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Exploration Results in the Tendaho Geothermal Field, Ethiopia

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ABSTRACT

This paper describes the geothermal exploration history of the Tendaho geothermal field. It presents a summary of the geoscientific and engineering studies conducted during the last 35 years. Tests conducted at the shallow productive wells are described. Problems encountered during a production test and measures taken to solve the problems are discussed.

1. INTRODUCTION

Tendaho geothermal field is located in the north-eastern part of Ethiopia, in the Afar administrative region (Figure 1). The field has been under investigation for geothermal resources for the last 35 years. It would have been possible to exploit most of the geothermal resource during this time if exploration activities in Tendaho were performed without interruptions. All the steps of the studies performed so far in Tendaho were concluded with positive results. Planning and execution of intensive investigation activities to further explore and exploit the geothermal resource started in the last ten years, despite encouraging results and power shortage in the locality.

The initial target of the Tendaho geothermal drilling project was to drill three deep wells. Four wells (3 deep and 1 shallow) were drilled from 1993-1995. Additional 2 shallow wells were also drilled from 1997- 1998 to further explore and exploit the shallow reservoir. Studies conducted so far proved the existence of a shallow 220-250°C liquid dominated reservoir.

Hydrothermal eruption has occurred at well TD6, one of the shallow productive wells. The major cause of the eruption is thought to be condition of the ground at the well site during discharge test. Remedial measures to be taken were recommended based on the accepted cause of the eruption. Surface and sub-surface of the well sites have been consolidated by spreading selected materials and injecting cement through 40 grout holes. Surveys conducted on well TD6 after the rehabilitation works, indicated that wellhead and downhole conditions (integrity of casing, temperature, pressure) are similar to condition before the eruption. This unchanged condition after the eruption at wellhead and downhole proves that the origin of the fluid that caused the eruption is not from the geothermal reservoir.

The Afar administrative region is under rapid development. The new capital city of Afar, Semera, is located in the vicinity of the Tendaho geothermal field. At present only diesel electricity is available. The shallow reservoir at Tendaho is able to sustain electrical production equivalent to or larger than the present local demand. A successful operation of a geothermal power plant in Tendaho may be come a key element in future living conditions in the area. The selection of Tendaho geothermal field as a fore-runner project in the African Rift Geothermal Development Facility (ARGeo) program will open the door for utilization of geothermal resources in Ethiopia.

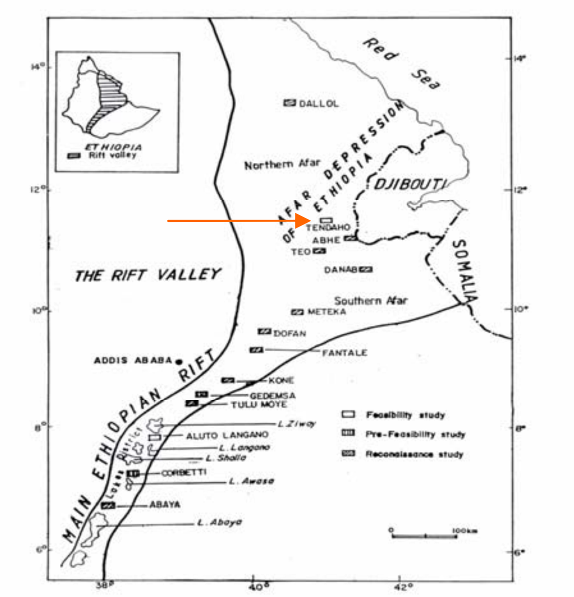

Figure 1: Location map of Tendaho geothermal field

2. EXPLORATION HISTORY AND RESULTS

A series of studies and surveys have been conducted since 1969 to identify and characterize the geothermal resources in the region. The studies performed are summarized as follows:

Reconnaissance Survey: In 1969/70 geothermal reconnaissance investigation was conducted in the Northern Afar depression, as part of the UNDP assistance. The investigation included geological, geochemical, hydrogeological and infrared imagery surveys (UNDP, (1973). It resulted in the selection of Tendaho as one of the potential areas for further detail studies.

