

THE MOMOTOMBO RESERVOIR PERFORMANCE UPON 23 YEARS OF EXPLOITATION AND ITS FUTURE POTENTIAL

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ABSTRACT

The Momotombo geothermal reservoir has been developed for more than twenty years since 1983 when the first unit of 35 MWe commissioned. And the second unit was installed in 1989 by increasing steam production rate. During this period, production wells show marked changes in flow rates, fluid chemistry and specific enthalpies of produced fluids. These changes are mainly attributed to reservoir pressure decline because of excessive fluid production. In 1995 the Italian consultant company DAL SpA proposed that Momotombo was able to generate up to 90 MWe by deep drilling, at that time four wells were drilled having as depth target 2500 m or deeper, however only one of them reached 2500 m finding low permeability but the highest temperature in the field (>320°C).

By 1999, where the power plant output dropped to 9 MW an international tender was issued for the rehabilitation of the project under a 15 year Concession.

Ormat won the tender and undertook to drill additional 3 wells. The subsequent drilling of 4 wells (instead of 3), and implementing a full reinjection for pressure support didn't produce satisfactory results so Ormat further increased its investment by installing a bottoming ORC unit. Since then the plant is producing about 30 MW supported by an intensive well maintenance.

Ormat's investment stands at about US\$ 40 Million, producing electricity at less than US\$5.22 Cents/kWh. Making the Momotombo plant the lowest cost electricity producer in Nicaragua.

At Ormat we still believe that the deep resource exists in Momotombo and that going beyond the 2500 m drilled previously, will enable to increase substantially the output above 30 MW by using the existing plant capacity. This of course requires further investment that Ormat plans to do provided the Government extends the concession beyond the present term.

1. INTRODUCTION

There are forty-seven wells in total that have been drilled in an area of about 2 km² in Momotombo. Production zone is divided into shallow and deep zones. Separated water has been reinjected since the start of development, but their scheme has been changed in terms of its magnitude of injection amount as well as reinjection water temperature.

A wide range of field measurements has been carried out starting from flow rates for steam and water of wells, wellbore monitoring, and chemical analysis of discharged water of wells. Thus, these measured data are examined in detail to understand reservoir performances upon exploitation.

2. WELL SPECIFICATION AND STEAM PRODUCTION HISTORY

Figure 1 shows location of the forty-seven wells drilled in Momotombo. The well depths range from a few hundred meters to as deep as 2839 m.

