

OLKARIA GEOTHERMAL FIELD RESERVOIR RESPONSE AFTER 35 YEARS OF PRODUCTION (1981 – 2016)

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ABSTRACT

The Greater Olkaria Geothermal Field is in the southern part of the Kenyan rift, south of Lake Naivasha, approximately 120 km northwest of Nairobi. Exploration for geothermal resources in Kenya started in 1950's with mainly geological investigations in the region between Olkaria and Lake Bogoria in the north rift. In 1970's, exploration was concentrated in Olkaria and by 1976, six deep wells had been drilled. After evaluation of these initial wells, development was found to be feasible. Utilization of the geothermal resource began in 1981 when the first 15 MWe generating unit was commissioned by KenGen at Olkaria I power plant in Olkaria East. Thereafter, unit 2 and 3, each 15 MWe, were commissioned in 1982 and 1985, respectively. Olkaria II power plant, in Olkaria Northeast, also owned by KenGen, was commissioned in 2003 with an installed capacity of 70 MWe. Additional 35 MWe unit was added to this plant in May 2010, bringing the total installation to 105 MWe. Olkaria III power plant, owned and operated by an Independent Power Producer (IPP), Orpower4 Inc, was commissioned in Olkaria West in 2000 with initial capacity of 13 MWe and currently generates 134 MWe. Between 2014 and 2015 KenGen commissioned additional 280 MWe in Olkaria Domes and Olkaria East. A Pilot Wellhead plant was installed in Olkaria East in 2012 with a capacity of 5.5 MWe. Following success of the Pilot plant, a total of 15 wellhead plants have been installed in Olkaria, with 81.1MWe generation capacity. The total power generation in the KenGen's concession area of the Greater Olkaria Geothermal Field now stands at 511.1MWe. Moderate pressure drawdowns have been observed in the field during exploitation. The representative pressure drawdown observed for Olkaria East is ~ 12 bars, Olkaria Northeast ~ 13 bars during the thirteen years of operation of the Olkaria II plant, which is an equivalent of average annual pressure drawdown rate of 1 bar/year. The rate of pressure decline for the Olkaria Domes is ~1.2 bar/year. Re-injection has helped to minimize the rate of pressure decline. Currently the total mass produced in the KenGen's concession area is ~5600 t/hr and ~50% of which is reinjected. The general trend indicates a rise in the Cl content for Olkaria East Production Field and a decline for Olkaria North East Production Field.

1. INTRODUCTION

Olkaria geothermal resource is located in the Kenyan rift valley. The Kenyan rift is part of the East African rift system, which runs from the Afar triple junction at the Gulf of Aden in the north to Mozambique in the south. In the Eastern Africa, the rift splits into two, the western rift and the eastern rift valley, with the Kenyan rift being a segment of the eastern rift valley. Geothermal activity is widely spread in many part of the Kenyan rift and 14 major geothermal prospects have been identified. However, only three prospects in the Kenyan rift have so far been drilled namely, Olkaria, Eburru and Menengai.

The Greater Olkaria Geothermal Field is in the southern part of the Kenyan rift. It is located south of Lake Naivasha, approximately 120 km northwest of Nairobi. Exploration for geothermal resources in Kenya started in 1950's with mainly geological investigations in the region between Olkaria and Lake Bogoria in the north rift. In 1970's, exploration was concentrated in Olkaria and by 1976, six deep wells had been drilled (Noble and Ojiambo, 1975). After evaluation of these initial wells, development was found to be feasible. Locations of geothermal prospects along the Kenyan rift (Figure1-World Bank. 2010).

