



RESERVOIR ASSESSMENT AND WELLBORE SIMULATIONS FOR THE OLKARIA DOMES GEOTHERMAL FIELD, KENYA

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ABSTRACT

The Greater Olkaria geothermal area is divided into seven sectors. Currently, three of the sectors are generating 90 MW of electricity and an additional 32 MWe will be commissioned by the end of 2003. Olkaria Domes field is the fourth sector to be considered for development. Three exploration wells were drilled in this field in 1998 and 1999 (OW-901, OW-902 and OW-903) and plans for drilling of 6 appraisal wells are at an advanced stage. Wells OW-902 and OW-903 discharge at wellhead pressures less than 5 bar-a for all lip pressure pipe sizes but well OW-901 can discharge at 5 bar through 4 and 5" lip pipes. A conceptual model shows that the Domes field has an upflow zone near Well OW-903 with a deep boiling resource. Wells in the Olkaria Domes field need to be cased deeper than the wells in the other sectors in order to seal off a cooler feedzone at 1000 m a.s.l. Higher output from each well can be obtained by drilling larger diameter wells and by cleaning up the wells after drilling to reduce the skin coefficient. Reserve estimates show that the areal extent of the Domes field is about 8 km² and can support 40 MWe for about 25 years with 60% probability.

1. INTRODUCTION

The Olkaria geothermal system is located on the floor of the East African Rift valley in Kenya about 120 km northwest of Nairobi. About fourteen (14) geothermal prospects have been identified in the Kenyan Rift valley but drilling has been done in only two of these, Olkaria and Eburru (Figure 1). The Olkaria geothermal resource is located within the Greater Olkaria volcanic complex which consists of a series of lava domes and ashes, the youngest of which was dated at 2000 years ago (Clarke et al., 1990). To date, 101 wells have been drilled in this area. The Eburru volcano is about 50 km north of the Olkaria geothermal field. As part of an exploration programme undertaken by KenGen within the Rift Valley, six wells were drilled between 1988 and 1990. The available data indicate that the high-temperature portion of Eburru geothermal field is about 2 km² and can support 15-20 MWe power using a condensing turbine. However, if a binary plant is considered, more electrical power could be generated (Omenda, 2003).

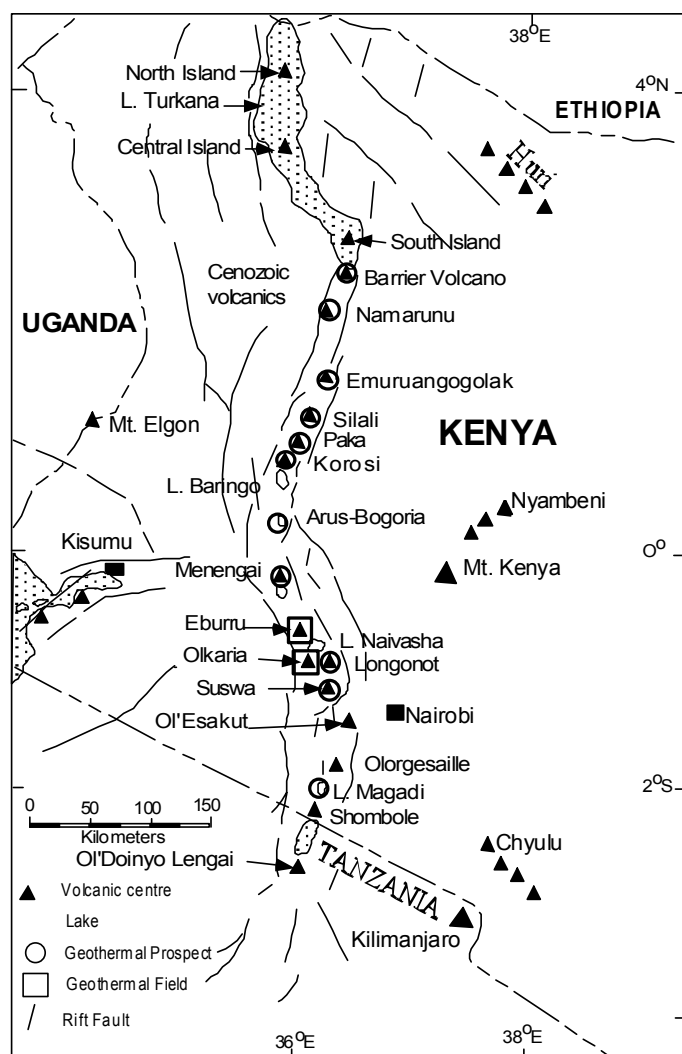


FIGURE 1: Location map of geothermal prospects in the Kenyan Rift valley

The Olkaria geothermal area has been divided into seven sectors which together constitute the Greater Olkaria geothermal area (Figure 2). Three of the seven sectors, have already been developed and are generating about 90 MWe. Olkaria East field, the site of Olkaria 1 power station has been generating 45 MWe since 1985. The Olkaria North East field will be supporting 64 MWe for the Olkaria II power plant. The first 32 MWe turbine was commissioned in August, 2003, and the second one will be commissioned later in the year. In the Olkaria West field, Olkaria III power plant is being developed by an Independent Power Producer (IPP). A 12 MWe, early generation Ormat plant has been in operation since the year 2000. More appraisal and production wells have been drilled and enough steam is available to generate 48 MWe in Olkaria III. Plans to build a 36 MWe power plant in the Olkaria West field are in the pipelines (Reshef and Citrin, 2003).

Exploration drilling has also been undertaken in other sectors of Olkaria, the most recent being in the Olkaria Domes field, located south of the Olkaria East field.

Kenya Electricity Generating Company (KenGen) which operates Olkaria I and Olkaria II power plants completed surface exploration in the Domes field in 1993.

Three deep exploration wells, OW-901, OW-902, and OW-903 were drilled from September 1998 to May 1999. The field is designated for development. It is expected to generate over 60 MWe for 25 years, and will be the site of Olkaria IV power plant.

Various tests have been conducted in the three deep exploration wells to determine reservoir characteristics, well productivity and therefore the power potential of this field. One such study is by Odeny (1999). No new wells have been drilled in this area but more data has been acquired through well tests. It should however be noted that with only data from three exploration wells, it is not possible to determine the actual generation capacity of any field. Appraisal as well as production wells need to be drilled, tested, and the data analysed in order to have a better estimate. Plans are at an advanced stage to drill six (6) appraisal wells in this field.

In this report, a reservoir assessment study on the Olkaria Domes field is put forward. The report covers the downhole temperature and pressure in the three wells in the Domes field and a few surrounding wells. The conceptual model of the Greater Olkaria geothermal area and that of the Domes field are also developed. Wellbore simulation using the Hola program was done for Well OW-902 using both the downhole and the discharge data to help determine the well's productivity, and the benefits of drilling large diameter wells. Power potential of the Domes field is estimated using the Monte Carlo method. These analyses are carried out to help determine the most appropriate method of resource exploitation.

3. ANALYSIS OF DOWNHOLE DATA

Downhole data obtained during and after drilling in a new field give very valuable information about the behaviour and the condition of the reservoir which dictates the mode of resource exploitation. Care should be taken when analysing the data in order to obtain reliable results. The information obtained also determines where to drill appraisal wells with beneficial results.

3.1. Well design and hydrological properties

A summary of the depth, elevation, and production casing shoe depth for the three wells drilled in the Domes field is given in Table 1. Completion and heat-up temperature and pressure data for the three wells drilled in the Domes field have been analysed earlier (Odeny, 1999). The analysis was done assuming the reservoir behaves as a Theis reservoir. Use of the Theis model is an over-simplification of a complicated system but the information obtained is quite reliable. Since 1999, more data have been obtained during well discharge and long shut-in periods, and some parameters have been modified (Table 2 and Figure 4).

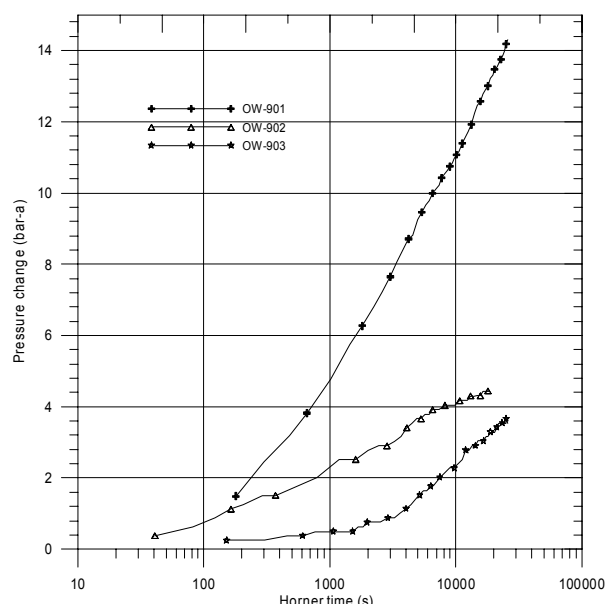


FIGURE 4: Pressure fall-off for the three Olkaria Domes wells

TABLE 1: Drilling summary of the Olkaria Domes wells

Well no.	Drilled depth (m)	Elevation (m a.s.l.)	Production casing shoe depth (m)
OW-901	2199	1890	758
OW-902	2201	1957	648
OW-903	2205	2043	697

TABLE 2: Properties of wells in Domes field

Well no.	Fall-off Horner gradient "m"	Transmissivity (m ³ /Pa s)	Permeability thickness (Dm)	Storativity (m/Pa)	Injectivity (l/s bar)	Pressure pivot point depth (m)
OW-901	12.2×10^5	0.4×10^{-08}	0.35	6.3×10^{-4}	1.23	1100
OW-902	1.9×10^5	2.6×10^{-08}	2.92	2.5×10^{-4}	3.89	900
OW-903	4.3×10^5	1.2×10^{-08}	1.23	58.6×10^{-4}	4.57	900

3.2 Downhole temperature and pressure

It is of interest to come up with the undisturbed temperature and pressure conditions in the Olkaria Domes wells. In order to do this, all downhole data obtained between 1998 and 2003 are plotted together for each well. The temperature and pressure recovery trend helps in determining the location of the feedzones as well as in developing the initial temperature and pressure. For the three Olkaria Domes wells, the latest static downhole data are more representative of the initial reservoir conditions since the wells have been

shut-in for almost 3 years (Table 3). Sometimes, however, the measurements are affected by cross-flow between feedzones and this should be identified and accounted for when determining the initial conditions.

