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INTERPRETATION OF DRAWDOWN TEST DATA FROM OLKARIA DOMES GEOTHERMAL FIELD – A CASE STUDY OF OW-907B, OW-912B AND OW-917

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ABSTRACT

The greater Olkaria geothermal field, located within the rift valley province of Kenya, is probably the most explored geothermal system in Africa. It is bounded by volcanic activities and features that form a part of the geothermal manifestations in the region. The Greater Olkaria geothermal area (GOGA), under study here, covers close to 204 km^2 and the Olkaria Domes production field is a part of this area. Quite intense exploitation as well as exploration drilling has been ongoing in the Domes production field since late 2009. The field is a high-temperature geothermal field with most of its wells producing a two-phase fluid, as established during the wells production testing processes. The completion tests data i.e. temperature and pressure downhole profiles, were cross-examined and critically analysed to establish where the major aquifers/feed zones occur, considering the three observation wells under study, OW-907B, OW-912B and OW-917.This includes an in-depth analysis of their reservoir characteristics that rendered them to be used as monitoring wells in the Domes area.

The main objective of this report is to critically analyse and interpret the pressure monitoring data from the three observation wells in order to determine the extent of drawdown occurring within the Olkaria Domes production field bearing in mind the upcoming Olkaria V 140 MWe power station. The program *Lumpfit* was used in the simulation. The three-tank closed model obtained from the lumped parameter modelling was used to predict an expected pressure drawdown for three different net production scenarios of 750, 1000 and 1250 kg/s, equivalent to an electric power generation capacity of 76, 176 and 230 MWe, respectively. The study is mainly aimed at helping Kenya Electricity Generating Company (KenGen) to estimate the future trends of the entire Olkaria reservoir and, thus come up with the best and most economical resource management strategies in order to ensure a more sustainable production.

1. INTRODUCTION

1.1 General overview

In a hydrological well test, for instance for a geothermal well, the pressure response of a given well and reservoir with respect to its production or injection is monitored continuously. Similarly, a good well testing and monitoring technique is also used to evaluate the conditions of a well during and after production discharge, recovery, heat-up, as well as in its shut-in state. Well discharge tests establish the well's flow and output capacity and the reservoir properties after the well has been drilled to completion in order to prove its viability. The two most common reservoir properties obtained include the transmissivity (permeability-thickness) and the storativity (formation storage coefficient) of the reservoir. However, these parameters cannot be evaluated directly from the data as some interpretation is needed. For instance, after the collection of raw pressure monitoring data from the field, some in-depth analysis and interpretation of the raw data, resulting in average values has to be undertaken so as to ensure the accuracy of the expected results. In addition, it is also worth noting that these properties are model dependent.

1.2 Scope of the study

The Greater Olkaria geothermal area (GOGA) is one of the largest volcanic geothermal systems on the African continent. It is in the Kenyan Rift system and lies along the larger East African system. The geothermal field is located to the south of Lake Naivasha, approximately 120 km from the country's capital city of Nairobi. More than 240 wells have been drilled so far in the Olkaria field since the early 1950s when the field's exploration started. Out of these, more than 45 wells have been drilled in the Olkaria Domes field, both production, re-injection, observation wells as well as make-up wells that are currently in use. This was due to the dire need of a renewable and economical electrical energy source for the country thus resulting in more extensive drilling activities steered by the Kenyan Government. Apart from Olkaria, two other major fields inside the Kenyan rift have also been explored, i.e. Eburru and Menengai geothermal fields. Figure 1 shows their location in rift valley.

The Olkaria geothermal area is divided into seven main segments with the main reference being the existing Olkaria hill situated in the western part of the area. These are:

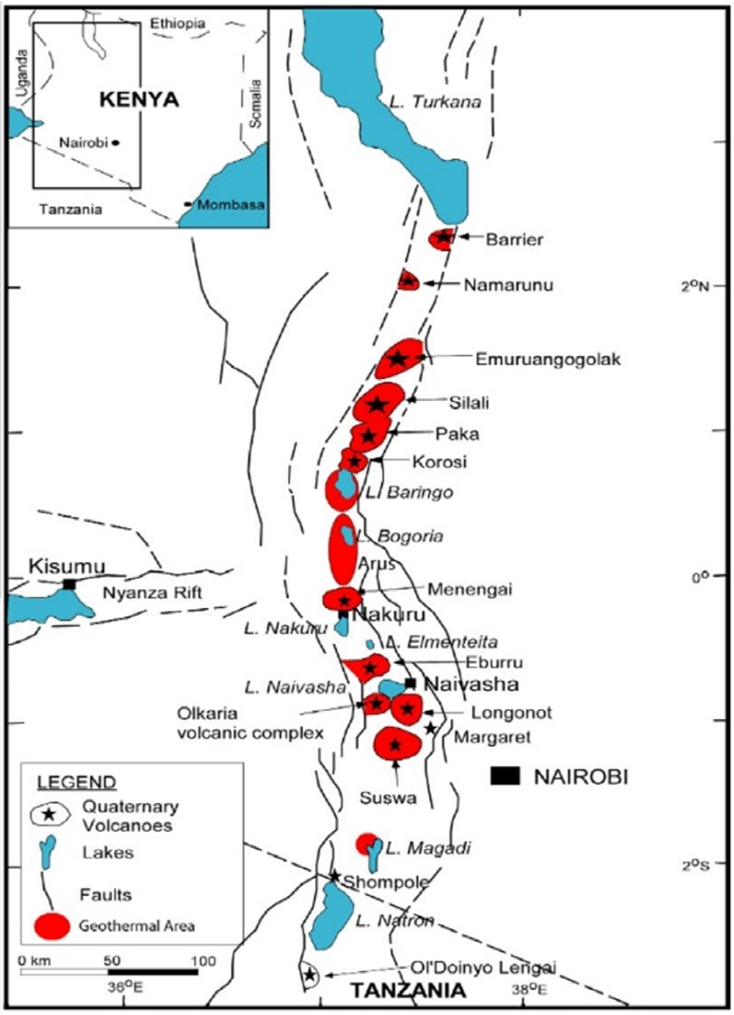

FIGURE 1: Map of the East African rift system showing the location of geothermal prospects in Kenya (Ouma, 2009)

a) Olkaria East production field (OE);
b) Olkaria Northeast production field (ONE);
c) Olkaria Southeast production field (OSE);
d) Olkaria West production field (OW);
e) Olkaria Northwest production field (ONW);
f) Olkaria Domes production field (OD); and
g) Olkaria Southeast production field (OSE).

Figure 2 below illustrates the seven segments of the Greater Olkaria geothermal area with Olkaria West covering the largest area (Opondo, 2007).

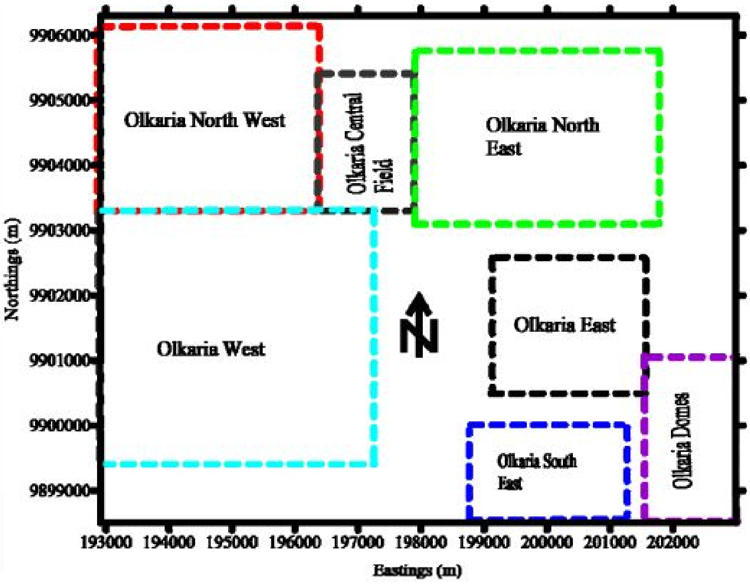

FIGURE 2: A map showing the seven segments of the Greater Olkaria geothermal area (Opondo, 2007)

The field under study is the Olkaria Domes production field (dotted with purple colour in Figure 2), which is the latest field under development within the GOGA. Olkaria's first exploration works, which began in the mid-1950s, led to exploration drilling of two wells in the Olkaria East field, namely OW-X1 and OW-X2 as shown in Figure 3 below. Unfortunately, neither of these wells were able to produce and thus they were later abandoned. In the mid-1970s, further studies were conducted in the areas targeting geothermal manifestations, particularly the geothermal hot volcanic grounds as wells as the fumarolic zones. This led to the drilling of additional six wells in the surveyed East production field for possible future generation (Ouma, 2009).

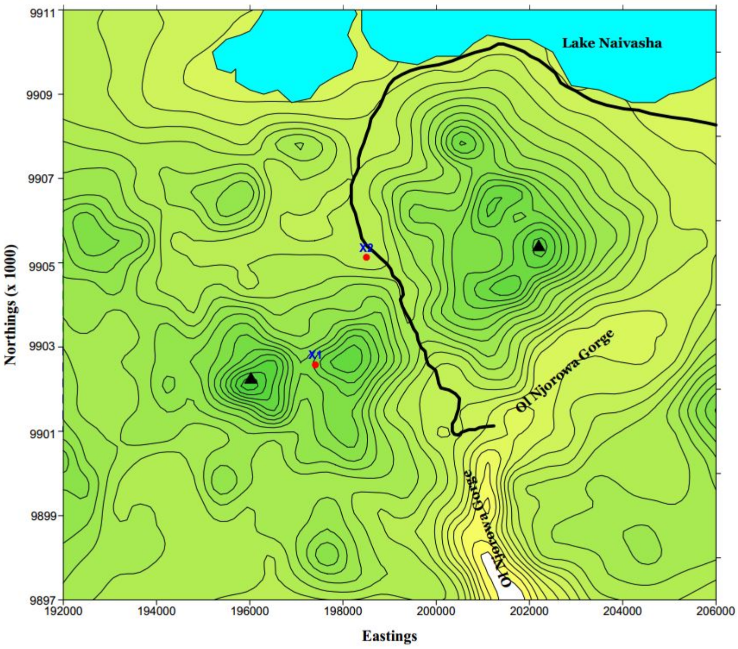

FIGURE 3: Location of the first exploration wells, OW-X1 and OW-X2 in the Olkaria East field (Ouma, 2009)

The first power plant (referred to as Olkaria I power station Unit 1) was constructed in early 1981. It had a total output generation capacity of 15 MWe harnessed from the first six wells successfully drilled in the Olkaria East field. Extensive drilling gave rise to more production wells with considerable increase in steam availability. This further led to the construction of more power plants within the area so as to ensure efficient utilization of the readily available steam. This included boosting the production in Olkaria I power station by installing two more units (Units 2 and 3), with each generating a total capacity of 15 MWe, like the first unit. By late 1985, the plant had a total output capacity of 45 MWe and it is still in operation. It is worth noting that though it is yet to undergo some refurbishment, it currently is the oldest geothermal power station in Africa having surpassed its designed lifespan efficiency of 30 years since its commissioning.