Pre-feasibility study Phase I: As the result of technical co-operation agreement between the Ethiopian and Italian governments, the first phase pre-feasibility study was carried out in 1979. The geoscientific studies included geology, hydrogeology, geochemistry and preliminary geophysics. The results of the study confirmed encouraging possibilities in the Tendaho area (AQUATER, 1979).

Pre-feasibility study Phase II: In 1980, the second phase of pre-feasibility study was carried out as a continuation of the first phase. It consisted of: geochemistry, geophysics and drilling of eight shallow temperature gradient holes (AQUATER, 1980). The results of the study allowed definition of a preliminary geothermal model for the Tendaho area, and location of the first deep exploratory well.

Techno-economical study: The pre-feasibility studies were followed by a technical-economical study (AQUATER, 1982). The local power demand and the economic advantage of covering demand with a geothermoelectric plant were assessed. The study also defined the technical features of a drilling rig for exploratory well drilling and listed the main equipment and accessories.

Drilling of 3 deep and a shallow well: Based on the promising results of the forgoing studies, implementation of Tendaho geothermal project commenced and drilling started in 1993. The project was financed by the Italian and Ethiopian governments. Three deep and one shallow wells were drilled in Tendaho from 1993-1995. The depths of the wells range from 466m (TD4) to 2196m (TD1). The drilling project, whose target was discovery of deep reservoir, ended up with 5-15 MW capacity shallow reservoir discoveries (AQUATER, 1996). Drilling of two additional shallow wells and installation of a back pressure power plant followed by further investigations to locate and assess the deep reservoir were recommended.

Drilling of two additional shallow wells: Based on the recommendation of the exploratory wells drilling project, two additional wells were drilled from 1997-1998, to further explore and exploit the shallow reservoir. The depths of the wells TD5 and TD6 are 516 and 505m respectively. Both wells are good producers. The expenses for the execution of the drilling were covered totally by the Ethiopian government. Except three expatriates (drilling supervisor, rig & vehicle mechanics), the rest of the scientific and technical staff assigned to the project were all Ethiopians. This demonstrates the capacity of the Geological Survey of Ethiopia to perform similar activities in the future.

Well testing and follow-up studies: From 1998 to present limited well testing and reservoir engineering studies as well as geochemical studies are in progress.

3. THE SHALLOW WELLS IN TENDAHO

3.1 General

The initial target of the Tendaho geothermal drilling project was to drill three deep wells to a total depth of 6000m. The first well (TD1) was drilled to a total depth of 2196m and completed with 7" slotted liner at a depth of 1550m, due to collapse of lower section of the well while preliminary testing. Despite high downhole temperature (278°C), the well is unable to sustain discharge due to poor permeability. The second well, characterized by limited production and low wellhead pressure, was drilled to a total depth of 1811m. Results obtained from well TD2 drilling (total circulation loss, temperature profiles at shallow depth) are the basis for the discovery of the shallow reservoir, in the vicinity of well TD2.

3.2 Well Testing at Shallow Wells

Three shallow wells were drilled inside the Dubti cotton plantation from 1995 to 1998. Surface and subsurface measurements were performed on these wells during and after drilling. Brief description of tests performed and results obtained are presented as follows:

3.2.1 Well TD4

It was drilled to a total depth of 466m at a distance of 120m from well TD2 in order to confirm the existence of the shallow permeable zone and to test its capacity (Figure 2).

Completion test: The test was performed after running the 7" slotted liner from 181 to 463m depth. There was no circulation return to the surface during pumping at a rate of $70m^3$, indicating high hydraulic transmissivity in the open hole section (AQUATER, 1996). Total circulation loss during drilling and temperature log during water loss test indicated that the major permeable zone is located between 240m and 260m depth. Multi rate injection test at pumping rates of 18.3 to 24.3 kg/s was performed in 6 steps followed by fall-off test at 240m depth. The results obtained were difficult to interpret due to small pressure changes generated by different injection rates and the cyclic behavior in temperature and pressure after the stop of coldwater injection. In spite of these problems the estimated injectivity index was in the order of 1000kg/s/MPa (AQUATER, 1996).