TABLE 3: Initial temperature and pressure for the three Olkaria Domes wells

Well OW-901				Well OW-902				Well OW-903			
Depth (m)	Form temp. (°C)	Depth (m)	Form press. (bar)	Depth (m)	Form temp. (°C)	Depth (m)	Form press. (bar)	Depth (m)	Form temp. (°C)	Depth (m)	Form press. (bar)
100	42			100	67			100	51		
200	83			200	84			200	79		
300	161	300	5	300	100			300	107		
400	200	400	14	400	116			400	135		
500	221	500	23	500	136	500	7	500	163	500	3
600	237	600	31	600	192	600	16	600	191	600	12
700	250	700	39	700	217	700	22	700	214	700	21
800	261	800	46	800	227	800	30	800	226	800	29
900	270	900	54	900	233	900	38	900	229	900	37
1000	278	1000	61	1000	237	1000	46	1000	219	1000	45
1100	285	1100	69	1100	239	1100	54	1100	214	1100	53
1200	292	1200	76	1200	239	1200	63	1200	210	1200	61
1300	298	1300	83	1300	239	1300	71	1300	210	1300	68
1400	304	1400	90	1400	239	1400	79	1400	214	1400	76
1500	309	1500	97	1500	239	1500	87	1500	226	1500	84
1600	314	1600	104	1600	239	1600	95	1600	258	1600	91
1700	319	1700	110	1700	239	1700	103	1700	277	1700	99
1800	323	1800	117	1800	240	1800	111	1800	295	1800	106
1900	327	1900	123	1900	240	1900	119	1900	311	1900	113
2000	331	2000	130	2000	238	2000	127	2000	325	2000	119
2100	335	2100	136	2100	236	2100	135	2100	332	2100	125
								2200	338		
								2300	345		
								2400	353		
								2500	360		

3.2.1 Well OW-901

The initial undisturbed pressure and temperature in this well appear to follow the boiling point with depth curve below 240 m depth. Flowing temperature and pressure profiles show existence of a shallow feedzone immediately below the production casing shoe producing saturated water at about 250°C. Major feedzones are observed around 1300 and 1600 m. The latest temperature logs taken after the well had been shut-in for about 3 years matches very closely with the boiling point with depth profile showing that initial conditions have almost been attained (Figures 5 and 6).

3.2.2 Well OW-902

Injection, heat-up and flowing profiles of Well OW-902 show feedzones at around 900, 1200 and 1600 m. This well seems to have been drilled in an outflow zone of vertical convection and 240°C temperature. The latest downhole temperature log is almost isothermal, about 240°C below 1000 m with a slight inversion, 3°C below 1700 m. The fluid in this well is single-phase water below the boiling point with depth condition at 450-700 m depth which boils off at about 700 m (Figures 7 and 8).

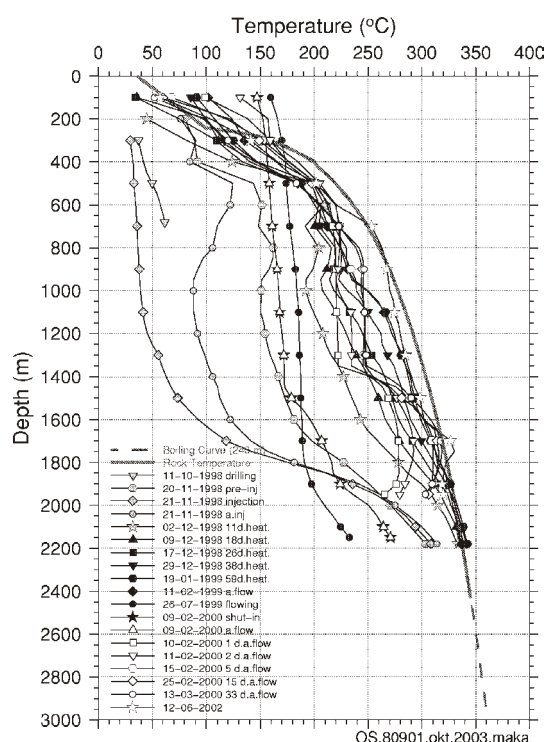


FIGURE 5: Temperature profiles in OW-901

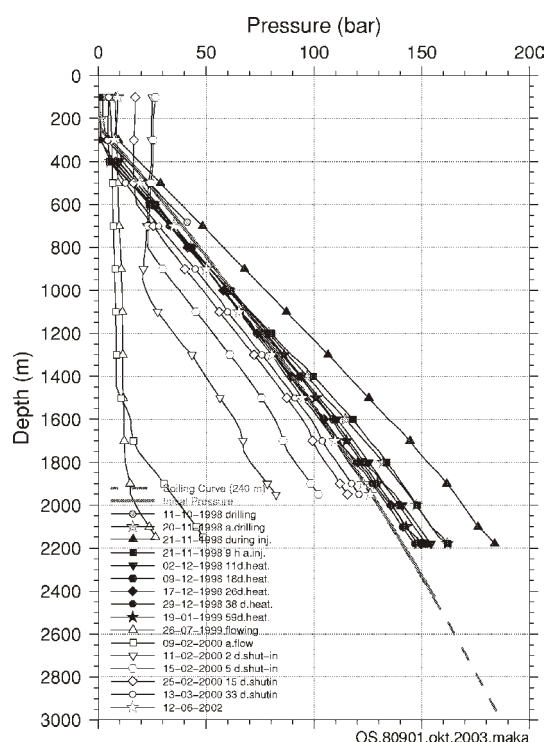


FIGURE 6: Pressure profiles in OW-901

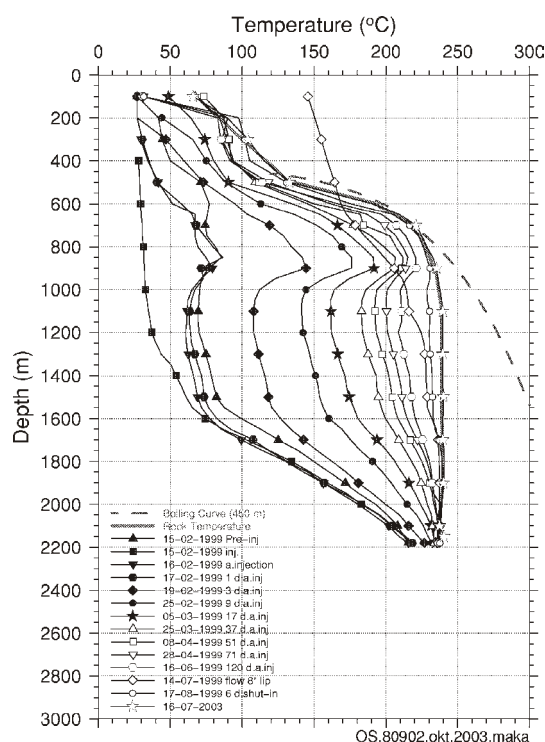


FIGURE 7: Temperature profiles in OW-902

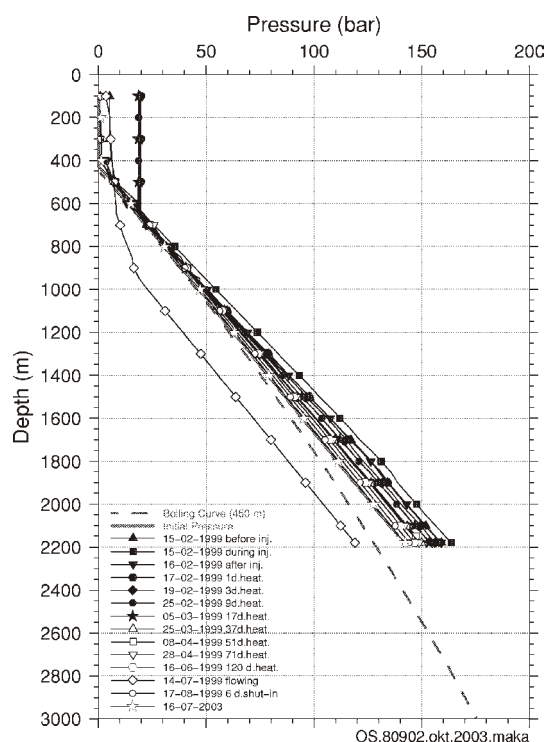


FIGURE 8: Pressure profiles in OW-902

3.2.3 Well OW-903

The latest temperature and pressure profiles in OW-903 show boiling conditions above 800 m and near the well bottom. Incurtion of cooler fluid at about 1000 m depth may cause a cross-flow between 1100 and 1600 m. Well OW-903 seems to have intercepted a fault bringing in cold water (Figures 9 and 10).