Further scientific studies together with improved drilling technology led to the availability of more steam in the entire field causing intense field development. This then influenced the construction of Olkaria II power station (a 35 MWe-unit I) which is located in the Northeast part of the production field. The power station is currently producing a total generated capacity of 105 MWe after two more units, 35 MWe each, were added to the existing system in 2010.

The Olkaria III power station, which is a binary plant, was put up soon afterwards. It is located in the Olkaria West part of the production field and is being operated by one of the Independent Power Producers (IPP) in Kenya (OR-Power IV Geothermal Corporation). It started with a 12 MWe binary plant producing from a few wells located in the western part of the production field., which was commissioned in 2009. Now ((at end of 2016), the IPP manages a total electric power generation capacity of up to 140 MWe.

Intense studies led to the realization of the geothermal resource in the Olkaria Domes production field. This happened after several research exploration works (including geophysical and geological surveys) were conducted in the area from 1993 leading to successful drilling of three more production wells, OW-901, OW-902 and OW-903, between 1998 and 1999 (Koech, 2012).

In late 2009, drilling in the Olkaria Domes field became intensive with the government acquiring five more deep drilling rigs after signing an 80 wells drilling contract with the Great Wall Drilling Company to undertake the exercise which lasted for almost six years. In late 2014, two more power plants were successfully constructed after an adequate steam gathering system was constructed. The 280 MWe power addition consisted of the 140 MWe Olkaria IV plant in the Domes segment, as well as its counterpart, the 140 MWe Olkaria IAU (I Additional Unit) located in the eastern part of the field. The Olkaria IV plant was commissioned in December 2014 whereas Olkaria IAU came online in March 2015. These two stations are currently up and running to the maximum load capacity with an all-time plant operating efficiency of approximately 96%. Currently, there are ongoing construction works for the 140 MWe Olkaria V power station, to be situated in the Northeast part of the Domes field and expected to be completed by late 2019.

In this report, pressure drawdown test data from OW-907B, OW-912B and OW-917 were critically analyzed in order to determine the extent of pressure decline that has occurred in the Domes field since its exploitation commenced. The reason is the massive mass extraction, which has taken place in the field since the Olkaria IV power plant was commissioned back in March 2015. This was a measure to counter the considerable reservoir pressure changes expected in the system, at the same time as KenGen gears up for the additional 140 MWe Olkaria V power plant. This plant, just like its counterpart Olkaria IV, is expected to withdraw close to 100% of the steam supply needed to run the plant from the already tested wells in the Domes field. Thus, this forms the main objective of the study since reservoir pressure cannot always be assumed to entirely remain constant in an actively producing field where most of its mass is extracted continuously.

2. GEOLOGICAL, GEOPHYSICAL AND GEOCHEMICAL STUDIES

2.1 Geological background

The Greater Olkaria geothermal system derives its heat from the Olkaria volcanic system. It is composed of several protruding hot lava domes and ashes, which are evidenced on the surface. It is believed that some hot magmatic heat sources might still be present at certain depths within the ring structure (Clarke et all., 1990). As indicated in Figure 4, several volcanic features, including faults and fractures do exist in the Domes and in other parts of the field as well. Some of the main volcanic features, still evident in the region include: the Ol'Njorowa gorge, Olkaria fault, Ololbutot and the Gorge farm fault. The Olkaria Domes field also has several eruptive features, which may still be active, with the main one being the Olkaria hill. The Ololbutot fault, which runs from northwest to southeast, is also believed to be responsible for providing a cold recharge to the larger part of the Olkaria system directly from Lake Naivasha.

It is thought that a NW-SE fault passing through the Ololbutot lava flow acts as a hydro-geological barrier, separating the fields close to it by forming a conduit to sustain constant pressure boundaries (Saitet, 2013). This might lead to the general assumption that some geological features do act as barriers, feeders or recharge avenues to the main reservoir for the geothermal system. Both the Ololbutot and the Gorge farm faults are also considered to be eruptive fissures. The recent volcanic eruption event associated with the Ololbutot fault produced some rhyolite flows dated close to 250 years BP (Clarke et al., 1990).

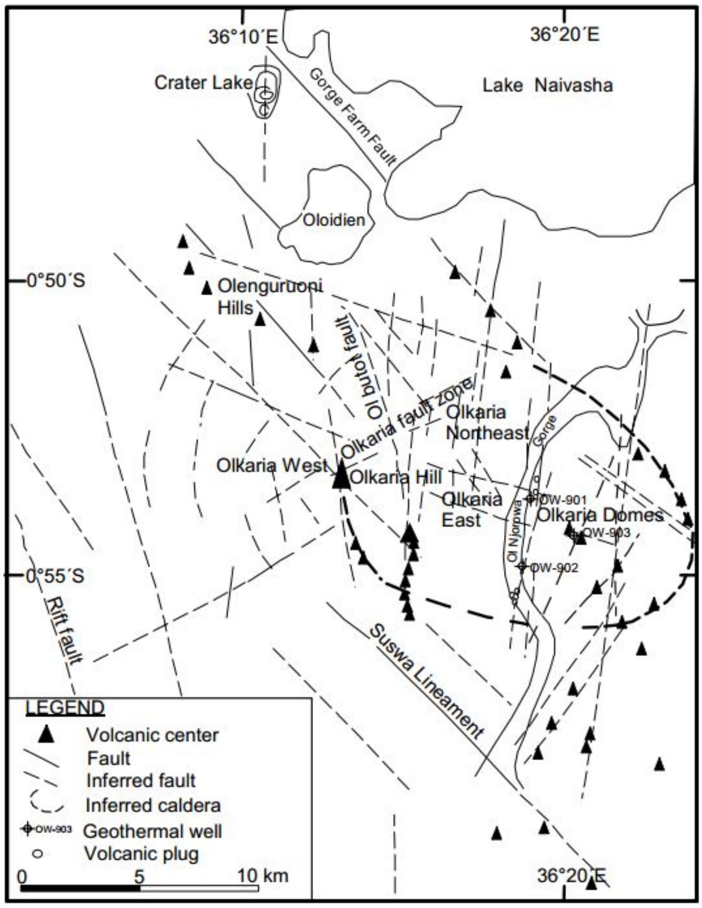

FIGURE 4: Main geological structures in the Olkaria geothermal field (Muchemi, 1999)

Apart from the faults and the fractures, several geothermal manifestations can be seen within the Olkaria geothermal field. Among the most common ones in the Domes area are steamy hot grounds, a few traces of fumaroles and some geothermal grasses, among others. All these are prevalent at the Domes field apart from fumaroles, which are not very common, possibly due to ash cover from the Longonot eruption as well as human activities in the area. The hot grounds are aligned along the complex geothermal structures beneath the earth's surface that are intersected in the process of deep drilling activity. This therefore confirms the permeability status and is as proof of the good production exhibited by wells targeting these areas. Similarly, the wells have also shown relatively high productivity and injectivity indices for production and re-injection wells, respectively. A good example of this are wells OW-923B, OW-924A, and OW-921A, which are directionally drilled wells targeting these permeable zones. Currently, OW-921A serves as the biggest producer in the GOGA with approximately 30 MWe capacity based on discharge testing. On the contrary, quite a number of wells also exhibited low permeability and thus are evidence of low production capacity within the same field. An example of these low producers are OW-927A, OW-926, and OW-922, among others.

2.2 Geophysical studies

The Olkaria geothermal area has undergone significant geophysical studies since the region was perceived to be a site of a geothermal resource. Different methods have been used to study the geophysical nature and characteristics of the Domes field, including but not limited to, resistivity methods, magnetic and electromagnetic methods, gravity methods, seismic methods and others. The most common and significant resistivity methods which have been used in the area include MT (MagnetoTelluric) and TEM (Transient Electro Magnetic) methods.

The documented studies include a joint 1D inversion of MT and TEM (Lichoro, 2009). The findings of this study revealed that the Domes field is characterized by a surface layer of relatively high resistivity (> 100 Ωm), which is associated with the presence of unaltered rocks, a second conductive layer (about 10 Ωm) associated with clay alteration of the cap rock and a deeper zone of high resistivity demarcating the geothermal reservoir. The study also correlated the resistivity structure to the alteration mineralogy and reservoir temperature from a few of the wells in Domes field, which were found to be in fair agreement.

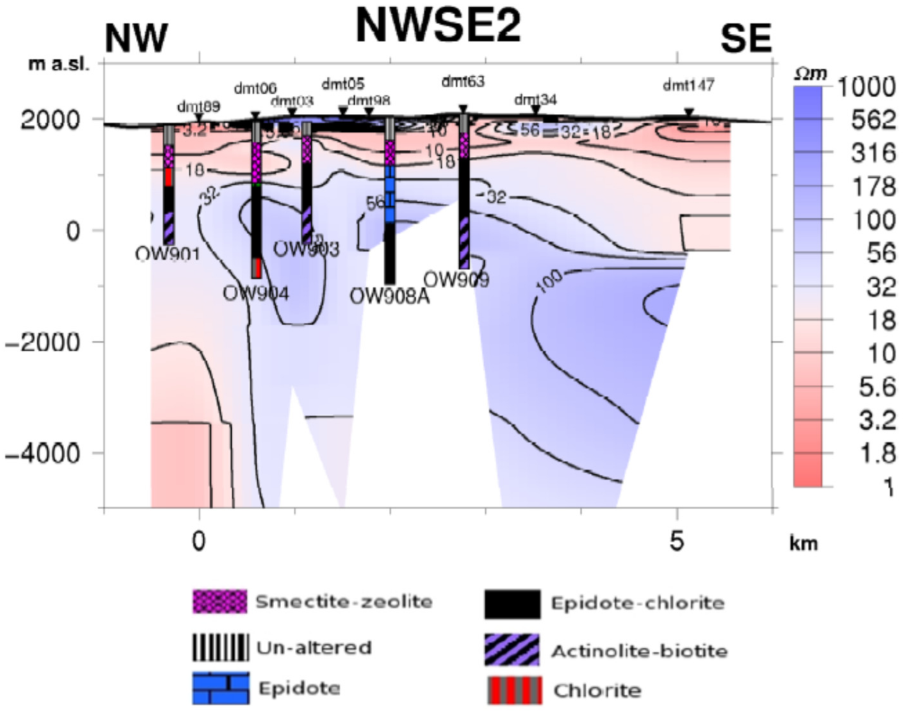

FIGURE 5: A cross-section of the resistivity structure in the Olkaria Domes field and correlated alteration mineralogy from a few of the wells (Lichoro, 2009)

Figure 5 represents an illustration of a cross-section showing the resistivity structure in the Olkaria Domes field and correlated alteration mineralogy from a few of the wells within the same field (Lichoro, 2009).

The field is marked by the presence of dykes and intrusions, which are more common in the central region of the Domes field. The occurrence of these dykes and intrusions in the region may explain some facts about the probability of finding a heat source in the area.

2.3 Geochemistry studies

The studies conducted by Giggenbach (1991) indicated that the Olkaria Domes reservoir is mostly composed of bicarbonate waters, which correspond to peripheral waters (Giggenbach, 1991). Similarly, the gas geothermometry in this area indicated relatively high temperatures between 250 and 300°C. This tends to coincide closely with the formation temperatures obtained in the Domes wells after being drilled to completion.

