Proceedings World Geothermal Congress 2023
Beijing, China, October 9 – 11, 2023

Silica, Boron and Lithium Concentrations in Olkaria Geothermal Brines: Theoretical considerations for extraction

Opondo Kizito, Lango Simeon, Naomi Gichuki

Kenya Electricity Generating Company PLC, P.O. Box 785, 20117 Naivasha

E-mail kopondo@kengen.co.ke

Keywords: Silica, Lithium, Boron, trace elements, economic, recoverable, technology,

ABSTRACT

Many of the chemical constituents in geothermal fluids are a potential source of valuable minerals and metals. Mineral recovery has been made at Larderello, Italy, as early as the turn of the last century where boric acid was extracted from geothermal steam. Some geothermal fields such as the Salton Sea, in the United States, Milos in Greece, Assal in Djibouti, Cheleken in Russia and Reykjanes in Iceland, the geothermal brines of the Franco- German basin to mention only a few, contain significantly rich mineral brines to make them potentially economically viable sources of some minerals. Pilot studies from the Alsace field in Northern France and the Imperial Valley in Salton Sea have demonstrated successful extraction of lithium on a pilot basis.

In various sectors of Olkaria the estimated separated brines from the Olkaria East, Olkaria North East and Olkaria Domes is ~ 3000 t/hr. There is a relatively large amount of brine available from the production fields in Olkaria obtained from the separated water at various re-injection points. Silica (SiO_2), Boron (B) and Lithium (Li) content of brines from the different sectors range between ~500 to ~1100 ppm, 0.6 to ~6 ppm and 1.32 – 3 mg/kg respectively. These elements could be of interest for mineral recovery. Other metal elements found in the separated geothermal water are Manganese (Mn), Cadmium (Cd), Chromium (Cr), Nickel (Ni), Cobalt (Co), Zinc (Zn), Mercury (Hg) at trace levels. Despite the low concentration of the metal elements in the separated waters the amount of recoverable minerals could be large given the large volumes of separated water that is re- injected. Silica, Boron and Lithium find use in various industries eg the manufacture, glass, soaps, toothpaste, pharmaceuticals, pesticide, as filler material, rechargeable nickel lithium batteries and battery storage. World market prices for some of these elements make it attractive for economic mineral recovery from geothermal brines. Recoverable minerals and metals from the geothermal brines at Olkaria can offer sources of alternative revenue stream. The choice of technology can be done after conducting initial pilot studies.

1. INTRODUCTION

The Olkaria geothermal field (Figure 1) is one of the largest geothermal fields in Kenya. The field is located within the Greater Olkaria Volcanic Complex (GOVC) in the central sector of the Kenya Rift Valley to the south of Lake Naivasha and 120 km from Nairobi, the capital city of Kenya. Olkaria is a high-temperature geothermal system, with reservoir temperatures ranging from ~200 °C to 360° C.