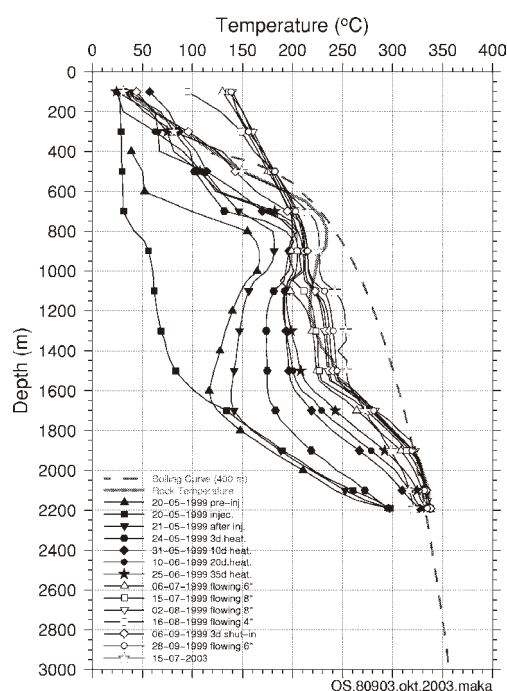


FIGURE 9: Temperature profiles in OW-903

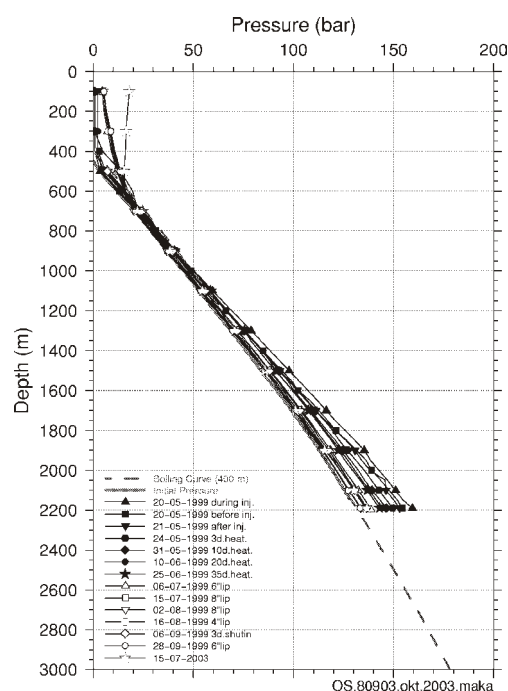


FIGURE 10: Pressure profiles in OW-903

3.3 Wells surrounding the Domes field

In developing the conceptual model of the Olkaria Domes field, a few wells surrounding the Domes field have been considered. This is done to help determine the reservoir boundaries. The analysis is based on earlier work (Ofwona, 2002). Wells OW-401 and OW-801 are drilled in an outflow area and therefore show relatively low temperature (OW-801), and a slight temperature reversal at depth (OW-401) as seen on Figures 11 and 12. The temperature profile of these two wells is similar to that of OW-902 indicating that OW-902 is also drilled in an outflow zone.

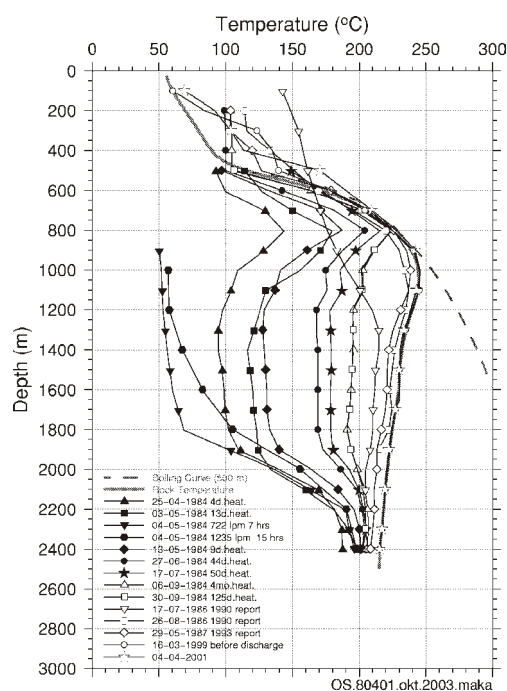


FIGURE 11: Temperature profiles in OW-401

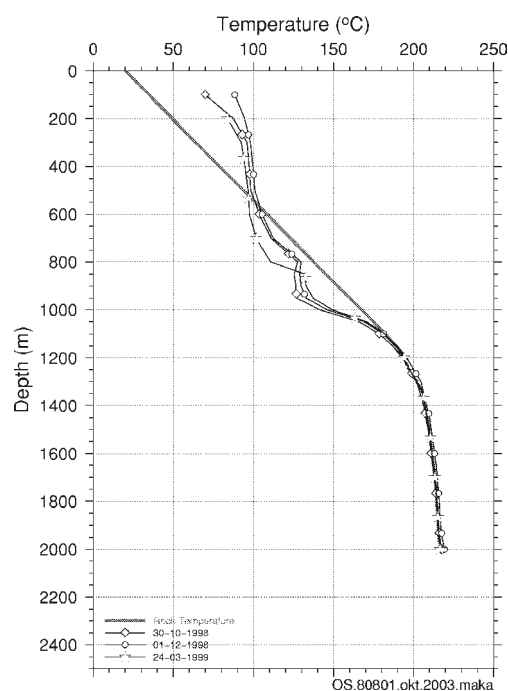


FIGURE 12: Temperature profiles in OW-801

Most of the wells in Olkaria East field show a boiling point with depth profile below a conductive cap-rock. A thin isothermal steam zone separates the cap-rock and the underlying boiling reservoir (Figures 13 and 14).

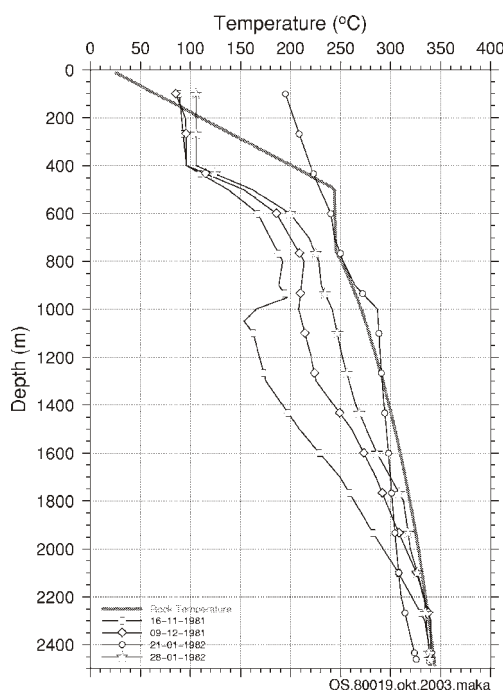


FIGURE 13: Temperature profiles in OW-19

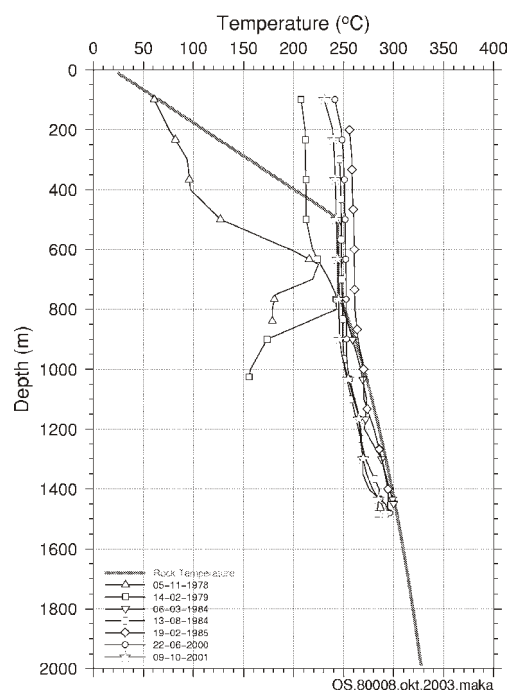


FIGURE 14: Temperature profiles in OW-08

4. CONCEPTUAL MODEL OF THE RESERVOIR

Modelling of a geothermal system is done to help obtain information on and to understand the conditions in a reservoir as well as the nature and properties of the system. Depending on the amount of data available, the model can be used to predict the response of the reservoir to future production and estimate the production potential of the system. The outcome of different management actions can be predicted (Grant et al., 1982).

Models are based on appropriate conservation and transport equations. A comprehensive programme of data collection during exploration of a geothermal system and careful monitoring during long-term production, are essential for any successful modelling. Modelling is done in three main phases:

- i. **Conceptual model:** A qualitative model which incorporates all essential features of a geothermal system that have been revealed by analysis of most, or all available data. It is not used for calculations.
- ii. **Natural state model:** A quantitative model which simulates the physical state of a geothermal system prior to production. Can be simple analytical or numerical.
- iii. **Exploitation model:** A quantitative model which simulate changes in the physical state of a geothermal system during long-term production. It is used for predicting future performance.

The most appropriate modelling approach is determined by the availability of data, time and the objective of a particular study. Very limited data and time is available for this study, therefore, only a preliminary conceptual model is developed.

4.1 Fluid phase in the reservoir

It is of paramount importance to know the state of fluid in the reservoir and its temperature after drilling because these parameters determine the mode of resource exploitation. After a well has fully recovered, the pressure conditions at feedzones are assumed to be the same as those of the reservoir at that depth since a well communicates with the reservoir only through the feedzone. These parameters should therefore be obtained after heat-up, during and after discharge, and after a well has been shut-in for a long period of time.

4.2 Temperature and pressure distribution in the Greater Olkaria area

In order to define a conceptual reservoir model of the Greater Olkaria geothermal area, several temperature and pressure plane-sections for the whole area have been plotted at different elevations. Figures 15 and 16 show the estimated temperature and pressure distribution plots at 500 m a.s.l. Analysis of the plots show upflow zones in Olkaria West, Northeast and East fields. The arrows in the figure show the direction of fluid flow. The well data behind the figures come mostly from the earlier work by Ofwona (2002), except for the Olkaria Domes wells where the new analysis (Chapter 3) are included. Investigations are done to find out the source of heat in Olkaria Domes field.

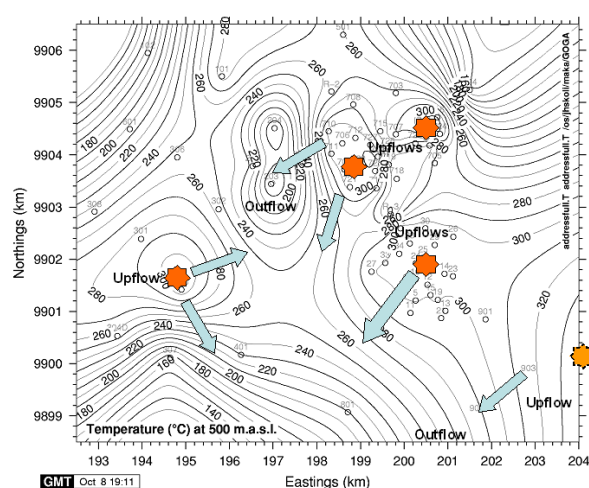


FIGURE 15: Temperature plane section at 500 m a.s.l. for the Olkaria area

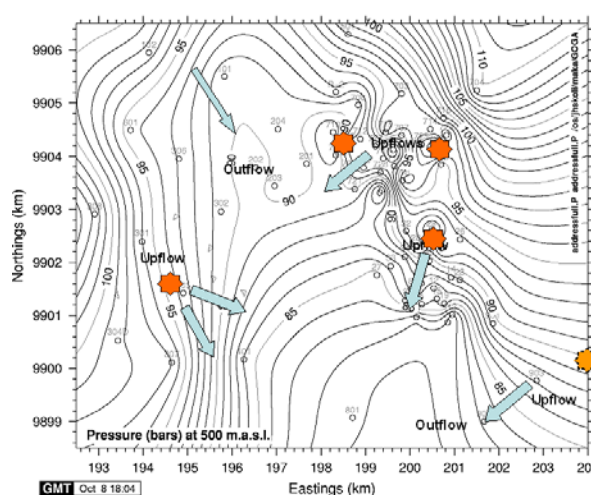


FIGURE 16: Pressure plane section at 500 m a.s.l. for the Olkaria area

4.3 Temperature and pressure cross-sections in the Domes area

A small area around the Domes field which includes well OW-401 in Olkaria West, well OW-801 in Olkaria Southeast and the Olkaria East wells has been considered in this model to help zoom in details of the Olkaria Domes field. The cross-sections are plotted using the estimated initial temperatures and pressures for the various wells (Section 3). From these plots, fluid flow directions can be identified. These sections help in making the conceptual model of the field. Figures 17 and 18 show NW-SE temperature and pressure cross-sections in the Olkaria East and the Domes field while Figures 19 and 20 show W-E cross-sections.