Figure 6 presents a ternary diagram illustrating the initial classification of the reservoir fluids produced from the GOGA. The area is also considered to have a low volume of calcium concentration associated with relatively low pH values. This then confirms the reason why there have been minimal cases of calcite scaling in the Domes field (Malimo, 2009). The same applies to silica scaling because the fluid separation is done at considerably high temperatures, in order to prevent its occurrence in the wellbore.

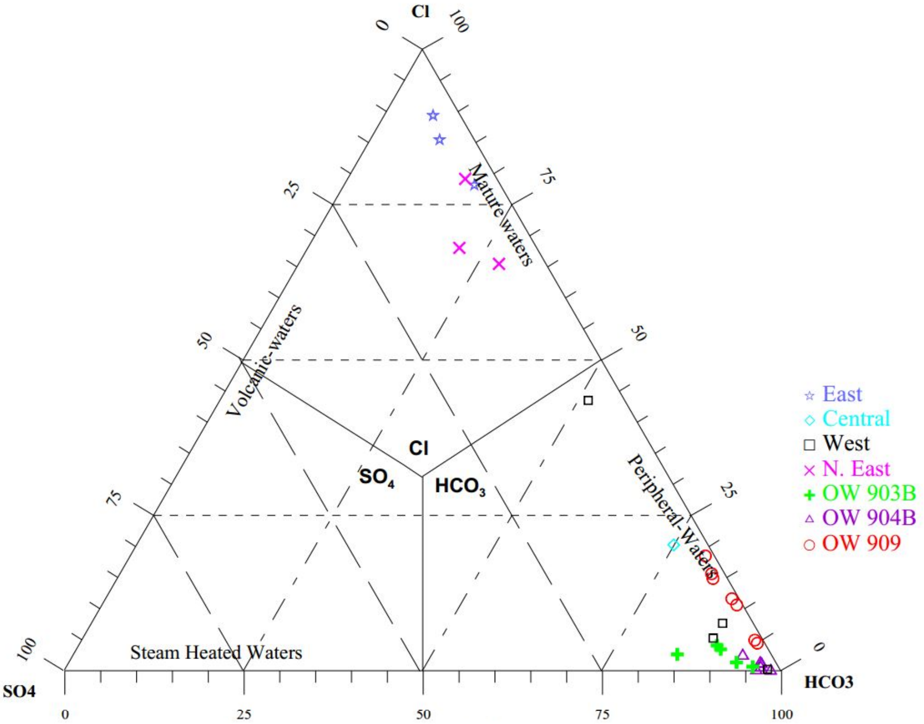

FIGURE 6: Ternary diagram indicating the types of fluids encountered in the Olkaria Domes geothermal field (Malimo, 2009)

3. OLKARIA DOMES RESERVOIR CHARACTERISTICS

3.1 Interpretation of completion tests, temperature and pressure profiles

3.1.1 OW-907B

This well was drilled to completion on December 4th, 2012 to a total depth of 3000 m with a maximum clear depth of 2993 m. It had a measured downhole temperature and pressure of 186°C and 222 bars, respectively. A presumed cold inflow zone was cased off at 1211 m with the mechanical logging tool stationed at a depth of 2600 m during the completion tests logging. After conducting several days of recovery heat up profiles, the well was assembled for a production discharge testing where the fluid enthalpy, well head pressures (WHP) as well as its power output equivalent was determined. This is necessary as it helps in determining physical downhole conditions as well as reservoir characteristics required for the modelling. Major feed zones were located at 900 and 1800 m depths while minor feed zones were evident at 2750 m and between 1200 and 1600 m depths. Figure 7 shows the well's completion test temperature-pressure profiles conducted immediately after drilling.

During the entire discharge and well monitoring test process which took place between April and May 2013, the well was established to have been discharging on low well head pressures (WHP) below the optimum 5 bars recommended as operating pressures. The WHP at the time ranged between 2.2 and 4.0 bars during a horizontal discharge test. The discharge enthalpy ranged between 780 and 1593 kJ/kg thus it could generally be considered to be producing from a medium-enthalpy reservoir. Its total mass flow rates fluctuated between 29 and 115 kg/s using the Russell James' lip pressure pipe method. Unfortunately, the well collapsed four weeks later while discharging through a 3" lip pressure pipe. This led to it being converted to a monitoring well for the Olkaria Domes field.

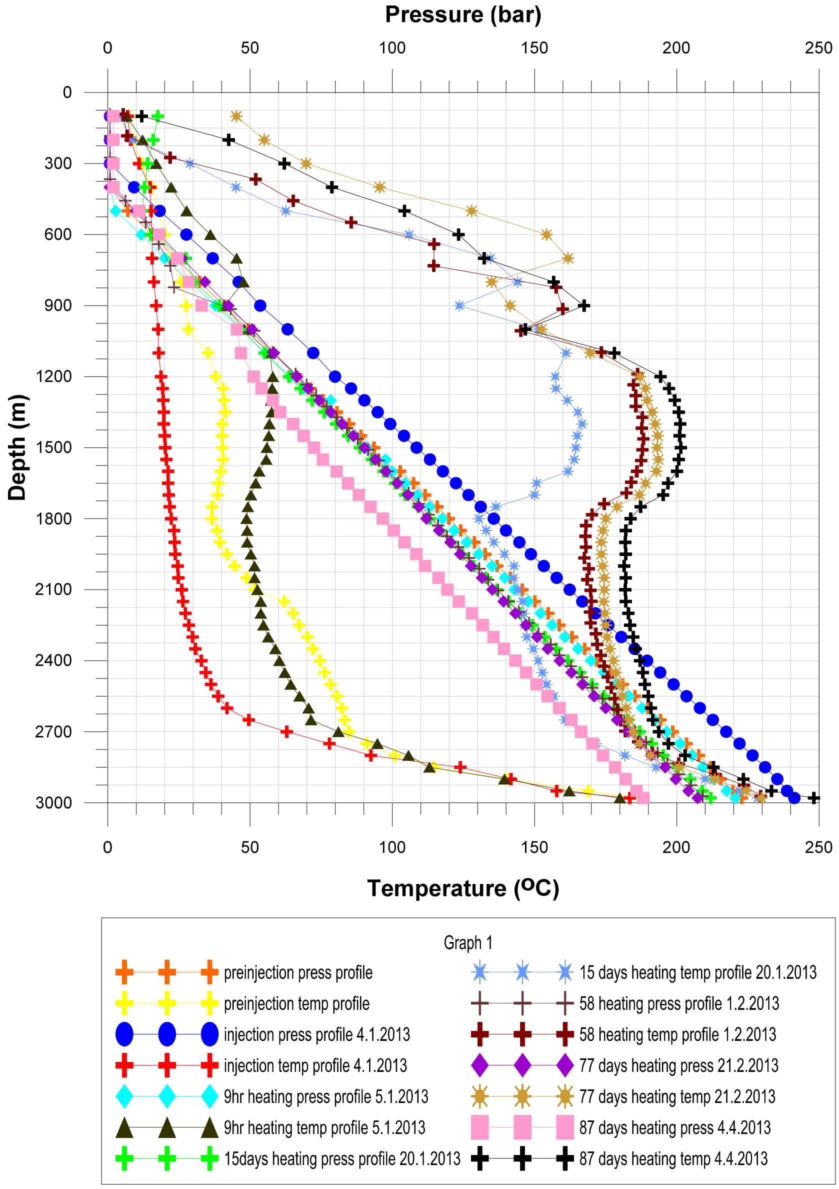

FIGURE 7: OW-907B, temperature and pressure profiles from the well's completion test on December 6th, 2013

3.1.2 OW-912B

This well was drilled to completion on February 7th, 2010 to a total depth of 3000 m. It had a measured downhole temperature ranging between 280 and 300°C at the time of completion, with the highest temperature recorded being 310°C. Its measured downhole pressure at the time was 240 bars. The 9⅝” casing shoe was conducted at 857 m depth. Temperature and pressure measurements during the warm-up period logging indicated a Water table at around 313 m depth. Results from the production test confirmed the well was a poor producer with very low injectivity and transmissivity values, i.e. 47 lpm/bar and 1.248×10^{-9} m^3/Pa s, respectively. Its storativity was also confirmed to be 2.27×10^{-4} m/Pa. During the discharge test process, major feed zones were also observed between 2200 and 2300 m while minor ones were observed at 1000, 1500, 2200 m and between 1300 and 1375 m depths. Figure 8 gives a clear indication of this as measured during the wells completion test.

In summary, the low injectivity value indicated that the well is a poor producer with the low transmissivity also indicating that the well´s permeability is quite poor. Similarly, the low storativity value indicated that the well is presumably dry.

3.1.3 OW-917

OW-917 was drilled to completion on December 6th, 2012, to a total depth of 3000 m and a completion test followed immediately. Its highest measured downhole temperature during the test period was 200°C with a corresponding reservoir pressure of 233 bars. The 9⅝” casing shoe depth was set at 910 m. Major feed zones were located in between 1000 and 1200 m as well as between 1250 and 1500 m depth. Unfortunately, this well was too tight to be able to initiate and sustain discharge even after several attempts of air compressions and was thus converted to a monitoring well to aid in pressure monitoring in the Domes field as well (see Figure 9).

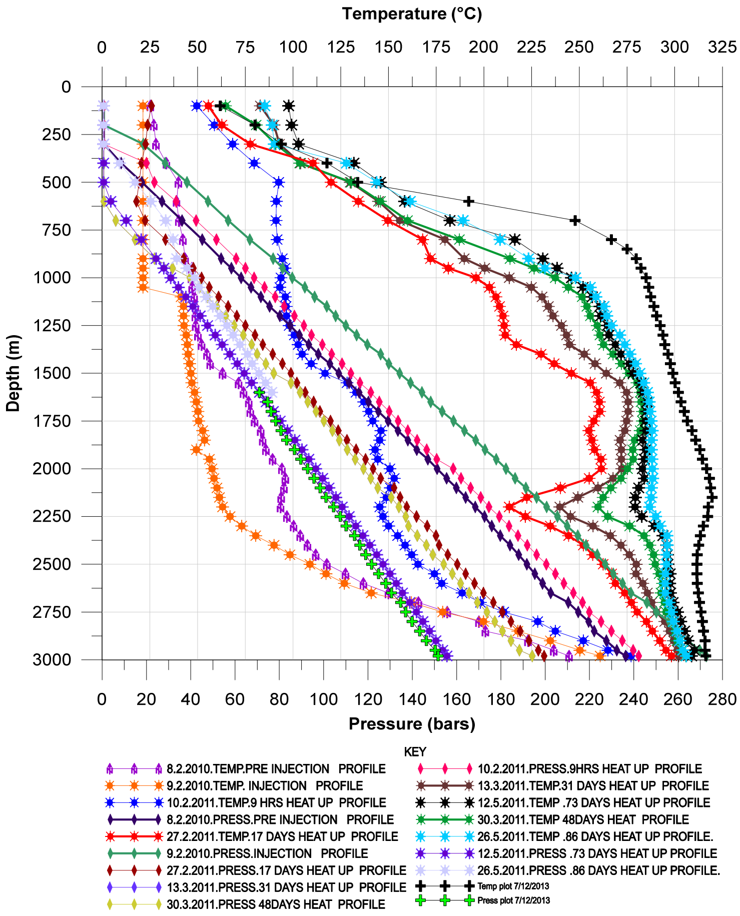

FIGURE 8: OW-912B, temperature and pressure profiles from the well's completion test on February 10th, 2010