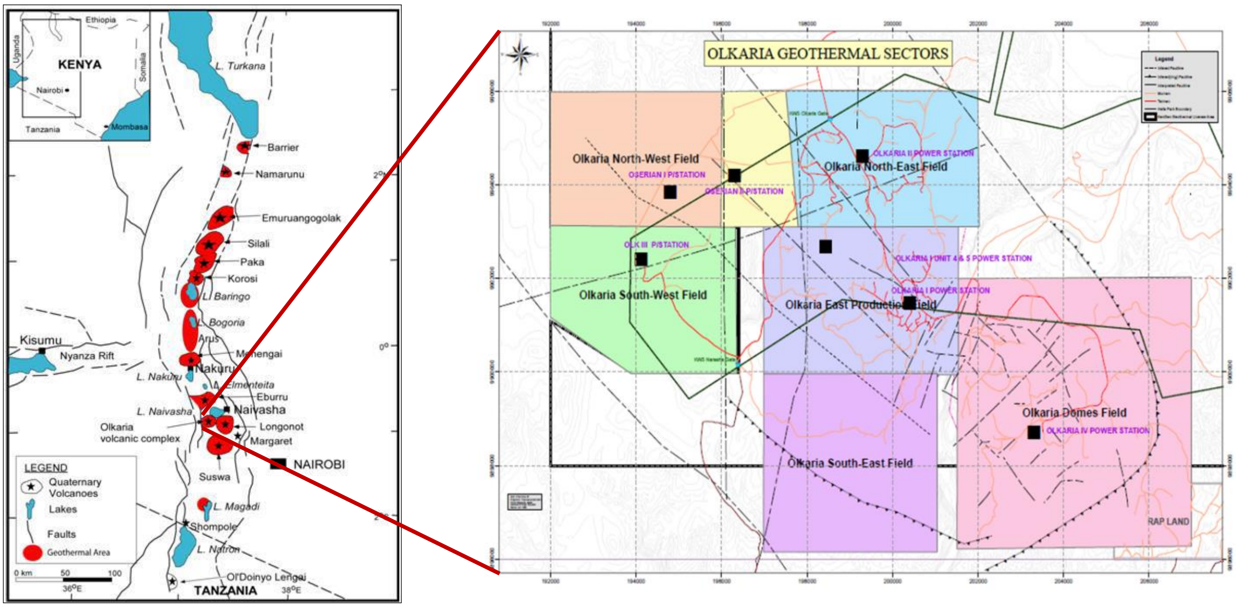


Figure 1; The Greater Olkaria Geothermal Area

The Greater Olkaria Geothermal Area (GOGA) is divided into seven smaller sectors, namely Olkaria East, Olkaria Northeast, Olkaria Central, Olkaria Northwest, Olkaria Southwest, Olkaria Southeast and Olkaria Domes for purposes of development. This is shown in Figure I above. The Olkaria East Production Field has been producing power since 1981 with the first power plant of 45 MWe being installed. An additional 150 MWe was commissioned in December 2014, Olkaria I Additional Unit 4&5 while in April 2022 Unit 6 was commissioned. Cumulatively the Olkaria East sector supports ~278 MWe. The Olkaria Northeast Production field has the Olkaria II power plant, commissioned in 2003 and produces 105 MWe. In the Olkaria Domes Production Field this supports two large power plants, the Olkaria IV power plant ~150 MWe commissioned in October 2014 and Olkaria V 172.5 MWe commissioned in July 2019. Besides the large conventional power plants there are a number of modular wellhead power plants spread across Olkaria with an installed capacity of ~83 MWe. In the Olkaria West Production field an Independent Power Producer (IPP) Orpower 4 Inc. generates ~ 150 MWe. The installed electricity generating capacity of geothermal power around Olkaria is close to 950 MWe.

2. Sampling and Analysis of Olkaria brines

The Olkaria production well fluids (water and steam) are sampled at the same pressure and temperature very close to the wellhead pressure. The steam and water phases are separated using a webre separator that is connected to the 2-phase line in accordance with ASTM 1675

Figure 2: Webre Separator connected to the brine line of one of the re-injection streams

Prior to sampling the Weber separator was flashed for around 10 minutes for equilibrium to be reached. Samples for major volatiles (water (H_2O)), hydrogen sulphide (H_2S), Carbon dioxide (CO_2), Hydrogen (H_2), Nitrogen (N_2), Argon (Ar), Methane (CH_4) analysis in the steam phase were collected into pre-evacuated gas bulbs containing 50% potassium hydroxide (KOH) (w/w), around10 mL per 100 mL of gas bulb volume.

Separated water samples for major elements (pH), Silicon (Si) or Silica (SiO2), Boron (B), Sodium (Na), Potassium (K), Lithium (Li), Calcium (Ca), Magnesium (Mg), Iron (Fe), Aluminium (Al), Chloride (Cl), Fluoride (F), Carbon dioxide (CO_2), Hydrogen sulphide (H_2S) in the liquid phase is sampled directly from the Webre separator. The samples were cooled using an in-line stainless steel cooling coil immersed in a bucket of water. Samples for analysis of pH and total carbonate carbon (CO_2) were preserved in amber glass bottles with ground glass stopper while hydrogen sulphide (H_2S) was analysed on site by titration with 0.001m mercuric acetate solution using dithiozine as indicator. For other major elements, the samples were filtered through a 0.2µm filter (cellulose acetate) using a Nalgene vacuum filter holder into High Density Polyethylene (HDPE) plastic bottles. For cation determination, the samples were further acidified by 1% Nitric Acid (HNO_3) (Merck Suprapur). For sulphate (SO_4) analysis, 1 ml of a 2% Zn-acetate solution was added 100 ml sample to precipitate sulphides and preserve the samples. For fluoride (F) and chloride (Cl) the samples were preserved raw without any further treatment: Samples for the analysis of silica (SiO_2) were diluted 10 times i.e., to 10 mls of sample was added 90 mls of distilled water.

Chemical Analysis of Samples.

For the liquid phase, dissolved H_2S was analyzed on site by Hg-precipitation titration using dithizone as an indicator (Arnórsson et al., 2006). pH and CO_2 were analyzed within a few days using a combination electrode (ng a metrohm pH meter model 827) and modified alkalinity titration (a Metrohm Dosimat model 665). The concentrations of major cations (Na, K, Ca, Mg, Li, Al, and Fe) were determined using Atomic Absorption Spectrophotometer (Shimadzu Model AA 7000) at the following wavelengths 330.2, 769.9, 422.7, 285.2, 670.8, 309.3 and 248.3 respectively in the flame. Major anions (F, Cl and SO_4) were analyzed using an ion selective electrode (ISE) for fluoride, Chloride by the Mohr titration using chromate as indicator and sulphates by turbidimetric method using barium chloride. Sulphates were run in the UV -Vis at a wavelength of 425nm. Trace elements were analysed by the Inductively Coupled Plasma- Mass Spectrophotometer (ICP-MS)

Silica (SiO_2) and Boron (B) were analyzed by ammonium molybdate and curcumin methods and run in the UV-visible at wavelengths of 410 and 540 nm respectively. UV-Vis model Evolution 201 was used for sulphates, silica, and boron respectively.

