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RESERVOIR ENGINEERING AND GEOTHERMAL POWER PRODUCTION IN OLKARIA

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ABSTRACT

Several geothermal prospect areas have been identified in Kenya and are mainly located within the Kenyan Rift System. Olkaria prospect was the first to be explored and developed as Olkaria geothermal field, which is about 80 km^2. Reservoir engineering methods are used during the resource exploration, development and exploitation. These include heat loss surveys, down-hole well logging, well flow tests, interference tests, tracer test, reservoir modelling and management. Olkaria reservoir produces two-phase mixture of steam and water in general proportion of about 70% to 30% respectively. Two types of power generation plants operate in Olkaria namely, the Ormat binary plants and the Mitsubishi geothermal condensing steam plants. A total of four power plants have been installed, two owned by KenGen and one each owned by Ormat International and Oserian Development Company Ltd. The total installed power generation capacity of the four plants is 130 MW$_e$. Thus geothermal power installation in Olkaria constitutes about 12% of the national power installation in Kenya and the plants operate as base load. Geothermal energy in Olkaria has mainly been utilized for electrical power production. Direct use has received little attention though recently Oserian Development Company Ltd leased a well from KenGen for direct use in horticultural farming. There are wells in Olkaria with extreme cyclic discharge characteristics and hence cannot operate with the other wells supplying steam to the power plants. Such wells, in the past, have either been turned to reinjection wells or simply rendered useless. Yet they are capable of supplying a lot of geothermal power for direct use. KenGen is looking at the possibility of economically selling geothermal energy from such wells to direct users either for recreational purposes or space heating.

1. INTRODUCTION

Several geothermal prospect areas have been identified in Kenya that are mainly located within the Kenyan Rift system. The Olkaria prospect was the first to be explored and developed and later became known as the Olkaria geothermal field, located 125 km North West of Nairobi (Figures 1 and 2). After extensive geo-scientific surveys, and exploration drilling in the early seventies, exploration drilling started in 1974 and continued through 1977. Following evaluation of the initial drilling results, a feasibility report was produced in 1977. The following year, 1978, production drilling commenced and continued until 1983. Sufficient resource capacity was confirmed for installation of the first power plant of 45 MW$_e$ at Olkaria between 1981 and 1985.

Further exploration continued in Olkaria and additional resource capacity was confirmed and the field size was estimated to be about 80 km^2. It was therefore found prudent to segment Olkaria geothermal field into seven sectors for ease of development. The sectors are namely, Olkaria East, Olkaria North

East, Olkaria Central, Olkaria South West, Olkaria North West, Olkaria South East and Olkaria Domes (Figure 2). Additional power plants have been installed in Olkaria recently. These include a binary plant at Olkaria South West (Olkaria III) in 2000, with a capacity of 12 MW_e, a condensing plant at Olkaria North East (Olkaria II) in 2003, with a capacity of 70 MW_e and another binary plant at Olkaria North West (Oserian) in 2004, with a capacity of 2 MW_e.

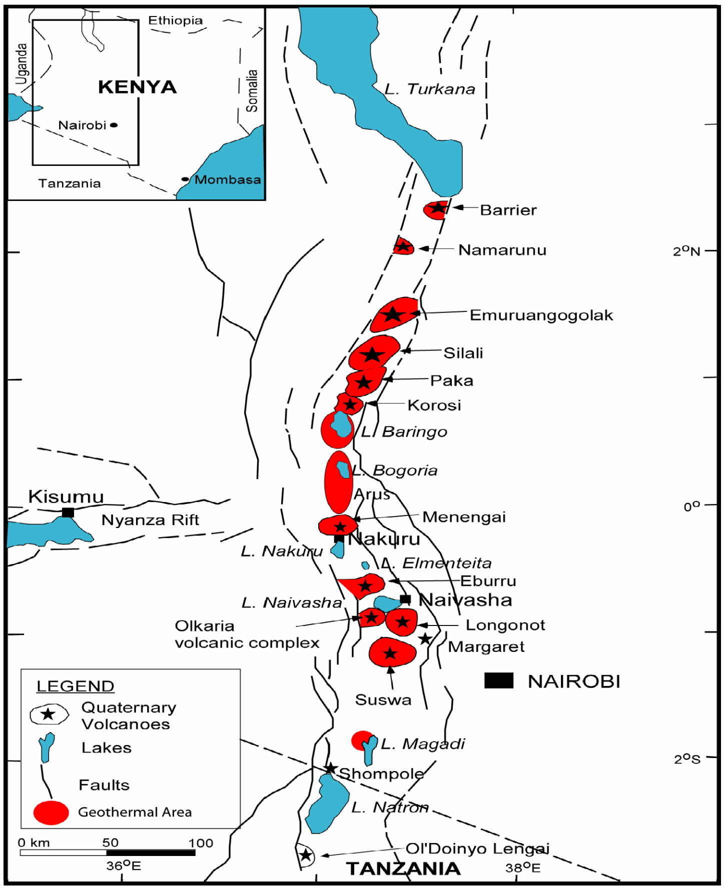

FIGURE 1: Location of Olkaria field

Since commencement of exploitation of Olkaria geothermal field, the steam output from the wells had an initial decline. This initial decline in output of wells was in line with the predictions of the numerical simulation studies carried out for the Olkaria reservoir (Bodvarsson and Pruess, 1981). As part of reservoir management and assessment, Olkaria reservoir has been monitored for thermodynamic and chemical changes. Routine downhole temperature and pressure surveys have been carried out in production wells during well outages or plant shut downs. Regular output metering and geochemical sampling of the production wells have been conducted. The data collected during the above exercises is used to prepare the field bi-annual status reports on steam production. The decline in output of the wells has been compensated for jointly by drilling and connecting of make-up wells and in-field reinjection of effluent from the production wells.