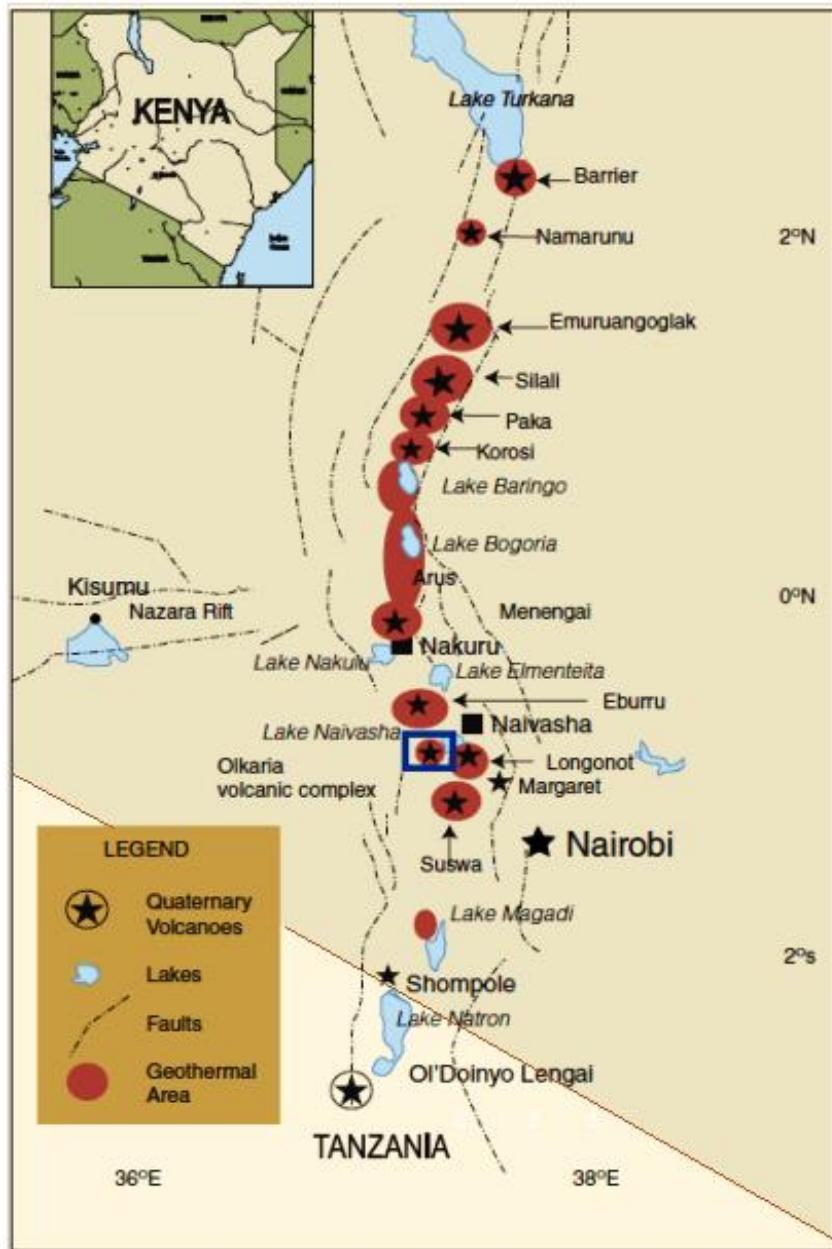


Figure 1: Location of Geothermal Resources in Kenya (World Bank. 2010)

Utilization of the geothermal resource began in 1981 when the first 15 MWe generating unit located in Olkaria East was commissioned and operated by KenGen. More wells were drilled and connected to the steam gathering system. Unit 2 and 3, each 15 MWe, were commissioned in 1982 and 1985, respectively. Olkaria II plant, also operated by KenGen and located in Olkaria Northeast, was commissioned in 2003 with an installed capacity of 70 MWe, consisting of 2 units of 35 MWe each.

Additional 35 MWe unit was later installed in this plant and commissioned in May 2010, increasing its generation capacity to 105 MWe. Olkaria West hosts Olkaria III power plant, initially 13 MWe commissioned in 2000 and which currently generates 134 MWe and owned and operated by an Independent Power Producer (IPP), Orpower4 Inc., a subsidiary of Ormat International. In the recent years, KenGen has embarked on capacity expansion which has seen it commission 280 MWe developments in 2014 and 2015. Aside from conventional power plants, KenGen has introduced wellhead generating units for early generation. The initial pilot plant installed in 2012 with a capacity of 5.5 MWe. To date, 15 wellhead plants have been installed in Olkaria with a total generating capacity of 81.1MWe. The total power generation in the KenGen's concession area of the Greater Olkaria Geothermal field to date is 511.1 MWe. The parts of the Olkaria geothermal field being utilized or under development have been subdivided into sectors as shown in Figure 2.

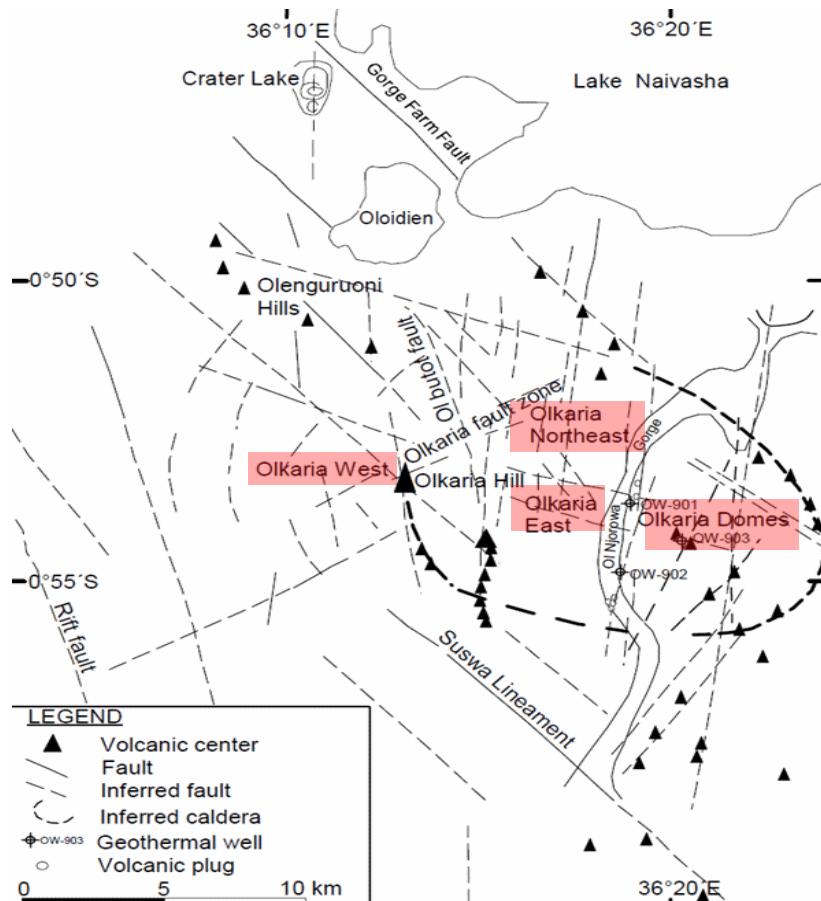


Figure 2: Map showing main geological structures of the Greater Olkaria geothermal system and the sectors

The Olkaria geothermal field is inside a major volcanic complex that has been cut by N-S trending normal rifting faults. It is characterized by numerous volcanic (mostly rhyolitic) domes, some of which form a ring structure, which has been interpreted as indicating the presence of a buried volcanic caldera. Other prominent structures in the complex are: the Ol' Njorowa gorge, the N-S trending Ololbutot fault, the NE trending Olkaria fault, the Olkaria fracture, the Suswa fault and the Gorge Farm fault. Eruptions associated with the Olkaria volcano and Ololbutot fault zone have produced rhyolitic and obsidian flows while eruptions in Longonot and Suswa volcanoes (Figure 2) have ejected pyroclastic ash, which has blanketed much of the area. Permeability in the Olkaria system is controlled by predominantly NW-SE and NE-SW trending faults (Omenda, 1998).