2. Chemistry of separated waters in Olkaria

The chemical composition of separated well waters in the Olkaria Geothermal Field have been discussed by various authors (Wambugu 1996, Karingithi 2000, Karingithi, 2002, Leech 2016, Kamunya, 2018). The composition of the well waters varies from sector to sector and also within the same sector. The well waters in the Olkaria Geothermal field can be classified as predominantly near neutral sodium chloride (Olkaria East, Olkaria North East and Olkaria South East), alkaline pH sodium bicarbonate (Olkaria West) and variable for Olkaria Domes and Olkaria Central) i.e near neutral Sodium Chloride, Sodium bicarbonate and mixed sodium chloride bicarbonate with alkaline pH. Typical separated water composition of wells from the Olkaria East, Olkaria North East and Olkaria Domes are presented in the ternary diagram below.

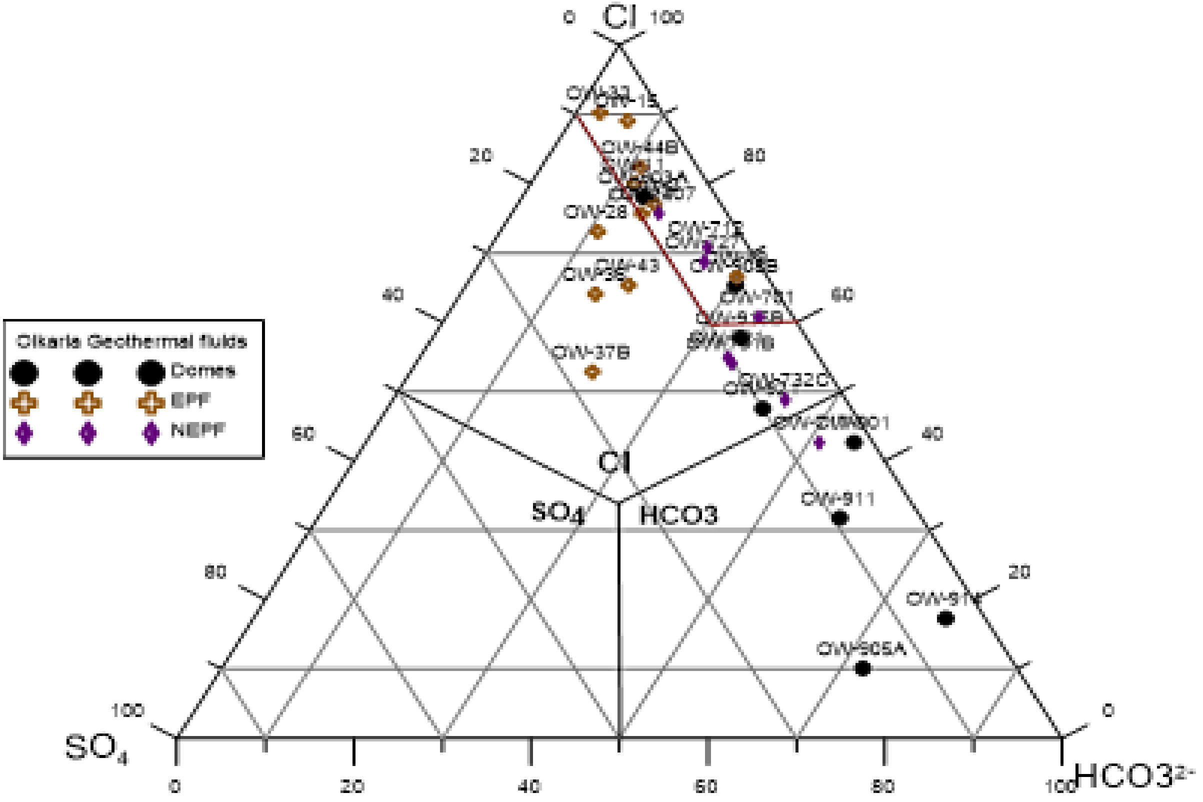
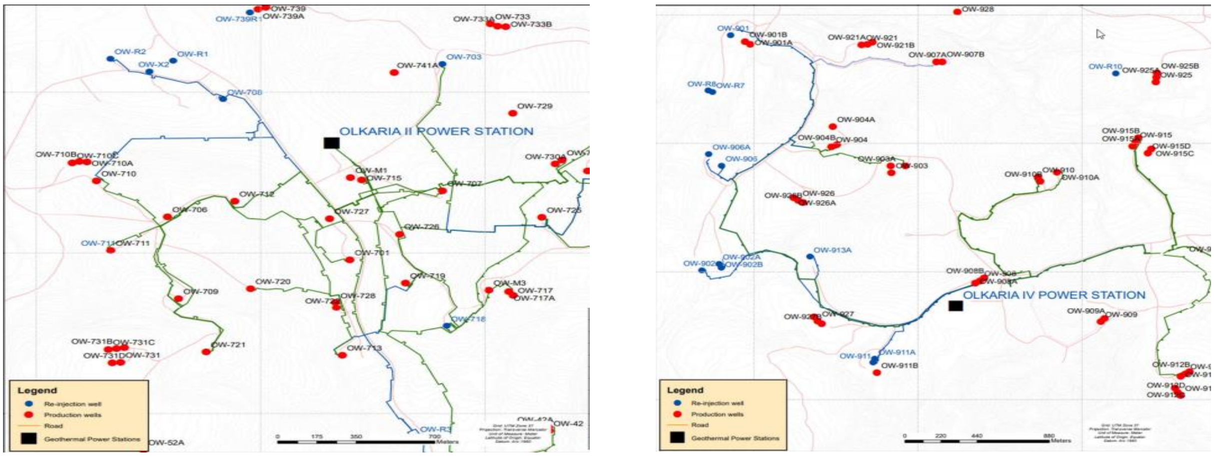