The geothermal resource in Olkaria has mainly been utilized for electrical power production. Direct use has had little attention though it is well known that even after utilizing the steam part of the resource for electrical power production, a lot of energy is left in the water. Except for the binary plants in Olkaria South West and North West that utilize both steam and water, the condensing plants in Olkaria East and North East only utilize the steam from the wells for electrical power production and separated water is rejected. However, there are wells with relatively lower enthalpy that produce more water than steam and hence if the energy in the water is rejected the result is very poor utilization of the resource. This paper discusses the reservoir engineering activities involved in exploration, development and management of the Olkaria geothermal resource and utilization of the resource for power production.

2. RESERVOIR ENGINEERING

Reservoir engineering activities starts during the surface exploration phase, when a survey is carried out to map the distribution of heat discharge features and quantify the natural heat loss from the prospect, and continues as the resource is proven by deep drilling and developed and into the exploitation phase.

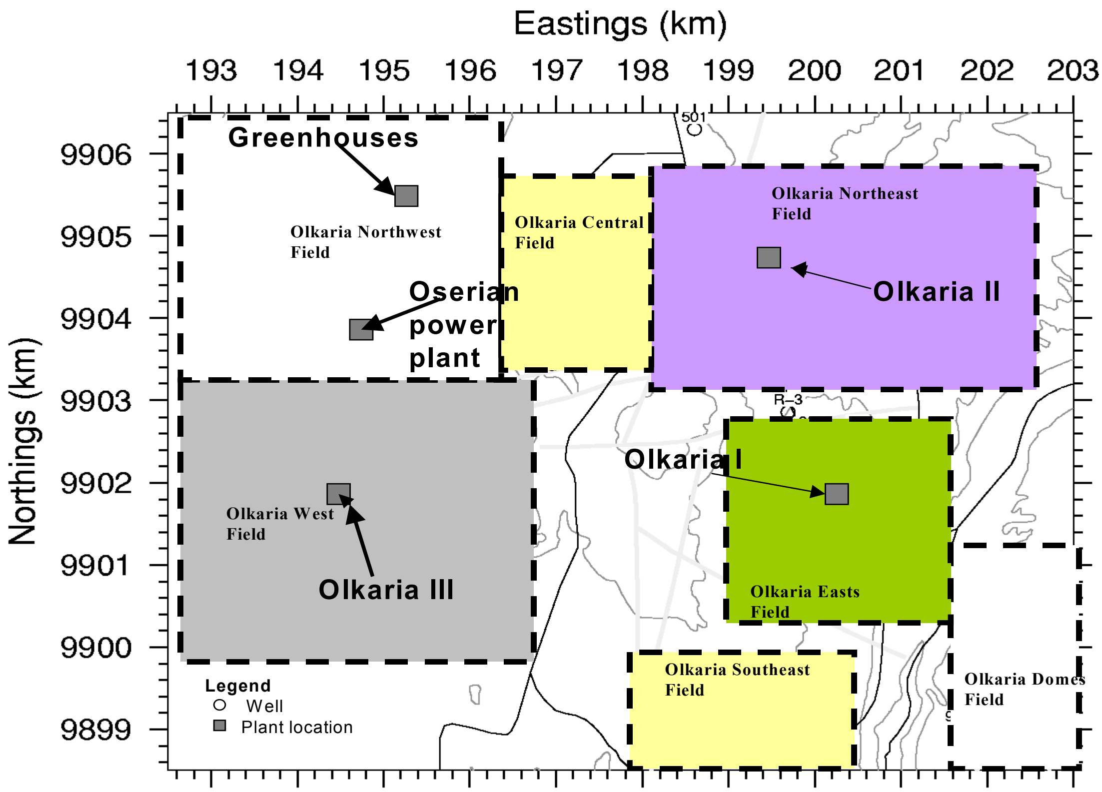

FIGURE 2: The greater Olkaria geothermal

2.1 Heat Loss Survey

It involved mapping of the distribution of heat discharge features within the geothermal prospect and quantification of the amount of natural heat loss (Glover, 1972). The result obtained from the heat loss survey became a vital input into the numerical simulation model. Mapping of the distribution of the heat discharge points over the prospect area strengthened for example the interpretation for the location of Ololbutot fault, which is an important hydro-geological structure for the Olkaria geothermal system.

