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A CONCEPTUAL RESERVOIR MODEL AND PRODUCTION CAPACITY ESTIMATE FOR THE TENDAHO GEOTHERMAL FIELD, ETHIOPIA

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ABSTRACT

In this report the 6 wells drilled in the Tendaho geothermal field are briefly described. Formation temperatures and initial pressures for each well are estimated and a conceptual reservoir model presented. The Tendaho reservoir is divided into a shallow sedimentary reservoir with temperatures of 220-250°C and a deep one in volcanic basalts, ranging from 220 to 270°C in temperature. Inflow comes from depth in the east and the fluid flows diagonally to the surface, causing reversed temperatures in the present wellfield. Production data analysis indicates permeability-thickness in the range of 3-10 Dm in the shallow reservoir. A wellbore simulator study shows that the present wells maintain high flowrates despite either a 5 bar reservoir drawdown or a 20°C reservoir cooling. Both volumetric reservoir assessment and TOUGH2 reservoir model indicate that the present wellfield can sustain a 70 kg/s production rate for 20 years. Installing a small 1-2 MWe back pressure pilot plant seems feasible as an intermediate goal in the research activities. This, however, requires up to 1 year of testing the flow in order to define the nature of the outer reservoir boundaries. As more production and subsurface data become available, this very pessimistic production capacity estimate should be reconsidered.

1. INTRODUCTION

Investigations for geothermal resources in Ethiopia date back to 1969, to a joint venture launched by the UNDP and the Ministry of Mines, Energy and Water Resources of Ethiopia. The reconnaissance survey identified around 20 geothermal prospect areas in the Ethiopian rift valley. The three areas chosen for detailed studies were Lakes District, Tendaho and Dalol (Figure 1). The first 8 deep geothermal exploratory wells were drilled in the Lakes District at Aluto-Langano geothermal field from 1981 to 1985. A combined binary cycle pilot power plant with a capacity of about 7.8 MWe from the 4 productive wells is under construction.

The Tendaho geothermal field is located in the northeastern part of Ethiopia, in the Afar administrative region. Out of the many geothermal prospect areas in the Ethiopian rift valley, it is the second geothermal field to be explored by drilling of deep exploratory wells.

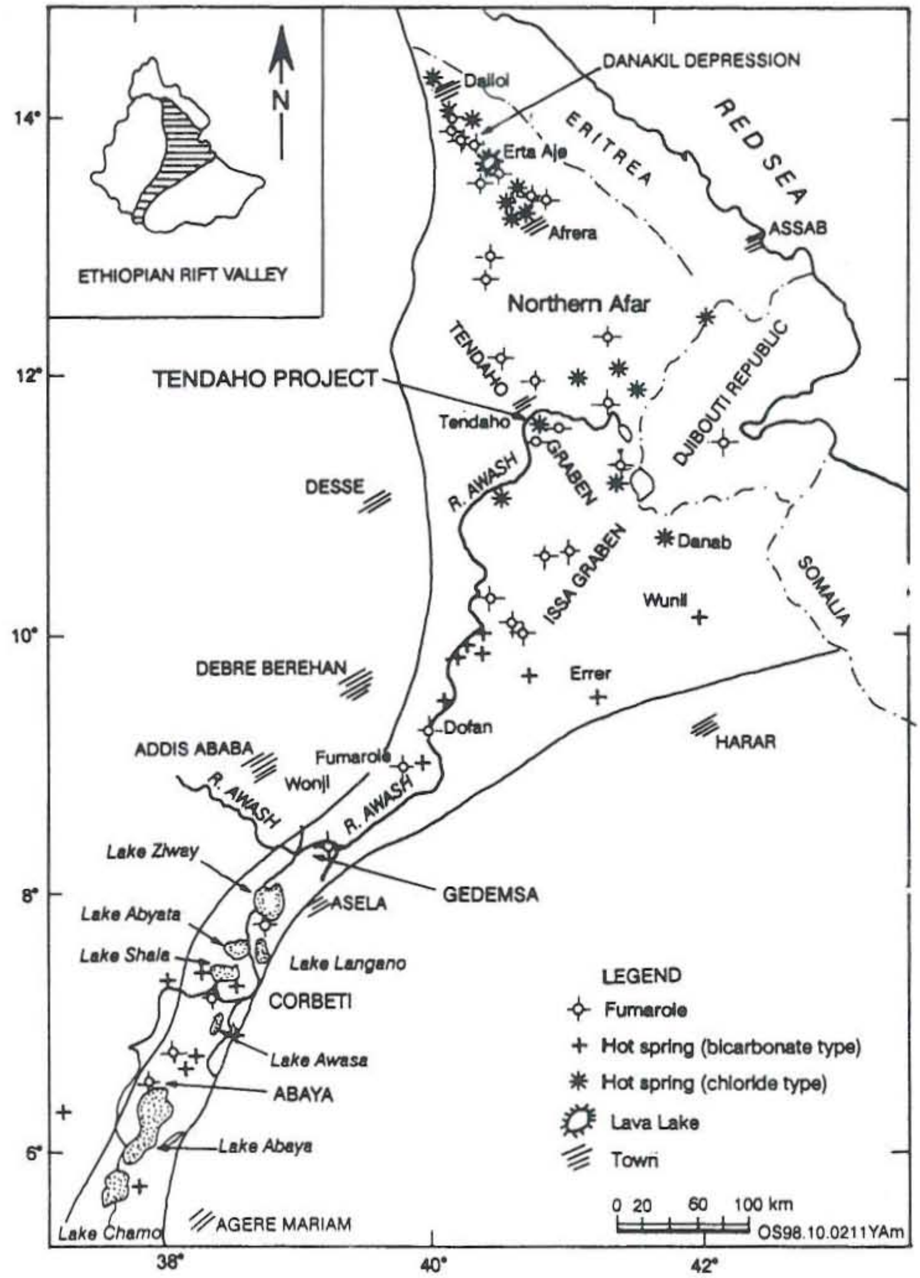

FIGURE 1: Geothermal areas in the Ethiopian rift valley

The geothermal exploration in Tendaho was carried out in three phases. During the first phase, geological, geochemical and geophysical surveys were conducted. Eight shallow temperature gradient wells were also drilled. The results of the different surveys indicated the availability of a geothermal reservoir. Drilling of three 2000 m geothermal wells was recommended.

Based on the recommendations of the first phase, drilling started in October, 1993. Three deep wells and one shallow well (1-4) had been drilled by May 1995 (Figure 2). These wells led to the discovery of a shallow reservoir in the vicinity of wells TD2 and TD4. Exploiting the shallow reservoir by drilling two additional shallow wells around well TD4 (wells TD5 and TD6) was recommended.

The first and second phases of geothermal exploration studies were carried out by Aquater, an Italian government company, in collaboration with the Ethiopian Institute of Geological Surveys. The drilling of 3 deep wells and one shallow well was concluded by submission of a final report (Aquater, 1996).

Phase 3 had the objective to prove the potential of the shallow reservoir and to study its characteristics. Drilling of the two shallow wells commenced on December 20, 1997 and was completed on February 20, 1998. The existence of a shallow 230-250°C liquid-dominated reservoir was confirmed in the Tendaho cotton plantation (often called Dubti). The three shallow wells TD4, TD5 and TD6 are all productive (Figure 2).

The Afar administrative region is under rapid development. The new capital city of Afar, Semera, is located within the premises of the geothermal field. The Awash river, which provides a steady supply

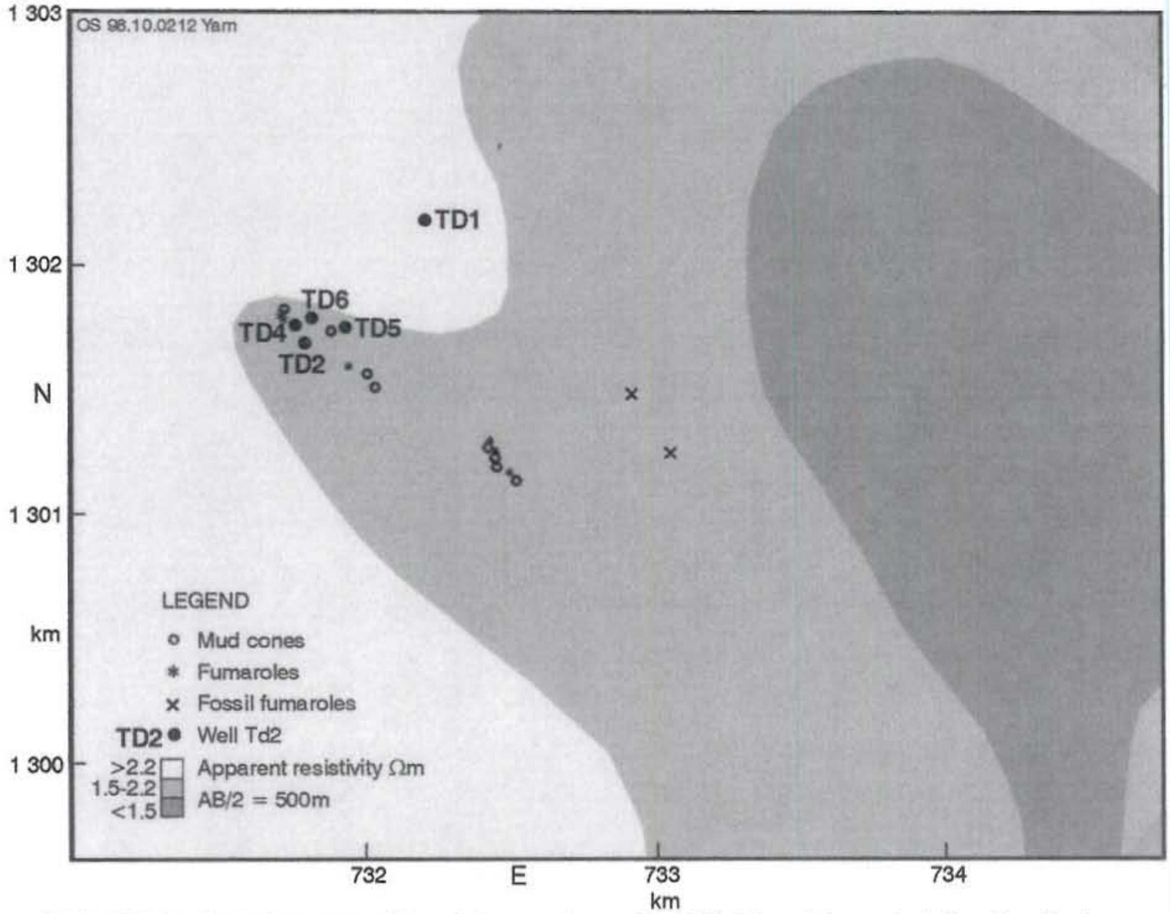

FIGURE 2: Location map of Tendaho geothermal wellfield and the resistivity distribution

of fresh water for agriculture, is close by the geothermal field. Faster growth of this area is, however, constrained by lack of electricity, both for households and irrigation. At present only diesel electricity is available. A successful operation of an electrical power plant in Tendaho may, therefore, become a key element in future living conditions in the area.