Development and exploitation of the Greater Olkaria Geothermal Field has been step wise incremental. This has been based on conceptual and numerical models which are continuously

updated as the understanding of the resource advanced with continued data acquisition. Chronology of exploration, drilling activities and power plants commissioning are as shown in Table 1.

Table 1 Greater Olkaria Geothermal Field development over the years

Year	Activity
1950s	Scientific investigations in Olkaria, Eburru and Lake Bogoria all within Great Rift Valley
1958	Two exploration wells X-1 and X-2 drilled in Olkaria. Encountered high temperature but unproductive
1981, 1982 and 1985	1 st , 2 nd and 3 rd 15 MWe generating units commissioned in Olkaria East (Olkaria I). A plant with total 45 MWe capacity operated by KenGen
1990s	Detailed Exploration and Later drilling of 3 exploration wells in Olkaria Domes (located in the southeast part of the Olkaria field)
2000	13 MWe unit commissioned in Olkaria west part of the field (Olkaria III) operated by Independent Power Producer (IPP) OrPower4 Inc.
2003, 2010	Olkaria II plant, located in Olkaria Northeast field, was commissioned with 2 units each 35 MWe, and later 3rd unit with 35 MWe, making a total of 105 MWe operated by KenGen
2009, 2011	Olkaria III production was increased by 36 MWe making the total installed capacity by OrPower4 Inc. to 48 MWe
2012	Well heads units introduced; 1 st pilot units with a capacity of 5.5 MWe (operated by KenGen) – 2012
2013	Olkaria III production was increased by another unit of 36 MWe bringing the total installed capacity by OrPower4 Inc. to 84 MWe
2014, 2016	<ul style="list-style-type: none"> • February 2014 OrPower4 Inc. commissioned its Plant 3 of 26 MWe achieving a total installed capacity of 110MW • Beginning of production in Olkaria Domes (units I and II) with combined capacity 140 MWe commissioned (operated by KenGen); Sept 2014 • Production in Olkaria East expanded with Olkaria I units IV and V, combined capacity 140 MWe, commissioning (operated by KenGen) ; Dec 2014 • 15 Well heads units commissioned; total capacity of 81.1 MWe (operated by KenGen); 2014-2016 • Second half 2016 OrPower4 Inc. commission Plant 4 of 24 MWe achieving a total installed capacity of 134MW

2. PRODUCTION AND RESERVOIR RESPONSE

2.1 Production and reinjection

Bi-annual output monitoring is done in wells that are delivering steam to the power plants. The main objective of the steam field monitoring is to help observe important changes taking place in the reservoir. These include changes in reservoir temperature and pressure, enthalpy and mass output changes as well as well's cyclic behaviours. These changes could result from reservoir boiling, over-exploitation, entry of cold water into the reservoir that can cause cooling, wellbore scaling or direct re-injection returns in the reservoir. Careful monitoring techniques help to map out thermodynamic and chemical changes before they cause adverse effects in the reservoir. Production monitoring in Olkaria field is a continuous exercise carried out since the start of exploitation with the aim of finding out and keeping track of the changes that occur in well output and mitigating measures taken if adverse changes are observed.

Figures 3 and 4 show the plot of total production and reinjection for the Greater Olkaria Geothermal Field under KenGen's concession. At the start of utilization total mass produced was 280 t/hr and most wells connected then to Olkaria I were shallow wells tapping from the steam cap overlying the deeper liquid dominated part of the reservoir. There was a decline in output towards 1992 due to the fact the wells were drilled shallow and hence were only tapping the steam cap. This was mitigated by connection of make-up wells which were drilled deeper and deepening selected shallow wells i.e. OW-05. By drilling deeper, permeable production zones which produced high mass flows and were more liquid dominated than the shallow steam dominated zones that were tapped in the older shallow wells were intersected. The total steam available increased and remained high exceeding what is required for generation of 45 MWe (Ouma and Koech 2012). Production from the North-eastern Production field commenced with the commissioning of the Olkaria II plant, which began operation in 2003 by commissioning units 1 and 2 and later unit 3 in 2010. As seen in Figure 3, since 2004, the average production has been around 1280 t/hr for Northeast field with an average injection of 550 t/hr, or 37%. The extracted brine and condensate is injected back into the system using four injection wells, OW-R2, OW-703, OW-708 and OW-201/204. In 2012 the Pilot Wellhead plant was commissioned and the production has been ramped up by gradual commissioning of the 15 wellhead plants currently in operation. The total production for wellhead plants currently is about 1000 t/hr and the associated total reinjection (i.e. hot brine and condensate) is 370 t/hr. The wellhead plants are located in Olkaria East and Domes fields.

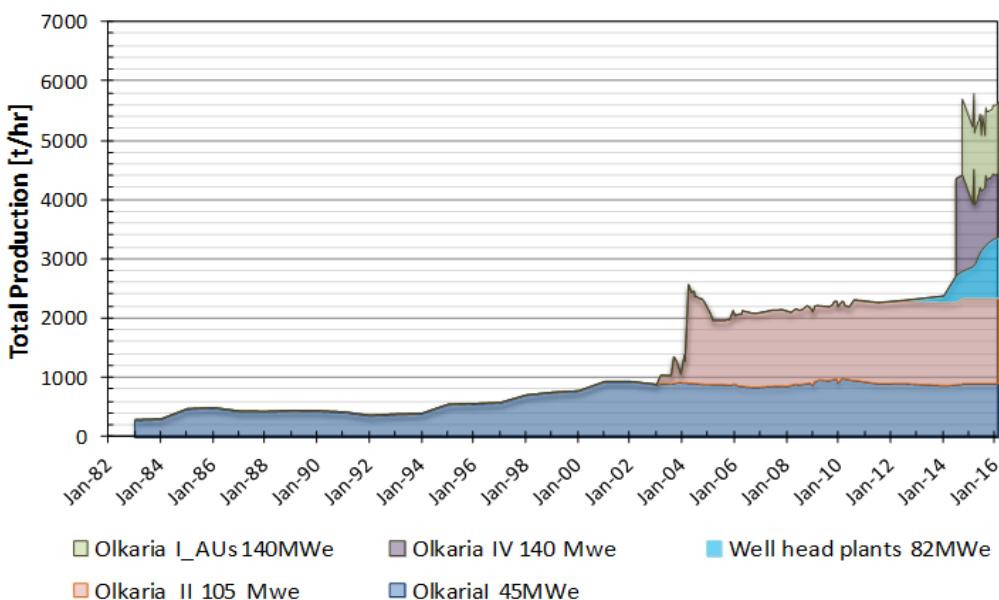


Figure 3: Total mass production for KenGen's concession area as increased over time