2.2 Down-hole Logging

During drilling and after drilling of geothermal wells, down-hole logging has been carried out to establish the reservoir conditions in terms of temperature and pressure (Figure 3). Besides Pressure and Temperature logs, other logs and tests carried out in Olkaria include Caliper Log, Spinner Log, Deviation Survey, Multirate Injection Test and Pressure Fall Off Test. The results of these logs and tests are analyzed in order to compute the reservoir parameters. These parameters include water rest level in wells, location of the well-feed zones, injectivity, transmissivity, storativity and skin factor. These are the global hydraulic properties of the portion of the reservoir near the well that determine how it can store and deliver fluid mass, and indicate the degree of improvement or damage suffered by the feed zones during drilling operations. Up to very recently the use of electronic logging tools was restricted to temperatures less than 150°C and yet in Olkaria reservoir temperatures go beyond 300°C. Thus most down-hole logs in Olkaria have been done using mechanical tools supplied by Kuster Company of USA. Sourcing is being done for electronic logging tools capable of surviving under such high temperatures, in order to improve the efficiency of acquisition and quality of data acquired.

2.3 Discharge Testing

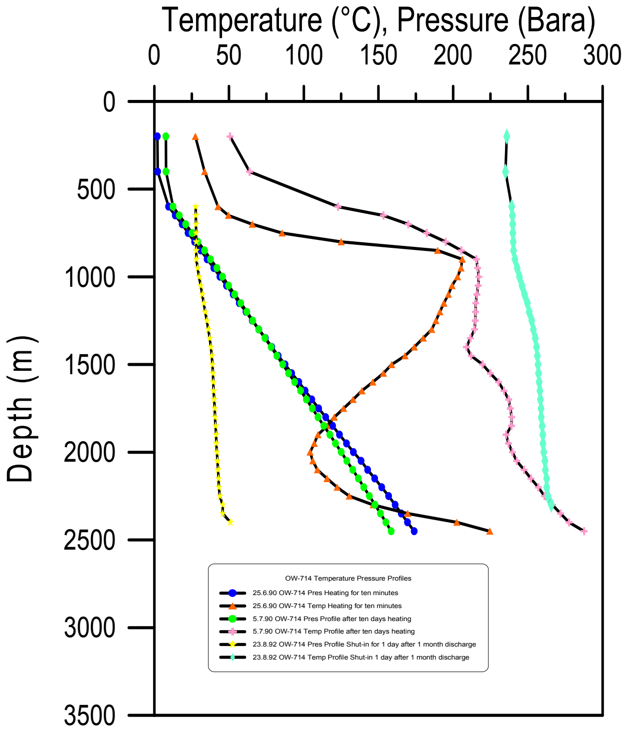

FIGURE 3: PT log of well OW-714

Once a well has undergone completion tests and has been capped, it is shut-in to allow heating up to recover from the cooling effect of drilling. In the meantime down-hole temperature and pressure logs are conducted and when the well has achieved discharge conditions, it is put on discharge testing in order to establish its discharge characteristics. Most wells in Olkaria take 4 to 6 weeks to reach discharge conditions following completion tests although some may take longer. In the cases where a well takes too long to reach discharge conditions it may be stimulated to initiate discharge. The discharge test results provide information on the capacity of the well to produce steam or water and combined with the discharge wellhead pressure, enthalpy and chemistry of the discharge fluid, it is possible to obtain the output of the well in terms of electrical or thermal power production. The test also determines whether the well is a steady or cyclic producer. The discharge test data is analyzed to determine the best way to utilize the geothermal resource and provides the design parameters for any intended use. Manual monitoring of discharging wells has been the practice. However, plans are underway to acquire electronic data loggers in order to improve the efficiency of data acquisition and the quality of the data collected.

2.4 Interference testing

It is a test in which pressure drop caused by producing wells is observed in some shut-in wells at a distance. This type of test is able to determine whether two or more wells are in pressure communication or in the same reservoir. When communication exists it provides estimates of transmissivity and storativity. It can also give other information on the reservoir properties that cannot be obtained from ordinary pressure build-up or drawdown tests. Such information could be useful as quantitative indications of reservoir heterogeneity and anisotropy, and indications of faults and barriers controlling general hydrology of the reservoir. The test can provide information on the extent of lateral communication between wells. That information is vital especially when choosing wells for re-injection. It was carried out concurrently with the reinjection and tracer tests in OW-704. Wells OW-714, OW-716 and OW-725 were put on discharge while pressure-monitoring devices were installed in observation wells OW-707, OW-723 and OW-724. The test results established existence of lateral communication between wells in this part of Olkaria North East field (Kagiri, 1994) and hence discredited the intended cold reinjection programme into OW-704 during exploitation.

2.5 Reservoir modelling

The main aim of reservoir modelling is to set up a computer model that represents the permeability structure, heat and fluid inputs and outputs of the real reservoir with sufficient accuracy so that the simulated behaviour of the model over 20 or 30 years can be used confidently as a prediction of the performance of the real reservoir. A computer model of geothermal reservoir must be preceded by a conceptual model; that is, a good understanding of the physical behaviour of the reservoir in its natural state.

A conceptual model is the picture that is created based on the analysis of the reservoir data collected and represents the understanding of the nature of the reservoir. There is no complete recipe for the development of a conceptual model. As wells have been drilled into the Olkaria reservoir, down-hole and discharge data has been collected and analyzed in order to better understand the nature of the reservoir and hence the conceptual model has been developing. Rough sketches showing various vertical and horizontal cross-sections through the reservoir should represent the concept. Major permeability features such as faults or contact zones should be shown especially if it is certain that they are hydrologically important. The major directions of fluid movement should be indicated on each sketch and approximate magnitude of heat inputs at the base of the reservoir and also heat outputs at the surface of the reservoir. Often the development of the conceptual model and the computer model is an interactive task; it may involve some smaller-scale modelling tasks along the way in order to test theories about the conceptual model and to test how it can best be represented on the computer.