Figure 2 : Ternary plot of Cl-SO_4 -HCO_3 for typical separated waters in Olkaria East, Olkaria North East and Olkaria Domes

The reservoir in Olkaria is a two phase reservoir and liquid dominated at depth. In the shallow parts of the reservoir in some sectors eg the Olkaria East and Olkaria North East it is overlain by a thin steam dominated zone.

Generally the separated water of wells in Olkaria is low in dissolved solids compared to discharge water from other high temperature geothermal fields eg Salton Sea, Assal, Reykjanes, Aluto Langano, Kawareu etc . Chloride concentration in waters discharged by wells in Olkaria range from ~ 500 to ~1100 ppm at sampling temperatures, with the exception of some wells that discharge very high enthalpy close to that of steam. Separated water from the Olkaria East and Olkaria North East Production Fields have the highest chloride content. High chloride content is also observed in the Olkaria South East Field. The reservoir water chemistry in the Olkaria geothermal field is characterized by Na-Cl-HCO_3 type with alkaline pH and relatively low chloride concentration, in most cases less than 1,000ppm at depth . The model of fluids chemistry of the east side of the Olkaria geothermal field sees the waters of all three sectors (East, North East and Domes sectors) having a common origin at great depth (well below production levels) (West JEC, 2009). Each upflow of the three sectors has common Cl, but slightly different Non Condensable Gases (NCG's) fractions and alkalinity levels caused by a secondary imprint. The secondary imprint could be as a result of separation of dissolved gases from the steam as the fluids ascend to the surface. Bicarbonate waters which are observed in the Olkaria West, parts of Olkaria Domes and Olkaria Central sectors could result from the dissolution of carbon dioxide (CO_2) gas into surfacial waters as the separated steam ascends to the surface. Wells OW-R2, OW-R3 , OW-708 and OW-703 which convey separated brine streams are found in the Olkaria North

East Sector while wells OW-911, OW-911A OW-913A and OW-928 and OW-902 are hot re-injection wells in Olkaria Domes sector. Below is a layout of the re-injection streams for the Olkaria North East and Olkaria Domes sectors.



a) b)

Figure 3 : Re-injection streams in a) Olkaria North East and b) Olkaria Domes Sectors of Olkaria (the blue lines)

Further typical chemical composition of separated water for re-injection from Olkaria North East and Olkaria Domes sectors of Olkaria are shown in Table 1 below.

A summary of the chemistry of separated water at re-injection wells OW-R2, OW-R3, OW-708, OW-703 and OW-911 are shown in Table 1 below.

Table 1 : Shows chemical composition of trace elements in separated waters from Olkaria at several re-injection wells

Well ID	SP (barg)	Cond (µΩ/cm)	TDS (ppm)	pH/20°C	B (ppm)	SO_4 (ppm)	Cl (ppm)	CO_2 (ppm)	F (ppm)	H_2S (ppm)	SiO_2 (ppm)	Ca (ppm)	Li (ppm)	Na (ppm)	K (ppm)	Mg (ppm)	Fe (ppm)	Al (ppm)
OW-911	10	1474	737	10.2	0.04	10	349	429	80.2	14	1081	0.00	1.5	621	175			
Ow-911A	10	822	411	7.0	0.04	60	192	473	65.9	31	916	0.00	1.2	464	116	0.00	0.88	
OW-913A	10	2920	1460	10.5	0	64	379	339	185.1	14	822	0.04	1.1	696	178	0.01	0.03	2.01
OW-703	6	2080	1870	9.7	2.73	21	622	252	26.8	65	774	0.34	1.5	528	107	0.06	0.10	0.69
OW-708	6	3780	1890	10.0	0.08	180	1062	364	33.1	18	930	0.01	0.8	1194	276	0.11	0.35	
OW-928	10	3420	1710	10.2	0.61	63	388	603	235.6	8	956	0.60	1.0	847	276	0.13	0.32	1.36
OW-R3	6		1930	9.6	2.30	39	658	196	73.0	32	836	0.35	1.4	538	112	0.02		
OW-R2	6	1047	524	9.7	0	126	534	270	49.6	31	845	0.30	1.6	692	105	0.01	0.13	

Alongside these is shown the chemistry of waters from other geothermal fields in the world.