4.4 A conceptual model of the Olkaria Domes

The pressure and temperature plane-sections at 500 m a.s.l. elevation for the Greater Olkaria geothermal

area (Figures 15 and 16) imply that several upflow zones reside within this large geothermal reservoir. Two upflow zones are located in Olkaria Northeast field, one in Olkaria West around well OW-305 and another one in Olkaria East. The latest downhole temperature and pressure profiles taken in the three wells in Domes field have been used to estimate the initial temperature and pressure in these wells (Table 3). Analysis of downhole data, plane-sections at different elevations, and various cross-section plots have given the following conceptual model for Domes field.

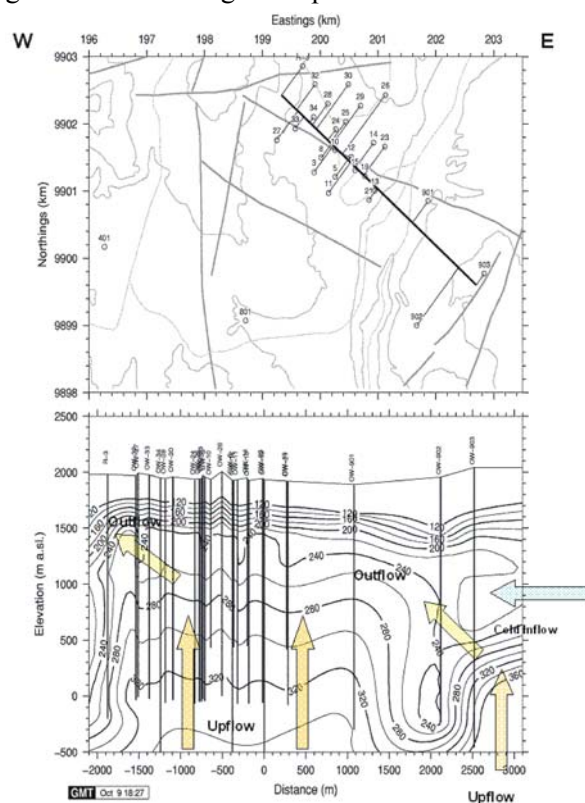


FIGURE 17: NW-SE temperature cross-section of the Olkaria field

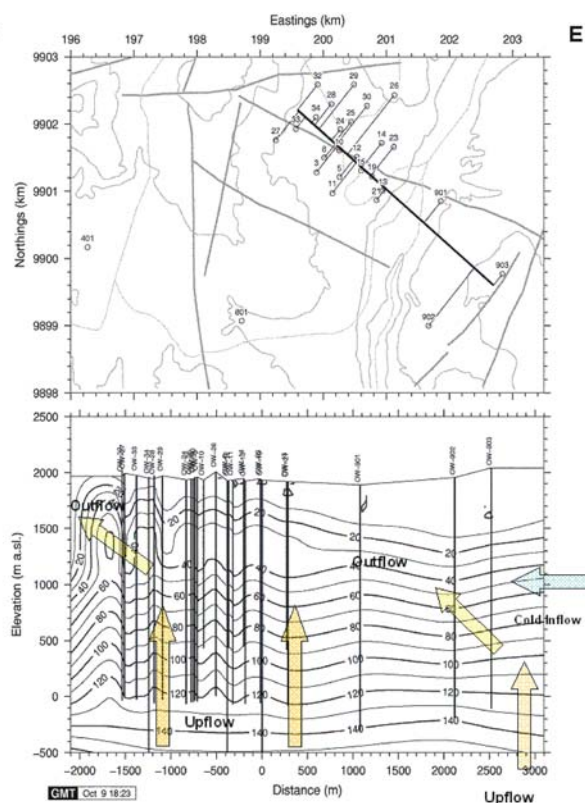


FIGURE 18: NW-SE pressure cross-section of the Olkaria field

Well OW-902 seems to have been drilled in an outflow zone. The other two wells, OW-901 and OW-903, show boiling point with depth profiles at depth which are taken here as indicators for an upflow zone in their vicinity. Bottomhole temperature and pressure for well OW-903 suggests presence of another upflow in the Domes field. This is also supported by the temperature and pressure cross-sections (Figures 17 to 20). An inflow of cooler fluid at around 1000 m depth distorts pressure and temperature contours. The water inflow could be through a fault which seems to have been intercepted by OW-903 (Figure 3). This can also explain the cycling effect of well OW-903 during discharge. Analysis of nitrogen gas concentration in the Olkaria wells shows maximum values in the Domes field around OW-903 indicating inflow of shallow, atmospherically contaminated water into the well (Karingithi, 2002). Well 901 seems to have been drilled between Olkaria East and Olkaria Domes upflows.

The Olkaria Domes field is a high-temperature resource with a large areal extent although the actual size is not yet known. Its upflow seems to be somewhere on the northern or eastern side of well 903 with an outflow zone around well OW-902. Appraisal wells should therefore be directed towards the north or on the eastern side to OW-903 in order to target the upflow area; and the wells should be cased deeper to seal off the cooler inflow at 1000 m a.s.l. Initial studies estimated the Olkaria Domes field to be about 4 km² (Odeny, 1999). The present conceptual model of the Domes field shows a larger area extending to the east or northeast of OW-903.

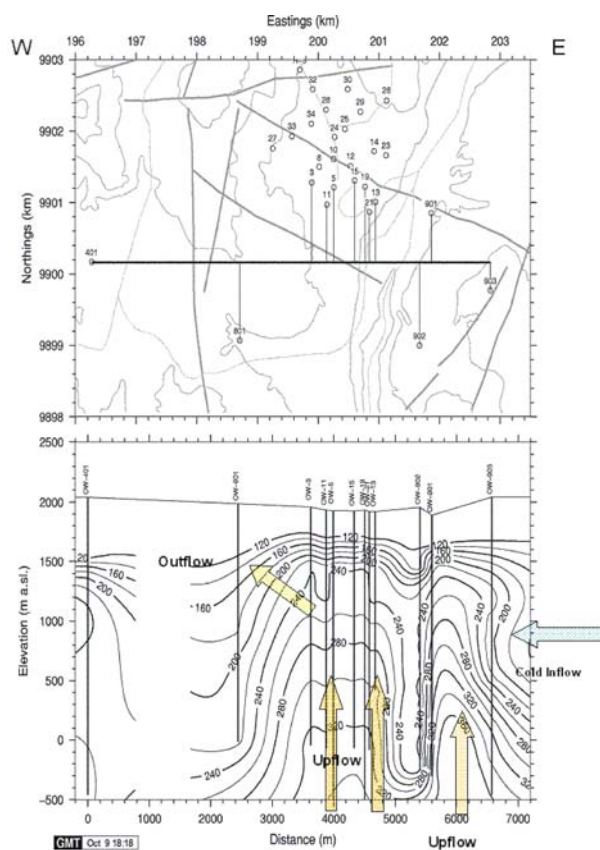


FIGURE 19: W-E temperature cross-section of the Olkaria field

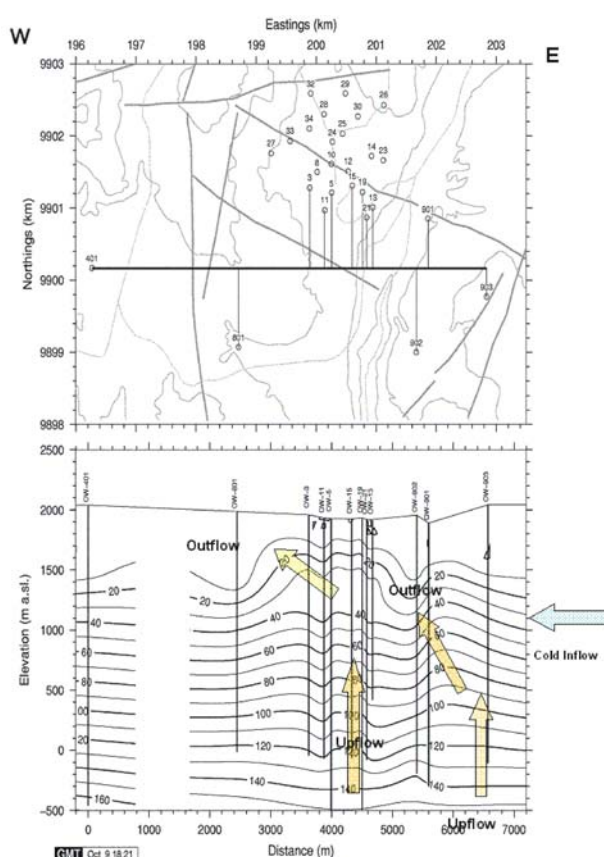


FIGURE 20: W-E pressure cross-section of the Olkaria field

5. PERFORMANCE OF DOMES WELLS

Various tests are performed in a well immediately after drilling. Although very valuable information about the undisturbed state of the reservoir can be obtained during drilling, interruptions of drilling operation to do these measurements are rarely done due to high rig time cost. These measurements should be taken every time there is an interruption in drilling operations, such as changing of the drill bits, as these are the only times to obtain almost near natural state conditions, especially at the well bottom.