Development of the conceptual reservoir model of Olkaria geothermal field was initiated by Sweko and Virkir (United Nations – Government of Kenya, 1976). Since that time the model (Figure 4) has been reviewed several times as additional information became available (KPC, 1980, 1982, 1985, 1986, 1997; KenGen, 1999; Bodvarsson, 1980; Bodvarsson and Pruess, 1981, 1984, 1988; Ewbank Preece – Virkir, 1989 and Virkir-Orkint and Bodvarsson, 1993). Over the years, the main concepts have remained more or less the same except that with more information, it has been possible to strengthen the model and add confidence to the understanding of the production characteristics of the reservoir. The major hydrogeologic features of the field include two upflow zones of hot fluids in the general area of OW-301 and OW-716. Large scale fluid movement in the field is dominated by major faults and fracture zones and large steam losses at the reservoir top, especially along the Ololbutot fault between wells OW-201 and OW-01.

The Olkaria geothermal reservoir is associated with the Olkaria volcanic centre. It is considered that the reservoir is bounded by arcuate faults forming a ring or a caldera structure. The magmatic heat source is expected to be intrusions at deep levels inside the ring structure. The reservoir is a two-phase liquid dominated one overlain by a thin steam dominated zone 100 to 200m thick at 240°C. This zone is widest in the south and thinnest in the north. Below the steam zone there is a two-phase system of boiling water. Above the steam zone, is a caprock that marks the top of the reservoir and is composed of impermeable basalt and trachytes, which lie 400 to 700m below the surface. The bulk of the reservoir rocks are mainly trachytic. The vertical extent of the reservoir is un-established but it is believed to be of the order of several hundred meters (Bodvarsson, 1984). Temperatures intercepted by the wells are generally high, (over 250°C) with bottom hole temperature about 300°C (Figure 4).

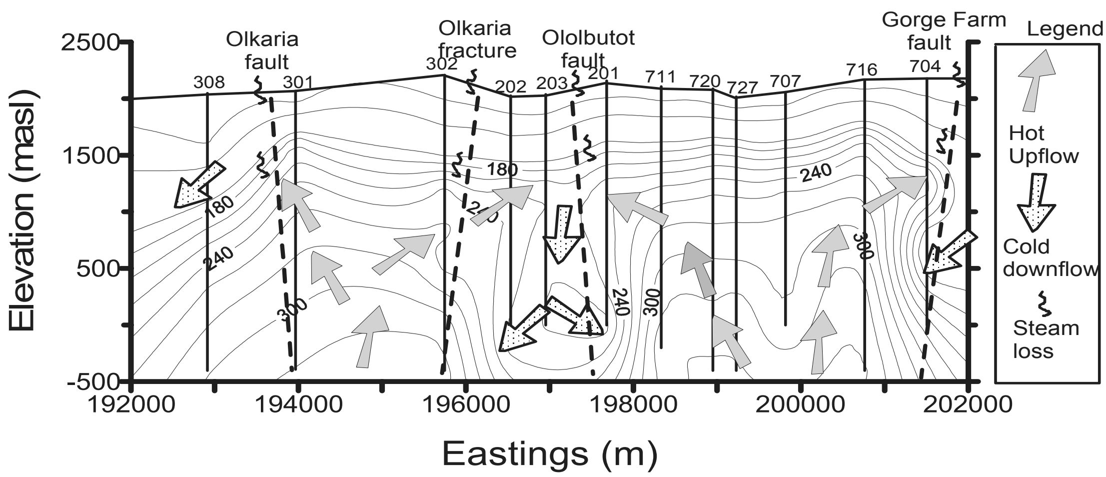

FIGURE 4: Conceptual model of Olkaria geothermal reservoir

The initial static water level varied between 400 and 700m. The initial pressure and temperature distribution in the field increases northwards while hydrological gradient indicated water movement was from North to South. This has been confirmed through drilling in the northern parts of the field where bottom-hole temperature in most wells exceed 310°C. The steam zone, that is present in the Olkaria East field, is replaced by a shallow two-phase zone in the Olkaria North East field (Ambusso and Ouma, 1991).

2.6 Reservoir management

The Olkaria reservoir has been under exploitation for the last twenty-four (24) years. Numerical studies of the generating capacity of Olkaria reservoir (Bodvarsson and Pruess, 1981) projected decline in deliverability of production wells with time and recommended monitoring of the production wells to determine the decline rate. The decline rate in the deliverability of the Olkaria wells would have major economical effects on the development plan for the field. However, the history match and performance predictions for Olkaria geothermal field (Bodvarsson and Pruess, 1984) indicated that injection of water into the geothermal reservoir would significantly increase the economic life time of production wells and thus save on the drilling of make-up wells. Therefore, as part of reservoir management requirement and general performance assessment, the reservoir has regularly been monitored for thermodynamic and chemical changes.