Table 2. Examples of Mineral composition at selected geothermal fields (Calamelii et al, 1975, *Bourcier et al, 2003, Gallup, 1998,Sanjuan,2010 Sanjuan et al, 2020,)*

Item	Salton Sea	Coso	Cerro Prieto	Wairakei	Milos	Reykjanes (RW-10)	Assal (A3)	Cesano	Franco-German Basin
Temp ° C	296	274	340	260	300+	290	280	300	225
Silica mg/kg	>460	>710	>864	>670	>950	731	520	130	179
Boron mg/kg	257	119	9.4	<0.01	125	7.60		13800	38.6
Lithium mg/kg	194-230	45	27	13.2	81	3.71	33	350	162

2.1 Brine at re-injection wells and ex tractable elements; Lithium

The total brine flow currently estimated in the respective sectors in the Greater Olkaria Field are presented in Table 3 below. These was estimated from the mass flows determination deliver ability of individual production wells as per extracts from binary plant study by WESTJEC, 2014 and Mbithi, (2019)

Table 3: Total Brine flows estimated from the production well tests (WESTJEC, 2014, Mbithi , 2019, 2022)

Area	**Total Brine Flow, t/h**
Olkaria I Connected	**271.1**
Olkaria II Connected (North East)	**686.0**
Olkaria II New Wells (North East)	**348.5**
Olkaria I AU (East and North East)	**303.6**
Olkaria IV (Olkaria Domes)	**1020.2**
Olkaria V (2019) Olkaria Domes	**165**
Total	**2794.4**

From table 3 above a relatively large amount of brine exists at Olkaria II (Olkaria North –East) and Olkaria IV (Olkaria Domes)

From the above table there is a relatively large amount of brine available for mineral recovery in Olkaria. Most brine is available from wells feeding Olkaria II, Olkaria IV and Olkaria V power plants. In a practical way the hot re-injection streams for Olkaria II and Olkaria IV & V could be the most probable sites for selection of pilot plant studies for mineral recovery. From the brine flowing into the hot re-injection wells, a few selected minerals can be estimated for mineral extraction.

The recoverable minerals concentration from the separated waters in Olkaria i.e waters from Olkaria East, Olkaria North East and Olkaria Domes are variable e.g lithium ranges between 2– 3 mg/kg, boron between 0.17 to ~ 7 ppm while Silica (SiO_2) contents range from 500 to 1100 ppm. This concentration is relatively low for lithium and boron. Considering all the brine from the re-injection streams a large amount of brine (aggregated) of ~2794.4 t/hr exists. When the amount of brine flows is taken into account, then commercial amounts of some minerals could be recovered. From the separated brine an estimate of recoverable amounts of minerals can be estimated from continuous flow streams (Mineral fluxes). Theoretical estimates of lithium and boron recoverable from the brine streams is shown in Table 4 below. This assumes all lithium and boron is recovered

Table 4: Estimated amounts of lithium from separated water streams/day

Area	Total Brine Flow, t/h	Total Brine Flow, t/day	Lithium mg/kg	Boron mg/kg	Lithium g/kg	Lithium kg/day	Lithium kg/Yr	Boron g/kg	Boron kg/day	Boron kg/Yr
Olkaria I Connected	271	6506.4	2.4	4.9	0.0024	15.62	5699.6	0.0049	31.869	11632
Olkaria II Connected	686	16464	3.1	1.84	0.0031	51.04	18629.0	0.0018	30.3	11057
OlkariaII New Wells	349	8364	2.5		0.0025	20.91	7632.2	0.0018	15.4	5617
Olkaria I AU	304	7286.4	2.3	4.9	0.0023	16.76	6116.9	0.0049	35.7	13032
Olkaria IV	1020	24485	2.5	1.4	0.0025	61.21	22342.4	0.0014	34.3	12512

Olkaria V (2019) Olkaria Domes	165	3960	3	1.4	0.0030	11.9	4336.2	0.0014	5.5	2024
Total	2794.4									

The above theoretical estimates suggest that the amount of lithium and boron available from the brine streams can be considered for extraction. The theoretical estimates assume that all the lithium and boron is extracted from the brine. The lithium concentrations in the Olkaria brine is low~3 ppm. For brine streams from Olkaria II and Olkaria IV which have the highest flowrates these could be the most suitable for lithium recovery. The focus on lithium recovery from geothermal brines has been in hyper saline and saline geothermal systems eg. those of Salton Sea, the Franco-German (the Rhine basin), Tuscany in Italy which have high lithium concentrations. For dilute brines like the Olkaria brines with low lithium concentrations extraction would first require the recovery of silica. (Lea and O'Sullivan, 2020+1) report extraction of lithium from brines in Kakonda, Japan with low lithium concentrations (~3 ppm) after recovery of silica from the brine. In their work packed columns containing pelletised specific lithium adsorbents were exposed to brine where silica had been recovered through an ultrafiltration process and re-heating. They reported a 95 % extraction of lithium from the initial trials on the ultra filtrate. Some level of success was achieved. A scoping study conducted on the economics of lithium extraction and concluded that this could be extracted from the processed geothermal water at a cost similar to extraction costs of salars of lithium brines. These technique could be applied to the low lithium concentration of the Olkaria separated water. Lithium extraction pilot studies have been trialed at Alsace and Cornwall Geothermal Fields in France (Eramet, EuGeLi 2021) and the United Kingdom (Cornish Lithium, 2022) and at Salton Sea (Geothermal Resource Group 2023) which managed to produce battery grade lithium.