In this report the 6 wells drilled in Tendaho are briefly described. The formation temperatures and initial pressures for each well are estimated. From the formation temperature and pressure distribution, a conceptual reservoir model is constructed. Production data are analysed and future well performance for two wells predicted. Pressure transient tests from the newly drilled wells are analysed and permeability estimated. Resource evaluation for the shallow reservoir is carried out by applying the volumetric method. In order to determine the confidence intervals of the volumetric resource assessment method, the Monte Carlo statistical method is employed. Additional modelling work is done by the reservoir simulator, TOUGH2, in order to support the conclusions drawn by the volumetric method. Finally, the size and pre-feasibility study of a small pilot power plant instalment is discussed.

2. DATA SOURCES

2.1 Stratigraphy, chemistry and resistivity

Tendaho geothermal field is located in the northeastern part of Ethiopia, some 600 km from the capital city, Addis Ababa (Figure 1). It is one of the three geothermal prospect areas within the Tendaho graben, which covers an area of about 4000 km^2. Two deep and three shallow wells have been drilled in the thermally active zone of the Dubti area and one additional deep well (TD3) was drilled 7 km away from the rest of the wells. Information about the wells in the Tendaho are summarized in Table 1.

The results of drilling indicate that in the Dubti area, the upper 600-700 m are lacustrine sedimentary sequences with interlayered basalts. The lower parts are the Afar Stratoid Series, a basaltic sequence that represents the floor of the Tendaho sedimentary basin (Aquater, 1996). The water discharged from the wells is of sodium chloride type, mature from a geothermal point of view and has not mixed with surface waters. Total dissolved solids (TDS) are relatively low, with a value of 2.2 g/l for TD4 at atmospheric separator. Non-condensable gases are less than 0.2 Nl/kg. Main recharge elevation for the Tendaho geothermal system was estimated to be 3000 m a.s.l. within the upper portion of the escarpment. The northeast boarder of the Tendaho cotton plantation, where intense thermal activity is concentrated and proven to be productive, also contains low- resistivity anomaly (Oluma et al., 1996). Figure 2 shows the resistivity distribution and the location of the wells.

2.2 Downhole temperature and pressure

Most of the temperature and pressure data for wells 1-4 were collected by Aquater (1994a and b; 1995a and b) as measurements and well testing were part of the drilling contract. The remaining data were collected by the Ethiopian Institute of Geological Surveys. A total of 131 temperature and pressure surveys are considered in this report. Downhole temperature and pressure surveys were carried out by using Amerada and Kuster mechanical gauges. As the elevation difference between the wells is less than 2 m, downhole profiles are plotted against depth from ground level. The location of the wells and the elevation data are based on recent geodetic survey results (Belete, 1998).

TABLE 1: An overview of the Tendaho geothermal wells

Well No.	TD1	TD2	TD3	TD4	TD5	TD6
Drilling date						
From	29/10/93	13/03/94	07/09/94	27/04/95	20/12/97	01/02/98
To	27/02/94	10/05/94	19/10/94	09/05/95	14/01/98	20/02/98
Location (UTM)						
East (m)	73237708	731412	728652	731363	731558	731670
North (m)	1303746	1302823	1309451	1302941	130290	1302919
Elevation (m a.s.l)	365.9	365.7	366.8	365.2	366.3	366
Well design						
Casing depth (m): 20"	130.5	111	62	24	47.6	40
13 3/8"	575	607	404.5	109	136	123
9 5/8"	850	854.5	830	210	220	217
7" liner	800-1500	809-1807	681-1362	181-463	202-508	209-504
Measured depth (m)	2196/1550*	1881	1989	466	516	505
Vertical depth (m)	2196/1550*		1989	466	516	505
Kick-off point (m)		885				
Inclination (°)		17				
Direction		N50E azimuth				
Status of well	Non-productive	Productive	Non-productive	Productive	Productive	Productive

* Current depth (re-drilled depth after well collapse)

3. INITIAL WELL TEMPERATURES AND PRESSURES

3.1 General information

Temperature is one of the most important parameters needed for geothermal reservoir analysis. Information obtained from temperature logs can be useful for heat flow estimation, location of aquifers, temperature distribution in geothermal reservoirs, reservoir assessment and efficient resource exploitation management. The initial reservoir pressure is also of importance. It delineates possible upflow zones of the reservoir as a pressure high or low. It also provides an important reference for analysing production data, including completion tests for estimating reservoir permeability. Repeated pressure logs during warm-up may also show the depth of the major feed zone of the respective well (pivot point analysis).

The cross-correlation of downhole pressure and temperature, with respect to boiling, is necessary in natural state analysis. Geothermal reservoirs often are characterised by vertical cross-flow of water and steam (heat pipe). In these depth intervals, pressure and temperature follow the so-called boiling point for depth curve (BPD). In the following analysis of downhole data, the BPD is used repeatedly for estimating the phase conditions of the Tendaho reservoir.

Temperatures recorded during drilling operations are generally lower than true formation temperature. These low temperatures result because of cooling by circulating drilling fluid. As soon as circulation stops, the temperature around the wellbore begins to increase. Complete temperature recovery in a new well may take anywhere from a few hours to a few months. A long wait for temperature recovery could cause a sizeable increase in drilling costs. Therefore, predictions of formation temperatures have to be done using other methods. The methods are based on temperature logs taken during drilling stops, or collection of such logs, forming a temperature recovery curve spanning several hours to months.

The formation temperature estimation for the Tendaho geothermal wells is done by applying one of the ICEBOX software packages (Arason and Björnsson, 1994; Helgason, 1993). The program BERGHITI used here, offers two methods of calculation.

The Albright method was developed for direct determination of bottomhole formation temperatures during economically acceptable interruptions in drilling operation, 12 to 24 hours, depending on depth and rock type. This method assumes an arbitrary time interval, much shorter than the total recovery time, and that the rate of temperature relaxation depends only on the difference between the borehole temperature and the formation temperature.

The Horner plot is a simple analytical technique for analysing maximum bottomhole temperatures to determine the formation temperature. The basic criteria for the technique is a straight line relationship between the bottomhole temperatures and $\ln(\tau)$:

$$\tau = (\Delta t + t_o)/\Delta t \qquad (1)$$

where Δt is the time passed since circulation stopped and t_o is the circulation time.

Using this and the fact the system must stabilize after infinite time, the bottomhole temperature as a function of $\ln(\tau)$ is then plotted. By drawing a straight line through the data and by extrapolating it to $\ln(\tau)=0$, the formation temperature can be estimated.

The following text describes briefly how the initial pressures and temperatures were estimated for the 6 Tendaho wells. Table 2 shows the numerical values of these 12 profiles.

TABLE 2: Formation temperatures and initial pressures in Tendaho wells

Well TD1			Well TD2			Well TD3			Wells TD4, 5, 6		
D (m)	P (bars)	T (°C)	D (m)	P (bars)	T (°C)	D (m)	P (bars)	T (°C)	D (m)	P (bars)	T (°C)
0	5.3	29	0	5.4	100	30	0.5	58.4	0	0	100
200	24.1	147.6	50	9.9	155.8	40	1.5	64.2	50	4.6	155.8
250	28.6	162.3	100	14.3	180.4	50	2.4	74.2	100	9	180.4
300	33	180.8	150	18.6	197.7	60	3.4	83.8	150	13.3	197.7
350	37.3	197.4	200	22.8	208.4	65	3.8	85.2	200	17.5	208.4
400	41.5	211.4	250	26.9	218.7	70	4.3	81.4	250	21.7	218.7
450	45.6	223.7	300	31	227.7	80	5.3	79.3	300	25.8	227.7
500	49.7	233.8	350	35.1	235.6	100	7.2	74	350	29.8	235.6
550	53.7	243.2	400	39.1	242.6	120	9.1	72	400	33.8	242.6
600	57.6	250.2	440	42.2	245	160	12.9	70	450	37.8	248.9
650	61.5	253.9	450	43	245	250	21.5	94.6	500	41.7	254.7
700	65.4	258.1	500	47	243	300	26.2	112.2			
850	76.9	267.8	600	55.1	226.8	350	30.8	130.4			
950	84.5	274	700	63.4	220.7	400	35.3	145			
1000	88.2	274.5	800	71.7	211.6	500	44.3	161.3			
1050	92	273.7	900	80.1	212	600	53.2	167			
1100	95.7	274.5	950	84.3	212.8	700	62	170			
1150	99.51	273.9	1000	88.5	213.6	800	70.9	171			
1250	107.1	271.3	1040	91.8	215.7	850	75.3	171.7			
1300	110.9	268.5	1200	105.2	220.2	900	79.7	172.1			
1350	114.7	267.5	1400	121.8	223.1	1000	88.5	173.1			
1400	118.5	266	1600	138.4	223.1	1100	97.4	174.1			
1500	126.2	267.5	1700	146.7	223	1200	106.2	176			
1600	133.8	272.6	1734	149.5	223	1300	115	177.2			
1830	151.2	279				1400	123.8	180.4			
1860	153.5	279.2				1500	132.5	184.3			
1890	155.7	279.7				1600	141.3	187.3			
1950	160.3	280.4				1700	150	190			
2160	176	282				1800	158.7	193.3			
						1900	167.3	196.3			
						1967	173.1	198.2			

3.2 Well TD1

Well TD1 was drilled to 2196 m. The formation collapsed while reaming from 944 to 973 m depth after air lifting. The present re-drilled total depth is 1550 m with a 7" liner from 800 to 1500 m depth (Table 1). Total loss of circulation occurred at 511 m which could have been a producing zone if the 9 5/8" production casing shoe was not set at 850 m. Despite the high temperature (>270°C) at depth, the well cannot sustain flow due to poor permeability.