Pressure Transient Tests: Attempts were made to perform pressure build tests. Interpretations were difficult because of cycling in the well and the very quick stabilization of pressure after shutting the well.

Downhole Temperature and Pressure: Temperature distribution at well TD4 follow the Boling Point for Depth curve (BPD), suggesting that the shallow reservoir is in pure water boiling condition (Figure 3). The initial pressure at the 250m depth (major feed zone) is about 22 bar. The wellhead pressure at shut-in condition fluctuates between 20 and 22bar, indicating a pure steam condition between the wellhead and the major feed zone. Stabilized pressure profile at static condition is shown in Figure 4.

Production Test: The well was discharged through 6, 5, 4 and 3inch diameter lip pipes for short periods during the last 9 years. The results of the tests performed in 1995 indicated that production capacity of the well is as high as 70kg/s total flow, at an enthalpy of 940kJ/kg (AQUATER, 1996). In 1996 the well was discharged through 4" diameter lip pipe for about 7 weeks. During the test production was relatively constant except for small variations due to cycling. The well produced 50.4kg/s total fluid at an average wellhead pressure of 14.4bar. The corresponding steam flowrate and enthalpy were 14kg/s and 1065kJ/kg respectively.

3.2.2 Well TD5

Well TD5 is also drilled inside the Dubti cotton plantation to a total depth of 516m, east of well TD4 (Figure 2).

Downhole Temperature and Pressure: Figures 3 and 4 show downhole temperatures and pressures profiles of the shallow wells at static condition. The temperature profiles of the three shallow wells follow the BPD curve.

Comparing the temperature curves for the three wells, TD5 has the highest downhole temperature. A maximum temperature of 253°C was measured in well TD5 at a depth of 475m. The initial reservoir pressure was estimated at 34.5bar (Amdeberhan, 1998). The wellhead pressure at shut-in condition has risen from 21.5 to 27bar in the last two years.

Pressure Transient Test: Two fall-off tests and a pressure build-up test were carried out at 290 and 490m depths. The analysis results indicated that the permeability-thickness product ranges from 2.4 to 10Dm, suggesting that the well is a good producer (Amdeberhan, 1998).

Production Test: Results of the first short production test through 6, 5 and 4inch diameter lip pipes indicated that the maximum total mass flow (48.5kg/s @ 10.4bar wellhead pressure) was attained during discharge through 5" diameter lip pipe. In year 2003, the well was discharged through 4" lip pipe for 20 days. Due to separated water disposal problem, it was discharged at throttled condition. At an average wellhead pressure of 18bar it produced 19kg/s total fluid at an enthalpy of 1270kJ/kg. The corresponding steam flow rate was 7kg/s.