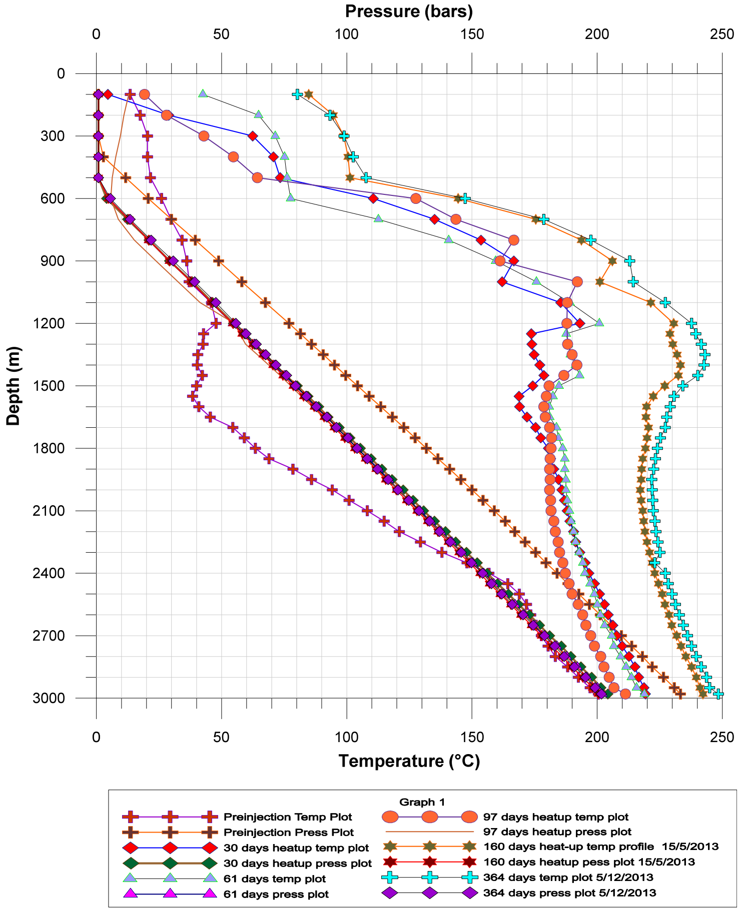

FIGURE 9: OW-917, temperature and pressure profiles from the well's completion test on December 6th, 2012

4. LUMPED PARAMETER MODELLING

4.1 General overview

There are several modelling techniques and approaches applied in resource evaluation and assessment. These include simple analytical models, reservoir assessment methods, lumped parameter models and detailed numerical models. Generally, a good approach to a comprehensive and reliable geothermal reservoir evaluation or modelling system involves several formidable aspects as shown in the chart diagram in Figure 10. If any one of these aspects are overlooked then the results from the model might not prove or disprove the question under review. Thus, a good model developed to be capable of simulating some or all available data from a geothermal system is essential.

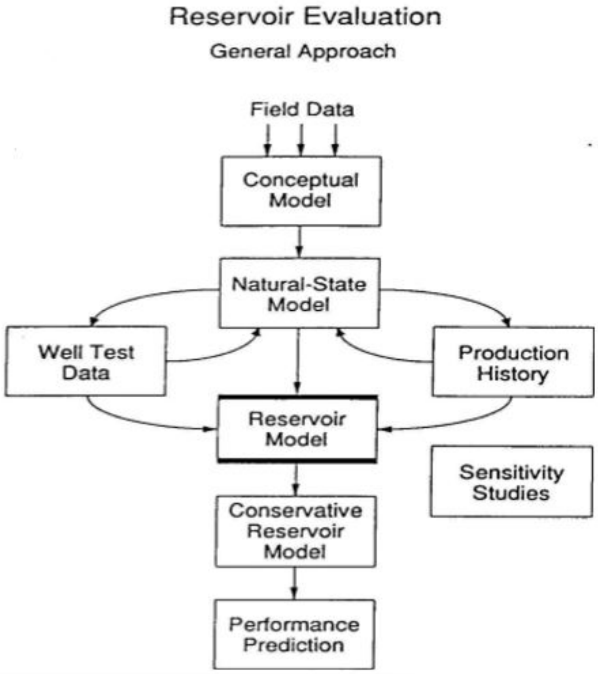

FIGURE 10: A general approach to a successful reservoir evaluation based on modelling principles (Egilson et al., 2012)

Such a model will go a long way in providing information on the reservoir conditions as well as reservoir properties of both formation and fluid. Consequently, an appropriate model is used for the following three main purposes (Axelsson et al., 2005).

i) Future prediction calculations;
ii) Production potential estimation and relevant field/resource assessment;
iii) Management purposes associated with efficient field monitoring practices.

Thus, the basis of a good model relies heavily on a comprehensive and accurate data collection during exploration superseded by a careful monitoring during long term production. In this regard, the Olkaria Domes geothermal field has been under exploitation since late 1998 and thus extensive data has been collected on the production and pressure monitoring history. Some of the basic monitoring aspects being measured in the Domes field include.

a) Reservoir temperature through well logs;
b) Reservoir pressure (response in observation wells);
c) Well-head pressure/water-level at production wells;
d) Mass-discharge history of production wells;
e) Fluid temperature or enthalpy of the produced fluid;
f) Chemical content of fluid.

Among the four basic modelling approaches stated above, a simple analytical lumped parameter modelling was adopted in aid of the interpretation of pressure drawdown in Olkaria Domes geothermal field. This is because, among other advantages, it requires less data, complex geometry is ignored so it is easier to analyse, and finally its responses are integrated into lumped values given by analytical functions. Besides that, the lumped parameter modelling approach discussed in this report focuses mostly on the pressure response of the system in terms of its production.

These models generally use either one, two or more blocks to represent the entire geothermal system. The first block represents the main reservoir or the productive area and the others act as recharge blocks/systems. The governing equations for these models can often be reduced to ordinary differential equations that can be solved semi-analytically (Axelsson et al., 2005). Lumped parameter models are generally calibrated against the pressure history and average production from the field. After a historical match is obtained, the model is used to predict the future water level or pressure decline with the present production rate. The main disadvantages of the lumped parameters are that they do not consider fluid flow within the reservoir and neglect spatial variations in thermodynamic conditions and reservoir properties. Similarly, they cannot consider questions of well spacing or injection well locations (Bödvarsson and Witherspoon, 1989).

4.2 Theoretical basis

The main reason for lumped parameter modelling is to help in the estimation of the production potential of a geothermal system by using observed pressure predictions as well as its effects under different prediction scenarios. This then illustrates the fact that the most important parameter during the monitoring of the geothermal reservoir is pressure. The main reason for this is that it will clearly show any relevant flow changes that might have occurred in a dormant or active field that is undergoing production or exploitation (Molina Martinez, 2009).

During this research, three monitoring wells from Olkaria Domes field were selected for analysis with respect to their measured pressure declines. These three wells were OW-907B, OW-912B and OW-917, highlighted in blue in Figure 11. As observed from the map, the three observation wells are all located closer to the margins of the ring structure which is presumed to be a colder region according to several temperature profiles carried out in wells around this area. The map also shows the location of the

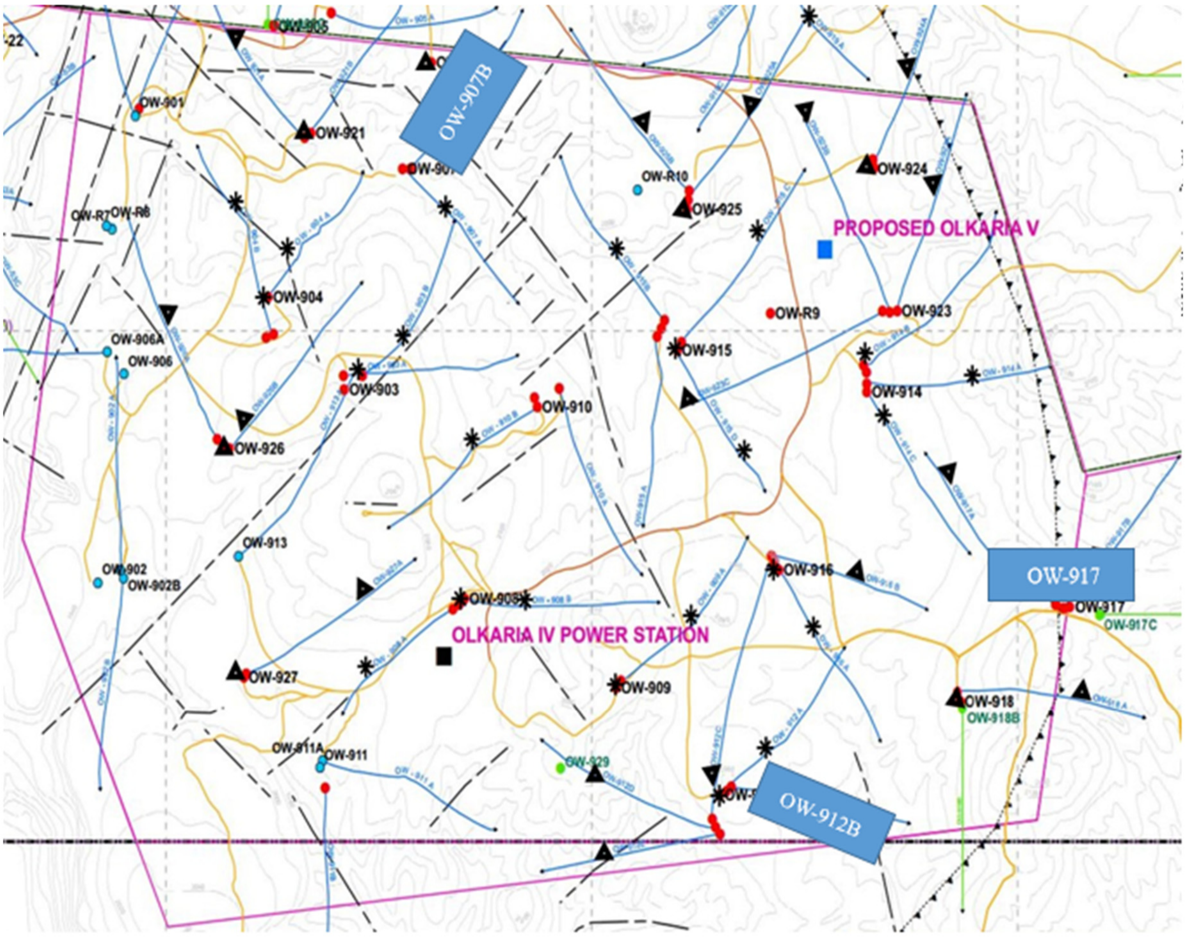

FIGURE 11: Olkaria Domes map showing the locations of the three observation wells under study, OW-907B, OW-912B and OW-917 (highlighted blue), connected wells (star symbols) and non-connected wells (black triangles)

connected (star symbol) and non-connected wells (black triangle) in the Olkaria Domes field. All the 29 currently producing wells were used as good producers as they are part of the wells being exploited in this field.