A total of 16 downhole temperature measurements are presented in Figure 3. A formation temperature estimate through application of the Horner method is also shown. Four temperature logs were used for the estimation of the formation temperature in the depth range 950-2196 m. The temperature build-up data at 573, 842, 955 and 1980 m depths were also analysed with the Albright and Horner methods. The Albright method gave similar results to the measured static temperatures, whereas the Horner method´s estimates are lower. This could be due to the effect of circulation time.

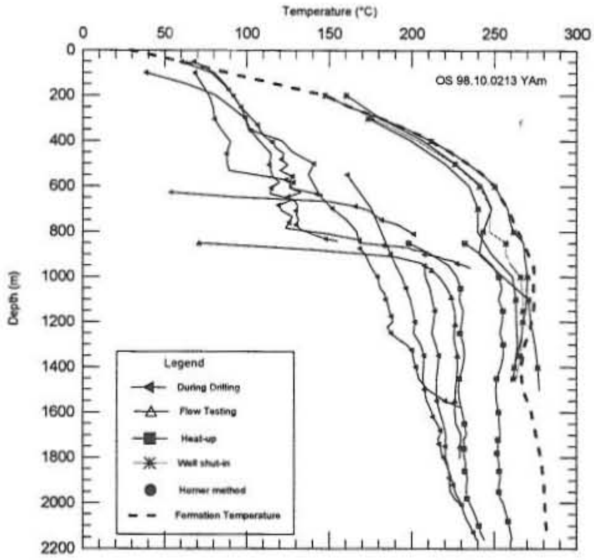

FIGURE 3: Temperature profiles in well TD1

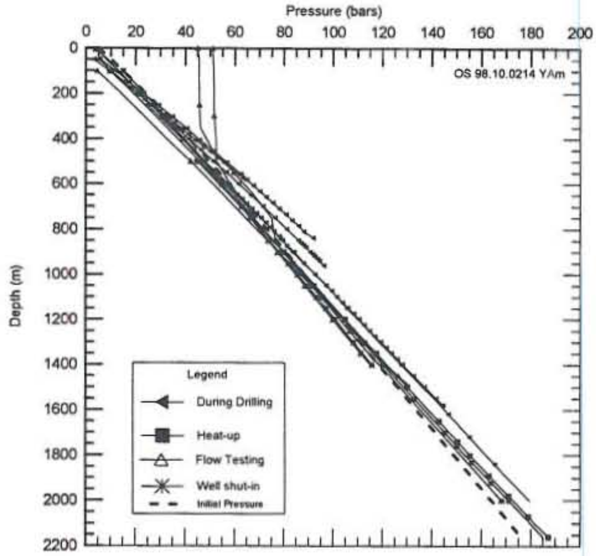

FIGURE 4: Pressure profiles in well TD1

The shape of the formation temperature suggests that the heat transfer in the upper 600 m is by conduction with an average temperature gradient of about 370°C/km. Temperature increases from the surface down to 950 m, and is constant to about 1100 m depth. From 1100 m to about 1400 m, there is temperature reversal. In the deepest part of the hole section (1700- 2200 m), the temperature gradient is positive with <20°C/km. By comparing the formation temperature profile and the boiling point with depth curve, one can conclude that the reservoir is under single phase liquid condition at all depths.

The measured pressure profiles and the initial pressure estimate are shown in Figure 4. A pivot point is observed around 900 m depth. The initial pressure is calculated from the estimated formation temperature by using the PREDYP program (Arason and Björnsson, 1994). The calculated initial pressure is almost identical to one of the measured static profiles. A feed zone is most likely at about 900 m depth with initial pressure of abut 80 bars and 270°C temperature. The shut-in wellhead pressure is stable at 5.3 bars showing that the deep reservoir is over-pressurized (well full of water).

3.3 Well TD2

Well TD2, which is located 1200 m from well TD1, was drilled to a total depth of 1811 m. It is a directional well with a kick-off point at 885 m. The reason for the drilling plan to change from vertical to directional was to cross an inferred vertical fault which was deduced from the alignment of active thermal features of the surface. The postulated vertical fault does not seem to be there. As the direction of inclination towards TD1 is not confirmed, the well is treated as a vertical well for later downhole temperature and pressure analysis.

Fourteen temperature measurements recorded at different conditions are shown in Figure 5. Five profiles were used for a formation temperature estimate applying the Horner method. The estimated temperature is near identical to a run which was measured in 1996 after 2 years of shut-in conditions. This implies that the well´s temperature is in equilibrium with the geothermal system. From the surface to about 425 m, the temperature follows the BPD curve. From 425 m to about 800 m, there is a temperature reversal. From 800 m to about 1400 m depth, temperature increases slightly and is nearly constant below 1400 m. The temperature reversal could indicate that the well is located in an outflow area of the geothermal field.

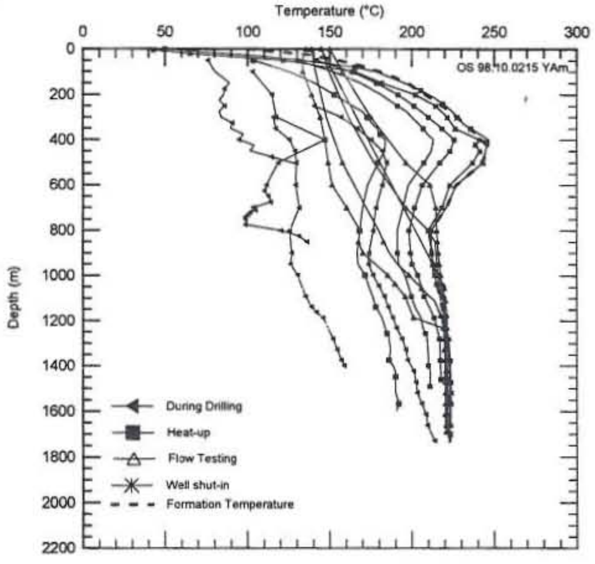

FIGURE 5: Temperature profiles in well TD2

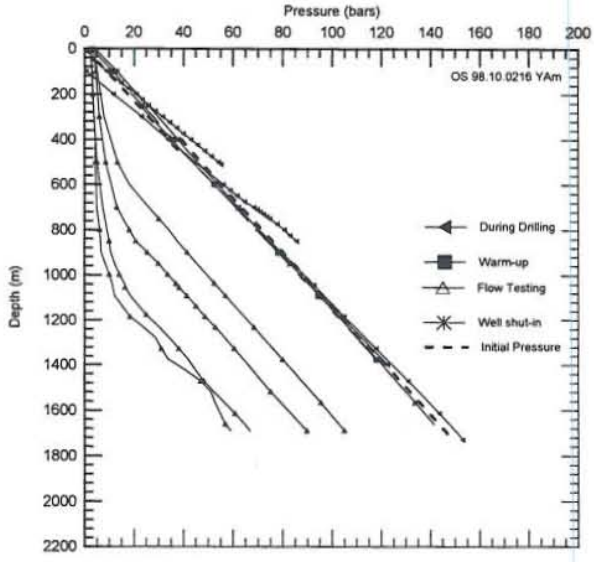

FIGURE 6: Pressure profiles in well TD2

All collected downhole pressure profiles are shown in Figure 6. A pivot point is observed at around 900 m depth, with a pressure of 80 bars. The estimated initial pressure follows the boiling depth curve from the surface to about 450 m depth, in good agreement with the measured temperature (Figure 5). Below this depth, the pressure gradient is slightly higher than that of the BPD in accordance with a shut-in wellhead pressure of 5.4 bars. This leads to the conclusion that the Tendaho reservoir can be divided into a deep and a shallow reservoir. The shallow reservoir is characterised by boiling and pressure potential in equilibrium with the surface, whereas the deep system is over-pressurised and in single phase water condition.

3.4 Well TD3

It is located at a distance of 7 km from well TD1 (Figure 2). There are no thermal activities around the well site but a high thermal gradient was measured in a nearby shallow well. The well was drilled to a total depth of 1989 m. Despite many trials to discharge the well by air lifting, the well was not able to flow because of poor permeability and low temperature.

The temperature build-up tests conducted during drilling were analysed. Estimates by the Albright method are relatively higher than the last static profile, whereas the estimates made by the Horner method are lower. The static temperature is almost the average of the estimates made by both methods (Figure 7). As it is most likely that the well temperature has stabilized in the last run, it is taken as the formation temperature. A zone of hotter fluid is clearly visible at 50 m depth from a temperature log during drilling. This indicates a geothermal outflow somewhere near the well.

The formation temperature profile suggests that the temperature gradient is about 250°C/km in the upper part of the well. Below 550 m the gradient is low (~ 20°C/km).

The initial pressure is based on the estimated formation temperature and the PREDYP program. It is presented together with pressure profiles measured during drilling and warm-up periods in Figure 8. The well has a stable water level at about 25 m depth.

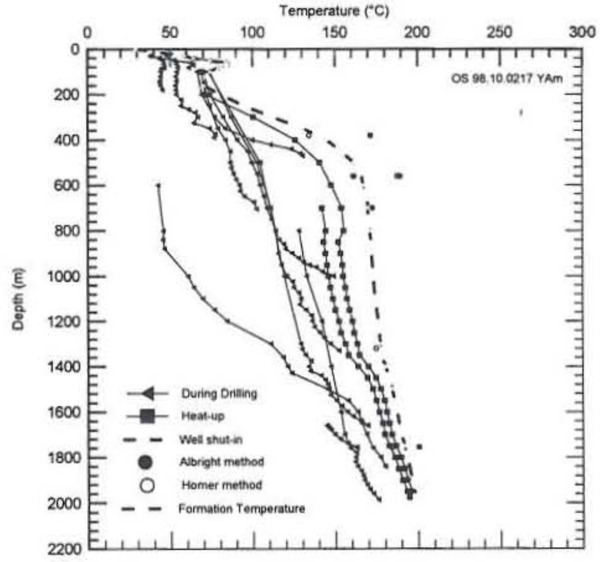

FIGURE 7: Temperature profiles in well TD3

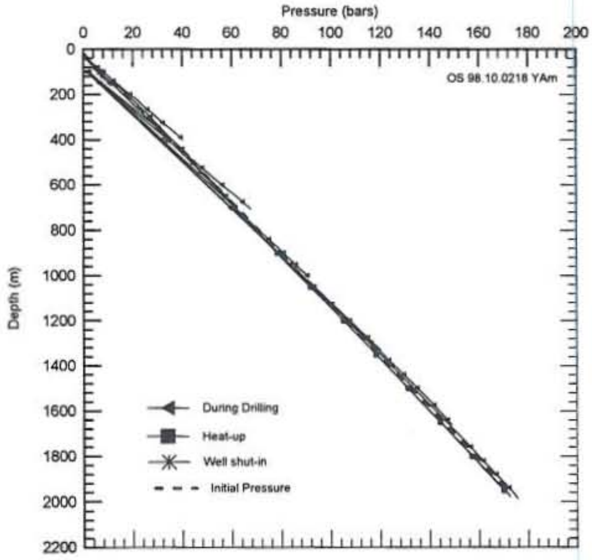

FIGURE 8: Pressure profiles in well TD3

3.5 Well TD4

It is the first shallow well (466 m) drilled in the thermally active part of the Dubti geothermal field at a distance of 120 m from the deep directional well TD2 (Figure 2 and Table 1). The well produces about 50 kg/s total of fluid at an average wellhead pressure of 13.6 bars. The corresponding enthalpy of the fluid is 1080 kJ/kg. The well produces from many feedzones, resulting in cyclic behaviour during flow.