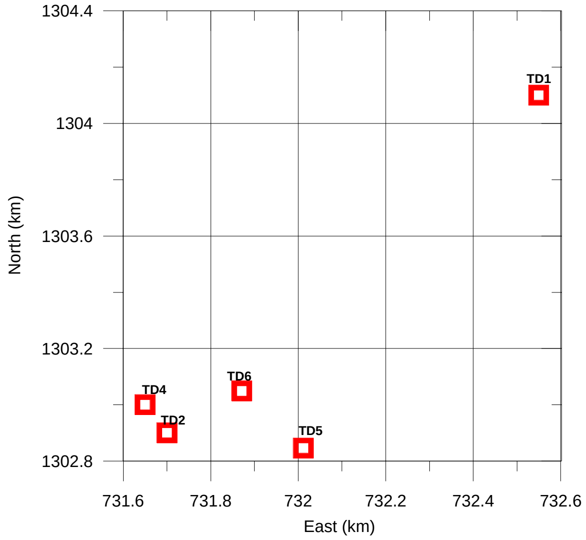

Figure 2: Location of Tndaho geothermal wells

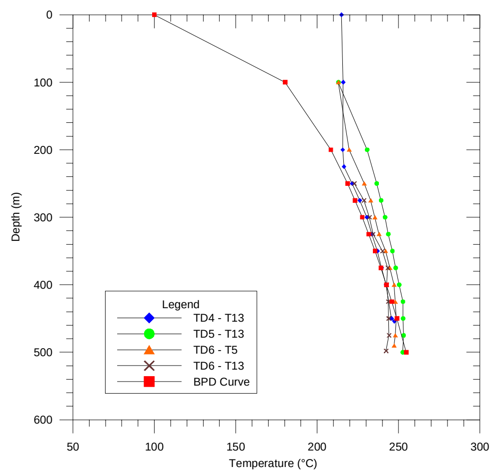

Figure 3: Downhole temperature profiles

3.2.3 Well TD6

It is the third shallow well drilled in 1998 to a total depth of 505m, north- east of well TD2 (Figure 2).

Downhole Temperature and Pressure: Static downhole temperature and pressure measured before (T5, P14) and after the hydrothermal eruption (T13, P21) are shown in Figures 3 and 4 respectively. The shapes of temperature profiles are similar to the previous two shallow wells. Comparing the temperatures measured before and after the hydrothermal eruption, there is a slight decrement (about 4°C). The pressure profiles also show similar trend. The latest temperature and pressure profiles of well TD6 are almost identical to well TD4.

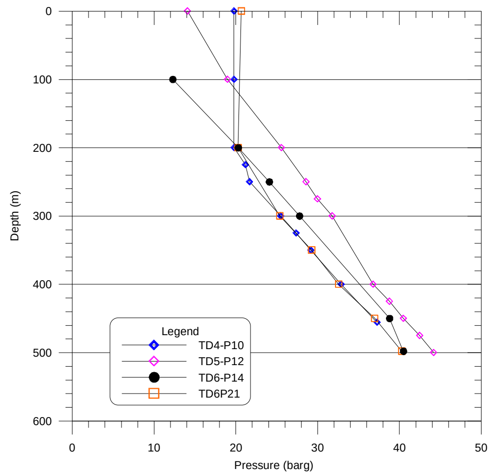

Figure 4: Downhole pressure profiles

Pressure Transient Tests: The Permeability-thickness products estimated from a fall-off and pressure build-up tests were 6.2 and 8.7 Dm respectively (Ambeberhan, 1998, 2002). The data indicates that there is sufficient permeability in the shallow part of the Tendaho geothermal field.

Production Test: The well was discharged through 6, 5 and 4inch diameter lip pipes from 1999-2000 for short periods. In year 2000 it was planned to discharge the well through 6, 5, 4 and 3inch diameter pipes for Output test. The test was terminated after one month discharge through 6, 5 and 4inch pipes by the hydrothermal eruption. The well produced 37kg/s total mass with an enthalpy of 975kJ/kg at an average wellhead pressure of 5.4bar. The corresponding average steam flows at 5.4bar was 9kg/s. The preliminary output characteristic curve (Figure 5) shows that steam flowrate increases with increasing wellhead pressure.

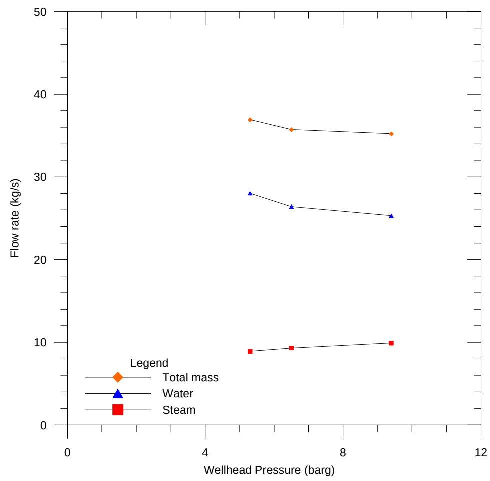

Figure 5: Well TD6 preliminary output curve

4 HYDROTHERMAL ERUPTIONS AT WELL TD6

4.1 General

Hydrothermal eruptions are violent events that have occurred in geothermal fields around the world. In geothermal fields susceptible to hydrothermal eruptions, liquid water or two-phase water mixture lies below the surface at boiling-point conditions. This hot fluid is then suddenly exposed to reduced pressure conditions due to some initiation events (Smith and McKibbin, 2000). If escape paths are provided the fluid will move towards regions of lower pressure and therefore move upwards. The upward fluid velocities provide lift to the rock above, and if this lift is large enough to overcome the weight and cohesive stresses of the rock, then a rock and fluid mix are ejected upwards. Despite many studies performed, exact causes of hydrothermal eruption are not yet known.