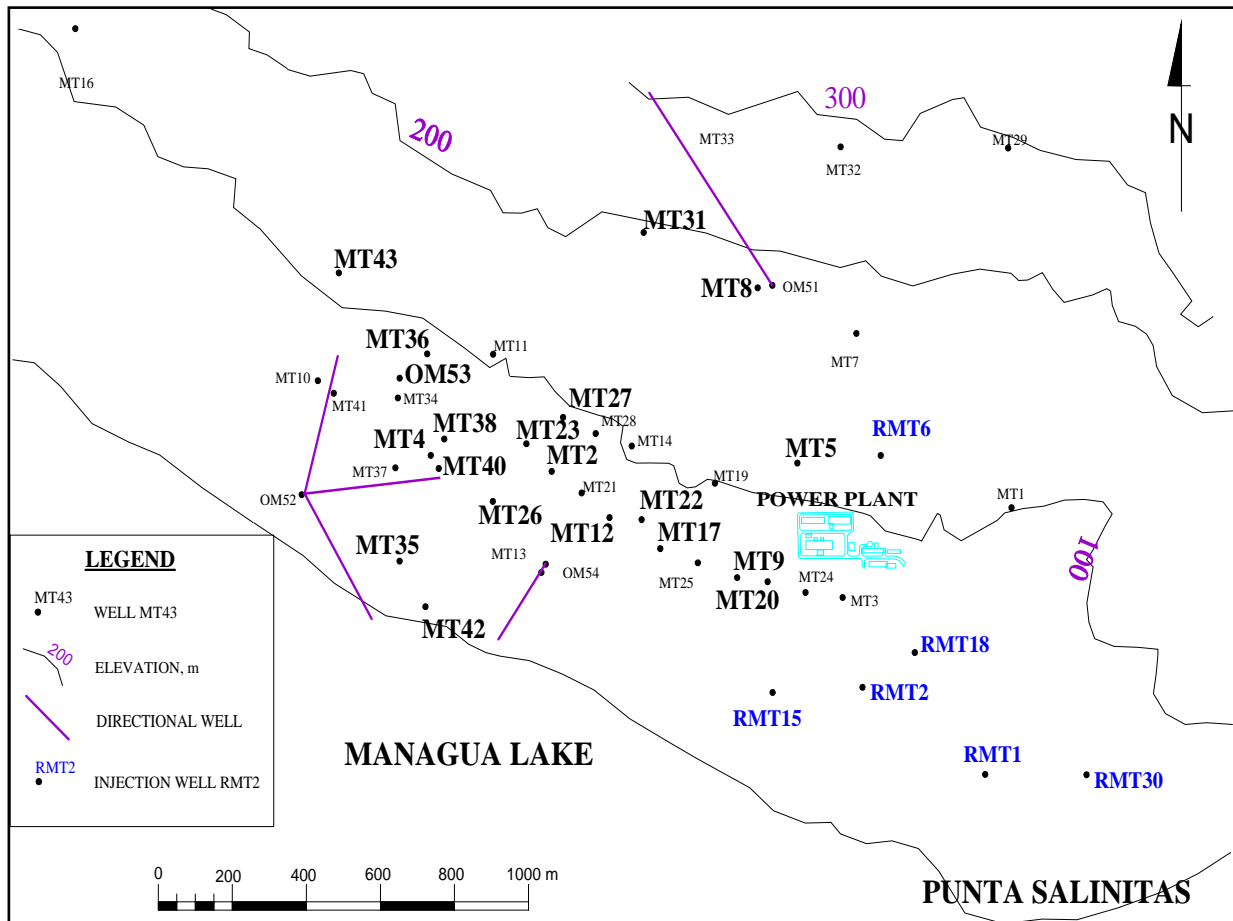


FIGURE 1: Wells location map

Among the 47 wells drilled so far, twenty wells have been connected to the steam gathering system in different periods. The drilling results revealed the existence of high temperature systems at three different depths: 200 - 400 m below sea level (m b.s.l.) with 200-230°C, 800 - 1400 m b.s.l. with 250 - 290°C, and a deep zone (>2000 m b.s.l) with temperature higher than 320°C. Two systems in

shallower zones have relatively high permeability, but the deep one has low permeability. A 7 MWe Ormat Electricity Converter (OEC) was commissioned in 2002 fed by brine, which was disposed for years to Lake Managua, this brine cools down from 155°C to 100°C before being reinjected. The binary unit has been in operation since October 2002 with a constant power generation level. Accordingly the total installed capacity of the field increased to 77 MWe with an output of 30 MWe assuring some pressure support and avoiding pollution of Lake Managua.

Shallow production wells have shown unsteady behavior both for flow rate and enthalpy due to changes of phase condition in reservoir. Some wells have changed their discharged fluid enthalpy from that of saturated liquid water (960 kJ/kg) at reservoir temperature to that of dry steam at separator pressure (2740 kJ/kg). Specific enthalpy of deep production wells remains stable, but varies in a wide range depending on wells such that from dry steam of 2740 kJ/kg at MT43 to saturated water of 260°C at MT40. There are six wells that have been reinjecting separated water to the reservoir.

Figure 2 illustrates a history of power output of the Momotombo power plant, which approximately represents the total steam production from wells in this field. Power output is relatively stable at about 35 MWe in the early period from August 1983 to November 1986. During this time, five shallow wells were producing steam and water, and they are MT9, MT12, MT20, MT23 and MT27. However, the output starts decreasing from the end of 1986 when MT9 stopped discharging because of casing collapse.

In March 1989 the second 35 MWe unit was commissioned when additional six shallow wells were online for this unit. The output increases to about 70 MWe for a short period, and then it drops down to 30 MWe because of a generator-turbine failure. At the same time, well MT36 was stopped production because of high concentration of non-condensable gases in the produced steam.