In September 2014 Olkaria IV units 1 and 2 were commissioned in Olkaria Domes taking in a total mass output of 1350 t/hr from the reservoir. Total reinjection in the Domes field is about 650 t/hr. Later that year in December 2014 Olkaria I units 4 and 5 were commissioned in Olkaria East field taking in a total mass output of 1250 t/hr from the reservoir. Total reinjection associated with Olkaria I additional units is about 550 t/hr. Currently the total mass output from the reservoir is about 5600 t/hr and the reinjection is 2800 t/hr.

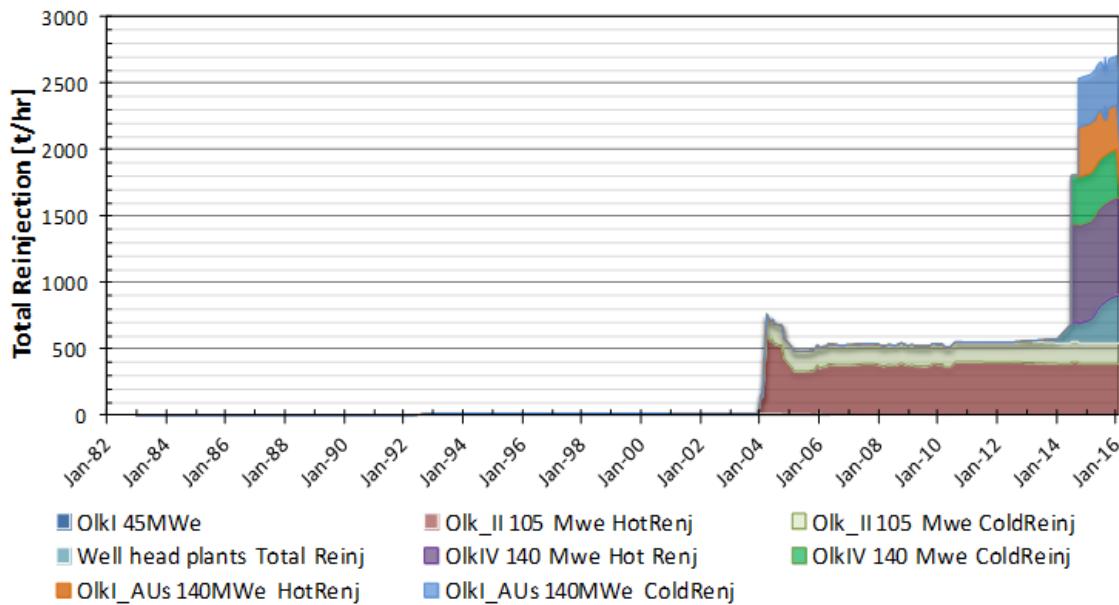


Figure 4: Total mass reinjected for KenGen's concession over time

2.2 Reservoir pressure response

Three parameters are vital in describing the response of a geothermal system to production. These include; the production history of the system comprising the mass extraction, the pressure measured in the observation wells along with the measurement of the enthalpy of the extracted fluid. Pressure logs are used to estimate drawdown due to production which show how much the pressure has declined due to fluid extraction. Pressure changes are important performance indicators for geothermal reservoirs. Ordinarily these changes would be propagated through the reservoir from points of production or injection to observation points. The field being close to boiling conditions implies that any localized pressure drawdown is countered by phase change that compensates the decline and pressure decline propagation may not be as fast. The chemical changes are far more rapid and which serve as early warning signals, are also monitored. Several wells are used in monitoring the response of Olkaria field in response to production.

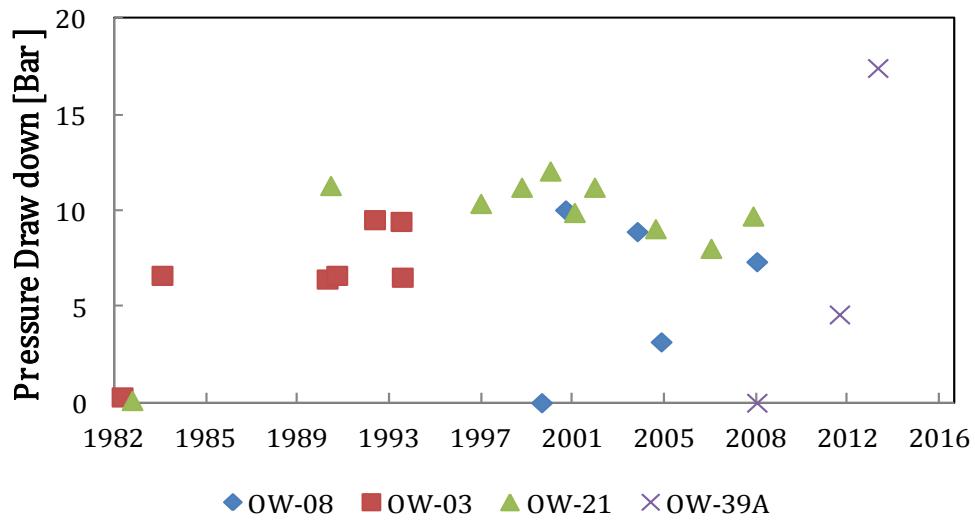


Figure 5: Olkaria East field pressure drawdown observed over time

The pressure decline in Olkaria East field has been moderate. Drawdown data come from 4 wells, two of those, wells OW-8 and OW-21, have the longest data series. Observed drawdown is 12 bars (Figure 5). OW-08 had been in production and this explains the off data points. 12 bars decline is representative of the Olkaria East field.