Quite often, temperature and pressure measurements are conducted simultaneously by joining together the temperature and pressure tools. The most common tests usually carried out in Olkaria wells are:

- Pre-injection (immediately after drilling is completed);
- Injection tests;
- Warm-up tests;
- Discharge tests;
- Shut-in tests.

These tests give valuable information about the state of the reservoir and the power output from a well. Discharge testing for each of the three Domes wells was carried out for a period of 3-6 months in 1999 and 2000. Detailed description of the tests and results are partially contained in a previous UNU-GTP report (Odeny, 1999). As more data has been acquired since 1999, some of the parameters have been updated (Table 4). These wells have been shut-in since 2000, but the latest temperature and pressure measurements were carried out in 2003.

TABLE 4: Summary of downhole parameters in the three Olkaria Domes wells

Well no.	Feedzone depths (m)	T hottest feedzone (C°)	T _{max} (°C)	Depth of T _{max} (m)	Pressure pivot point depth (m)
OW-901	900 1200 1600	300	341	2150 (bottom)	1100
OW-902	900 1200 1600	240	248	700- 1900	900
OW-903	600 900 1100 1600	270	327	2190 (bottom)	900

5.1 Discharge testing

One of the basic tasks of a geothermal reservoir engineer is to measure the fluid from a discharging well and its energy content and to analyse the flow characteristics. Wells are discharge tested after they have been allowed to heat up after drilling for 2-4 months. The well is opened up and allowed to flow to the atmosphere. Geothermal high-temperature wells are usually discharged into a silencer which also acts as a steam-water separator at atmospheric pressure. The two-phase mixture is made to flow through different sizes of lip pressure pipes into the silencer. The steam disappears up into the air but the liquid water is measured as it flows from the silencer over a V-notch weir. The following flow parameters are then measured:

- Wellhead pressure (WHP);
- Lip pressure (Pc);
- Height of water in the V-notch weir.

Using the James lip pressure method (Equation 1), the output parameters from the discharging well are calculated (Grant et al., 1982):

$$Q = 1,835,000 A \frac{P_c^{0.96}}{H^{1.102}} \quad (1)$$

where Q = Total mass flowrate (kg/s);
 A = Cross-sectional area of the lip pipe (m²);
 P_c = Critical pressure at the end of the lip pipe (bar-a);
 H = Fluid enthalpy (kJ/kg).

Since the well is being discharged into the atmosphere, the specific enthalpies of steam and water at atmospheric pressure should be used:

$$Q = W \frac{(H_s - H_w)}{(H_s - H)} \quad (2)$$

$$Q = W \frac{2256}{(2676 - H)}$$

where W = Water fluid flow (kg/s);
 H_s = Steam enthalpy at atmospheric pressure (kJ/kg);
 H_w = Water enthalpy at atmospheric pressure (kJ/kg).

Combining Equations 1 and 2, we get:

$$1,835,000 A \frac{P_c^{0.96}}{H^{1.102}} = W \frac{2256}{(2676 - H)} \quad (3)$$

The enthalpy H , is the only unknown variable in Equation 3 and after obtaining it, the following parameters are calculated

- Total mass flowrate;
- Water flowrate;
- Steam flowrate;
- Flow enthalpy;
- Electrical power.

As a rule of thumb, total mass output plotted against wellhead pressure (WHP) should give a smooth curve. If not, the calculation or measurements are suspect. For all short-term flow tests, a continuous record of WHP should be made. This is a simple indication of stability of flow conditions. For a liquid reservoir, the well output (and WHP) may stabilise within minutes of changing the throttle conditions, whereas wells producing from a two-phase reservoir may require days of running at constant throttle conditions before stability is even approached. In some such wells and in dry steam producers, conditions of constant flow at constant throttle may never be obtained, and transient analysis must be made of such flow data (Stefánsson and Steingrímsson, 1990).

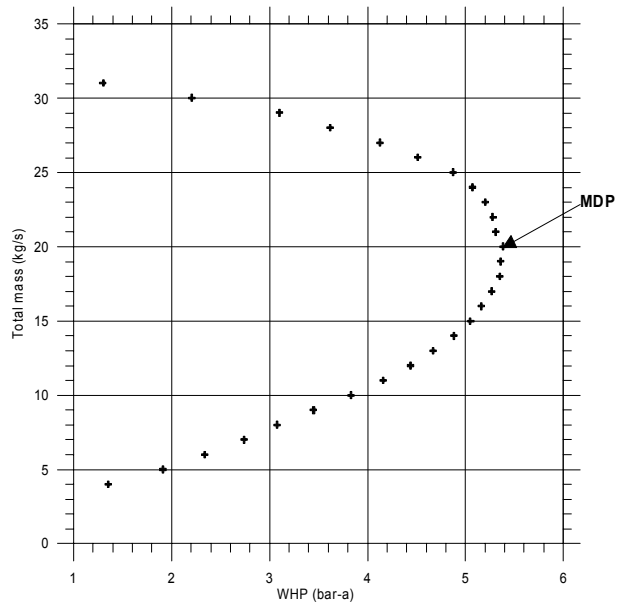


FIGURE 21: A typical output curve of a geothermal well

Analysis of discharge data from all three wells in Olkaria Domes shows a small change in WHP when different lip pipe sizes are used. A well discharging on 8" lip pipe should give maximum flow and lowest WHP and lowest enthalpy. Throttling of the well by use of a smaller lip pipe is expected to result in lower mass flowrate at higher WHP. An output curve shows a maximum discharge pressure (MDP) (Figure 21).

5.2 Analysis of discharge data

5.2.1 Well OW-901

OW-901 was tested with four lip pipes (3, 4, 5 and 8"). The well could not sustain discharge on a 3" pipe, and was very cyclic for all lip pressure sizes (Figure 22). Table 5 shows an average output summary for this well. Although a 4" lip gives stable enthalpy, the mass output is very small.

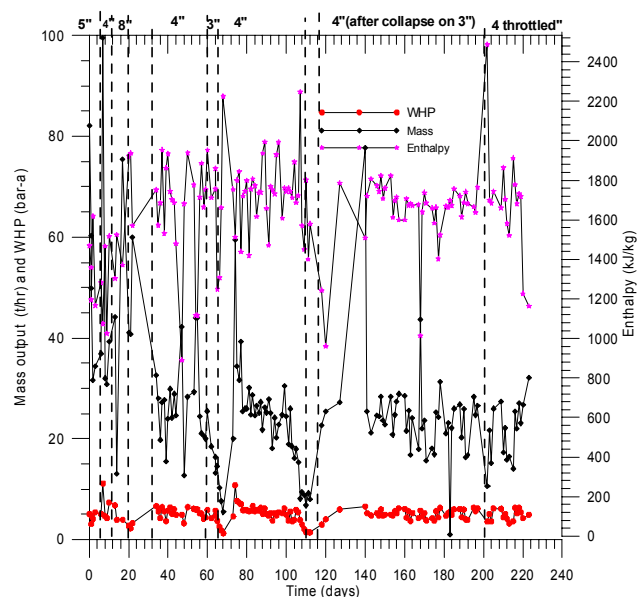


FIGURE 22: Discharge history of OW-901

TABLE 5: Output summary for OW-901

Lip pipe size (")	Flow parameters measured		
	WHP (bar-a)	Mass flow (kg/s)	Enthalpy (kJ/kg)
8	3.8-2.4	17-21	1300
5	4.4-5.2	10-15	1200
4	4.5-5.5	5-10	1700

5.2.2 Well OW-902

Well OW-902 was the second well to be drilled in the Domes field. Temperature and pressure profiles during injection and heat-up show feedzones at 900, 1200 and 1600 m. After about three months of heating up, the well was opened up for discharge for about three months. Stable conditions were achieved for flow through 6" and 8" lip pipes. The 6" lip pipe has higher and more stable enthalpy than the 8" pipe. Well OW-902 shows stable values for the various lip pipe sizes (Figure 23) and the output characteristics can be determined easily. Table 6 shows the summary of the output.

All the lip pipe sizes used resulted in a WHP of less than 5 bar-a (Table 6) which is the operating turbine pressure for Olkaria I and Olkaria II power plants. If a lower pressure turbine (3-4 bar-a) is used, a pipe of 5 or 6" should be used as it gives a relatively stable flow from well OW-902.

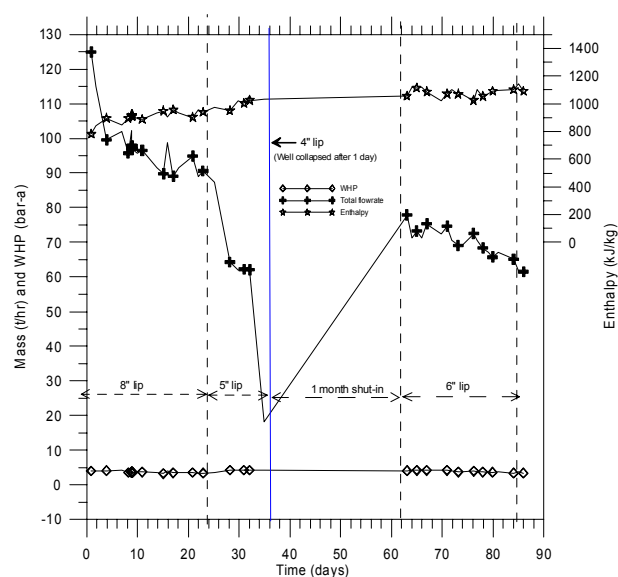


FIGURE 23: Discharge history of OW-902

TABLE 6: Output summary for OW-902

Lip pipe size (")	Flow parameters measured		
	WHP (bar-a)	Mass output (kg/s)	Enthalpy (kJ/kg)
8	4.2 - 4.6	31-35	940-970
6	3.8-5.0	21-28	1040
5	4.6	9.7	1100

5.2.3 Well OW-903

Well OW-903 was discharged for about 3 months. Several lip pipe sizes were used but stable conditions were not achieved with any of them. This shows that more discharge time was needed. The prevailing conditions after three months show that the WHP was less than 5 bar-a (Figure 24). Table 7 shows the summarised results for well OW-903.