4.2 Well and Site Conditions Prior to Eruption

Well TD6 was drilled in February 1998 to a total depth of 505m. Since well completion, it was discharged for a total of 8 weeks. The first test was done in 1998 by discharging the well through 6" diameter lip pipe for a week. In 1999, it was discharged through 6 and 5" pipes for 3 weeks. Output test was planned for the year 2000. The test commenced on 22/03/00 by bleeding the well through 3" diameter pipe. It was then discharged through 6, 5 and 4inch lip pipes from 23/03/00 to 27/04/00 for a total of 28 days.

During discharge through 6 and 5inch pipes, flow parameters (mass flow, wellhead pressure, wellhead temperature, lip pressure) were relatively constant where as none of the flow parameters were constant during discharge through 4" pipe. In addition to the fluctuation of the discharge parameters, muddy water and cuttings were coming out of the well.

Despite the trial to keep the wastewater level in the nearby evaporation pond below ground level, there was an overflow of brine from the pond. The well was then shut from 10/04/00 to 17/04/00 to pump the brine from TD6 pond. On 17/04/00, about 10cm high boiling water level was observed inside well TD6 cellar. Near the silencer and under the discharge pipe, marshy and steaming ground covering an area of about 12 m^2 was seen. The next day, intensity and area covered by the hydrothermal activities were increased. Boiling water was also observed inside the pipes, at well TD6 cellar fence.

On April 23, 2000 the pond at well TD6 was full. In addition to an overflow of the brine towards well TD5 site, there was infiltration of water in to well TD6 cellar, reaching as high as 40cm. On 27/04/00 the well was discharging through 4" lip pipe. Despite the relatively longer discharge period (10 days), the flow from the well was not stable. Boiling water inside the cellar has almost reached the ground level. The ground at the cellar and flow line area was hot and marshy.

4.3 The Eruption and its Consequences

On the 27th of April 2000, the well was left discharging through 4" lip pipe after recording discharge parameters at 17:49 hour. The wastewater pump was also pumping at its full pumping capacity.

Hydrothermal eruption occurred at about 21:00Hrs. Well testing group at Semera geothermal camp was informed about the eruption at well TD6 at 00:30 hrs. (28/04/00). The group left immediately for the well site and arrived at about 1:30 AM. The well site was covered by hot mud of about 15cm thickness. The well was discharging through the collapsed production test line into the pond and through the ½ inch side valve. The heat from the hot mud and steam around the well, sticky mud at well site, terrible noise from bleeding through the ½ inch valve and the darkness were the main problems that made operation of immediate well control activities difficult. The first trial to reach the wellhead using ladders was not successful due to its limited length. After modifying a floating system made of three empty barrels, it was possible to reach the wellhead and shut the valves. After successful well control operation, two operators came out of the danger zone safely. The last person, a mechanic was hurt at his legs. His leg slipped in to the boiling water while trying to sit on the floating system. He was given medical treatment and has recovered completely from the injury.

4.4 Magnitude of Eruption

The area of the new pond created by the hydrothermal eruption at well TD6 was about 600m^2 (20m x 30m). Assuming an average depth of 2.5m, the volume of the ejected material was estimated at 1500m^3. The ejected material has reached as far as 300m from well TD6, in the NW direction. Trees near the TD6 pond were buried by the mudflow. A big rock weighing about 60 kg was found at a distance of about 50 m from the eruption center. Due to their composition, most of the ejected rocks were broken into pieces during landing. The formation blown out is composed of siltstone, mudstone, sandstone and clay. From the volume of the material ejected and dispersion radius of the ejecta, one can imagine that the energy released by the explosion is remarkable.