The pressure drawdown of the Olkaria Northeast production field (NEPF) is available from OW-M1, OW-M2, OW-M3, OW-723 and OW-724. Drawdown has been moderate \sim 13 bars during the operation of the Olkaria II plant (Figure 6). The rate of decline is 1 bar/year.

Olkaria Domes field drawdown as plotted in Figure 7a show declines that are attributed to well testing and localized drawdown before commissioning Olkaria IV. Some monitoring wells which were initially drilled as production wells and upon testing and establishing them as low or non-producing wells were then converted to serve as monitoring wells. The drawdowns observed are thus transient and are affected by incomplete recovery after testing. The drawdown as monitored by Pressure chamber (Bubbler tube) is approximated as \sim 1.2 bar. This is observed in OW912B for production period of almost a year and no observable decline for OW907B and OW917B that are also monitored on continuous pressure logging system (Figure 7b). This gives the rate of pressure decline as \sim 1.2 bar/year. This is being monitored closely as the system will establish steady state condition.

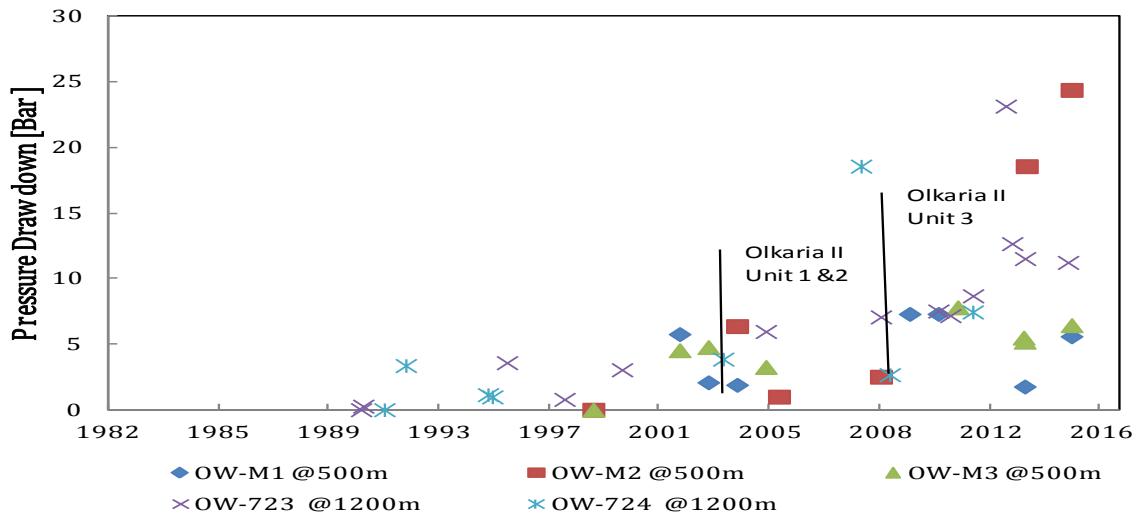


Figure 6: Olkaria East field pressure drawdown observed over time

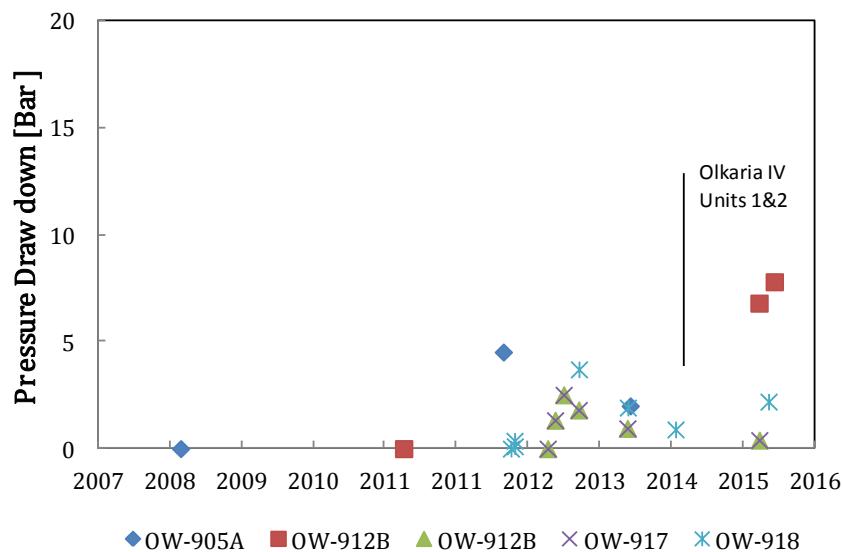


Figure 7a: Olkaria Domes field pressure drawdown observed over time - down hole periodic logs