2.6.1 Temperature and pressure

Routine down-hole temperature and pressure logs have been carried out in production wells during well outages or plant shutdowns. Availability of wells for down-hole logs has been very limited due to the high steam demand hence limited information is available on the changes in reservoir temperature and pressure across the field. However, from the available data, the most significant change in this field over the last twenty-four (24) years of production is pressure decline. This is more pronounced at the centre of Olkaria East field where it has led to boiling. OW-18 that is centrally located in Olkaria East field had a maximum drawdown of 44 bars and cooling of about 4°C at 1300m by 1999 (Figure 5). Down-hole temperature and pressure logs show that wells located at the central and western parts of Olkaria East field are almost dry (Figures 5 and 6) while those in the south show temperature inversion at the bottom, indicating incursion of cooling fluid (Figure 7).

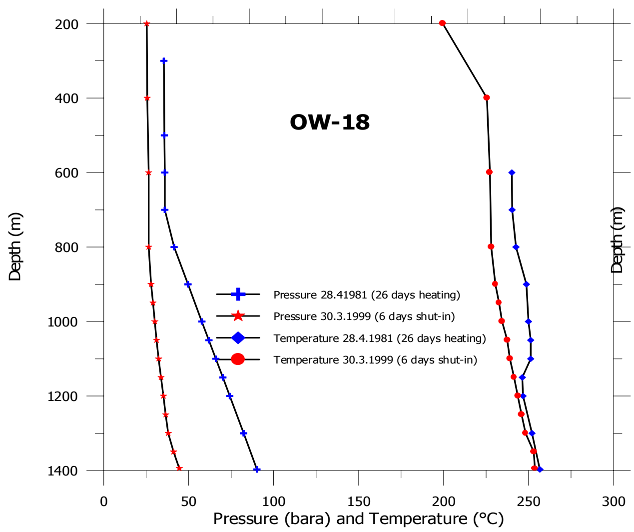

FIGURE 5: Down-hole profiles in OW-18

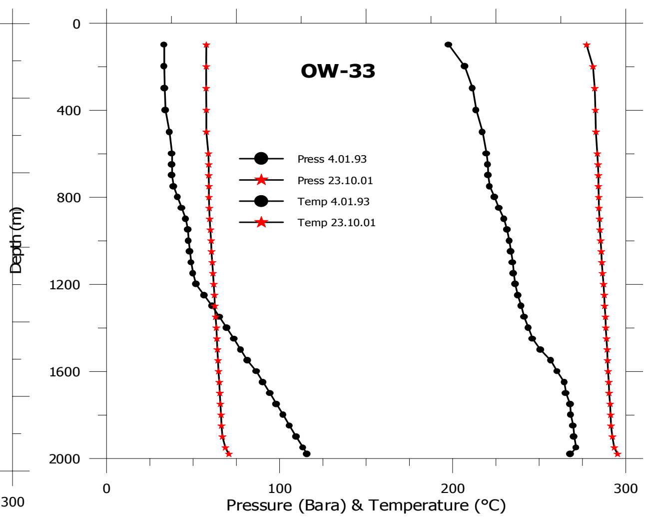

FIGURE 6: Down-hole profiles in OW-33

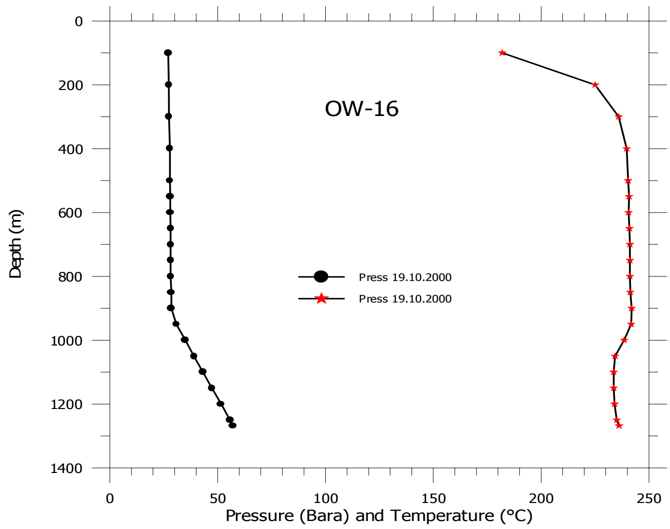

FIGURE 7: Down-hole profiles in OW-16

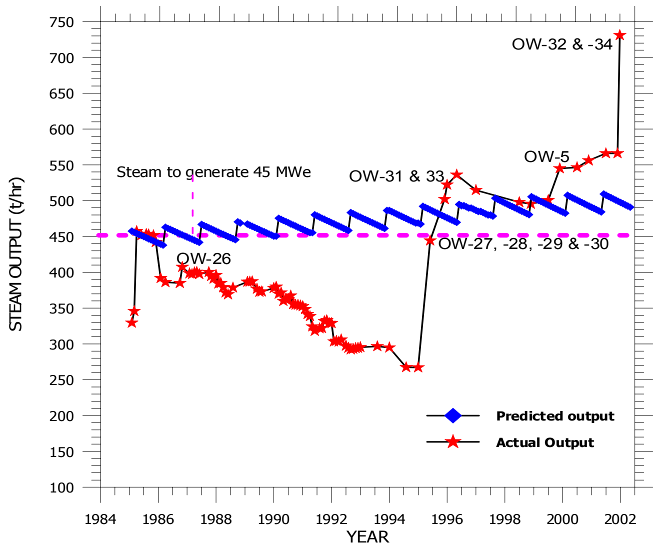

FIGURE 8: Steam decline trend at Olkaria East field

2.6.2 Wells deliverability

From the time the third unit was commissioned in 1985 at Olkaria East, the field has experienced pressure drawdown and hence decline in output from the wells resulting in decline in steam supply to Olkaria I plant. The decline in pressure has also introduced severe cyclicity in some of the wells in Olkaria East (Ouma, 1992). The field has shown various regimes of annual steam decline from an initial 5-6% decline to the current near zero. From 1981 to 1988 the average steam decline was about 5.5 % per annum (Ambusso and Karingithi, 1993). This led to the connection of OW-26 in 1986 raising the steam output by about 35 t/hr. The decline rate between 1988 and 1992 was about 4% per annum that reduced to less than 4% between 1993 and 1998 with some wells experiencing almost no decline while others experienced an increase (Ouma and Karingithi, 1998). Six make-up wells were connected between 1993 and 1998 raising the output by about 230 t/hr. In 1998, the steam decline was 4.6% (Ofwona and Wambugu, 1999) whereas between 1999 and 2000 Olkaria East field experienced steam increase of about 1% instead of a decline (Kariuki and Opondo, 2001). The trend of steam increase continued with a value of about 3.7% increase being observed in 2001. After connection of make-up wells OW-32 and OW-34, the total steam available became 730 t/hr equivalent to about 73 MW_e (Kariuki and Opondo, 2002). Except for the problem with well OW-34 (Ofwona and Opondo, 2003) the total steam available in Olkaria East field has remained at about 707 t/hr between 2002 and 2004 (Karingithi and Mburu, 2005). Generally it has been observed that steam deliverability from Olkaria East field has a significantly reduced decline rate compared to what was predicted by the numerical simulation models (Figure 8).