Worth to note is that, in an unexploited reservoir, the vertical pressure gradient is fairly close to that of a static column of water/steam at the reservoir temperature unlike its horizontal pressures, which under normal circumstances are very small (Grant et al., 1982). However, once such a field is exploited, the pressure patterns tend to change considerably over time, and it is this change in pressure that is being investigated in this report.

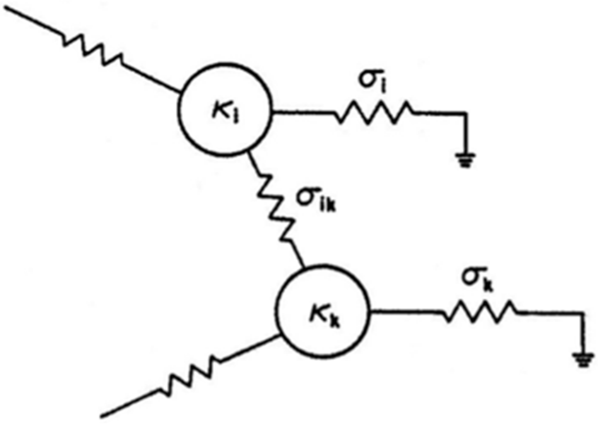

FIGURE 12: A simplified sketch of a two-tank lumped parameter model (Axelsson, 1989)

The selection of the three observation wells was made on the basis that, a.o., they are the most predominantly used monitoring wells in the Domes field. In order to simulate and clearly interpret and predict the pressure response of the Olkaria Domes geothermal system, a simple lumped parameter model with three tanks was used. Figures 12 and 13 below show a simplified two- and three-block lumped model used with its respective two main properties defined by Figure 13. Here:

k_1 - indicates the central part of the reservoir;
k_2 - refers to outer parts of the reservoir; and
k_3 - illustrates the outer as well as deeper parts of the entire reservoir (Axelsson, 1989).

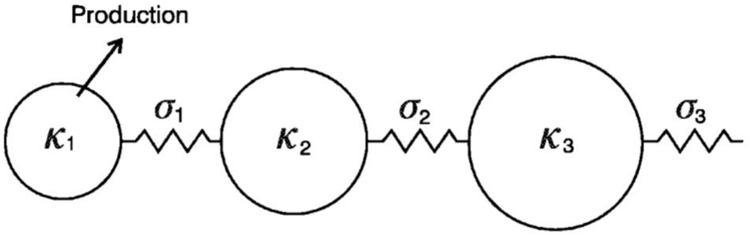

FIGURE 13: A simplified block of a three-tank lumped parameter model (Axelsson, 1989)

In this report, a three-tank closed model was used for the analysis as well as the final interpretation of the drawdown extent in the area under study. The simulation was done using single-tank, two-tank and three-tank models before the best fit was considered for final interpretation. The models are mainly composed of a tank and a conductance. The open models, for instance, are connected by a resistor to an infinitely large imaginary reservoir, which maintains a constant pressure. For the case of the one-tank lumped parameter model, two equations can be used for calculating the reservoir properties of the system. In the calculations, it mainly considers the application of one tank which acts as a capacitor and a resistor which acts as a conductance to majorly simulate the flow resistance (permeability) in the system. The same principle was applied in the case of two tanks and three tanks, both open and closed models. Figure 14a gives illustrations of a tank and conductance in a one-tank lumped parameter model system.

The two main reservoir parameters associated with the properties are the storage and the conductance coefficients which can be calculated using Equations 1 and 2 as follows;

$$\kappa = \frac{m}{p} \tag{1}$$

$$\sigma = \frac{q}{\Delta p} \tag{2}$$

where κ = Total storage coefficient;

m = Mass increase within the system;
p = Pressure increase;
σ = Conductance;
q = Mass flow rate;
Δp = Differential pressure.

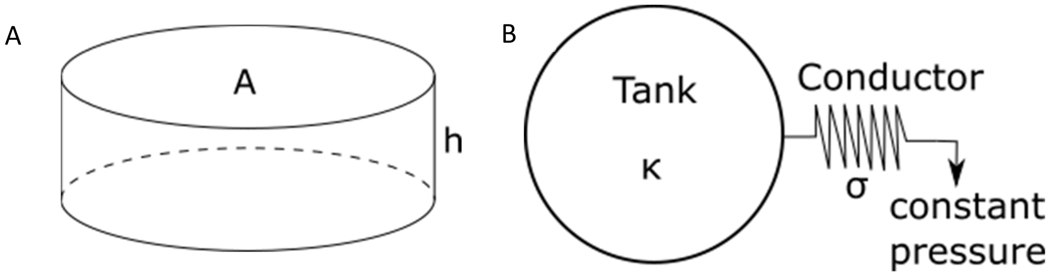

FIGURE 14: a) A one-tank model sketch; b) An illustration of a one-tank lumped parameter model

Similarly, a detailed general equation for obtaining conductivity between the tanks in the case of a 1-D flow (as illustrated in Figure 14b) in a one-tank closed model can be calculated using Equation 3 as follows:

$$\sigma = \frac{k\,A}{vL} \tag{3}$$

where L = Length of the resistor;
A = Cross-sectional area of the resistor;
k = Permeability;
v = Kinematic viscosity of the applied fluid.

Using this method, the observed pressure data from the three unexploited wells were used to simulate the pressure response inside the Olkaria Domes geothermal field, with the input for the model considered to be the production history from the 29 producing wells and the injection history from the 9 reinjection wells. After obtaining the best possible fit against the monitored pressure data, a calibration of the model from the corresponding simulations was done. Thereafter it was used to establish the prediction for future production scenarios. In an optimistic open model, the reservoir pressure is expected to reduce with production until it reaches a steady state. Similarly, a good fit should also establish future predictions in different scenarios, which are supposed to lie between the open and closed system. Figure 15 represents an illustrative sketch of the modelled outcome as expected from open and closed systems in a normal geothermal reservoir.

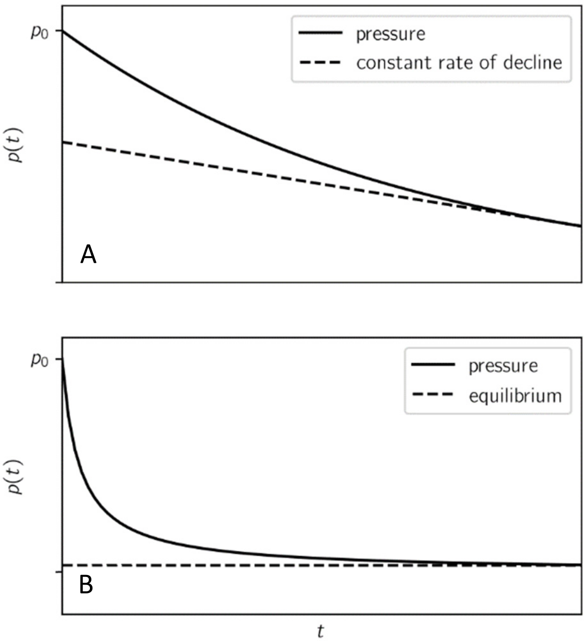

FIGURE 15: a) Open lumped model;
b): Closed lumped model (Axelsson, 1989)
p_o = Initial pressure; p (t) = Pressure at constant time, t; t = Time period

The definition of an open system is a geothermal system where there is no or limited pressure change with respect to the production time once it reaches a steady state. This type of system is considered to be optimistic since there is an equilibrium between the production and the systems recharge over the production time. Indeed, after a longer period of time, this may most likely lead to a stabilization in its pressure drawdown. On the contrary, a closed system refers to a geothermal system where there exists a constant rate of decline over time. This system is more pessimistic as there is no recharge to the system and thus a steady decline is observed in the water level as well as in the measured reservoir pressures.

4.3 Methodology

4.3.1 Observed pressure histories in OW-907B, OW-912B and OW-917

As was mentioned earlier on, the static pressure logs from the observation wells (OW-907B, OW-912B and OW-917) were obtained by using a remote data logger system installed at the wellheads of each of the three monitoring wells. The pressure logs were recorded continuously over a given monitoring period at one hour intervals. The pressure monitoring equipment in use was located at approximately 1800 m depth for OW-907B (that being an estimate of major feed zone) as determined from the recovery heat-up profiles. Similarly, for OW-912B, the pressure measurements were obtained from its biggest feed zone located at 2200 m. In the case of OW-917, its measured pressure values were recorded at a depth of 1150 m estimated to be the biggest feeder zone of the well. This was then averaged to get more accurate results for future predictions.

TABLE 1: The 29 currently producing wells at Olkaria Domes geothermal field

Power station's name	Well no.
WHG-905	OW-905A
WHG-914	OW-914
	OW-914A
	OW-914B
	OW-914C
WHG-915	OW-915C
	OW-915D
WHG-919	OW-919A
Olkaria IV power station	OW-903A (SD-1)
	OW-903B
	OW-904
	OW-904A
	OW-904B
	OW-908 (SD-2a)
	OW-908A
	OW-908B
	OW-910
	OW-910A (SD-2b)
	OW-910B
	OW-909 (SD-2c)
	OW-909A
	OW-915 (SD-3a)
	OW-915A
	OW-912 (SD-3b)
	OW-912A
	OW-916A
	OW-915B (SD-3c)
	OW-916
	OW-907A (SD-4)

4.3.2 Production and injection history data

A total of 38 drilled production and reinjection wells at the Olkaria Domes field form the main steam gathering system for the Olkaria IV 140 MWe power station as well as for the four existing wellhead power stations in the field as illustrated in Table 1. The total production data was obtained by summing up the individual production from the 29 producing wells at the Domes field. The same was done with the reinjection wells in order to get the total reinjection rate in the Domes field. There is a total of nine reinjection wells in the Domes field, with seven of them being used for hot brine reinjection while two are used for cold reinjection as shown in Table 2.

TABLE 2: The nine reinjection wells at Olkaria Domes geothermal field

Reinjection type	Well no.
Hot reinjection wells	OW-901
	OW-902
	OW-906
	OW-906A
	OW-911
	OW-911A
	OW-913
Cold reinjection wells	OW-902
	OW-902B

Unfortunately, the reinjection at OW-906 was stopped in mid-2016 after a tracer test confirmed a breakthrough in some of the wells including nearby OW-926, OW-926A and OW-927. Despite this, its data was still incorporated in the analysis of the total reinjection rate considering the fact that it had been in operation since production commenced in the field prior to its stoppage. Figure 16 shows the total mass extracted from the Domes reservoir as well as the corresponding net mass production obtained after subtracting the reinjection rate from the total mass produced. This indicates that more than 25% of what is extracted from the Olkaria Domes production field is injected back to the reservoir, both as hot and cold re-injection, and thus helps in balancing and maintaining the system´s reservoir pressures.