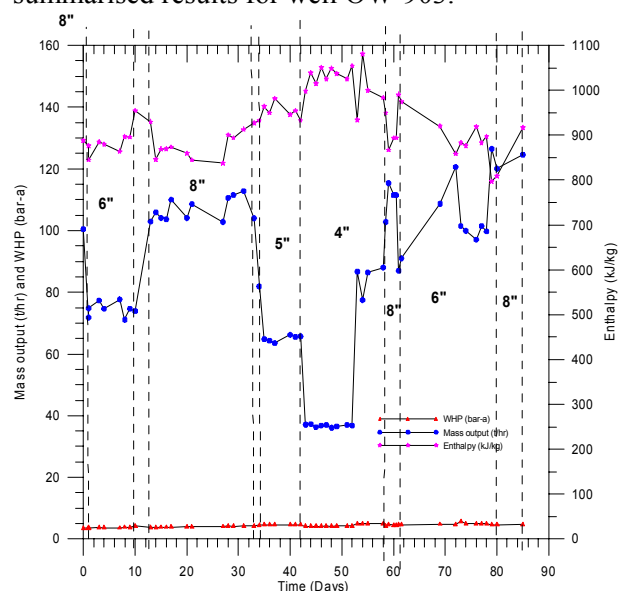


FIGURE 24: Discharge history of OW-903

TABLE 7: Summary of output from OW-903

Lip pipe size (")	Flow parameters measured		
	WHP (bar-a)	Mass flow (kg/s)	Enthalpy (kJ/kg)
4	4.2	9.5	1030
5	4.6	18	950
6	4.95	27.8	930
8	4.6	34.5	920

This well seems to have a cold water column at the top since the water level has to be compressed in order to discharge the well. Two attempts to do a vertical discharge on a 6" lip pipe failed

5.2.4 Wellhead output curves

Since wells OW-902 and OW-903 showed relatively stable values during discharge with different lip pipe sizes, the output curves for the wells can be drawn. The output curve for well OW-902 (Figure 25) shows more stable values with a maximum discharge pressure (MDP) of about 4.25 bar-a. Well OW-903 has an MDP of 4.9 bar-a, but it has not fully recovered (Figure 26).

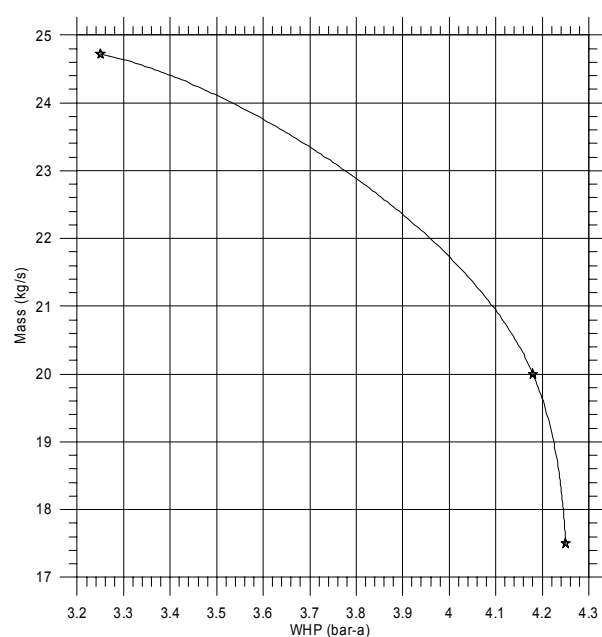


FIGURE 25: Output curve for OW-902

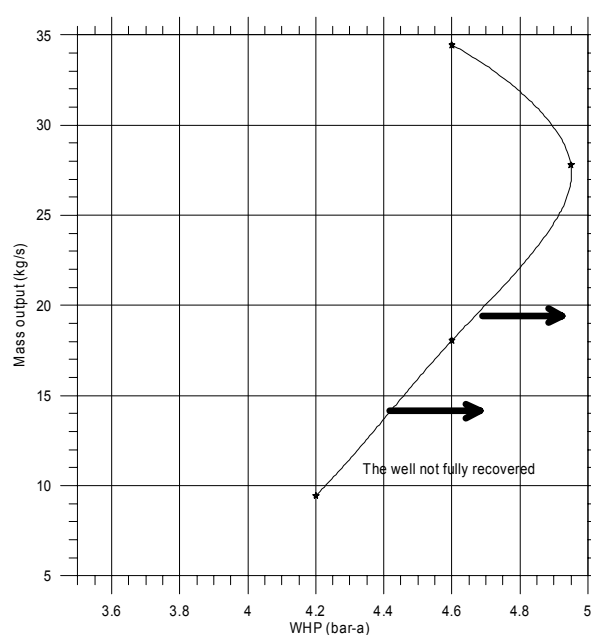


FIGURE 26: Output curve for OW-903

6. WELLBORE SIMULATION

Wellbore simulation basically refers to modelling a well output by varying the parameters that control fluid quality and flow into and out of the well. There are different types of wellbore simulators but all of them use the principle of balancing mass, energy and momentum flow in a vertical pipe for steady state flow. In this analysis, the program HOLA is used.

6.1 The program Hola

The program Hola which is one of the “Icebox” programs (Arason et al., 2003) was developed in Lawrence Berkery Laboratory, University of California (Björnsson, 1987; Björnsson et al., 1993). It is used to help solve numerically the differential equations that describe the steady state energy, mass and momentum flow in a vertical pipe (Equations 2-4).

The flow of fluid in geothermal wells can be represented by two sets of equations. Between the feedzones, the flow is represented by one dimensional steady-state momentum, energy and mass balances. When a feedzone is encountered, mass and energy balance between the fluid in the well and the feedzone is performed. The solution of these equations requires fully defined flow conditions at one end of the system (inlet conditions), and fully defined boundary conditions (wellbore geometry, lateral mass and heat flow). The governing equations are then solved in small finite steps along the pipe. Whenever a feedzone is encountered, the mass and energy of inflow (or outflow) are known, and the mass and energy balances performed, allowing for continuation of the calculations.

The governing steady-state differential equations for mass, momentum and energy flux in a vertical well are the following (Björnsson, 1987):

$$\frac{d\dot{m}}{dz} = 0 \quad (4)$$

$$\frac{dP}{dz} - \left[\left(\frac{dP}{dz} \right)_{fri} + \left(\frac{dP}{dz} \right)_{acc} + \left(\frac{dP}{dz} \right)_{pot} \right] = 0 \quad (5)$$

$$\frac{dE_t}{dz} \pm Q = 0 \quad (6)$$

where \dot{m} = Total mass flow (kg/s);
 P = Pressure (Pa);
 E_t = Total energy flux in the well (J/s);
 z = Depth coordinate (m);
 Q = Ambient heat loss over a unit distance (W/m).

The pressure gradient consists of three terms: friction, acceleration and potential as denoted by the subscripts in Equation 5.

The governing equation of flow between the well and the reservoir is:

$$\dot{m}_{feed} = PI \left[\frac{k_{rl}\rho_l}{\mu_l} + \frac{k_{rg}\rho_g}{\mu_g} \right] (P_r - P_w) \quad (7)$$

where \dot{m}_{feed} = Feedzone flowrate (kg/s);
 PI = Productivity index of the feedzone (m³);

- k_{rl} = Relative permeability of water;
 k_{rg} = Relative permeability of steam;
 μ = Dynamic viscosity (kg/ms);
 ρ = Density (kg/m³);
 P_r = Pressure in the reservoir (Pa);
 P_w = Pressure in the well (Pa).

Note that in the Hola program: $K_{rl} = 1 - S$ and $K_{rg} = S$.

where S is the volumetric steam saturation of the reservoir (Björnsson, 1987)

The computational modes of Hola: The simulator Hola offers six modes of calculating downhole conditions in geothermal wells (Björnsson et al., 1993). These are

1. Outlet conditions at the wellhead;
2. Required wellhead pressure and multiple feedzone;
3. Required wellhead pressure and two feedzones;
4. Required wellhead flow and two feedzones;
5. Required wellhead injection rate and two feedzones;
6. Variation in wellhead pressure and enthalpy for a constant flowrate and given reservoir pressure history at two feedzones.

6.2 Simulating well OW-902 downhole and output data

The data obtained during the discharge tests of well OW-902 is modelled using the Hola program. For simplicity, it is assumed that the well has one major feedzone at 1600 m. The initial reservoir temperature and pressure is obtained from the latest static measurement while the downhole data is obtained when the well was flowing (July 14th, 1999).

- Downhole temperature at 1600 m = 240°C
- Flowing pressure at 1600 m = 72 bar-a
- Initial pressure at 1600 m = 94 bar-a (feedzone pressure)

6.2.1 Determining productivity index

The above parameters are used to determine the productivity index (PI) of well OW-902 by matching the output curve to the measured data. Using computational mode 2, the simulator finds the downhole conditions that fulfill the required wellhead pressure. The result of wellbore simulation has been directed to finding the productivity index which matches the simulated values to the measured data. A productivity index of $1.28 \times 10^{-12} \text{ m}^3$ matches the output for well OW-902 (Figure 27).