From 1992 to 2004, discharge enthalpy for the centrally located wells in Olkaria East field has increased by as much as 600 kJ/kg. This is mainly due to large reservoir pressure drawdown leading to drying up of wells as a result of boiling. Peripheral wells unlike the centre ones have had a decrease in discharge enthalpy (maximum 400kJ/kg). This is caused by cold water incursion at the bottom of the wells as demonstrated by down-hole temperature logs.

2.6.3 Fluid chemistry

Chemical changes in this field have been diverse and vary both in type and degree across the field. The cyclic nature of most wells and multiple production zones make the data interpretation complicated. However, for a number of wells, the extent of variation has been minimal and such wells have been used to infer the changes in the reservoir. These changes have been evaluated in terms of concentration

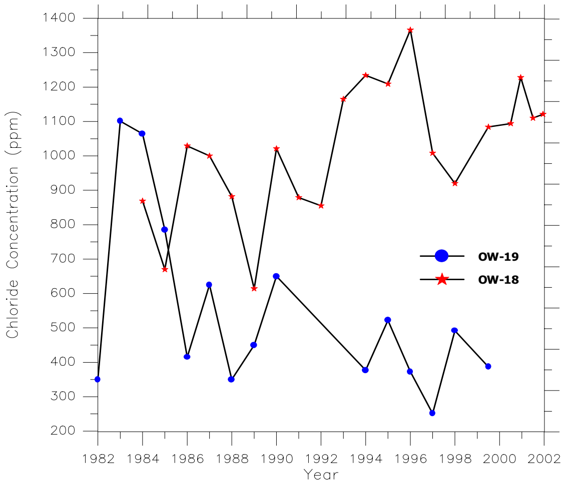

FIGURE 9: Chloride concentration for OW-18 and OW-19

of reservoir chloride, silica, sulphate, discharge enthalpy, calculated geothermometer temperatures and variation in gas composition of the discharge fluids. Gases considered include nitrogen, hydrogen, hydrogen sulphide and carbon dioxide in the steam. Wells located at the centre of the field have shown a gradual increase in concentration of dissolved constituent like chloride. Some peripheral wells have shown stable or decline in chloride concentration (Figure 9).

2.6.4 Reinjection

Numerical simulation studies suggested that reinjection into this field would reduce well deliverability decline rate and hence reduce the number of make-up well requirements (Bodvarsson and Pruess, 1984; Bodvarsson, 1993). This was considered economically favourable and hence cold and hot re-injection has been implemented in Olkaria geothermal field. Cold reinjection was carried out in OW-12 from July 1996 to August 1997 with a total of 137,000 tonnes of water being re-injected. Accompanying tracer test showed that OW-12 has hydrological communication with wells OW-15, OW-18 and OW-19. Monitoring of these wells indicated improved mass output but enthalpy drop due to cold reinjection and therefore was discontinued before the affected wells started recovering (Figure 10). Hot reinjection of separated brine from OW-27, OW-31 and OW-33 into OW-3 has been going on since May 1995. A total of 1,750,000 tonnes of brine has been re-injected into this well resulting in improved output in wells OW-2, OW-6, OW-8 and OW-11 without causing excessive decline in enthalpy (Figure 11). Currently, about 5% of the total brine generated from Olkaria East field is being re-injected hot into OW-3 and plans are underway to increase this amount. Recently cold reinjection of condensate from Olkaria I plant into OW-6 was commissioned in which about 13% of the condensate generated is re-injected.

In Olkaria North East field we have 100% reinjection of effluent generated by the production wells. Hot brine is re-injected into wells OW-R2, OW-R3, OW-703 and OW-708 whereas cold condensate is re-injected into well OW-201 or OW-204. Tracer was introduced into the re-injected fluid at OW-708 with returns reported in OW-706 and OW-712 and at OW-R3 with returns reported in OW-25 and OW-32.