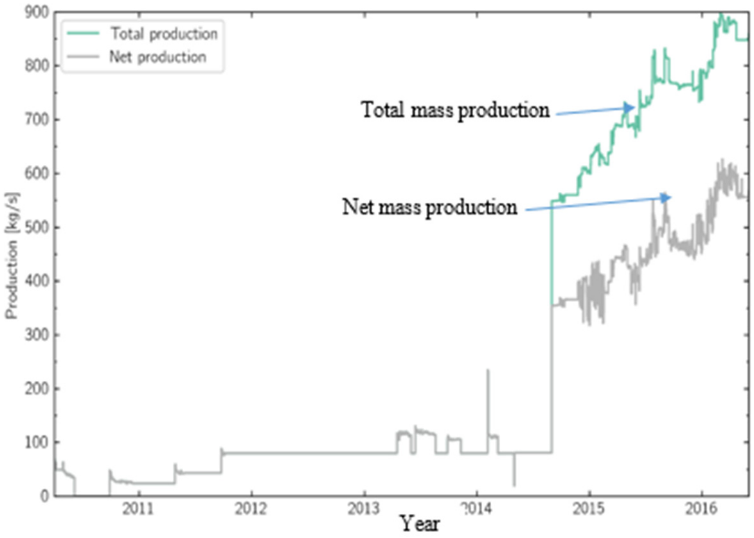

FIGURE 16: A comparison between the Olkaria Domes total mass production to its effective net production after reinjection

4.3.3 General LUMPFIT simulation methodology

The pressure drawdown from the three observation wells occurring as a result of discharge by other nearby wells tapping from the same reservoir was measured and reservoir estimates obtained thereafter. This was achieved by critically analysing both the pressure drawdown as well as the production history data from the Olkaria Domes geothermal field from 2010 to 2016. The rate of production used in the establishment of the production history was calculated from the summation of all the individual flow rates from all the 29 producing wells in the area under study. The time interval (for the observation wells) was determined from the time series data available, which had been collected from the field. The average production rate from mid-2010 to mid-2016 was also calculated by summing up the individual totals of the measured flow rates with relation to production time. Thereafter, the wells' data files containing the area name, units of time, pressure and total production were created before being converted into text files and simulated using a *Lumpfit* program. Individual predictions were later made over a 10-year long prediction period with expected increase in production representing the upcoming 140 MWe Olkaria V power station that is currently under construction.

In this report, a general method as described by Axelsson et al. (2005) was applied in the lumped parameter modelling as well as its findings, interpretations and discussions. Several procedural steps involved in finding a good specific model fit were also put into perspective with equations detailing the means of finding the reservoir parameters using calculation methods using the stated formulas. The systemic procedures involved first finding the best fit in one-tank closed and open systems, then in two-tank closed and open systems and finally a best fit was found by simulating the models using three-tank closed and open systems. After estimates of the values for total storage coefficients, κ and conductance coefficients σ, were obtained using the *Lumpfit* program, other major reservoir properties were then determined by way of calculation. These parameters include the permeability of the reservoir, volume of the reservoir and the storativity. The volume is estimated from the parameter κ which in turn depends on one of two storage mechanisms for liquid-dominated systems, which is either controlled by the liquid/formation compressibility described by Equation 4 or by the mobility of the free surface described by Equation 5.

The volume of the reservoir for 2-D flows can be calculated using Equation 4 below:

$$\kappa_1 = V_1 \rho C_t \ , \ \kappa_2 = V_2 \rho C_t \ \text{ and } \ \kappa_3 = V_3 \rho C_t \qquad (4)$$

where ρ = The liquid density (kg/m^3);
V = The reservoir volume (m^3);
C_t = The total compressibility of the liquid-saturated formation (Pa^{-1});
κ = The storage coefficient.

$$\kappa = \frac{A\varphi}{g} \tag{5}$$

where A = Surface area (km^2).

a) For a confined liquid-dominated reservoir, its storativity is given by Equation 6 as follows:

$$s = \rho_w\{\varphi c_w + (1 - \varphi)c_r\} \tag{6}$$

where s = Storativity (kg/m^3/Pa);
p_w = Liquid density (kg/m^3);
c_r = Rock compressibility (Pa^{-1});
c_w = Water compressibility (Pa^{-1});
g = Acceleration of gravity (m/s^2);
φ = Formation porosity.

In the same case, the equation for the total compressibility for the liquid-saturated formation is stated by Equation 7 below:

$$C_t = \varphi C_w + (1 - \varphi)C_r \tag{7}$$

where c_t = Total compressibility.

Equation 8 gives the permeability, k (which is model dependent), and can be estimated with the parameter σ for the storage mechanism as it largely depends on the geometry as well as reservoir structures within the system:

$$k = \sigma_1 ln \frac{\left(\frac{r_2}{r_1}\right)}{2\pi h} v \tag{8}$$

where k = Permeability (m^2);
v = Kinematic viscosity of the fluid (m^2/s);
h = Thickness of the reservoir (m);
r = Radius of the tanks (m).

b) For an unconfined liquid dominated reservoir, the storage mechanism is given by:

$$s = \frac{\varphi}{gh} \tag{9}$$

where g = Acceleration due to gravity (m/s^2);
h = Reservoir thickness (m).

c) For a dry steam type of reservoir, its storage mechanism is obtained by:

$$s = \rho_s \frac{\varphi}{p} \tag{10}$$

where ρ_s = Steam density.

d) For a two-phase type of reservoir, i.e. a reservoir producing both liquid and steam phases:

$$s = \rho_t \left[\frac{\langle\rho_\beta\rangle T}{(H_s - H_w)x^2}\right] \frac{(\rho_\omega - \rho_s)x^2}{\rho_\omega \rho_s} \tag{11}$$

Generally, lumped parameter models do observe the equations of conservation of mass and its extracted mass flow between the systems. This law is described by Equations 12 and 13 as follows:

For the law of conservation of mass:

$$\kappa_i \frac{\partial \rho_i}{\partial_t} = \sum_{i=1}^{N} q_{ik} - \sigma\,(\rho_i - \rho_o) - Q_i \tag{12}$$

Equation 13 below gives the basic equation for calculating the mass flow between the tanks:

$$q_{ik} = \sigma_{ik}\,(\rho_k - \rho_o) \tag{13}$$

where N = The number of tanks used.

In summary, the general solutions for the lumped parameter models are mainly of two types. The first one represents an open system for N number of tanks while the second (which was applied in this study) represents a closed system for a similar number of tanks in question. Equations 14 and 15 below describe this, respectively:

Open N-tank model:

$$\rho(t_i) = \rho(t_o) - \sum_{j=1}^{N} Q(t_i)\frac{A_j}{L_j}\,\langle 1 - e^{-L_j t_i}\rangle \tag{14}$$

Closed N-tank model:

$$\rho(t_i) = \rho(t_o) - \sum_{j=1}^{N-1} Q(t_i)\frac{A_j}{L_j}\,[1 - e^{-L_j t}] - QBt \tag{15}$$

The coefficients A_j, L_j and B refer to the complex functions of the storage coefficients (model parameters) of the tanks κ_j and the conductance coefficients of resistors σ_j, for $j = 1, 2, 3 \ldots N$.

These parameters can be estimated by the *Lumpfit* program embedded in the full ICEBOX program package. It mainly helps in the modelling by interpreting the simulation program as an inverse problem by fitting the analytical response functions of the lumped models to the observed data by using a non-linear iterative approach in estimating its modelled reservoir parameters (Axelsson, 1989).

5. PRESSURE MODEL RESULTS

5.1 OW-907B three-tanks closed model fit

After correctly matching the production and the pressure data with the time when the measurements were collected, the final data was converted to a text file and run through the *Lumpfit* program. The best fit was obtained with a three-tank closed model and pressure drawdown determined thereafter using the best model fit obtained. Thus, using this model, the Olkaria Domes field was deduced to have undergone a 0.8 bar drawdown for a period of six years from 2010 to mid-2016 (see Figure 17). However, going by the limited data set used, which was ranging from mid-2014 to mid-2016, the field is seen to have had a considerable pressure drawdown of approximately 0.65 bars as shown in Figure 17.

5.2 OW-912B three-tanks closed model fit

The pressure model from OW-912B indicated a considerable drawdown of approximately 1.3 bars from June 2010 to June 2016. However, the available measured data from mid-2014 to mid-2016 indicated a pressure drawdown of approximately 1.0 bars over the two-year long production period as illustrated in Figure 18.

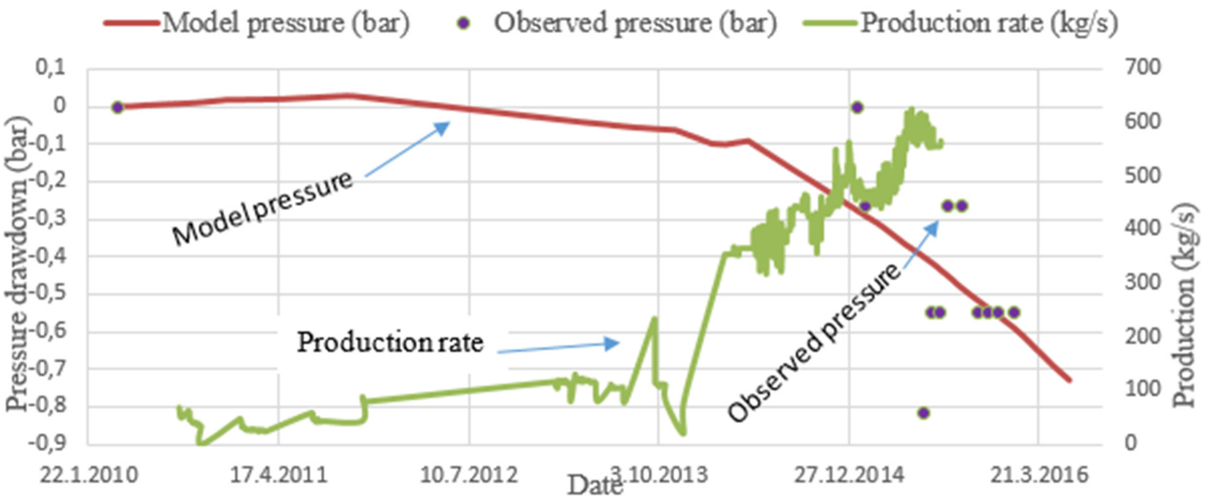

FIGURE 17: Pressure drawdown in Olkaria Domes field as estimated in OW-907B using a three-tank closed model fit