Figure 6: Hydrothermal eruption at well TD6

4.5 Possible Causes of Eruption

The three shallow and one deep well are located at the thermally active part of the wellfield. Due to the thermal activities around the shallow wells, the ground is relatively unstable. The loose sediments that form the top part of the formation were not consolidated. It has been previously experienced that, during discharge tests intensity of thermal activities around the wells increases with waste water level rise in the near by evaporation ponds. Water leaking from the pond is heated and boiled, making the ground around the wellhead smoky and marshy. In 1996, well TD4 was discharged continuously through 4" lip pipe for 26 days. The well was shut due to the unsafe working condition created by the hot and steaming ground.

There are three possibilities for the origin of the fluid that caused the hydrothermal eruption at well TD6:

1. The fluid is emanating from the reservoir and escaping though the crack formed in the production casing due to casing failure,
2. The fluid is originating from the reservoir and flowing to the surface outside the well due to

poor cement bondage between the casings and formation,

3. Water from the nearby evaporation pond has percolated through the loose sediments into the ground, heated and boiled by the flowing well increasing its temperature and pressure, hampered by the relatively consolidated ground around the cellar and erupted due to pressure rise exceeding the overburden pressure.

Build-up of wellhead pressure to its initial value (stable wellhead pressure at shut-in condition prior to the eruption) after the eruption and extinction of the geyser like activities after pumping out the water from the evaporation pond suggests that;

- The source of the geothermal fluid escaping through the explosion center is outside the well
- Wellhead and casing string has not suffered major structural damage
- The most likely cause of the hydrothermal eruption at well TD6 is percolated water from the wastewater disposal pond.

5. WELL SITE REHABILITATION

5.1 Well Site Rehabilitation Project

A project entitled "Dubti Geothermal Wells Rehabilitation Project" was initiated to rehabilitate the well affected by the hydrothermal eruption and to take preventive measure for avoidance/reduction of similar incidents at the shallow geothermal wells. The project was implemented in two phases.

5.2 Surface and Subsurface Consolidation

Before commencement of geothermal drilling, well sites are selected based on the results of the geoscientific studies. Specifications for drill sites are then prepared considering geology of the area, depth of geothermal wells to be drilled, space required for drilling rig and accessories. Depending on the geology of the area, depth of drilling and conditions of the sites, geothermal well sites are prepared by leveling the ground, spreading selected material, compacting and then injecting cement through grout holes.

Well sites at the Tendaho geothermal field, were prepared simply by leveling the ground, spreading selected material (scoria) and compacting to some extent. Due to thermal activities in the vicinity of the shallow geothermal wells and the type of formation at the shallow level (sediment composed of siltstone, sandstone, clay etc.) previously spread selected material had deteriorated. In addition to consolidation grouting, it was therefore necessary to strengthen the weakened surface of the well sites by spreading and compacting better quality selected material.

After pumping out water accumulated in the ponds at the well sites, previous ponds at well TD6, TD5 and TD4 were filled with earth and leveled. Sufficient amount of selected material was then dispersed around the wells and compacted. 40 grout holes were drilled and a total of about 360 quintals of cement injected to strengthen the formations at the three shallow geothermal wells.

5.3 Construction of Venting System at Well TD6

Closer monitoring of well TD6 and eruption activities were performed for about two months after the main eruption. There was no flow from the well except the small leakage through the discharge pipe, since well closure on 28 April 2000. The leakage was stopped later by further closing the master valve. The activities at the eruption center continued for two weeks with decreasing eruption frequency and magnitude (Figure 6). A mixture of hot water and steam was erupting at irregular intervals. At the beginning, the height of the eruption has reached as high as 12 meters and it was behaving like a geyser.