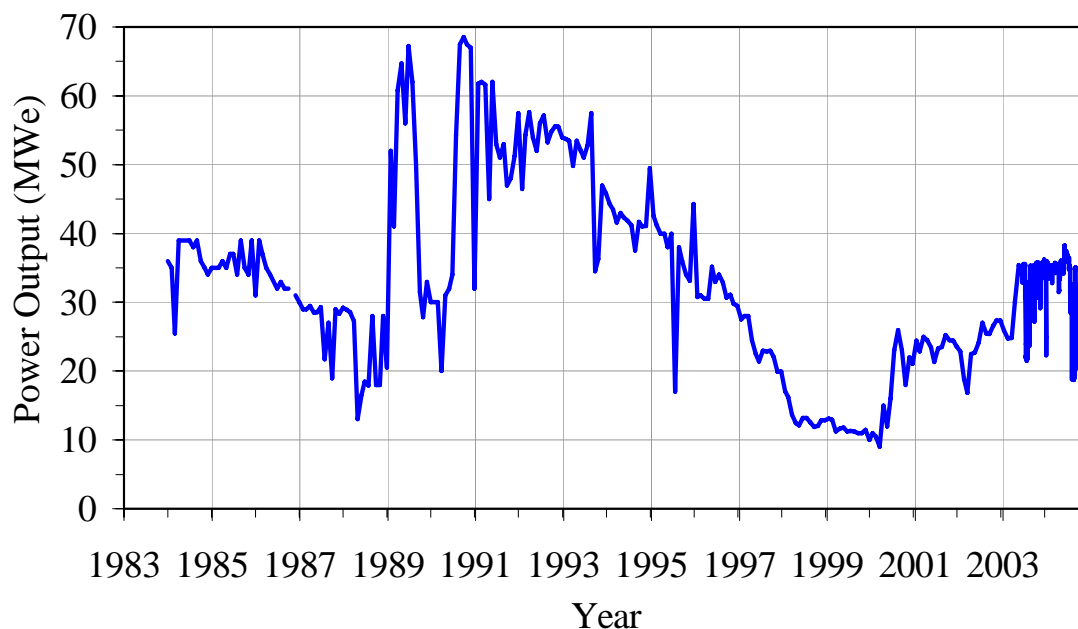


FIGURE 2: Power output history of Momotombo

The highest output of 69 MWe was recorded in 1990, and then followed by a continuous decrease with time. Quick decrease of power output promoted drilling three makeup wells from 1992 until 1997. In spite of these additional wells, decrease of output remains because of productivity decline of other wells.

Wellbore survey in 1996 and 1997 revealed that most of the shallow wells located in the central part of the well field were damaged by scaling, and other shallow production wells located in the eastern part were suffered from cooling. In 1999, the output dropped down to about 9 MWe when only 7 wells were producing. These wells have deep feed zones (800 and 2000 m b.s.l.) except MT27 (300 m b.s.l.).

As a result of an international bid, in March 1997 ORMAT signed a 15-year Concession and PPA contract with ENEL (Nicaragua National Power Company), to rehabilitate the Momotombo Geothermal Power Plant. As mentioned above, in 1999 7 wells were producing steam for a power output of 9 MWe. Figure 2 shows a quick recovery of power output from 2000. This is because of the result of a rehabilitation program started in 1999 to improve reservoir management as well as to sustain stable operation of the plant. This program consists of,

1. Work over for existing production wells. This includes cleaning of calcite scale in wellbore, repairing mechanical failures and cementing jobs. After the completion of mechanical cleaning in wellbores, calcite inhibitor pumping was started into some of the shallow to medium depth wells. Other production wells were also treated with acid (HCl) to dissolve calcite scale formed in the formation in the vicinity of wellbore.
2. Drilling four deep wells (>2000 m) in the western part of the field. As a result of this drilling campaign, well OM53 that produced about 85 t/h of steam (more than 30 % of the total steam supplied to the power plant in 2000). This attempt to reach deep zone with drilling failed mostly because rig limitations.
3. Reinjecting all the separated water into the formation to moderate reservoir pressure decline and to avoid contamination of the lake water by discarding the brine.
4. As the 4 wells drilled didn't increase sufficiently the output, ORMAT decided to invest in a 7 MW OEC unit (beyond its commitment and without increasing the electricity price). Utilization of the separated hot brine for generation of electrical energy resulted in increased capacity of the flash-type geothermal power plant without further well drilling. The risks of increased silica and other mineral scaling in the heat exchanges and piping system were reduced or eliminated by proper field management and by treating the brine to maintain a required pH level.
5. To implement 100% re-injection for environmental reasons and mitigating cooling effect of re-injection.

As a result of this program, the power generation reached a peak power of 35 MWe between July 2003 and August 2004. However, the power output started decline in 2003 due probably to decrease both in enthalpy and flow rate of four shallow production wells. These wells may also reduce their productivity because of plugging in reservoir by removed calcite scale after mechanical cleaning, which may result in decrease in permeability of the formation in the vicinity of the well. On the other hand, scale was formed again at feed zone of wells MT42 and MT35, and in wellbore of MT36. By intensive well maintenance including chemical treatment and mechanical cleaning, power output was stabilized around 30 MWe.

3. PRODUCTION DATA OF WELLS

Large amounts of data have been collected for the mass and energy production of the individual wells since 1986; data before this year are not available. However, total flow rates and specific enthalpy from the wells were estimated during this period (1983-1986) on the basis of discharge test conducted in 1980's.