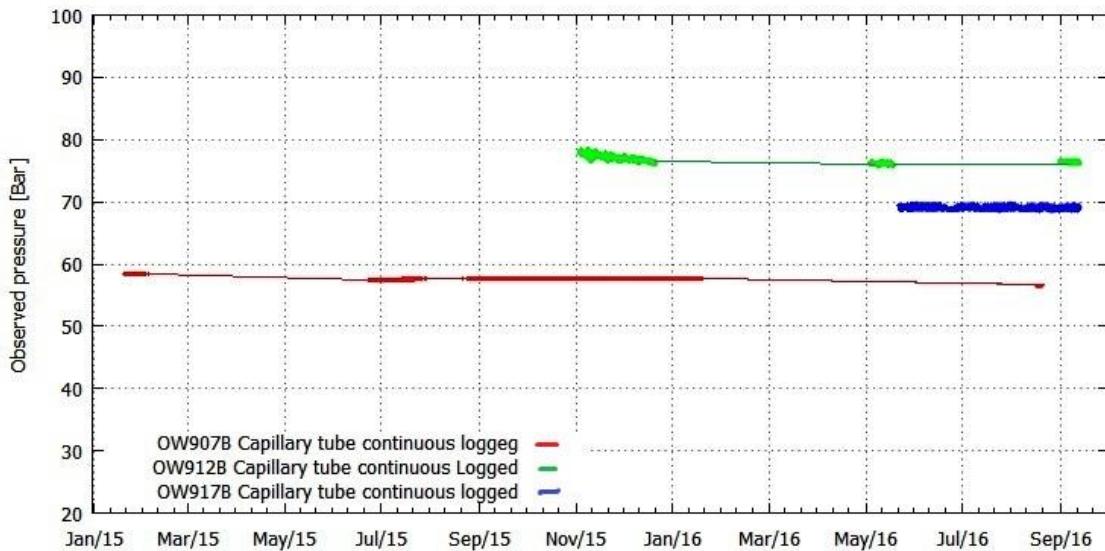


Figure 7b: Olkaria Domes field pressure drawdown observed by continuous Logging system Pressure chamber -Bubbler/capillary tube draw down monitoring

3. WELL DISCHARGE ENTHALPY FOR EAST PRODUCTION FIELD (EPF) AND NORTH EAST PRODUCTION FIELD (NEPF)

Olkaria East and North East production fields have the longest time series data and are discussed. For Olkaria East field, in 1985 at the centre of the field area around wells OW-05, OW-10, OW-15, OW-18, OW-19 and OW-20 had the highest enthalpy and are the wells that are tapping on the steam cap. Following cold reinjection trials in 1997 in OW-12 there was an observed decline of enthalpies in well OW-15, 16, and 19(Mawongo 2004). Effects of drilling are noted in OW 16 and 19 where there is enthalpy decline as drilling fluid found its way to the well. Olkaria north east wells have relatively lower enthalpy as compared to East field wells.

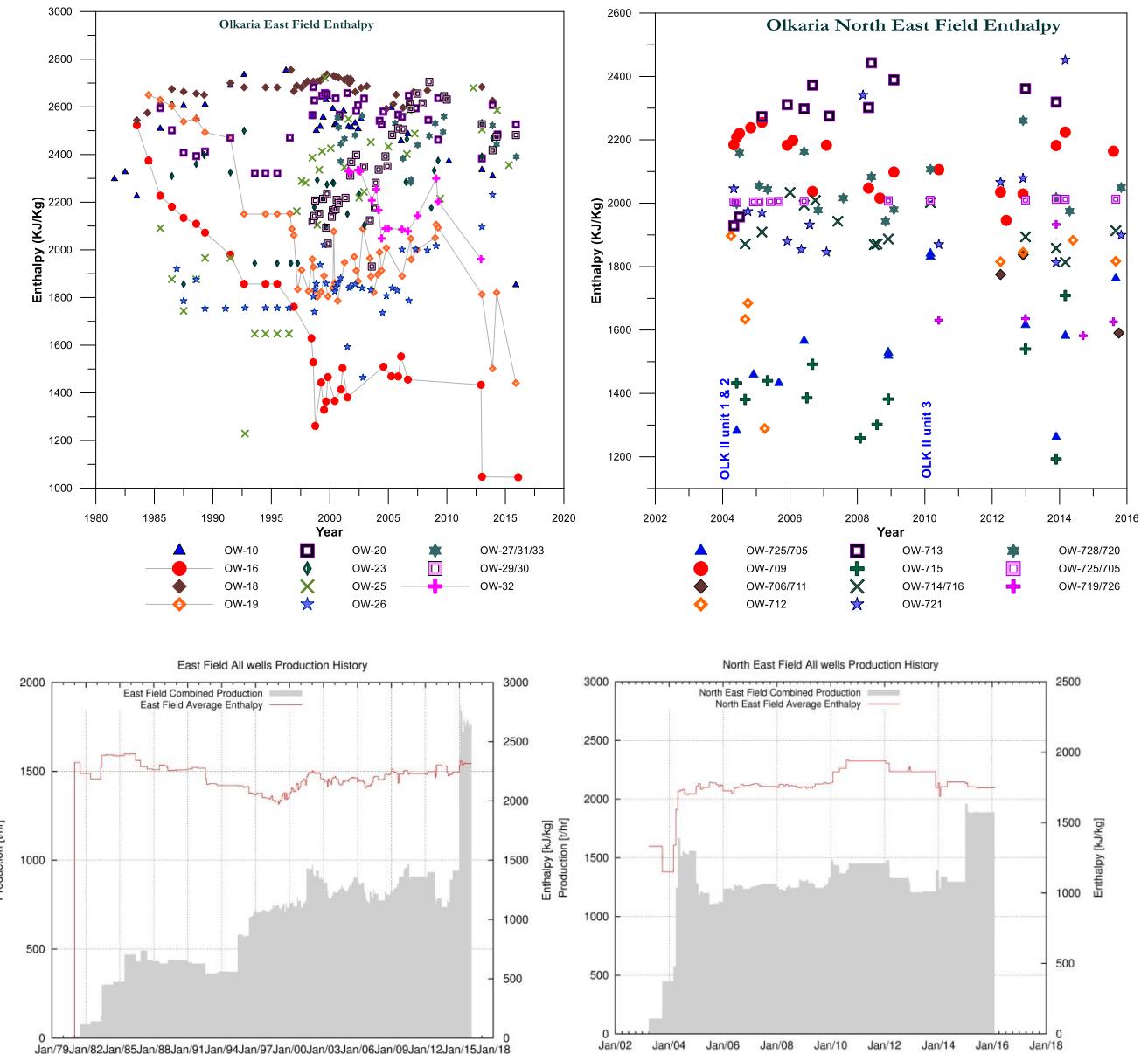


Figure 8a: Olkaria East Field well enthalpy observed over time (Left) and Olkaria North East Field well enthalpy observed over time (Right)

