Th. and Sveinbjörnsdóttir, Á. E. (1987*).* Reservoir Studies of the Seltjarnarnes Geothermal Field, Iceland. *12th Annual Workshop, Geothermal Reservoir Engineering, Stanford University, California, January 20-21*, 1987, 67-76.

Tulinius, H. Axelsson, G. Tómasson, J. Kristmannsdóttir H. and Guðmundsson Á. (1996) Stimulation of Well SN-12 in the Seltjarnarnes Low-temperature Field in SW-Iceland. *Proc. Twenty-First Workshop on Geothermal Reservoir Engineering, Stanford University, California,* 489-496.

Vatnaskil engineering company. (1994*)" Reservoir model of the geothermal field on Seltjarnarnes".* (In Icelandic), Vatnaskil report 06.94, 39 pp.

Vatnaskil engineering company. (2002*)"Reservoir model of the geothermal field on Seltjarnarnes".* (In Icelandic). Vatnaskil report 02.02, 134 pp.