As the drilling of well TD4 was not part of the pre-planned drilling programme, the drilling and testing time was short. As soon as the drilling was completed, the well was put to discharge. The downhole temperatures measured at different well condition are shown in Figure 9. Due to a leakage through the 10" side valve during downhole measurements, static conditions could not be attained. This is clearly visible from the similarities of the temperature profiles at shut-in and flowing conditions (Figure 9). Almost all temperature profiles follow the boiling point for depth curve below the casing. The formation temperature is, therefore, assumed to be the same as the boiling point for depth curve. Two major feed zones at around 250 m and 330 m depth are identifiable from temperature profiles taken during drilling.

Figure 10 shows pressure profiles measured during drilling, flow testing and the estimated initial pressure. The pressure pivot point is not visible, most likely due to the presence of more than one feedzone. For the major feedzone at 250 m, the initial reservoir pressure is about 22 bars. The wellhead pressure at shut-in conditions fluctuates between 20 and 22 bars, indicating a pure steam condition between the wellhead and the feedzone at 250 m. The fluctuation may be due to the cycling boiling level in the well, around 250 m depth.

3.6 Well TD5

Well TD5 is the second shallow well drilled inside the Tendaho Cotton Plantation (Dubti area), some 300 m from well TD4 (Figure 2 and Table 1). Despite indications of possible feedzones at about 300 and 500 m depths, cyclic behaviour is not observed either during discharge tests or at shut-in condition. This could mean that the production zone is from 300 m to total depth. The short term flow testing indicates that the well can produce 48 kg/s of fluid (steam and water) at 9.4 bars wellhead pressure.

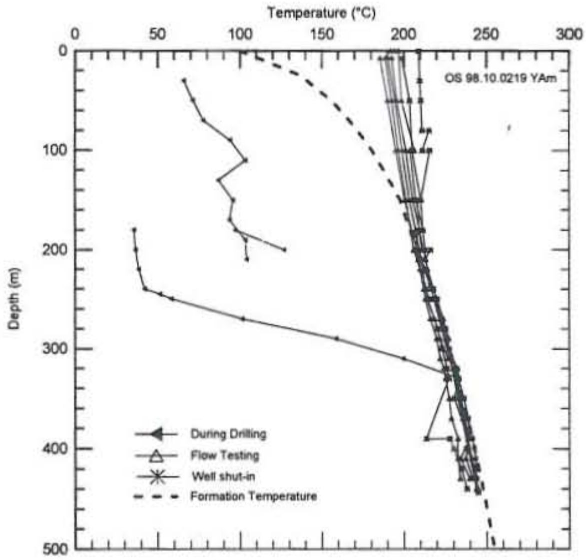

FIGURE 9: Temperature profiles in well TD4

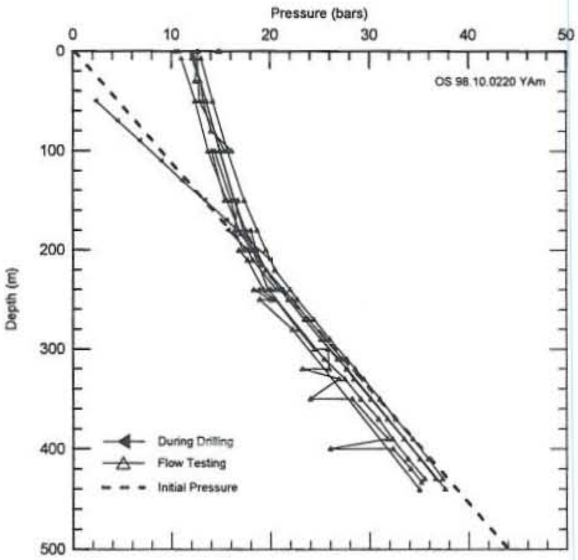

FIGURE 10: Pressure profiles in well TD4

Figure 11 shows downhole temperature profiles logged during drilling, heat-up and flow testing. The heat-up temperature profiles are almost identical. They coincide with the boiling point for depth curve from bottom hole to about 440 m depth. The formation temperature is, thus, assumed to be the same as the BPD curve. Above this depth the temperature is higher than the BPD due to the presence of gas and steam inside the casing at shut-in conditions. The measurements during flow testing through 4, 5 and 6" diameter lip pipe, respectively, show that downhole temperature decreases with increasing discharge pipe diameter. The BPD curve is crossed at 270, 140 and 100 m depth during the flow testing through 4, 5 and 6" pipes, respectively. This means that during flow, boiling will propagate into the reservoir.

The measured pressure profiles and the initial pressure profile are shown in Figure 12. The initial reservoir pressure is 34.5 bars at 400 m depth, where the pivot point is located. The wellhead pressure at shut-in condition is 21.5 bars.

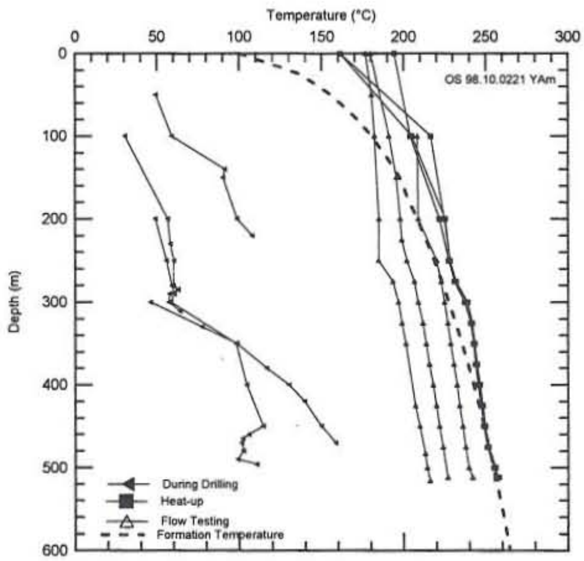

FIGURE 11: Temperature profiles in well TD5

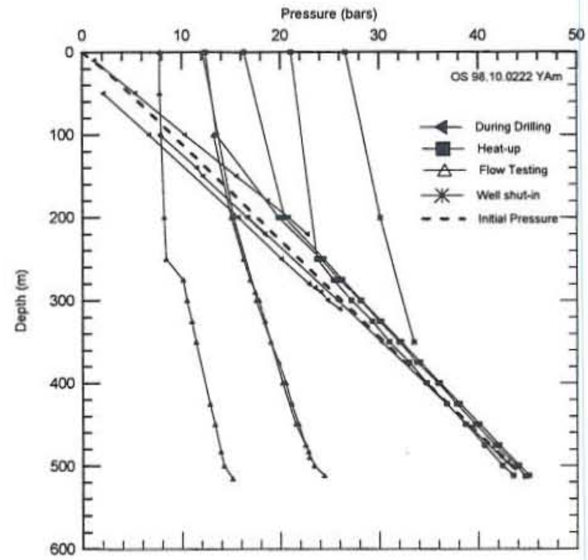

FIGURE 12: Pressure profiles in well TD5

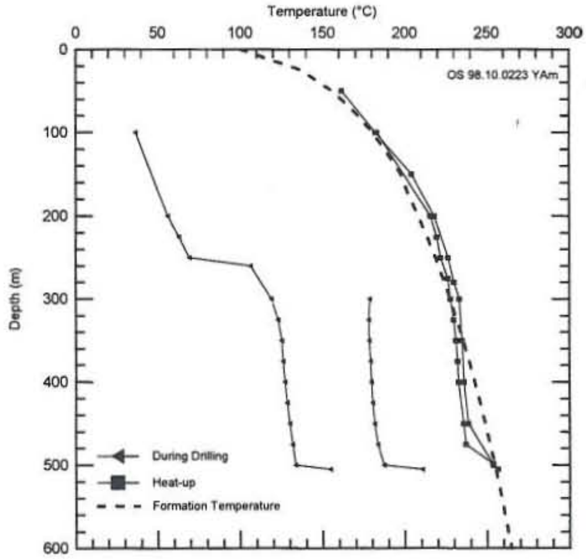

FIGURE 13: Temperature profiles in well TD6

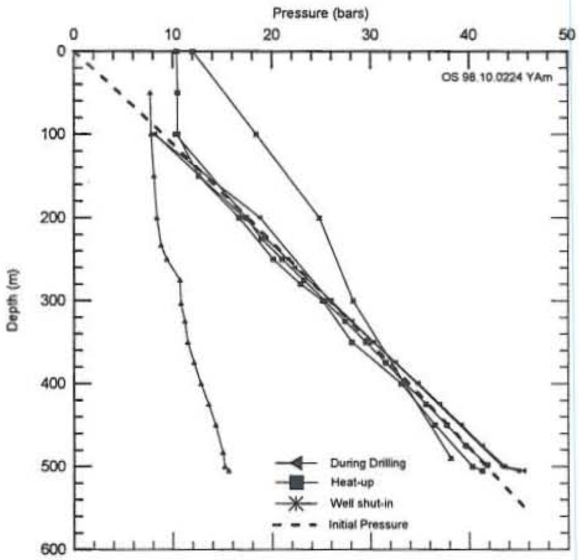

FIGURE 14: Pressure profiles in well TD6

3.7 Well TD6

It is the third shallow well drilled recently to a total depth of 505 m. The well is located between TD5 and TD4 (Figure 2 and Table 1). Due to limited drilling time, only few downhole measurements have been carried out. Furthermore, temperature and pressure measurements during the first three weeks of the heat-up period were not possible because of rig maintenance work at the wellhead.