The separated water from Olkaria II (Olkaria North East) and Olkaria IV & V (Olkaria Domes) present the highest flowrates and the highest estimated recoverable lithium and boron. The estimated recoverable lithium from Olkaria North East and Olkaria Domes is ~ 26 t/hr and 27 t/yr respectively while that of boron is ~ 17 t/hr and 15 t/hr respectively. These estimated amounts of lithium and boron are low for reasonable quantities of the two elements to be recovered from the separated waters

Silica

Silica solubility increases with increase in the reservoir temperatures and in high temperature geothermal systems, the silica concentrations could have economic values in the brine. In general brines that contain low total dissolved solids (TDS), and high levels of silica could produce high-value silica products which could be economically exploited. Brines with high (TDS) values eg hyper saline brines pose challenges to process and extract silica (SiO_2) economically. Bourcier et al (2006) have demonstrated a silica extraction pilot plant at mammoth lakes geothermal field in California. The wells in Mammoth Lakes produce low TDS brine (~1500 mg/kg). Masatake et al 2020+1 have demonstrated- recoverable colloidal silica in the silica concentration range of 500 to 1000 ppm silica in the Kakonda Geothermal Brines. Colloidal silica was successfully recovered and this lowered the risk of silica scaling in brine injection wells. Further they demonstrated that from an original silica concentration of ~ 1200 ppm the residual concentration of silica after silica recovery was ~ 243 to 333 ppm in the brines. In New Zealand, Lea and O'Sulivan, 2020+1 report on pilot studies for silica extraction at Wairakei, Ohaaki and Kawareau Geothermal fields. They concluded that colloidal silica could be successfully recovered from brine with 135 ºC and silica concentrations of 670 ppm. This would greatly reduce the risk of silica scaling in injection wells and increase electricity production due to increased temperature difference for extraction.

Bourcier, 2006 suggests that brines with low concentration of silica eg Mammoth lake brines (250 ppm) require pre-concentration to silica concentration of ~500 ppm. The Olkaria brines have a silica concentration that range from ~500 to 1100 ppm for brine re-injection streams in Olkaria East, Olkaria North East and Olkaria Domes. Silica solubility in separated brine is governed by the amorphous silica temperature dependent equation. Equation 1 below

Amorphous silica solubility equation

$$Logc = \frac{-731}{T} + 4.52 \qquad \text{---}$$

(1)

In Olkaria there are several separation pressures at which brine is separated from the single flash process. For wells feeding the old power plants i.e Olkaria I and Olkaria II, brine is separated at ~150º C . In Olkaria IAU , Olkaria IV and V power plants separation is done at ~180º C .

The Olkaria wells produce low TDS brines of ~2500 ppm in the separated water. The silica concentrations in the separated waters is ~1000 ppm . Applying the above criterion for silica extraction with concentration it can be considered that the separated Olkaria waters is good for silica recovery. For this exercise the recoverable silica is the silica in excess at the water separation temperature. Àn estimate of recoverable silica from the separated Olkaria waters at 6 and 10 bar separation pressures is shown in Table 2 below.

Table 4: Estimated amounts of silica from separated water streams/day

Area	Total Brine Flow, t/h	Total Brine Flow, t/day	Silica at @6 bar g mg/kg	Silica @ 10 barg mg/kg	Excess Silica @ 6 bar mg/kg	Excess Silica kg/day
Olkaria I Connected	271.1	6506.4	700		80	520.5
Olkaria II Connected	686	16464	850		230	3786.7
OlkariaII New Wells	348.5	8364		950	144	1204.5
Olkaria I AU	303.6	7286.4		950	144	1049.3
Olkaria IV	1020.2	24484.8		1100	294	7198.5
Olkaria V (2019) Olkaria Domes	165	3960		1100	294	1164.2
Total	2794.4					

The estimated recoverable silica is suitable for re-injection streams for Olkaria II (in Olkaria North East) and Olkaria IV power plants (Olkaria Domes). These have the highest flows of separated waters with each being ~1040 t/hr for Olkaria II and 1020 t/hr for Olkaria IV. From the estimates indicated in the table 3 above Olkaria II re-injection streams could provide recoverable silica of ~4.99 t/day while from Olkaria IV & V the estimates are higher of ~8.362 t/day. These amounts could provide commercially viable quantities for recoverable silica from the brine flow rates.

A simplified process flow diagram for the extraction of silica and other minerals e.g lithium from separated geothermal water is shown in Figure 4 below. A series of membranes, filters and adsorption materials are used to extract value able compounds and elements like silica and lithium.