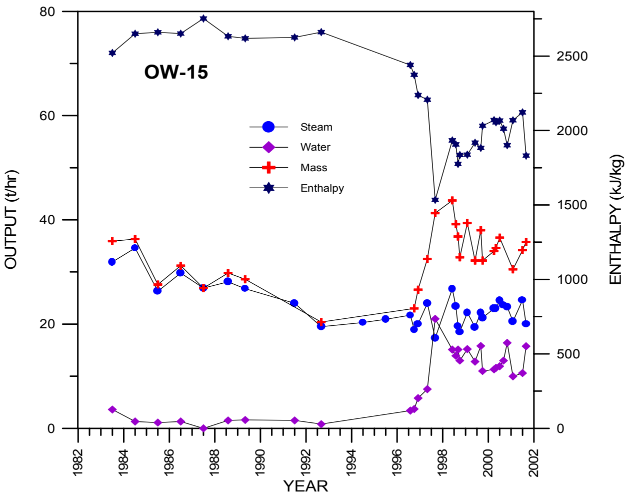

FIGURE 10: Effects of cold reinjection in well OW-15 from July 1996 to August 1997

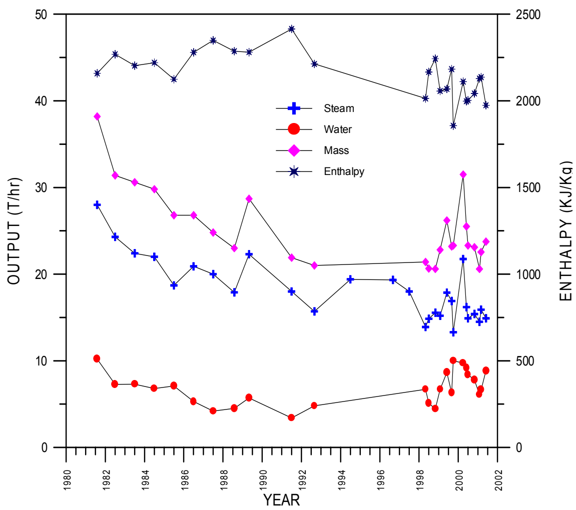

FIGURE 11: Effects of hot re-injection on well OW-2 as a result of hot re-injection into well OW-3 since May 1995

3. POWER PRODUCTION

Olkaria reservoir produces two-phase mixture of steam and water in general proportion of 70% steam and 30% water. However, there are a few wells that produce near dry steam or mostly hot water with very little steam. Two types of power generation plants operate in Olkaria namely, the Ormat binary plants and the Mitsubishi condensing plants. In all there are four power plants, two owned by Kengen and one each owned by Ormat International and Oserian Development Company Ltd (ODCL). The total installed power generation capacity of the four plants is 130 MW_e. Thus geothermal power installation constitutes about 12% of the national power installation and the plants operate as base load.

3.1 Olkaria I plant

It is the oldest plant in Olkaria and has been in operation since 1981 (24 years) with an installed power generation capacity of 45 MW_e. It consists of three (3) Mitsubishi condensing units each of capacity 15 MW_e. The plant has achieved an overall load factor of 81.9% and availability factor of 92.5% and continuous operation of up to ten months in one year has been realized. The steam conversion rate has been maintained at 9.2 t/hr per MW_e (Figure 12).

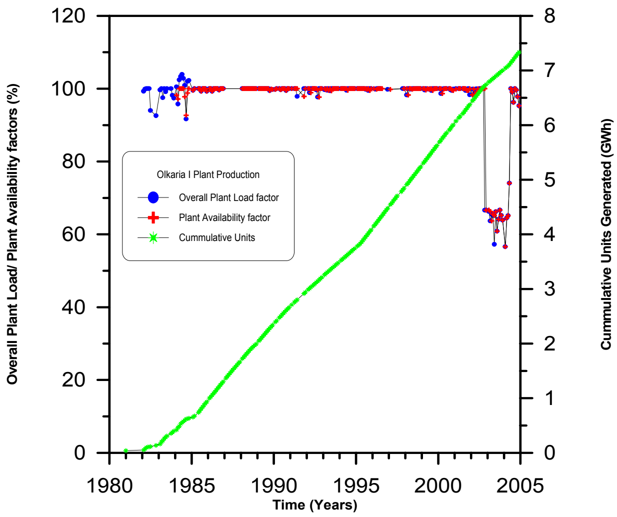

FIGURE 12: Olkaria I Plant Production

3.2 Olkaria II plant

It is the second geothermal plant installed by Kengen in Olkaria and has been in operation since October 2003 (2 years) with an installed power generation capacity of 70 MW_e. It is similar to Olkaria I plant but consists of two (2) Mitsubishi condensing turbo-generating units each of capacity 35 MW_e. The plant has achieved an overall load factor of 80% and availability factor of 83% in the last two years it has been in operation. This plant has steam conversion rate of 7.3 t/hr per MW_e, which is better than that of Olkaria I plant (Figure 13).