The few available temperature profiles are shown in Figure 13. Due to the limited drilling time and the shortage of accurate low range temperature elements, temperature build-up tests were not carried out. The profiles measured during heat-up show that the boiling point for depth curve is attained. The formation temperature is, therefore, assumed to be similar to the boiling point for depth curve.

Figure 14 shows the pressure profiles of well TD6. The pivot point of the pressure profiles indicates that the major feed zone is at about 300 m. The corresponding initial reservoir pressure is then estimated to be 25.6 bars. The estimated initial pressure profile is shown in Figure 14. The shut-in wellhead pressure is about 18.5 bars.

4. A CONCEPTUAL RESERVOIR MODEL

Conceptual models are used in all stages of geothermal energy exploration and exploitation. Typically, exploration wells are located to delineate a resource, and production wells to intersect areas of high temperature and permeability. The location of these wells are, in most cases, based on a conceptual model of the reservoir. In turn, the data from new wells are then used to confirm, or more likely, improve the conceptual model (Okandan, 1988). Conceptual reservoir models also serve as an integral part of numerical reservoir models, as they provide the basis for model geometry, boundaries, recharge sites, etc.

The formulation of a conceptual model for the Tendaho geothermal field is based on the available temperature and pressure distributions, which shall be improved in the future by the drilling of new wells and longer production history.

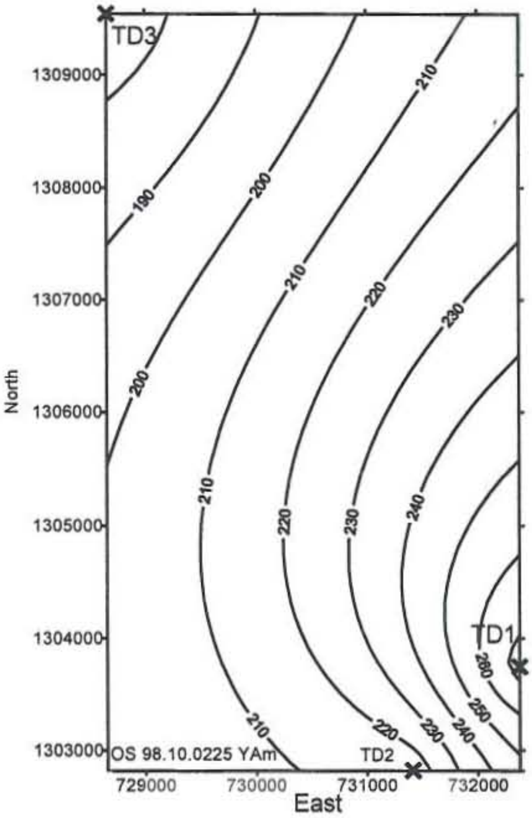

FIGURE 15: Temperature contours at 1000 m depth

Figure 15 shows a temperature contour map at 1000 m depth. The data in the figure are taken from the formation temperature profiles estimated in Chapter 3. A hot fluid recharge from east to west in the present wellfield is suggested. A temperature contour map at 450 m depth is shown in Figure 16. The low temperature and poor permeability well TD3, which is located at a distance of about 7 km, is not included in this map. The highest temperature at this depth is around the shallow wells TD4, TD5 and TD6.

Figure 17 shows a NE-SW temperature cross-section through wells TD1, TD5, TD6, TD2 and TD4. The distance between the wells shown is not exact but approximation is made for clear presentation. The higher temperature at shallow depths around well TD2 suggests that the high temperature fluid flows from depth around TD1 and then laterally to a shallower level towards TD2. The temperature reversal at TD2 is also noticeable.

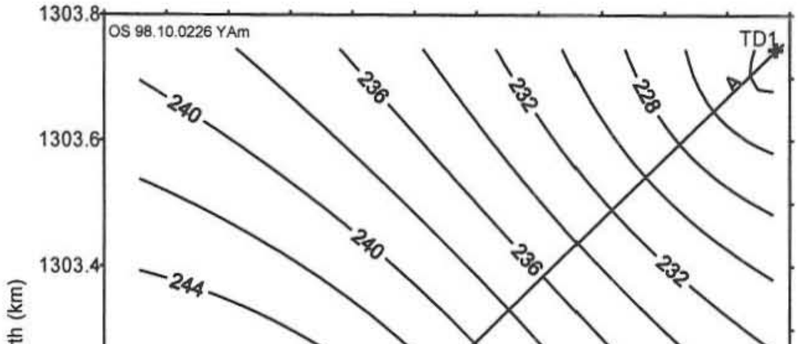

FIGURE 16: Temperature contours at 450 m depth

Figure 17 also serves as a conceptual model for the Tendaho geothermal field. A hot fluid recharge at a temperature of about 270°C flows from the east towards well TD1. This is also suggested by the location of the low-resistivity anomaly (Figure 2). Around TD1 the recharge rises to about 1100 m and then flows towards TD4. Two reservoir domains are suggested for the Tendaho area. A shallow reservoir BPD may have a reservoir thickness of about 300 m and a temperature of 230-250°C. Due to the close spacing and the limited number of the shallow wells, the areal extent of the reservoir is unknown. From the temperature cross-section, one may assume that the geothermal reservoir lies at relatively greater depth east of TD5. In the vicinity of wells TD4 and TD2, feed zones are at a shallower level compared to that of TD5.

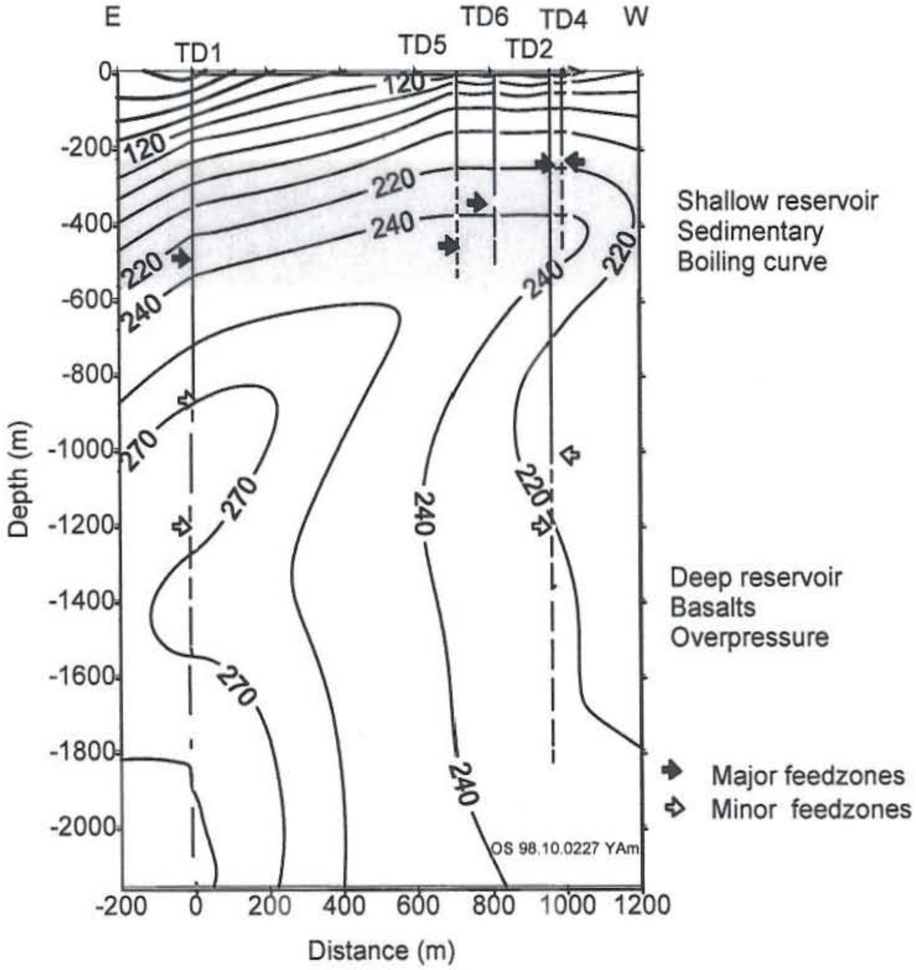

FIGURE 17: A temperature cross-section from northeast to southwest and a conceptual model for the Tendaho geothermal field

5. PRODUCTION TESTING

The output testing of two-phase geothermal wells consists of measuring mass flow rate, wellhead pressure and mixture enthalpy. The lip pressure method, which was proposed by Russel James (1970) was employed in Tendaho. The method is based on a relationship observed between the flowing pressure at the end of a horizontal pipe discharging to a silencer, enthalpy and the flow rate in the pipe. The water flow rate was measured by a 90° V-notch weir.

Due to the limited capacity of the waste water disposal ponds and other reasons, the wells at Tendaho have been tested for production only for a short period of time. The tests performed and the results obtained are summarized as follows (Table 3):

Well TD1: Is non-productive. During a spontaneous discharge through a 1" bleed line, the well produced a few kg/s fluid of high enthalpy for a few hours.

Well TD2: The well discharged through 3, 4, 5 and 6" diameter lip pipes for a total of 23 days. It produces about 15 kg/s total fluid at a wellhead pressure of about 3 bars. The enthalpy of the discharged fluid is estimated at 920 kJ/kg. The low wellhead pressure is most likely due to low reservoir permeability and temperature. The well produces from several feed zones.

TABLE 3: Summary of production tests for the Tendaho wells

Well No.	Wellhead pressure (bar-a)	Total mass (kg/s)	Steam (kg/s)	Enthalpy (kJ/kg)	Remarks
TD2	2.4	17.5			
	2.5	18			
	2.6	18.4			
	3.2	13		916	
	3.3	13.5			
	3.4	14.3			
	3.8	9.6			
	4.0	9.7			
TD4	13	70.7			
	13.1	50.8		940	
	13.3	69.7			
	14	32.2			
	14.3	32.9			
TD4	14.4	50.4	14	1065	27 days test average
TD5	7.8	44.6	15.1	1185	7 days test average
	10.4	48.5	14.5	1095	5 days test average
	13.4	37.5	9.9	1010	6 days test average
TD6	4.9	33.2	8.5	995	7 days test average

Well TD4: The results of short term tests through 3, 4, 5 and 6" lip pipes indicate that the production capacity of the well is as high as 70 kg/s total flow. The estimated enthalpy is 940 kJ/kg (Table 3). A long term production test was planned in 1996. The well discharged through 4" lip pipe for 26 days. The test was interrupted because intense thermal activity around the wellhead created unsafe working conditions. The problem was intensified by increasing water levels in nearby wastewater disposal ponds. The result of the 26 days discharge test indicates that production is relatively constant except for small variations because of well cycling. The average production of the well through the 4" pipe was 50.4 kg/s total fluid at a wellhead pressure of 14.4 bars. The fluid enthalpy was about 1065 kJ/kg and the steam flow rate 14 kg/s.