Figure 8b: Olkaria East Field total production and average enthalpy (Left) and Olkaria North East Field total production and average enthalpy (Right)

Figure 8a and 8b shows the individual wells historical time series trending and the field weighted average enthalpy and the total production from the field over time respectively. In the Olkaria East Production Field, the average enthalpy has typically been around 2200-2300 kJ/kg whereas in the NEPF it has been considerably lower, between 1700 and 1800 kJ/kg (Wanyonyi, 2014). It has generally been observed that wells drilled deeper in Olkaria East Production Field (EPF) have lower enthalpy than the earlier wells which were drilled to shallow depths and which only tapped the steam cap. The decline in observed enthalpy is attributed to drilling of deeper wells that tapped deeper aquifers which produced more liquid dominated fluid than the shallow steam dominated aquifers tapped by the older shallow wells. These deeper wells have higher mass flows and relatively lower enthalpy and when field wide average enthalpy is computed it effectively reduces it. However there is a general field wide gentle increase in the observed average EPF enthalpy. Field average enthalpy for Domes field has been fairly steady at 1850 kJ/kg for the period it has been in operation. The

introduced injection/reinjection schemes are contributing in maintaining the enthalpy of the produced fluid in Olkaria East Production Field (EPF).

4. CHEMICAL CHANGES - CHLORIDE CONCENTRATION

The procedure for monitoring has flexibility in sampling frequency so that parameters that change quickly are appropriately monitored. For this reason, monitoring is done on a quarterly basis during the initial stages of production and then changed to at least once a year after experiencing minimal changes and the trends in the chemistry of the reservoir fluids. During well flow monitoring, water and steam are sampled from the well discharge.

4.1 Olkaria East Production Field Chloride distribution

Overall, chloride concentrations are variable between 350 to 750ppm in 2012 compared to 340 to 680 ppm range of 2015 (Figure 9). The highest chloride concentration was around well OW-15 and low around wells OW-22, OW-23 and OW-31. This is different from the 2012 and 2013 monitoring period that had high values also in wells OW-5 and OW-10; which now have moderate Cl concentrations. The general trend indicates a rise in the Cl content from the year 2000. This coupled with a rise in the enthalpy is an indication of boiling in the aquifers in the vicinity of the wells.

4.2 Olkaria North East Production Field Chloride distribution

Overall, chloride concentrations are variable between 120 to 680ppm (Figure 9). The 2012 data show highest chloride concentration around wells OW-715 and OW-725 and lowest around OW-711. This is replicated in the 2013 period i.e. the Cl concentration forms a doming around OW-726 that then reduces on the sides to OW-711 on the West and OW-705 on the east. This can be attributed to the fact that OW-726 may be located in the up flow zone with the upwelling of Cl rich fluids from depth. OW-705's low concentration may be attributed to the well receiving less mineralized water that has low Cl concentration. A general field wide decline in chloride has been observed in the recent monitoring periods (Figure 9) with just a few wells like OW-701, OW-712, OW-714, OW-716 and OW-719 having almost constant trends. This is due to dilution by mixing of fluids that are cooler and of lower chloride content possibly steam condensates or cooler waters that have less solute component Ruth (2014).

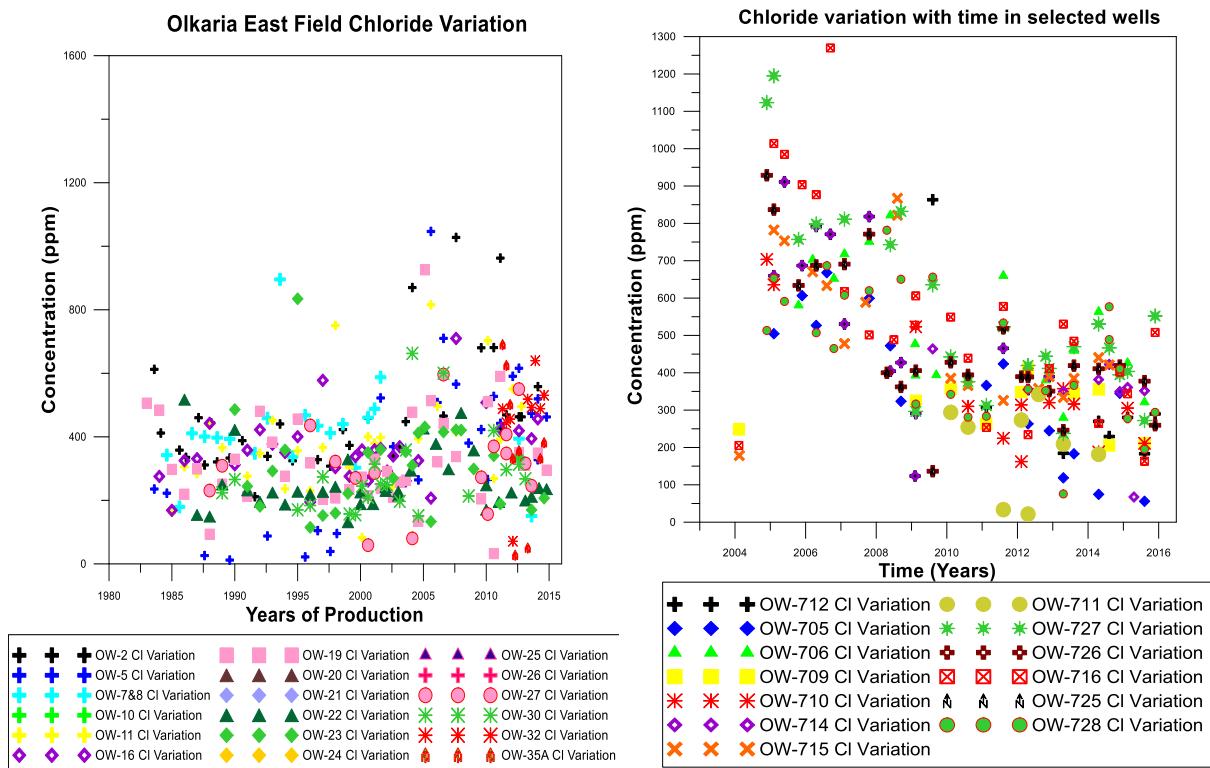


Figure 9: Olkaria East Field well Chloride concentrations observed over time (Left) and Olkaria North East Field well Chloride concentrations observed over time (Right)