After extinction of geyser activities, hot water springs were filling the crater to some height (about 1.5 m below cellar). The water was pumped out several times in order to study the continuity of the flow and its volume. It was observed that the recharge rate was about 40l/min and its level was maintained constant most likely by the weight of accumulated water, balancing discharge pressure. The source of the fluid discharging around the wellhead is at present unknown.

During well discharge, there will be heat transfer from the geofluid inside the casing to the surroundings of the well. This will heat the fluid flowing around the wellhead and may initiate blowout. It was therefore necessary to create a venting system before filling the active part of the eruption crater with selected material. The venting system is designed to collect fluid from the main source of hot water flow, covering an area of about $3.5 m^2$ and transmit to the surface through the outlet pipe. The system placed on the main up-flow area, has a triangular shape (4.5mx2.5mx2.5m) and is made of 6-inch diameter pipes. The pipes were perforated by drilling holes for fluid entry. An L-shaped 6-inch diameter pipe was connected to the triangle for venting (Figure 7). It is anticipated that the venting system will minimize chances of blowout from shallow depth by providing an outlet for the geofluid, incase of pressure rise during well discharge. After putting the venting system in place, the crater was filled with selected material and compacted.

Figure 7: Well TD6 after rehabilitation.

5.4 Present Condition of Well TD6

After rehabilitating the well site (Figure 7) it was possible to check the downhole conditions of the well on March 27, 2002. Shut-in wellhead pressure has reached the maximum value recorded before the eruption (21.5bar). Conditions of the wellhead and integrity of the casing were checked by running sinker bar followed by downhole pressure and temperature measurements. The results of the surveys indicated that the wellhead and the casings are in good condition. Downhole temperatures and pressures measured before and after the hydrothermal eruption are nearly similar. These unchanged conditions at wellhead and downhole, prove that the origin of the fluid that caused the hydrothermal eruption at well TD6 is not from the geothermal reservoir. The major cause of the eruption should be then percolating water from the evaporation pond at the well site.

6. CURRENT STATUS AND FUTURE PLAN FOR TENDAHO GEOTHERMAL FIELD

The deep and shallow exploratory wells drilled in Tendaho have proved the existence of a commercially attractive geothermal resource at shallower level. Surface and sub-surface measurements conducted so far have determined that the shallow reservoir's temperature is 220-250°C. The permeability is relatively high (3-10Dm). Salinity and non-condensable gas contents of the fluid are low. About 3 MW electric power can be generated from the existing shallow wells.

Production tests were carried out only for short periods due to limited capacity of evaporation ponds and flat topography of the well sites. At present limited reservoir engineering and geochemical studies are in progress. It is planned to perform long-term discharge tests and geochemical monitoring in the coming years. Under the African Rift Geothermal Development Facility (ARGeo) program, Tendaho geothermal field is one of the target geothermal fields to be further investigated and promoted to development. The three phased project proposal for Tendaho consists of surface investigation, pilot power plant installation and evaluation drilling.

7. CONCLUSION AND RECOMMENDATION

Exploration studies conducted for over three decades in Tendaho have proved the existence of commercially attractive geothermal resource at shallower level. Even though the deep reservoir hasn't been located yet, it is believed that the shallow reservoir is fed from depth. The deep reservoir has to be discovered by further investigations while utilizing the shallow reservoir. The opportunity created by the African Rift Geothermal Development Facility (ARGeo) for Tendaho geothermal field allows delineation and characterization of the deep reservoir and advancement of the field to development stage.

The downhole surveys conducted at well TD6 after well site rehabilitation proved that the well is in a good condition. Comparing wellhead and downhole conditions/parameters before and after the hydrothermal eruption, no changes were observed, leading to a conclusion that the origin of the fluid that caused the eruption is outside the reservoir. In addition to preparation of waste water disposal ponds away from the well sites, consolidation of the shallow well sites will avoid occurrence of hydrothermal eruptions.

Based on the experiences gained so far, it is recommended to consolidate future well sites by grouting before commencement of drilling geothermal wells at the Tendaho geothermal field. It is also recommended to closely monitor changes around the wellheads due to production. Care should also be taken not to drill wells on thermally active part of the geothermal field.

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