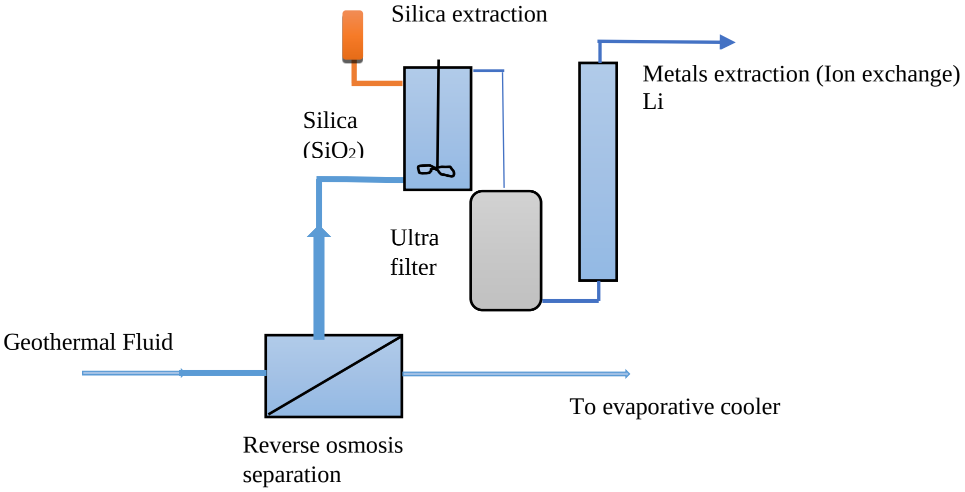


Figure 3: A simplified schematic diagram of reverse osmosis plant for silica removal and metal extraction e.g Lithium (Modified from Boucier 2006)

3 Summary of applicable technologies for Lithium, Silica and Boron Extraction.

3.1 Lithium is one of the most commonly used metals in industry with a wide variety of applications including batteries, lubricating grease and pharmaceutical products. With the increasing adoption of electric vehicles and for the world to get to net zero for vehicular emissions the demand for lithium is projected to grow over 3 million tonnes by 2030. Therefore, there is a pressing need to develop new sources of lithium to support this anticipated increase in demand.

Lithium can be extracted from salt brine or minerals and then processed to obtain lithium carbonate, which is used to produce various lithium compounds. Salt brine is the most abundant lithium source available in the world, comprising about 60% of all known lithium deposits. Producing lithium by evaporating salt brine is also less costly than directly extracting it from minerals.

There are diverse processes available for lithium extraction from lithium salars with limitations: 1) Precipitation:_Precipitate formed has a small size and is hard to filter, resulting in significant lithium loss. 2) Carbonization: _Process is not easy to control, resulting in low lithium yield. 3) Calcination and Leaching :_Magnesium removal rate is low and energy consumption is high,.4) Adsorption :_Low production efficiency due to low capacity of adsorbent.

In separated geothermal waters various methods for lithium extraction have been have been reviewed. Climo et al 2020+1 reviewed lithium extraction technologies based on separated geothermal waters for various geothermal fields in New Zealand. Techniques reviewed were manganese oxide spinels and cation exchange resins, co-precipitation with aluminium hydroxide, electrodialysis; and evaporation. A few laboratory scale trials have been undertaken without being scaled up to pilot studies.

3.2 Silica extraction from separated geothermal waters has been the most extensively studied. This is because this mineral limits the amount of energy extraction from geothermal fluids. In the work done in New Zealand (Climo et al 2020+1) the techniques reviewed included those for extracting metal silicates (as Calcium Silicate): precipitation by metal silicates and cation flocculants, dissolved air flotation, deposition onto seed particles and ultra filtration, electrocoagulation, flash crystallization, deposition and polymerization. Pilot scale studies for silica extraction have been implemented in New Zealand (Wairakei) and Japan (Kakonda), Masatake et al 2020 +1. They concluded that a high market value colloidal silica and additional energy could be extracted from the geothermal fluid by lowering the re-injection temperatures of the water.

4.0 Conclusions

Mineral recovery from geothermal brines is a new frontier to which separated geothermal brines can be utilized. From several pilot studies at the Salton Sea, USA Alsace in the Franco- German Basin, Wairakei New Zealand and Kakonda, Japan a number have demonstrated the feasibility of silica extraction and other minerals for extraction after the extraction of silica. This had the effect of lowering the temperatures of hot re-injected well fluids and could increase the amount of available energy that can be recovered.

At Olkaria the aggregate amount of hot separated waters is ~3000 t/hr. This water is available for re-injection and varies in quantities from sector to sector within the Greater Olkaria Geothermal Field. The highest separated water streams are found in Olkaria North East and Olkaria Domes sectors of the Greater Olkaria Geothermal Area. This is ~1034 t/hr in Olkaria North East and ~11185 t/hr in Olkaria Domes Sectors. Recoverable minerals concentration from the separated waters in Olkaria i.e waters from Olkaria East, Olkaria North East and Olkaria Domes are variable e.g lithium ranges between 2– 3 mg/kg, boron between 0.17 to ~ 7 ppm while Silica (SiO_2) contents range from 500 to 1100 ppm. Lithium and boron are in relatively low concentrations in the separated waters of Olkaria.

In separated water from Olkaria II (Olkaria North East) and Olkaria IV &V (Olkaria Domes), recoverable lithium and boron are low. Estimated amount is 26 t/hr and 27 t/hr for lithium while for boron this is ~17t/hr and 15t/hr. Respectively. These two elements are low in quantities. This may not provide commercially viable quantities for the extraction of the two elements. Estimated recoverable silica from the hot re-injection streams

Silica was estimated from the re-injection streams as the other viable mineral that could be extracted. Silica concentrations are high in the brine streams ranging from ~500 to ~1100 ppm. Separation was done at ~150 º C and 180 º C. bars respectively. Estimated recoverable silica is suitable for re-injection streams for Olkaria II (in Olkaria North East) and Olkaria IV power plants (Olkaria Domes). These have the highest flows of separated waters with each being ~1040 t/hr for Olkaria II and 1185 t/hr for Olkaria IV & V. Estimates indicate re-injection streams could provide recoverable silica of ~4.99 t/day in Olkaria II(Olkaria North East) while from Olkaria IV & V the estimates are higher of ~8.362 t/day. These amounts could provide commercially viable quantities for recoverable silica from the brine flow rates.