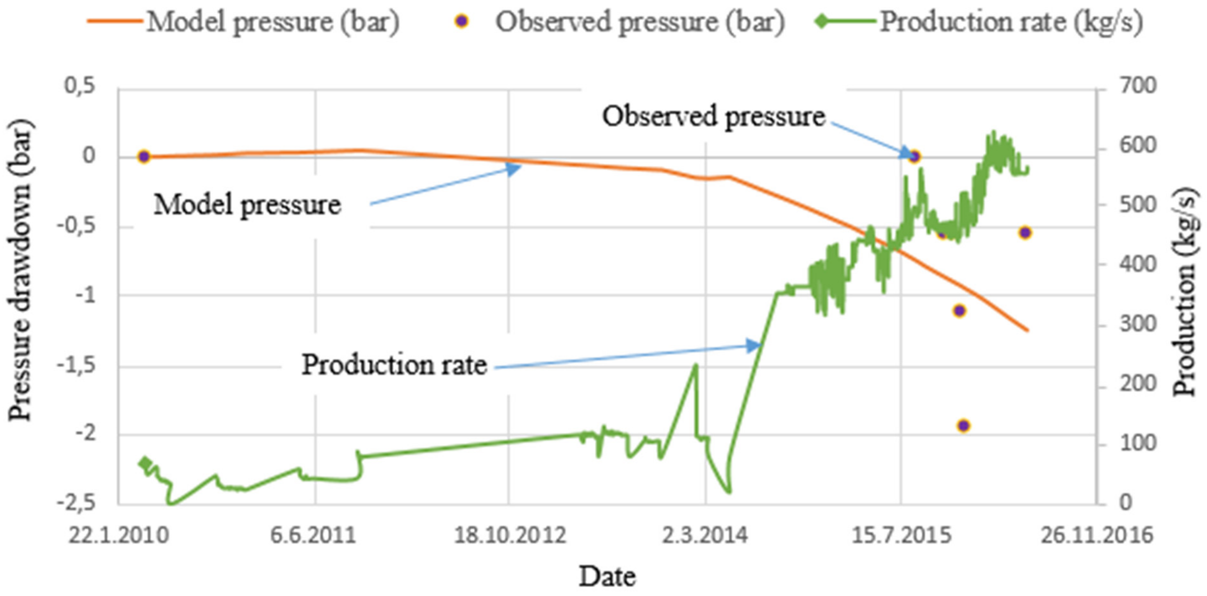

FIGURE 18: Pressure drawdown in Olkaria Domes field as estimated in OW-912B using a three-tank closed model fit

5.3 OW-917 three-tanks closed model fit

The results of the pressure model for well OW-917 were not used in the final interpretation as they were quite unique in nature. This was evident from the measured pressure values, which indicated an increase in pressure with a corresponding increase in production rate, which is considered to be unusual in an actively producing geothermal reservoir. This is because, as for a normal geothermal system, the reservoir pressures is expected to decline with a steady increase in its production. Thus, the model could not be created using this data. Furthermore, the model generated could not be able to demonstrate the sharp visible changes expected in the drawdown parameters occurring as a result of a production increase as had been anticipated.

5.4 The model parameters and tank properties

As has been previously stated in the theoretical overview of this report, a *Lumpfit* model is associated with the establishment of some model parameters (or reservoir properties) that can describe the system. Indeed, these parameters are normally model dependent as they are determined mostly by the type of model outcome obtained. Thus, the two most common ways of which storage mechanisms in a reservoir can affect the liquid-dominated geothermal systems are: for confined aquifers, the storage mechanism can be affected by liquid and formation compressibility (rocks compressibility and water compressibility) as was defined by Equation 4. Otherwise, if the aquifers are unconfined, then their storage mechanism is only controlled by the mobility of the free surface of the reservoir (refer to Equation 5). In this case, the Olkaria Domes reservoir was confirmed to be unconfined. This was ascertained by calculating the reservoir volumes for both confined and unconfined systems in both wells. OW-907B revealed an estimate of the storativity value of 5.1×10^{-5} kg/m^{3}Pa with OW-912B having a much smaller value of 5.1×10^{-7} kg/m^{3}Pa. This lower storativity value in an unconfined reservoir depicts the scenario that indeed wells OW-907B and OW-912B are presumably dry.

TABLE 3: Reservoir properties for the Domes field using a three-tank closed model

Reservoir properties	Value
Temperature	250°C
Pressure	39.8 bar-a
Density	798.9 kg/m^3
Porosity	10%
Kinematic viscosity	1.3×10^{-7} m^2/s
Fluid compressibility	1.5×10^{-9} 1/Pa
Rock compressibility	2×10^{-11} 1/Pa
Total compressibility	1.6×10^{-10} 1/Pa
Unconfined storativity	5.1×10^{-5} kg/m^{3}Pa
Confined storativity	1.3×10^{-7} kg/m^{3}Pa

TABLE 4: *Lumpfit* model parameters for the Olkaria Domes geothermal field

Model type	**Closed**
Number of tanks	**Three**
Parameters	**Value**
A_1	9.4×10^{-7}
L_1	2.6×10^{-8}
k_1 (kg/Pa)	291243.7
A_2	5.7×10^{-7}
L_2	2.6×10^{-8}
k_2 (kg/Pa)	228699.9
B	1.9×10^{-6}
σ_1 (kg/s/Pa)	3.3×10^{-3}
σ_2 (kg/s/Pa)	4.5×10^{-8}
K_3 (kg/s/Pa)	1.76
Root Mean Square error (Pa)	1.7×10^{4}

Similarly, the reservoir formation temperature in the Domes field was estimated to be 250°C as obtained from the completion test temperature profile loggings. The porosity of the rock considered was assumed to be 10% as it is the most optimistic value used in the *Lumpfit* program for the simulation. Other reservoir properties estimates, including the liquid density, kinematic viscosity, compressibility of the rock and water as well as the total compressibility, are as shown in Table 3.

TABLE 5: *Lumpfit* model unconfined tank properties from OW-907B for a two-tank closed model

Model type	**Open**
Number of tanks	**Two**
Properties	**Value**
A_1 (km^2)	28.6
V_1 (km^3)	5.7
k_1 (mD)	921.0
A_2 (km^2)	22.5
V_2 (km^3)	4.5
k_2 (mD)	2.0×10^{-3}

Consequently, further estimates of the *Lumpfit* parameters and properties as obtained from the model fits after calibration are as tabulated in Tables 4 and 5, respectively.

The values in Table 6 and 7 below represent the estimated reservoir properties obtained from the two-tank open and closed models for well OW-907B, for both confined and unconfined tanks.

TABLE 6: Unconfined tank properties from the OW-907B model fit

Properties	Two-tanks closed model	Two-tanks open model
A_1 (km^2)	28.6	25.4
V_1 (km^3)	5.7	5.1
k_1 (mD)	921.0	1369.3
A_2 (km^2)	22.5	76.3
V_2 (km^3)	4.5	15.3
k_2 (mD)	2.0×10^{-3}	891.4

TABLE 7: Confined tank properties from the OW-907B model fit

Properties	Two-tanks closed model	Two-tanks open model
A_1 (km^2)	1.2×10^4	1.0×10^4
V_1 (km^3)	2.3×10^3	2.0×10^3
k_1 (mD)	2.1×10^2	4.1×10^2
A_2 (km^2)	9.3×10^2	3.4×10^5
V_2 (km^3)	1.9×10^3	3.5×10^2
k_2 (mD)		1.8×10^7

5.5 Model predictions

For accurate reservoir assessment, both in terms of pressure drawdown and future production response, a prediction is necessary in order to foresee and counter the adverse effects of over-exploitation. This was done and the calibrated model was used to predict the drawdown over the next 10 years, both at current production rates and at a constant increase in production. In normal circumstances, a good lumped parameter model should be able to make accurate future predictions with regard to its pressure drawdown caused by continuous production in the system. Bearing this in mind, the prediction for the future behaviour of the Olkaria Domes geothermal reservoir was then estimated based on its past production history in the field from 2010 to mid-2016. After several simulations to obtain the best fits for both closed and open models, a three-tank closed model (for both OW-912B and OW-907B) was considered for future model predictions as well as for the interpretation of the Olkaria Domes geothermal field drawdown status. The drawdown was estimated to be 0.8 bar from mid-2010 to mid-2016 (Figure 19). The predictions were based on the following scenarios:

1) Constant net production at 566 kg/s (obtained by subtracting the total injection rate from the current total production rate in the Olkaria Domes geothermal field);
2) Net production rate at 750 kg/s;
3) Net production rate at 1000 kg/s;
4) Net production rate at 1250 kg/s.

A prediction for OW-917 was not plotted for reasons given later in the discussion section.

5.5.1 First case using OW-907B three-tank model

Figure 19 shows the prediction outcomes as calibrated by the OW-907B model fit. From the figure, it is evident that the well is withdrawing from an open system since the pressure drawdown seems to converge at an equilibrium. This then gives an indication that the projected increase in production will have no big impact on the system's reservoir pressure as the drawdown is expected to stabilize over a period of continuous production. For instance, an increase in production from the current 566 kg/s to the anticipated 1000 kg/s needed in order to run the upcoming Olkaria V power station, seems to have

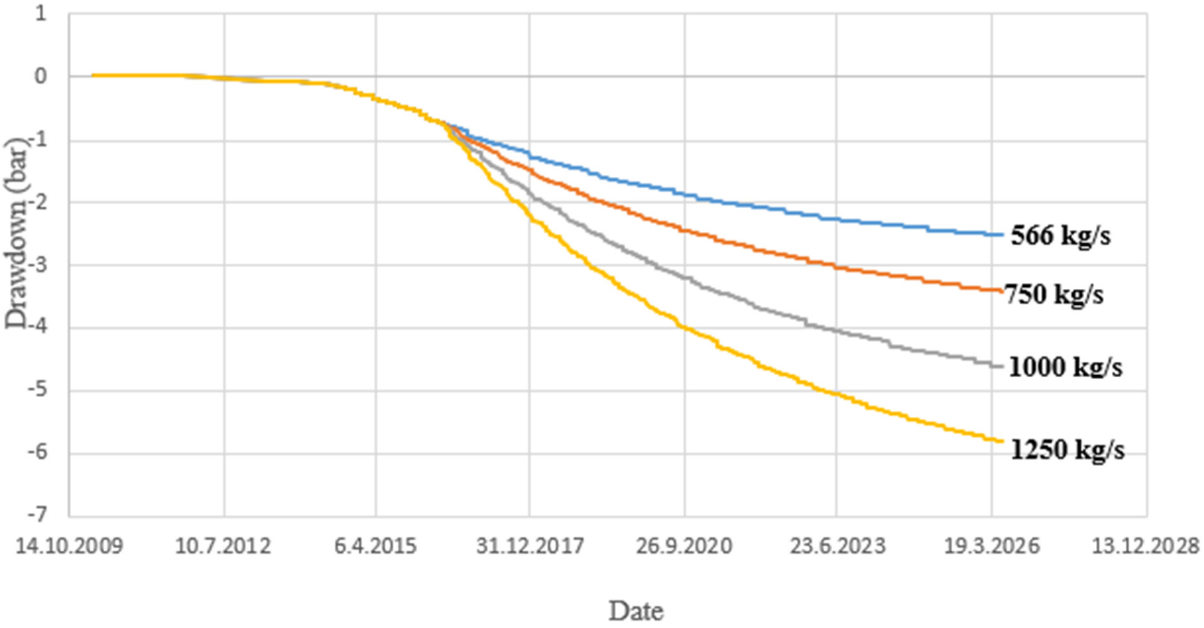

FIGURE 19: OW-907B model predictions for four different production scenarios as envisaged for the Olkaria Domes geothermal field

an escalated drawdown of 3.5 bar over 10 years. This seems to be the most optimistic scenario for the available data used for the Olkaria Domes geothermal field for the predicted 10 years production period.