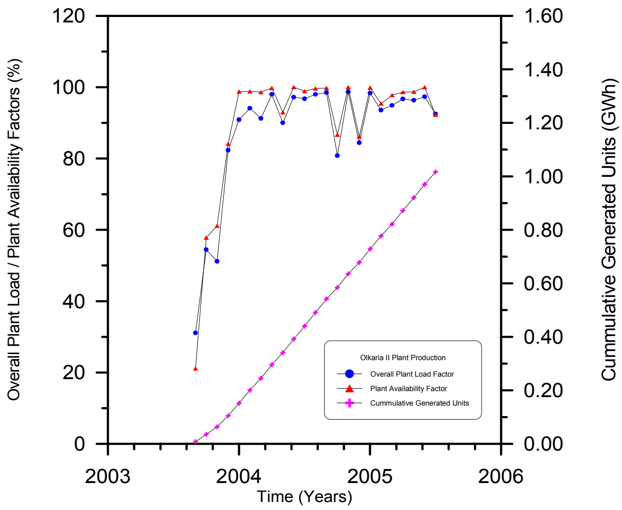

FIGURE 13: Olkaria II Plant Production

3.3 Ormat type binary plants

These were installed one each by Ormat International (Orpower 4) and Oserian Development Company Ltd. (ODCL) at Olkaria South and North West sectors. They utilize both steam and water phases of the discharge from the wells for electrical power generation.

The Orpower 4 plant with an installed capacity of 13 MW_e has been in operation since 2000 (5 years). It was installed as a pilot to test the performance of that sector of Olkaria reservoir, utilizing some of the exploration wells that had been drilled in the eighties plus the first drilled appraisal and production wells, ahead of the bigger plant planned for Olkaria South West.

The Oserian plant with an installed capacity of 2.0 MW_e has been in operation since 2004 (1 year). It utilizes discharge from one well (OW-306) that was drilled as an exploration well in Olkaria North West sector but which falls within the land owned by ODCL. The electrical power generated from this plant is all consumed by ODCL and supplements the electrical power supply from The Kenya Power and Lighting Company Ltd.

3.4 Energy utilization

Geothermal energy in Olkaria has mainly been utilized for electrical power production. Direct use has received little attention though it is well known that even after utilizing the energy for electrical power production, a lot of energy is still left in the water. Whereas the Ormat binary plants installed at Olkaria South and North West utilize both steam and water parts of the discharge from wells for electrical energy production, the Mitsubishi condensing plants installed by KenGen in Olkaria East and North East only utilize the steam part. Furthermore, there are wells with relatively lower enthalpy and hence produce more water than steam and if energy in the water for such wells is rejected can imply very poor energy utilization. For instance Olkaria I plant in Olkaria East field generates 45 MW of electrical power from steam but rejects 46 MW of thermal power in the water (equivalent 4.6 Mwe). Similarly, Olkaria II plant in Olkaria North East field generates 70 MW of electrical power from steam but rejects 142 MW of thermal power in the water (equivalent to 14.2 MWe)

Recently Oserian Development Company Ltd (ODCL) leased OW-101 from KenGen for direct use in horticultural farming. OW-101 is one of the exploration wells drilled in Olkaria North West in the early eighties and is capable of supporting generation of only 1 MW of electrical power. However, it has proved capable of supplying up to 10 MW of thermal power to ODCL for direct use in flower farming. With geothermal energy from OW-101 ODCL is able to heat approximately 30 Ha of green-houses.

There are wells in Olkaria with extreme cyclic discharge characteristics and hence cannot operate with the other wells supplying steam to the power plants. Such wells, in the past, have either been turned to reinjection wells or simply rendered useless and yet they are capable of supplying a lot of geothermal power for direct use. KenGen is looking at the possibility of economically selling geothermal energy from such wells to direct users either for recreational purposes or space heating. One such well is OW-724 drilled in Olkaria North East field. It is productive but because of its cyclic discharge characteristics, was found unsuitable to connect to the Olkaria II power plant. It was also found unsuitable for reinjection and hence so far no use has been found for it. However, this well is capable of providing 15 MW of thermal power for direct use and is being considered for supply of thermal power to interested direct users.

4. DISCUSSION AND CONCLUSION

Reservoir engineering activities have been active throughout the development of Olkaria geothermal resource and remain active during its exploitation. Most of the work has been done in-house at KenGen except for numerical simulation. However, significant efforts have been put into the development of in-house capability and in future this aspect will also be carried out in-house. The tools that have been in use for down-hole logging have been mechanical type because of the temperature limitations of the electronic alternatives. Recently, electronic down-hole tools capable of operating at higher temperatures as encountered in Olkaria have come into the market and sourcing is being done so that they can replace some of the mechanical tools. Electronic tools are considered to be more accurate and efficient for data acquisition and handling. Use of data loggers for production monitoring is also being considered for the future instead of relying on manual approach in which human beings are utilized to physically collect the data.

The geothermal resource has mainly been used for electrical power production utilizing the steam portion of the discharge from wells. The water portion of the resource has mostly been sent to waste either through surface rejection or re-injected back into the reservoir. This has resulted in very poor utilization of the resource and KenGen is exploring the possibility of economically selling energy contained in the water part of the resource to neighbouring flower farms and hotels for direct use.

Reservoir engineering activities were active during the exploration and will continue to be active during the development and exploitation of Olkaria geothermal resource. Energy efficiency of the Olkaria resource will remain low unless some use is found for the energy contained in the water portion.

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