5. CONCLUSION

Olkaria East part of the reservoir has been in production since 1981 and has performed quite well. Initial decline in the first ten years was due to production from the shallow reservoir and depletion of the steam zone. Deep wells that tapped into the water dominated zone are still producing. Re-injection in Olkaria East field has increased well output but resulted in initial drop in enthalpy which then recovers with stoppage of the cold injection.

Currently the total production in the KenGen's concession area is about 5600 t/hr which sustains the total installed capacity of 511 MWe, about 50% of the produced fluids are reinjected. Re-injection of all separated brine in Olkaria Northeast field has maintained enthalpy and minimized requirement for make-up wells, moderate pressure drawdown has also been observed. Olkaria Geothermal field has been developed stepwise and resource is better understood with comprehensive monitoring adopted through time. This reduces the risk of overexploitation. Overall, reinjection has been embraced and enhanced so as to supplement natural recharge and contain boiling in the reservoir. This will also enhance pressure support and restrict incursion of cooler fluid with contamination effect. In the design of reinjection schemes tracer tests, simulation and analysis is employed.

The representative pressure drawdown observed for Olkaria East field is moderate at 12 bars and Olkaria Northeast field has an observed drawdown of ~ 13 bars during the operation of the Olkaria II plant which gives an annual drawdown rate to be 1 bar/year. The rate of pressure decline for the Domes field is approximated to be ~1.2 bar/year.

The average enthalpy for Olkaria East Production Field has typically been around 2200-2300 kJ/kg whereas in the North East Production Field it has been considerably lower, between 1700 and 1800 kJ/kg, and for Domes field is 1850 kJ/kg.

The general trend indicates a rise in the Cl content from the year 2000 for Olkaria East Production Field. This coupled with a rise in the enthalpy is an indication of boiling in the aquifers in the vicinity of the wells.

There is a general field wide decline in chloride observed in the North East Production Field. This could be due to dilution by mixing of fluids that are cooler and of lower chloride content possibly steam condensates or cooler waters that have less solute component.

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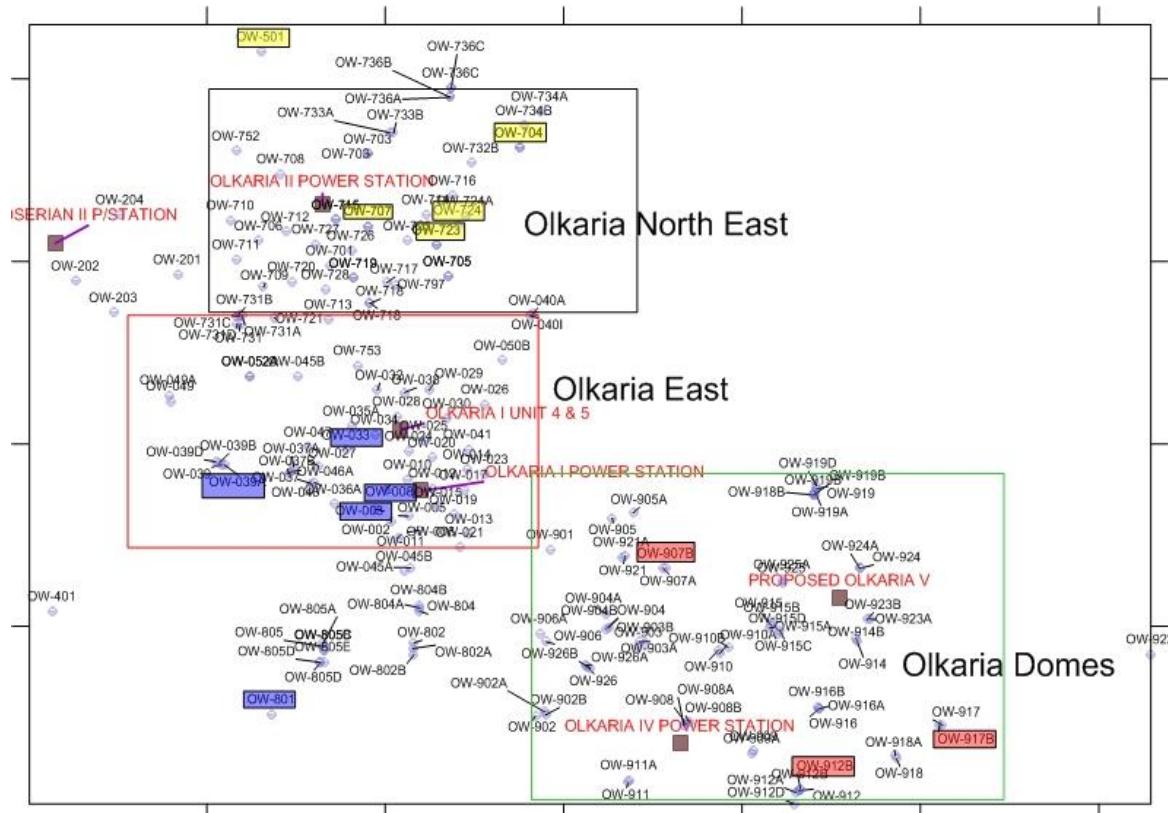
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APPENDICES



Olkaria Field development sectors; production well locations in the field serving major plants and the well heads, locations of the Injection well and pressure monitoring well (shown in colored rectangles for the various sectors).