Sections of Your Paper

Please include an Abstract, an Introduction, and Conclusion sections. Please check that you put the authors' names in the second and third page headers.

REFERENCES <HEADING 1 STYLE>

Bourcier,W., Lin, M., Nix, G.,; Name, A., and Name, B.: Recovery of Minerals and Metals from Geothermal Fluids, *Lawrence Livermore National Laboratory, Livermore, CA, USA 18pp, Rekjavik, Iceland (2003).>*

Bourcier,W., Ralph, W., Johnson, M., Bruton, C., and Guitierrez, P.,: Silica Extraction at Mammoth Lakes, California, *Proceedings of the International Mineral Extraction from Geothermal Brines Conference, Tucson, Arizona* (2006)

Calamelii,A., Citaldi, R., DallÁglio, M., and Ferrara, G.C.: Preliminary report on the Cessano hot brine deposit (Northern Latium, Italie). *Proceedings of second United Nations Symposium on the development and use of Geothermal Resources, San Francisco, Carlifornia, (May 1975).*

Climo,M., Carey1,B., Mroczek. E: Update on Geothermal Mineral Extraction – the New Zealand journey,*Proceedings of World Geothermal Congress, Reykjavik, Iceland (2020+1)*

Successful commissioning of geothermal Direct Lithium Extraction plant, Cornwall, WWW.CORNISH LITHIUM.COM (2022)

Success in lithium extraction from geothermal brine, Alsace, France,WWW.ERAMET.COM (2021)

CTR achieves efficient lithium extraction from Salton Sea geothermal brine.,WWW.CONTROLLED THERMAL RESOURCES.COM, (2023)

Gallup, D: Geochemistry of Geothermal Fluids and well Scales, and potential for mineral recovery, *Ore Geology Reviews* ***Vol. 12*** (1998) pp 225-236.

Kamunya, K.M: δD and δ^{18} O Systematics in geothermal fluids, Olkaria Geothermal System, Kenya, Unpublished MSc thesis, *University of Icleand, 32 pp, Rekjavik, Iceland (2018).*

Karingithi, C; Name, A., and Name, B.; Geochemical characteristics of the Greater Olkaria Geothermal Field, Kenya *United Nations University- Geothermal Training Programme (UNU-GTP), Report No.9 24 pp , Rekjavik, Iceland (2000).*

Karingithi, C: Hydrothermal Mineral Buffers controlling reactive gases concentration in Greater Olkaria Geothermal System, Kenya, *University of Iceland, Unpublished MSc thesis., Rekjavik, Iceland (2000).*

Leech C.N: Modelling the Geochemical effects of geothermal fluid geothermal fluid injection in the Olkaria Geothermal Field, Kenya, *United Nations University- Geothermal Training Programme (UNU-GTP), Report No.16 20 pp, Rekjavik, Iceland (2016).*

Lea, J., and O'Sullivan, M., Silica and other minerals extraction from geothermal brine in New Zealand. *Proceedings of World Geothermal Congress, Reykjavik, Iceland< (2020+1)*

Masatake, S., Kaichiro, K., Kazumi, O., Kazuharu, Y., Haruo, O., Andrew, M., Callum Ward., and Betsy,B：Application Results of Silica Extraction Technology at Kakkonda Geothermal Area and Evaluation of Extending the Life of the Reinjection Well，*Proceedings of World Geothermal Congress, Reykjavik, Iceland (2020+1)*

Mbithi, U., *Presonnal Communication* (2019, 2022)

Sanjuan, B., Millot, R., Innocent, Ch., Deyzes, Ch., Brach, M., Mian geochemical characteristics of the deep geothermal brine (5km) at Soultz -sous-Forets (France) determined using geochimcal trace and test data, *C.R Geoscience*, **342**, (2010) pp 546-559

Sanjuan, B., Negrel, G., Le Lous, M., Poulmarch, E., Gal, F., Danny P.C.: Main Geochemical Characteristics of deep geothermal brine at Vendenheim(Alsace, France) with constraints on temperature and fluid circulation, *Proceedings of World Geothermal Congress, Reykjavik, Iceland, (2020+1),*

Wambugu, J.M; Name, A., and Name, B.: Assessment of Olkaria North-East Reservoir based on well discharge chemistry,*United Nations University (UNU-GTP), Report No.20 29pp , Rekjavik, Iceland (1996).*

WestJec: Olkaria Optimization Study, optimised development report(Phase II), *Unpublished Kengen Internal Report* - (2009)

WestJec : Feasibility Study for Geothermal Power Generation from brine at Olkaria, *Unpublished KenGen internal report.* (2014)