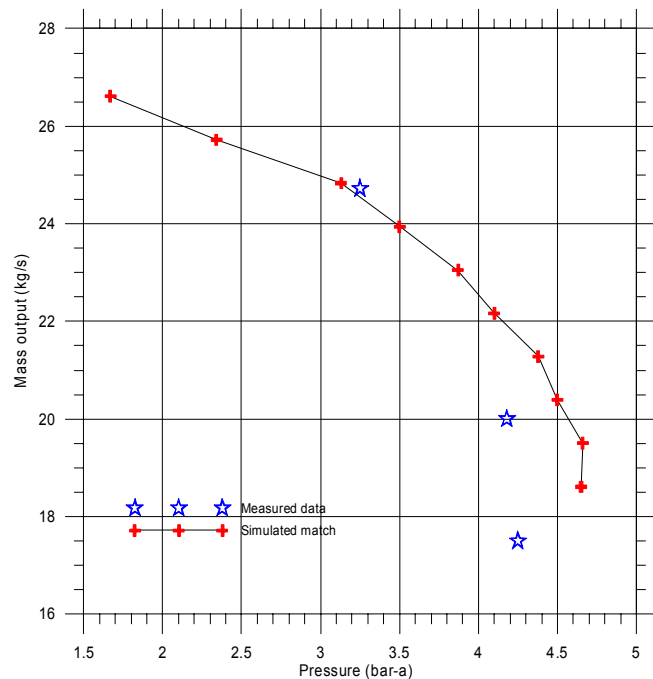


FIGURE 27: A match between discharge and simulated data from OW-902

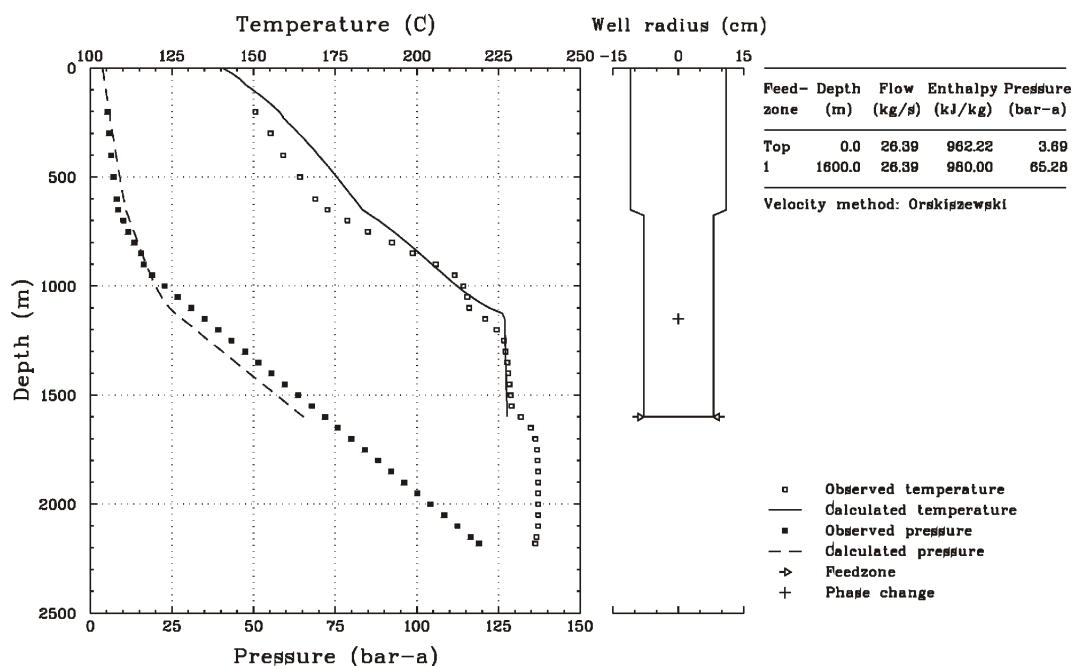


FIGURE 28: A match between downhole and simulated data from OW-902

6.2.2 Matching the downhole data

The downhole temperature and pressure measurements taken on July 14th 1999, about ten (10) days after the well OW-902 was opened up for discharge are hereby matched with the simulated data by using the prevailing conditions at the well's feedzone (Figure 28), and a close match is obtained for the simulated productivity index. Taking into consideration that the well may not have fully recovered within the first ten days, the simulated data is quite reliable.

6.2.3 Large diameter wells

High-temperature wells can be drilled to conventional size (9⁵/₈" production casing and 7⁵/₈" slotted liners) or to have a large diameter (13³/₈" production casing and 9⁵/₈" slotted liners). In the Olkaria Geothermal project, all wells are of the conventional size. Wellbore simulation for OW-902 output data has been done for both sizes assuming an ordinary size wellbore and also for a large diameter well (Figure 29). All the other parameters are kept the same for the two cases.

Analysis of these two curves show that OW-902 would give more than 20 kg/s higher mass output at a wellhead pressure in the range of 1.5-3 bar-a, and about 10 kg/s flowrate at WHP of 4.25 bar-a if a large diameter design had been selected for the well. It is, however, noted that increasing the wellbore size does not increase the maximum discharge pressure. The cost of drilling a large diameter well is

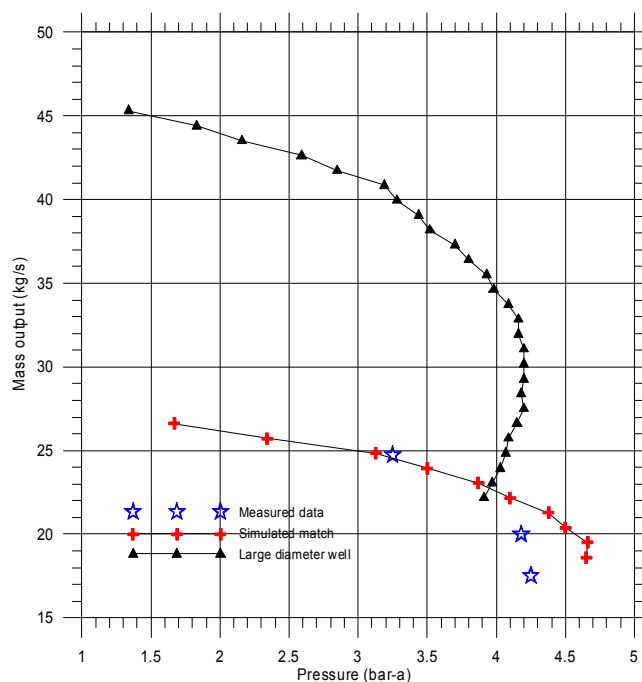


FIGURE 29: Comparison of output of a large diameter and a conventional well, for well parameters from OW-902

about 1.3 times that of a conventionally drilled well (Thórhallsson, 2003). Analysis of comparison between the benefits of the increased output and the extra cost due to large diameter drilling should be done and quantified.

6.2.4 Increasing the productivity index

Sometimes, the permeability next to a well is different from the rest of the reservoir. This is referred to as the skin effect, and may result from the effects of drilling or by long-term scaling of natural flow paths in the reservoir. The skin may be positive (less permeability) or negative (increased permeability). Positive skin can be caused by formation of a mud-cake and infiltration of mud into the production area. The situation can also result from invasion of drill cuttings into the feedzones which reduces the effective porosity by partially blocking the feedzones. The negative skin is due to formation fracturing near the wellbore during drilling, especially if the formation is brittle or when a well intercepts permeable features such as dykes, fractures and interbeds.

Formation damage and consequently a positive skin reduces the productivity index of a well. Cleaning of the wellbore after drilling often removes the mud-cake and the cuttings blocking the fractures hence resulting in a higher productivity index and hence higher mass output after cleaning (Figure 30). For well OW-902, the 20% increase in productivity index would increase the wellhead pressure to above 5 bar-a which is the minimum wellhead pressure required for the Olkaria wells due to the prevailing turbine pressures at the power plants.

Productivity index of a well can also be changed through thermal fracturing. This can be achieved by injecting cold water in a hot well several times. Thermal expansion and contraction causes the reservoir rocks to break-up, increasing the permeability.

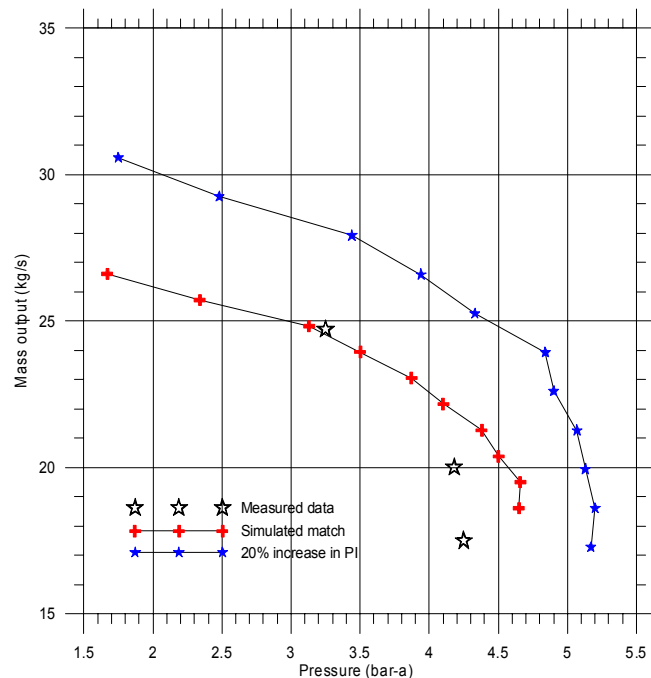


FIGURE 30: Output curves for different PI for OW-902

6.2.5 Result of wellbore simulation analysis

The wellbore simulation of well OW-902 gives a well productivity index of about $1.3 \times 10^{-12} \text{ m}^3$. For comparison, the value of PI for high-temperature wells in Iceland ranges from 10^{-13} to 10^{-11} m^3 (Björnson et al., 2003). The productivity index values for well OW-902 is within this range, but is considered relatively low, explaining why well OW-902 is a poor producer (Björnson et al., 2003).

An advantage of drilling a large diameter well is seen in terms of increased well output but not necessarily in higher wellhead pressure. This is due to low flow resistance inside the wellbore. This shows that more fluid can flow with less resistance and hence more output. Increase in the productivity index of a well through cleaning or thermal fracturing also shows increase in mass output and therefore wells with positive skin should be cleaned up after drilling to reduce the resistance to fluid flow into the well.

Since the cost of drilling a large diameter well is an initial capital cost, and the benefit of higher output will be realised throughout the life of the well, drilling of large diameter wells should be considered for production wells in Olkaria.

7. RESERVE ESTIMATE

Upon completion of exploration well drilling in a new field, it is important to undertake a preliminary resource estimate. The result of the preliminary resource estimate should indicate whether development drilling could go on and if so, should identify the probable target of future wells. In many cases, the studies also include an initial estimate of the field capacity. Update of the resource assessment should be performed as more wells become available.

7.1 Resource assessment

Reserve estimation is one of the main tasks of reservoir evaluation. Any development cannot continue without the assurance that the field has reserve capacity to produce over the desired life of the field. The three methods usually applied in the estimation of potential reserve of a geothermal resource without production history are:

- Volumetric method (stored heat calculations);
- Lumped parameter model;
- Distributed parameter model.