Well TD5: Short term production tests were carried out in three steps by discharging the well for 6, 5 and 7 days, respectively. The test results are shown in Table 3. This short term test indicates that the maximum total flow rate is attained during discharge through 5" diameter lip pipe (48.5 kg/s at 10.4 bars). This implies that during discharge through 6" pipe, the flow in the well is choked through larger diameter pipe resulting in no flow rate increment.

Well TD6: The well was discharged for one week through a 6" diameter pipe. The average production rate at a wellhead pressure of about 5 bars was 33 kg/s total fluid with an enthalpy of 990 kJ/kg. The production capacity of TD6 seems to be less than for well TD5. The output test summary is in Table 3.

6. ANALYSIS OF PRODUCTION DATA

Only limited amounts of production data are available so far for the Tendaho geothermal reservoir. The data available can be grouped into two categories, 1) short term completion tests and 2) short term discharge tests. In the following section, the production data is analysed in terms of reservoir permeability and future well performance.

TABLE 4: Summary of well test analysis

Well No.	Test type	Depth (m)	*q* (kg/s)	*m* (bar/cycle)	$kh/\mu\ 10^{-8}$ ($m^3/s/Pa$)	*kh* (Dm)	Injectivity index (kg/s/bar)
TD5	Fall-off	290	14.1	1.3	2.4	2.4	3.7
	Fall-off	490	14.1	0.7	4.5	4.5	3
	Pressure build-up	490	37.5	0.8	10	10	
TD6	Fall-off	300	14.1	0.5	6.2	6.2	5

$\mu = 1 \times 10^{-4}$ kg/ms, at 230°C; $\rho w = 827$ kg/m^3, Dm = 10^{-12} m^2

6.1 Permeability estimation

In the field, a record of downhole pressure with time is measured. Here we work with the pressure decline observed after injection stops (fall-off). Given that the injection time is t_p and that dt is the time which has passed after injection terminated, one can plot the pressure as a function of the logarithm of $(t_p+dt)/dt$. This should give a straight line of slope m, where m is the pressure change over one log cycle in time. The permeability-thickness, *kh*, is then related to *m* by the relationship (Sigurdsson, 1998; Matthews and Russel, 1967)

$$kh/\mu = 0.1832q/m \tag{2}$$

where μ (kg/m.s) is the dynamic viscosity and q (m^3/s) is the flow rate.

Well TD5: Two fall-off and one pressure build-up tests were carried out at 290 and 490 m depths. The analysis results indicate that the well has good permeability. The injectivity tests at 290 and 490 m depths also indicated that the well is a good producer. Table 4 shows the summary of the well test analysis results and Figure 18 shows the data on a Horner plot for pressure build-up after discharge.

Well TD6: Only one fall-off test at 300 m depth is available for analysis. The permeability thickness-product is higher than that of TD5 at 290 m depth. The injectivity index is estimated at about 5 kg/s/bar. The results are shown in Table 4.

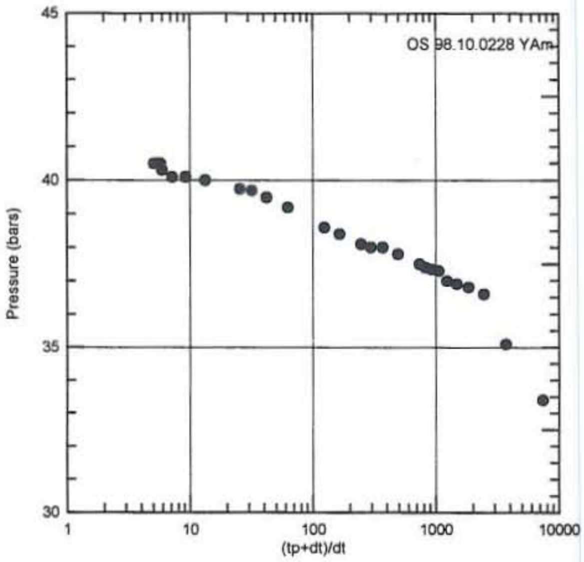

FIGURE 18: Pressure build-up data in well TD5 (Horner plot)

The data in Table 4 show sufficient permeability in the shallow parts of the Tendaho wellfield. For comparison, a common value of the permeability-thickness product in various geothermal systems is in the range 1-100 Dm (Björnsson and Bödvarsson, 1990). The short term production data points, therefore, towards favourable production characteristics for the shallow Tendaho system. Also noticeable is the high injectivity index of the wells. It ranges between 3 and 5 (kg/s)/bar. Recent survey in the Svartsengi field in Iceland shows an injectivity index in the range 2-10 (kg/s)/bar in a reservoir of 100 Dm permeability and 240°C temperature (Björnsson, 1998). Well productivity there has proven to be above average in the long run, suggesting that the Tendaho system is also favourable for production. The limited extent of the shallow wellfield, however, is of concern and must limit the long term production capacity (i.e. the heat in storage limits the production capacity rather than the fluid in storage).

6.2 Well performance

The wells at Tendaho have been tested for production only for a very short time. The output test results obtained during these short term tests are presented in Table 3.

As it is of interest to predict the future performance of the Tendaho wells, a simple, quantitative study was performed on the well output data. By applying the wellbore simulator HOLA (Björnsson et al., 1993) one can predict the influence of future reservoir pressure and enthalpy changes on well output. The method is based on the following:

1) The well output curve is simulated by the HOLA program, given the well design and the present reservoir enthalpy and pressure at the bottomhole feedzone (Chapter 3). By iteration a productivity index, PI, is defined for the feedzone. This is a geometric property of the well connection to the reservoir.
2) Knowing the productivity index, one can vary the reservoir pressure or enthalpy and predict new wellhead output curves at these variable reservoir conditions.

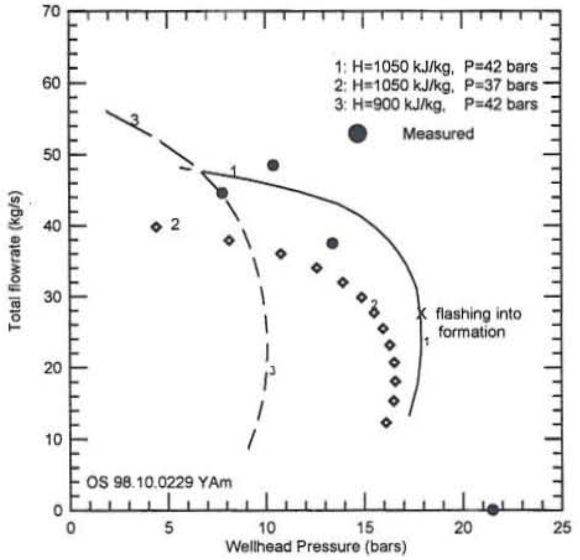

FIGURE 19: Simulated output curves for well TD5

Although the above procedure has no connection to time, it provides insight to possible well output characteristics in the future and provides, thus, confidence for additional investment in the present wellfield.

Figure 19 shows present and possible output curves for the newly drilled shallow well TD5. The estimated productivity index for the feedzone is $6x10^{-12}$ m^3. Using this productivity index, output curves were calculated for different reservoir conditions. The simulation exercise suggests that a reservoir pressure drawdown of 5 bars causes 10 kg/s mass flow rate reduction. Figure 19 also shows predicted output curves for stable reservoir pressure but an enthalpy decline to 900 kJ/kg, which corresponds to 210°C reservoir temperature instead of the 220-240°C at present. The well can still produce at high flowrates, but this may require flowing wellhead pressures close to separator pressure.

TD4 was also simulated for possible output curves. The simulation indicates that the productivity index of the well is high ($60x10^{-12}$ m^3). A best fit for the output data was obtained for an enthalpy of 970 kJ/kg.

7. RESOURCE ASSESSMENT

7.1 General

Evaluation of geothermal resources requires knowledge of many parameters such as the area extent of the field, the thickness of the reservoir, temperature and pressure distribution, porosity, density and heat capacity of the rock. The quantity and quality of available data are the limiting factors for the accuracy of the resource estimate.

Following is a resource evaluation carried out for the Tendaho shallow reservoir. It is based on a rough calculation on the available thermal energy in the reservoir. An estimate for the production capacity is made by the volumetric method (Sarmiento, Z., 1993). As several of the factors/parameters used for the estimate are only known approximately, an attempt is made to define the accuracy of the calculations by applying random distribution to some of them.

7.2 The volumetric method

The volumetric method involves the calculation of thermal energy contained in a given volume of rock and water and then the estimation of how much of this energy might be recoverable. The thermal energy in the subsurface is calculated as follows:

$$E = E_r + E_w = VC_r\rho_r(1-\Phi)(T_i-T_o) + VC_w\rho_w\Phi(T_i-T_o) \tag{3}$$

where

- E = Total thermal energy in the rock and water (kJ);
- V = Reservoir volume (m^3);
- T_i = Initial reservoir temperature (°C);
- T_o = Reference temperature (°C);
- $C_{r,w}$ = Heat capacity of rock, water (kJ/kg°C);
- $\rho_{r,w}$ = Density of rock, water (kg/m^3);
- ϕ = Porosity.

For the Tendaho shallow geothermal reservoir the following assumptions were made:

T_i = 240°C, T_o = 200°C, ϕ = 0.2, ρ_r = 2700 kg/m³, C_r = 1000 J/kg°C;
r = 700 m (radius of shallow reservoir), h = 300 m (reservoir thickness)

Here it should be noted that the above values are based on the analyses in Chapters 3 and 4. The shallow reservoir temperature and radius are, for example, based on Figure 16. Inserting the above values in Equation 4 results in an estimated heat energy of 5.2×10^{16} J.