5.5.2 Second case using OW-912B three-tank model

Figure 20 shows the prediction outcomes as calibrated by the OW-912B model fit. The figure indicates that the well is withdrawing from a closed system as the pressure drawdown seems to increase steadily with time. This gives an indication that the projected increase in the field's production capacity will have a large impact on the system's reservoir pressure as the drawdown is not expected to stabilize anytime soon. For instance, an increase in production from the current 566 kg/s to the anticipated 1000 kg/s needed to run Olkaria V power station increases the drawdown from 6 to 13 bar over 10 years, which is more than double.

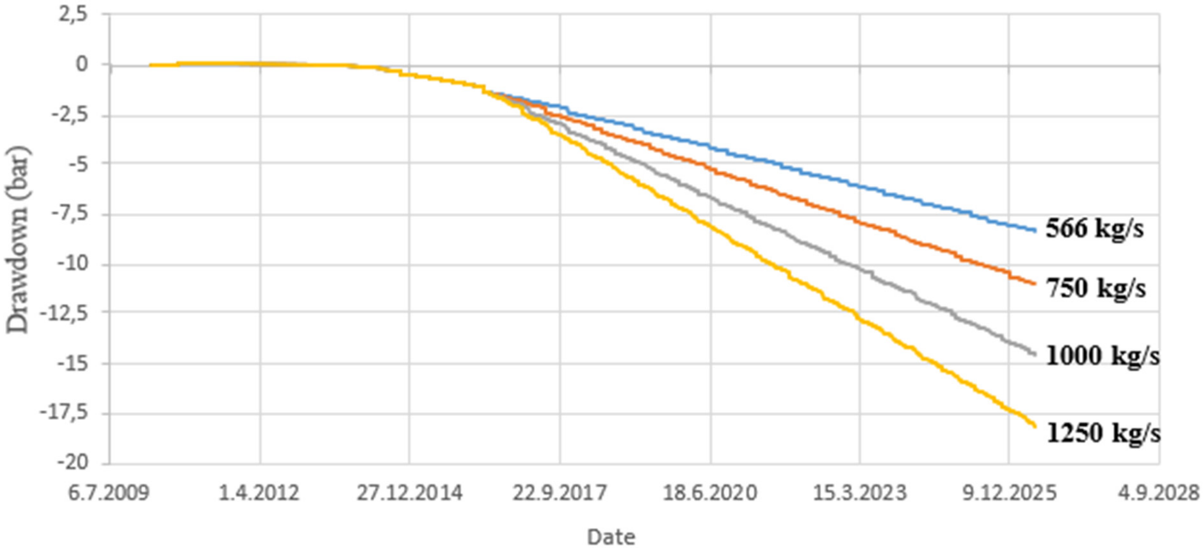

FIGURE 20: OW-912B model predictions for four different production scenarios as envisaged in the Olkaria Domes geothermal field

In general, considering the case of an optimistic scenario 3 (production at 1000 kg/s rate), the model indicates a possible drawdown of 13 bars for a 10-year production period. This might seem to be quite difficult to achieve and sustain as the reservoir stands to be depleted if no action is undertaken to counter or reduce the drawdown effects.

It is worth to note that in both cases described by Figures 19 and 20, a normal estimate of the predictions was based on production scenario 3, which was with reference to the upcoming Olkaria V 140 MWe power station. The plant, together with the current production for Olkaria IV (566 kg/s) is estimated to need to extract an average net mass production of 1000 kg/s. The third prediction scenario arose in result of the need for an increase of an estimated 400 kg/s, at least, to the current 566 kg/s production rate. Scenario 2 with 750 kg/s mass production was considered the most optimistic one, whereas scenario 4, which predicted a mass production of up to 1250 kg/s, was considered a pessimistic scenario for the future.

6. DISCUSSION OF THE RESULTS

As estimated by the two models, the Olkaria Domes geothermal field indicates a systematic drawdown trend ranging between 0.75 and 1.3 bars over a production period of six years. This decline is however considered relatively low due to the fact that the field's exploitation began close to the end of 2014 when Olkaria IV was commissioned, i.e. with barely three years of production time so far. However, with the anticipated doubled production rate from Olkaria V, a large decline is expected unless good strategies are upheld (See Figure 20).

The drawdown model from OW-917 was not used in making the final conclusive findings since it did not produce a good fit that could give realistic results. This is presumably due to the fact that the observed available pressure data were too limited to permit an accurate model fit after its calibration.

Going by the results obtained from the calibrated models, it can then be deduced that an increase in the cumulative production rate in the Olkaria Domes geothermal field will certainly lead to an increase in the pressure drawdown rate. This then brings up the urgency to have re-injection strategies within the field, in order to ensure a balance with regards to the systems reservoir pressures once Olkaria V will be up and running.

The test also gave a drawdown curve that matches the solution for a homogeneous aquifer, but unfortunately, it could not tell whether the reservoir where the fluids are tapped from are laterally bounded or not. However, it was able to show some details about the Olkaria Domes reservoir structure such as its heterogeneous nature (as depicted by different physical properties and values obtained by the model) and deduce a common possibility that the permeable regions are tapping from within or along these structures.

The use of a net mass production concept in this study has also proved beneficial, as it has helped in evaluating a clear benefit of re-injecting spent fluids back into the reservoir. Thus, it is encouraged that for Olkaria V to produce sustainably, and with minimal or no drawdown effects, then re-injection and interference tests together with chemical tracer flow tests have to be conducted to enhance the results based on the reservoirs sustainability and potential.

The test is also confirmed that the Olkaria Domes wells are producing from an unconfined reservoir. This was evidenced by the fact that the storage mechanism of the three wells under study was confirmed to be mainly controlled by the mobility of the free surface as opposed to fluid compressibility as described by Equation 5, which was used in the determination of their storativity values. The decline in pressure may also lead to a corresponding decline in water levels thus causing a reduction in its reservoir pressures.

Considering the three-tank model (in Figure 19), it can also be observed that from the scenario of a 750 kg/s production rate, the pressure drawdown has reduced to 3.5 bars over a 10 year production period. However, with the scenario of an increased rate of 1000 kg/s, the same pressure drop of 3.5 bars is seen to have come into effect after a 5-year period. This then confirms that the two different production scenarios might prove to be difficult to achieve and sustain over a long production time period based on the power plant life time of operation.

Table 8 gives the results for the predicted calculated pressure drawdown values for the four different prediction scenarios obtained from the two models for the Olkaria Domes geothermal field.

TABLE 8: Calculated pressure decline results (in bar) for the four different production scenarios based on the OW-907B and OW-912B model predictions in Figure 19

Model type & rate / **Time (Years)**	**3-TO 566 kg/s**	**3-TC 566 kg/s**	**3-TO 750 kg/s**	**3-TC 750 kg/s**	**3-TO 1000 kg/s**	**3-TC 1000 kg/s**	**3-TO 1250 kg/s**	**3-TC 1250 kg/s**
2016	1.0	2.0	1.0	2.0	1.0	2.0	1.0	2.0
2021	2.0	5.0	2.5	6.0	3.5	7.6	4.2	9.5
2026	2.5	8.0	3.5	11.0	4.6	14.5	5.8	18.1

In general, the measured pressure decline data in the Domes field indicated a substantial drop in reservoir pressures. For instance, in the case of OW-907B, the measured pressure data indicated a considerable decline in pressure values since intensive exploitation commenced in 2014. The same applies to the case of OW-912B. However, despite the witnessed pressure decline in these two observation wells, the rate was confirmed to be slower than had been expected since the field is currently being exploited extensively. This slower decline rate may most likely be inferred to have occurred as a result of good re-injection strategies which are currently being practiced within the Domes field. However, there was an unrealistic scenario in the case of OW-917 where its measured pressure values tended to increase instead of decrease with time. This was seen as strange although it might have been attributed to a shut-in of the production wells during the annual maintenance shut-down that may have lasted for three weeks or more depending on the power plant´s equipment and machines operating condition.

6.1 Monitoring of the Olkaria Domes geothermal field

A good monitoring system is vital in order to achieve quality data, which enhances a good model for optimistic predictions. Since exploitation in the GOGA commenced in the early eighties, the field has been undergoing an intensive production and pressure monitoring within all the geothermal wells as well as gathering all the necessary data required for proper modelling. Table 9 shows a proposed Olkaria

TABLE 9: Proposed production and pressure monitoring program for wells in the Olkaria Domes geothermal field

Domes production wells	**WHP measurements (bar)**	**Flow rate (kg/s)**	**Temperature/ pressure logging**	**Name of observation well**	**Pressure in observation wells (bar)**
All production wells	1 per week	2 per year	1 per year	OW-907B	1 per day
	1 per week	2 per year	1 per year	OW-912B	1 per day
	1 per week	2 per year	1 per year	OW-917	1 per day
All re-injection wells	2 per month	2 per year	1 per year		1 per day

Domes field monitoring program recommended for adoption in order to ensure an efficient and consistent data gathering process for better modelling and interpretation. The table incorporates the monitoring of both observation, production and re-injection wells with wells scheduled to be used after Olkaria V began its power generation.

7. CONCLUSIONS AND RECOMMENDATIONS

The drawdown test results as well as methods used has led to the following main conclusive remarks:

- From the calibrated models discussed, it is evident that from mid-2010 to mid-2016, the Olkaria Domes geothermal field has undergone a pressure drawdown of between 0.75 and 1.3 bar. However, considering the monitoring period under review (between mid-2014 to mid- 2016), both models indicated a drawdown between 0.3 and 0.6 bar per year.

- Similarly, the predicted increase in production (from 566 to 1000 kg/s) needed for the upcoming Olkaria V power plant is expected to cause a considerable drawdown effect since the field seems to have an escalating reservoir pressure decline with increased cumulative production. This is evidenced in both models in the predictions cases shown in Figures 19 and 20.

- The more than nine re-injection wells already drilled in the Domes field have played a key role of supporting and maintaining the system's reservoir pressure by acting as a recharge to the fields productive reservoir.

- During the research, it was noted that the test served as a partial predictor of the reservoir performance under exploitation, based on the different prediction scenarios obtained from the calibrated models.

- It is also evident that the lack of consistent measured pressure data compromised the end results of the models especially for OW-917, as well as data inconsistency in the other two monitoring wells under study.

For a more successful future analysis of this test, the following aspects are recommended to be to be put into practice, as through that, a more credible and accurate model will be obtained, essential for good predictions as well as resource management:

- Strict adherence to the field's monitoring management program.

- Adequate calibration of all pressure and production equipment prior to field installations to guarantee accurate data with no or minimized doubts of integrity.

- It is advisable to convert one unproductive well in the central part of the Olkaria Domes field to a monitoring well to be able to confirm the extent of the reservoir cooling as depicted by the pressure drawdown results.

- To update the drawdown test findings by using the appropriate methods to build a numerical model for the Olkaria Domes geothermal field for more conclusive results.

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