The most appropriate method to use in a new field with only 3 exploration wells is the volumetric method. This method involves calculation of the heat present in the reservoir rocks and in the fluid entrapped in the formation. The recoverable heat is then converted into electrical energy using conversion efficiencies of Muffler and Cataldi (1978). Their technique, however, does not show the uncertainties involved in the determination of each rock and reservoir properties. The reservoir properties, such as porosity, lie within a certain range rather than having one fixed value. This is also the case with the other reservoir properties used to determine the energy reserve. This uncertainty is addressed using Monte Carlo simulation (Sarmiento et al., 1993).

A preliminary resource assessment for the Domes field (Odeny, 1999) gave power potential of 3.5 MWe for the next 30 years. Only a few well tests had been carried out at that time and therefore the estimate was very conservative. With more data now available, the reserve estimate can be re-assessed.

By using the basic principle in Equation 8, that total heat energy in a geothermal system is the sum of the heat energy from within rocks and in the fluid:

$$E = E_r + E_w = VC_r \rho_r (1 - \phi)(T_i - T_o) + VC_w \rho_w \phi (T_i - T_o) \quad (8)$$

Electrical power potential of the reservoir is calculated from the heat energy using the relationship:

$$\text{Electrical energy available (MWe)} = \frac{\text{Heat energy} \times \text{recovery factor} \times \text{conversion efficiency}}{\text{plant life} \times \text{load factor}} \quad (9)$$

7.2 Monte Carlo simulation

The Monte Carlo simulation method is used to deal with the complex scenario that describes the distribution of known reservoir parameters by using uncertainty or probability distribution. The uncertainty distributions for every parameter involved in the analysis (Equations 8 and 9) should be defined. A random number generator then solves the algorithm relating the uncertainty distribution by randomly accessing the values for each distribution individually many times. The result is an overall probability distribution for the reserve estimate that quantitatively incorporates the uncertainties involved in all the parameters used (Parini and Riedel, 2000). The four most commonly applied uncertainty distributions are:

- *Constant (rectangular) distribution:* Mostly used when a constant is possible over a certain range of values and when any value within definable limits is considered equally likely;
- *Triangular distribution:* This is used when the best guess value for a parameter (most likely model value) can be specified along with high and low extremes.
- *Normal distribution:* A normal probability distribution is used when the high and low values are of equal sizes and are considered a better representation of many natural resources if a standard deviation can be computed.
- *Log Normal distribution:* This usually fits a series of measurements like porosity and permeability. Sizes of pebbles on beaches, and sizes of petroleum reservoirs as they occur from geological provinces have been observed to follow this distribution.

For simplicity of analysis in this study, parameters are assumed to have either a square or triangular distribution varying within specified limits. Some few parameters are taken to be constant (Table 8).

TABLE 8: Parameters used in Monte Carlo analysis for Olkaria Domes field

Parameter	Best guess	Probability distribution	Minimum	Maximum
Area (km ²)	7.5	Square	5	10
Reservoir thickness (m)	1000	Triangular	500	1500
Reservoir temperature (°C)	260	Triangular	240	280
Porosity (%)	8	Triangular	5	15
Rock density (kg/m ³)	2800	Triangular	2400	3000
Abandoned temperature (°C)	190	Triangular	180	200
Conversion efficiency (%)	12	Triangular	10	15
Plant life (years)	25	Triangular	20	30
Load factor (%)	90	Square	85	95
Fluid density (kg/m ³)	783	Square	750	815
Recovery factor (%)	23	Square	15	30
Specific heat capacity of rock (kJ/kg °C)	1000	Constant	-	-
Specific heat capacity of the fluid (kJ/kg °C)	4200	Constant	-	-

Monte Carlo simulation involves random sampling of the independent variables in a complex problem in order to establish a frequency distribution for possible outcomes. A triangular distribution shows more certainty about the outcome while a rectangular distribution shows less certainty. The variables are varied using the generated random with a range (ranges between 0 and 1). A large matrix (15 x 1000) with all variable parameters and the random numbers is created in an Excel spreadsheet. The results show a complete range of possible outcomes as well as the probability of occurrence for a given outcome. Table 9 and Figure 31 show this analysis for the power output for the Olkaria Domes field. An example of triangular distribution are the porosity values which vary from 5 to 15%; the most probable value from the analysis is 8% (Figure 32).

According to the frequency distribution for power output the Olkaria Domes field can support more than 40 MWe for the next 25 years, cooling the reservoir to 200°C (Figure 33). The probability of getting 40 MWe is more than 60%. This analysis should be updated as more data become available.

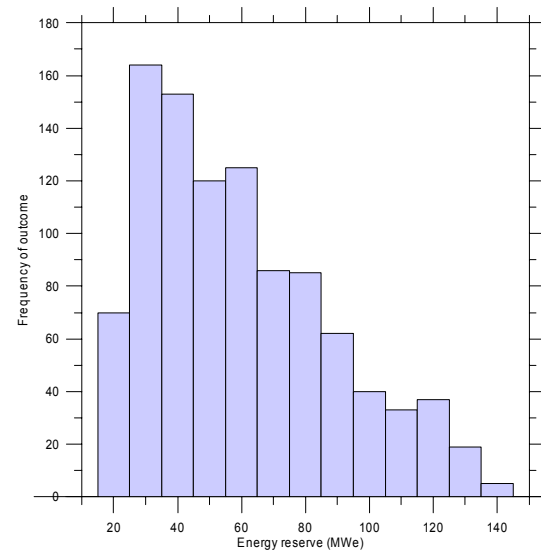


FIGURE 31: Electrical energy reserve of the Olkaria Domes field

TABLE 9: Power output probability data for the Olkaria Domes field

MWe	Outcome frequency	% cumulative
0	0	
10	0	0
20	66	7
30	141	21
40	135	34
50	144	49
60	129	62
70	94	71
80	79	79
90	63	85
100	45	90
110	47	94
120	30	97
130	12	99
140	9	99
150	5	100
160	0	100

8. CONCLUSIONS AND RECOMMENDATIONS

1. Wells OW-901 and OW-903 show a boiling point with depth (BPD) profile suggesting that they are drilled in or near an upflow zone. Well OW-901 seems to have been drilled in the Olkaria East resource, while OW-903 has tapped into a new upflow zone (Domes resource).
2. Well OW-903 seems to have intercepted a fault which acts as a conduit of cooler water causing temperature inversion at about 1000 m depth. Wells in this area should therefore be cased deeper to seal off that cool inflow.
3. Well OW-902 is drilled in an outflow zone and therefore shows a convective temperature profile below 1000 m with a slight reversal at depth. This can be the outflow of the Olkaria East and the Olkaria Domes field.
4. Since well OW-902 is drilled in an outflow zone, and has low wellhead pressure, it can be used for reinjection of colder fluids with low possibility of the fluids returning to the production field. This possibility should be considered when production in this field commences.
5. Temperature and pressure plane-sections for the whole of Greater Olkaria geothermal field show upflow zones in Olkaria West, Olkaria Northeast and Olkaria East. An upflow zone can be seen in the Domes on the north or the eastern side of well OW-903.
6. Wells OW-401 and OW-801 show a temperature inversion at depth suggesting that these wells are drilled in an outflow zone.
7. The result of wellbore simulation of OW-902 shows a well productivity index of only $1.3 \times 10^{-12} \text{ m}^3$. This is a relatively low productivity index which explains why well OW-902 is not a very productive well. Its flowrate is moderate, and it can only flow at very low wellhead pressures.

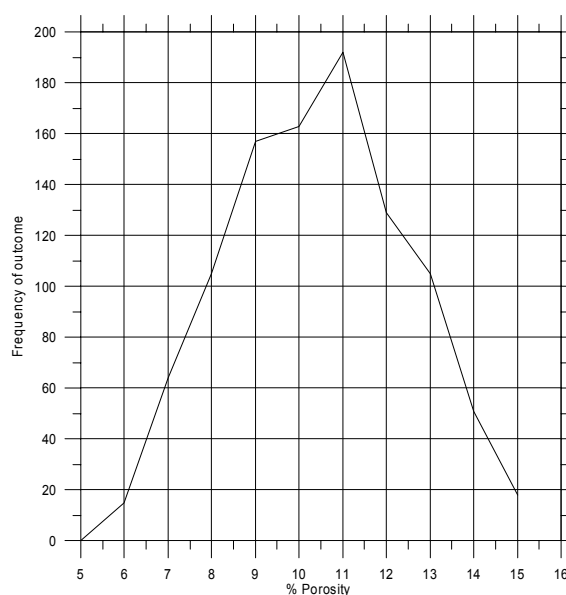


FIGURE 32: Porosity distribution curve for the Olkaria Domes field

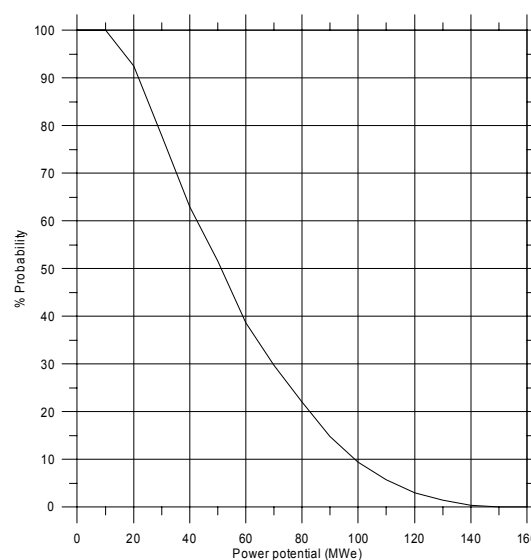


FIGURE 33: Percentage probability curve for the Olkaria Domes field

8. Drilling of large diameter wells should be considered during production drilling in the Domes field as this will result in higher mass output.
9. Wells with positive skin should be cleaned after completion to improve the wells' productivity. Of the 3 existing wells, OW-902 seems to be a good candidate for stimulation.
10. Reserve estimates show that the Olkaria Domes field can support about 40 MWe for about 25 years with 60% confidence.

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DEDICATION

This project is dedicated to my husband Simon Mburu and our daughter Noam Wachuka for their support, prayers and encouragement throughout my stay here in Iceland. I will forever be grateful.

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