The electrical power potential of the reservoir is calculated as follows:

$$Reserve\,(MW_e) = \frac{heat\ energy \times recovery\,factor \times conversion\ efficiency}{plant\ life \times load\,factor} \tag{4}$$

Here we assume a *recovery factor* of 0.25, a *load factor* of 0.8, a *conversion efficiency* from thermal to electrical power of 0.05 (back pressure turbine) and a *plant life* of 20 years. This gives an electric power energy estimate for the shallow reservoir as **1.3 MWe.**

This estimate should be taken as a best guess for the small wellfield known at present. Although one may find it tempting to use a larger value for reservoir area, it would only provide an estimate for a possible reservoir volume. Note also that by using the same presumption for the deep system except that now the reservoir thickness is 1200 m, radius 1 km and temperature 260°C, an electric power estimate of 160 MWe is attained. Larger power plant operation in the area should, therefore, concentrate on the deep reservoir system.

7.3 The Monte Carlo probability method

The Monte Carlo probability method deals with the quantification of the uncertainties or probability distributions in the parameters involved in reserve estimation (Sarmiento, Z., 1993). Uncertainty distributions are given for some parameters involved in the mathematical equation used in estimating the resource potential. Random number generation then solves the algorithm relating to the uncertainty distribution by randomly assessing the values from each distribution individually many times. The result is an overall probability distribution for the reserve estimate that quantitatively incorporates the uncertainties involved in each parameter.

The method was applied for the Tendaho shallow reservoir. The randomness of the uncertain values was defined either by square or triangular probability distributions. Square probability distribution was assigned to the reservoir area and thickness, which means that the minimum possible reservoir area is as likely as the mean and maximum ones. The rock density, porosity and initial reservoir temperature were assumed to follow triangular distribution. This means that the possibility of using either the minimum or the maximum value is negligible, whereas the mean value has the highest probability.

The procedure of calculating the production capacity of the shallow reservoir is as follows:

1) A matrix of 10 x 1000 was created in Excel spreadsheet, each column in the matrix containing random numbers, according to the specified distribution type.
2) The parameters were calculated one at a time using the random numbers.
3) The power output was calculated according to Equation 4 by inserting the numerical values from the matrix that contains all the parameters. This was repeated 999 times for all the lines in the matrix.
4) The estimated production capacity was finally plotted as a histogram.

Table 5 shows the numerical values that were used for the calculations and Figure 20 illustrates the result of the Monte Carlo simulation. The histogram indicates the range of probability estimate from 0.5 to 4.5 MWe with the most likely value in the range 1-1.5 MWe.

TABLE 5: Best guess and probability distributions for the Monte Carlo analysis

Property	Unit	Best guess model	Probability distribution		
			Type	From	To
Area	km^2	1.5	square	0.3	3
Reservoir thickness	m	300	square	200	400
Rock density	kg/m^3	2700	triangle	2400	3000
Rock specific heat	J/kg°C	1000	constant		
Porosity	%	20	triangle	10	40
Reservoir temperature	°C	240	triangle	220	260
Reference temperature	°C	200	constant		
Water density at reservoir temp.	kg/m^3	814	square	780	840
Water specific heat at reservoir temp.	kJ/kg°C	4.2	constant		
Recovery factor for reservoir	%	25	constant		
Thermal efficiency in turbine	%	5	constant		
Plant load factor	%	80	constant		
Plant life period	Year	20	constant		

Note that for generating the randomly distributed reservoir parameters, only the Excel function RAND was used. RAND produces random numbers between 0 and 1. A square distribution of reservoir thickness, L, is then given by L=200+(400-200)*$R1$, where $R1$ is the random number generated. For a triangular distribution, the mean of two random numbers $R2$ and $R3$ is used. As an example, for rock density, ρ = 2400 + ($R2$ + $R3$)/2*(3000 - 2400).

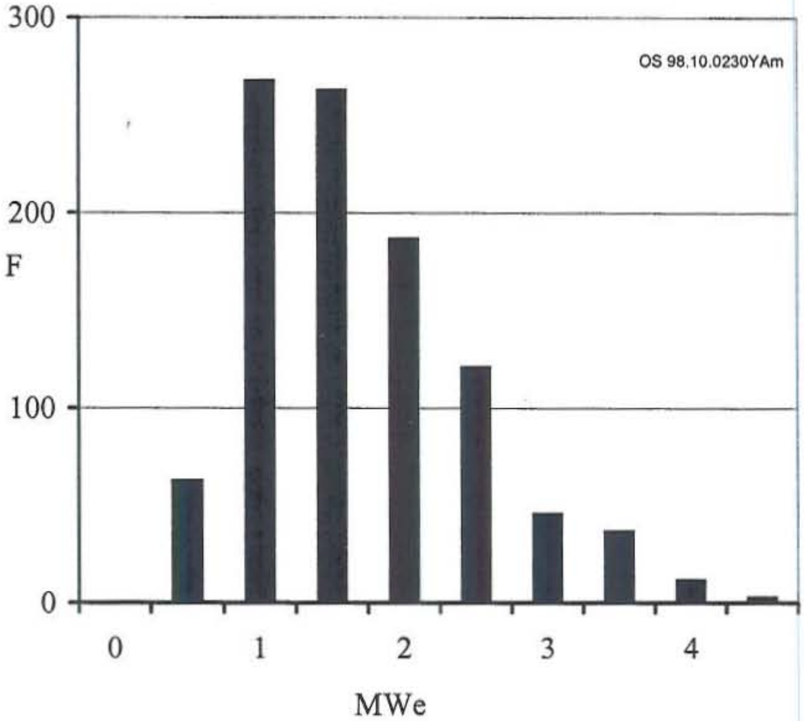

FIGURE 20: A frequency distribution of available electric power in the shallow Tendaho reservoir

8. NUMERICAL MODELLING

It is of interest to confirm the results of Monte Carlo statistical method by using some kind of a distributed parameter, numerical model. The model should, in particular, account for phase changes and the different nature of the outer reservoir boundaries. In the following, a simple production analysis is performed with the aid of the TOUGH2 simulator.

8.1 TOUGH 2

TOUGH, which stands for "Transport of Unsaturated Ground water and Heat", is a multi-dimensional numerical model for simulating the coupled transport of water, vapour, air and heat in porous and fractured media. It is a member of the MULKOM family of multi-phase, multi-component codes, which is being developed at Lawrence Berkeley Laboratory (Pruess, 1987). In 1993, the TOUGH2 version was released. It differs from the former one mainly by much faster execution time.

The governing equations used by the code are the basic mass- and energy balance equations. They are written in integral form for an arbitrary flow domain V_n as follows (Pruess, 1987):

$$\frac{d}{dt}\iiint_{V_n} M^k dV = \iint_{\Gamma_n} F^k n d\Gamma + \int_{V_n} q^k dV \tag{5}$$

where k = 1 for water;
k = 2 for heat;
$M^{(k)}$ = Mass and heat accumulation term;
$F^{(k)}$ = Mass and heat flux;
$q^{(k)}$ = Sink/source.

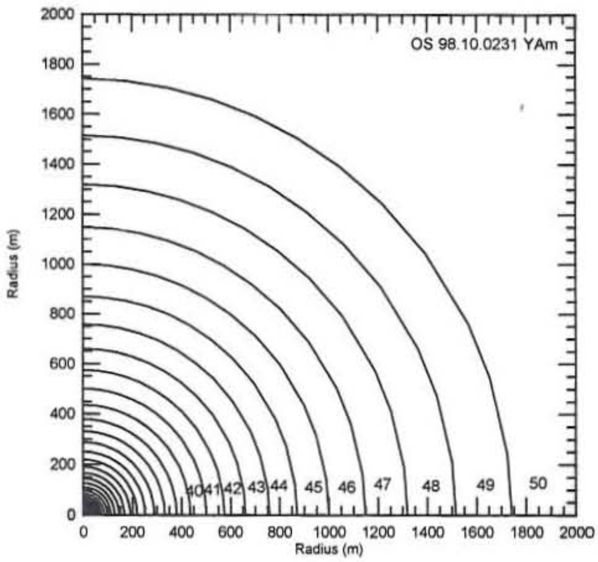

FIGURE 21: One quarter of the TOUGH2 grid

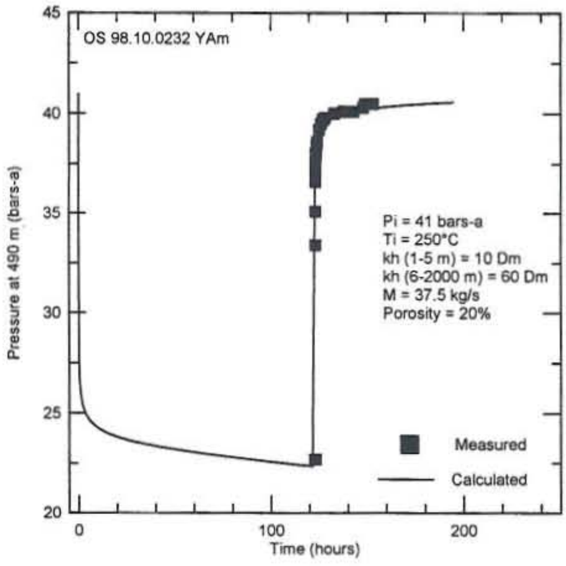

FIGURE 22: Measured and simulated pressure build-up in well TD5

The above formula states that the mass/heat accumulated in a reservoir block V_n with time, must equal the flow of mass/heat through it´s surfaces together with a possible source of heat/mass within the block.

8.2 The numerical reservoir model

For convenience a simple, radial grid was used as a reservoir model for the Tendaho geothermal field. Figure 21 shows the grid. A simple 1-D, radial flow in a single layer horizontal reservoir of 300 m thickness is assumed. The computational mesh consists of 10 grid blocks with $\Delta R = 1$ m, and 40 additional grid blocks with $\Delta R_{i+1} = \alpha \Delta R_i$ out to a radius of 2000 m. The grid is identical to that of sample problem 4 in the TOUGH manual, except that the thickness is 300 m instead of 100 m (Pruess, 1987).

8.3 Model calibration

Pressure build-up data from well TD5, which was collected after 123 hours discharge at an average flow rate of 37.5 kg/s, was used to calibrate the model in Figure 22. A good fit was obtained by using an inner permeability of 33 mD and an outer permeability of 200 mD (*kh* is 10 and 60 Dm, respectively). A constant 20% model porosity was used. The model permeability next to the well is similar to the ones presented in Table 4, but 10 times higher in the outer part. The simulation results as well as the measured data are shown in Figure 22.

8.4 Future performance of the shallow reservoir

As limited production from the Tendaho reservoir puts no constraints on reservoir volume, or the nature of recharge, a total of 8 prediction cases was performed. Table 6 gives an overview of these. Both a closed and fully open reservoir were considered, with a constant 250°C reservoir temperature or declining temperature from 250°C in the grid centre to 150°C 2 km away, in accordance with the temperature of the low-permeability well TD3. The permeability of the outer grid blocks was either constant as 200 mD or a combination of 200 mD permeability out to 700 m and then a reduction to 20 mD.

Rather than allowing variable production through a productivity index, it was decided to request a constant flow of 70 kg/s. Of these, 35 kg/s were taken from the centre grid block, and the other 35 kg/s from block 34, 200 m away from the centre. The 70 kg/s value was chosen as it provides 10 kg/s of high pressure steam under no boiling conditions in the 230-250°C reservoir.

TABLE 6: An overview of the different model cases studied for the Tendaho reservoir

Case No.	Temperature	Permeability	Boundary
1	constant	constant	closed
2	constant	constant	open
3	variable	constant	closed
4	variable	constant	open
5	constant	variable	closed
6	constant	variable	open
7	variable	variable	closed
8	variable	variable	open

Simulated pressure, temperature, mass flow and enthalpy are shown in Figures 23 through 26.

Figure 23 shows the pressure in the grid centre with time. Out of the 8 model cases, 4 sustain the 70 kg/s total production easily. Of them, 3 have an open boundary but one is closed. Cases number 5 and 6 decline rapidly in pressure. This will not happen in the field; a decline in well flowrate is a natural consequence of the pressure drawdown. In cases 3 and 7 (not shown), the pressure drawdown is so rapid that major flow problems occur in a few months. In Figure 24 the flow of high pressure steam from the feed points considered is shown. What is noteworthy in the figure is that 4 cases easily sustain 2-4 MWe production in a back pressure turbine, 5 kg/s per MW. In cases 5 and 6, a substantial boiling occurs resulting in higher enthalpies and, hence, higher steam flowrates. These cases are, therefore, also considered here to be reasonable for the predecision period, since the total production will be reduced from the 70 kg/s requested and the pressure drawdown.

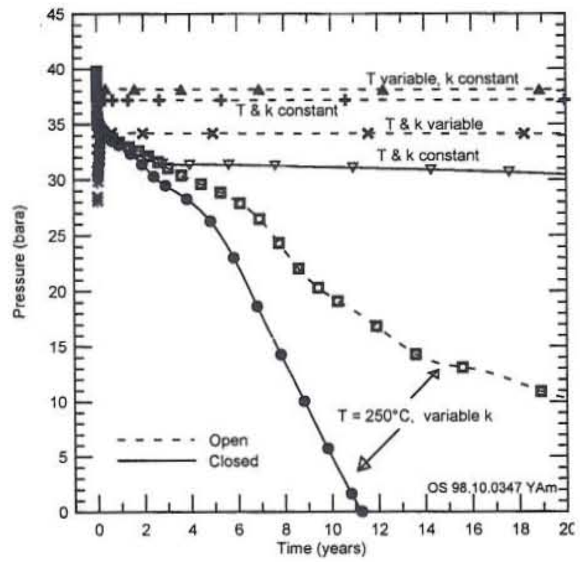

FIGURE 23: Pressure changes with time

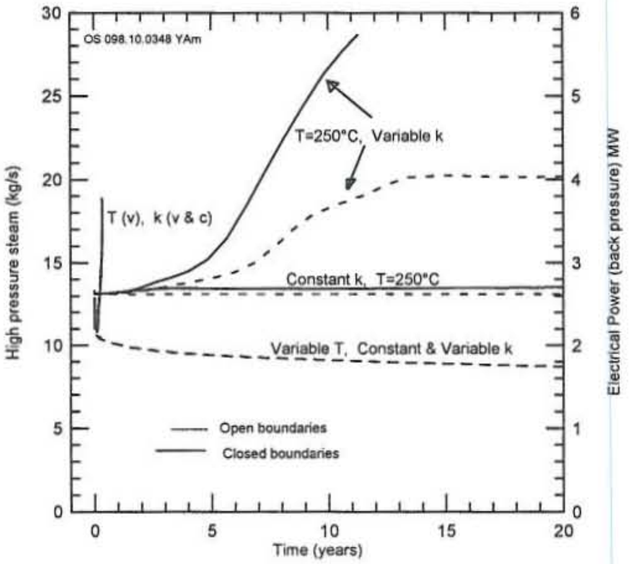

FIGURE 24: Results of performance study

Figures 25 and 26 show the model pressure and temperature status at the end of simulations. Most noteworthy in Figure 25 is the different locations of boiling fronts in the model. Also noticeable in Figure 26 is the rapid pressure drawdown in the first 5 grid blocks. As stated before, this is the consequence of abnormally high flowrate and will not happen in nature; a flowrate will take place in these cases. When the curves are practically zero, boiling is prevalent in the model elements.

The simulation time is 20 years for cases 1, 2, 4, 6 and 8, 10 years in case 5 and 0.3 years in case 3 and case 7.

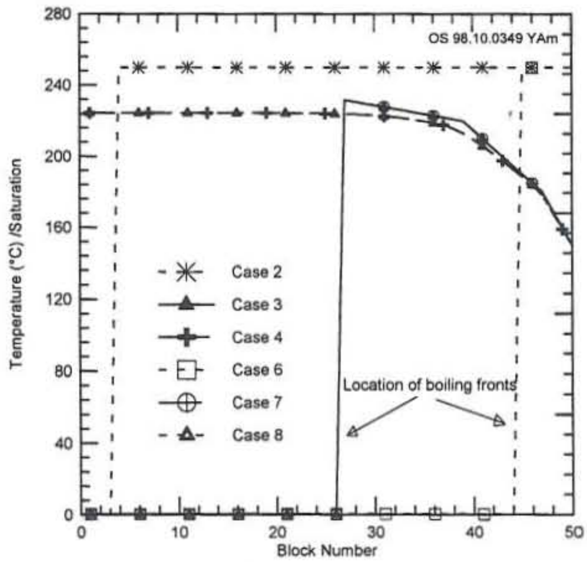

FIGURE 25: Model temperature/saturation at the end of simulation

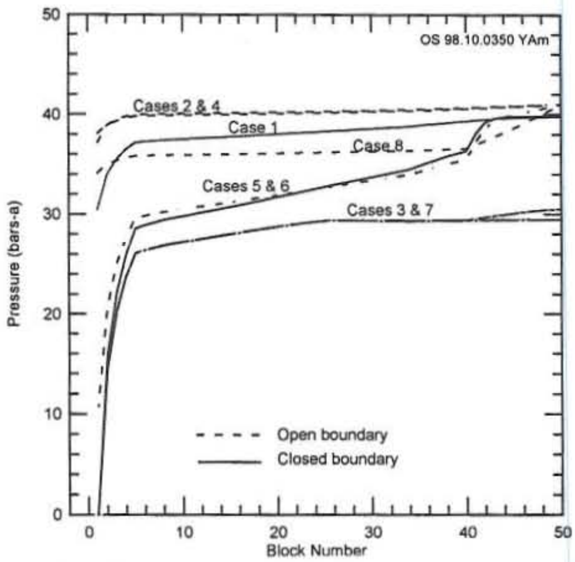

FIGURE 26: Model pressure at the end of simulation time

In summary, the above sensitivity study shows that all but 2 cases of 8 sustain 2 MWe electrical production in a back pressure turbine for up to 20 years. In the two failing cases, flowrates may constrain maximum power generation. These two, however, have in common very rapid enthalpy change in comparison with the other 6 cases. A 0.5- 1 year flow testing period is, therefore, recommended before a decision of building a pilot plant is taken. If the total flowrate, enthalpy and the chemistry of the produced fluid remain relatively constant through the test, building a pilot plant seems reasonable; otherwise, longer testing or a smaller turbine size may become necessary.

9. CONCLUSIONS AND RECOMMENDATIONS

The main conclusions and recommendations of this study are

1. The Tendaho geothermal field appears to be divided into two reservoirs; a shallow reservoir and a deep one. The shallow reservoir is hosted in sedimentary formation but the deep one in volcanic basalts.
2. The shallow reservoir is characterised by boiling and pressure potential in equilibrium with the surface. Its thickness is around 300 m and a temperature of 230-250°C is observed.
3. The deep system is over pressurised by about 5 bars and is in single-phase water condition. The temperature ranges between 220 and 270°C.
4. A hot fluid recharge at a temperature of about 270°C flows from the deep reservoir towards well TD1. Around TD1 it rises to about 1100 m and then flows diagonally towards TD4.
5. As short term well testing indicates adequate permeability in the shallow reservoir (kh = 3-10 Dm), one may conclude that the heat in storage limits production capacity rather than the fluid in storage.
6. A wellbore simulation study shows that the present wells will maintain high flow rates, despite a reservoir pressure drawdown of 5 bars or a cooling down to 210°C. The cooling, however, may reduce flowing wellhead pressures below general separator pressures (7 bars-a).
7. Volumetric analysis and a numerical model indicate that the present known shallow reservoir will likely sustain a 1-2 MWe power generation in a back pressure turbine for 20 years.
8. Before deciding to build a pilot power plant, a ½ to 1 year flow test is recommended. This will

provide much better insight on the reservoir boundaries and possible phase changes during production.

9. The suggested 1-2 MWe size of a pilot plant should not be taken as the final capacity of the Tendaho reservoir. Purposely, the study concentrated only on a small sub-volume of the presently known geothermal reservoir. Further exploration, drilling and exploitation most likely will raise this estimate substantially.

In summary, the shallow Tendaho reservoir appears to be able to sustain electrical production equivalent or larger than the present local demand. At this point it, therefore, seems feasible, as an intermediate goal, to divert the research activities from drilling to production. In order to make that decision, a financial study should accompany a long term flow test. This is to secure a financial basis for power plant installation and operation. When in operation, the next step in the Tendaho area is to identify the deep and hot reservoirs with increased production capacity in mind.

Recommendations for the future are:

a) Long term production test of at least one well (6-12 months);
b) Downhole temperature and pressure measurements of all wells at static and dynamic conditions;
c) Interference tests, to study the response of the deep and the shallow reservoir;
d) Monitoring of ground level changes due to discharge from the wells (subsidence study);
e) Further exploration for siting of the deep geothermal reservoir;
f) Drilling of additional exploratory/exploitation wells;
g) Further development of a numerical reservoir model.

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