4. ANALYSIS OF THE PRODUCTION DATA

Production data such as flow rates and specific enthalpy of produced fluid, reservoir pressure and temperature, as well as chemistry of produced fluid have markedly changed during 20 years of exploitation of the reservoir.

4.1 Total flow rate and reservoir pressure

Relationship between downhole pressure in well MT11 and total flow rate of the wells is shown in Fig. 3 together with the average specific enthalpy of the produced fluids. The total flow rate shows about 300 kg/s from 1983 to 1987. Then, it starts quick decline in 1987 corresponding to stop of production at MT9. During this period, pressure of well MT11 located above the upflow zone drops from 58 bar to 41 bar.

In 1989, the production rate was doubled compared with the previous two years as the second unit of 35 MWe came on line. Pressure drop in MT11 continues down to 35 bars. On the other hand, the average specific enthalpy of the produced fluid jumps up from 1600 kJ/kg to about 2000 kJ/kg. This increase is initially followed by a rapid decrease of the total flow rate down to 320 kg/s in 1992. Since then, specific enthalpy gradually declines with time. On the other hand pressure in MT11 remains constant until 1996. During this period (1992 – 1996) the total flow rate slightly increases because of two additional wells: MT38 and MT8. However, shallow wells in the center of the well field (MT17 and MT22) stopped production due to low temperature at feed zone and scaling in wellbore as well.

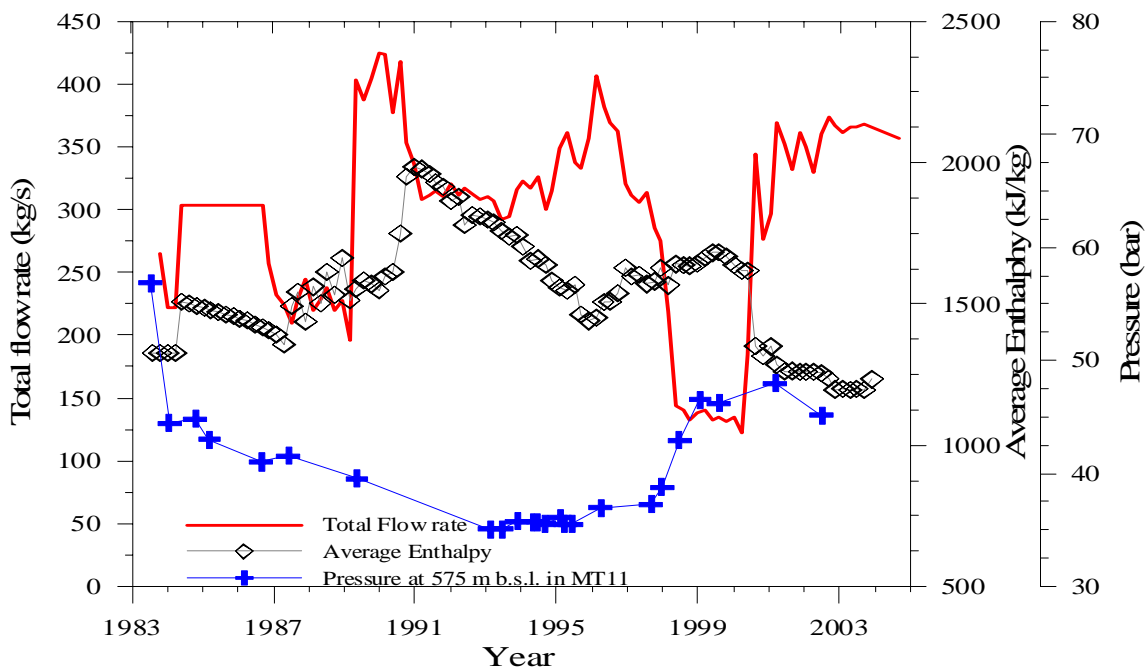


FIGURE 3: Pressure in MT11, total flow rate and average specific enthalpy history

In March 1996 the total flow rate reaches the maximum value of about 410 kg/s followed by an increase in average specific enthalpy whereas pressure in well MT11 remains constant. This jump of the total flow rate is due to two new wells (MT4 and MT40) that started production. Figure 3 shows that from March 1996 until 1998, the total flow rate drastically drops, even though make up wells MT42 and 43 started production at the end of 1997. Average specific enthalpy increases because of high specific enthalpies of these two wells. During this period, well MT5 started production for only

fifteen months. Most of the shallow wells stopped production due to scaling and cooling between 1996 and 1998, which resulted in decrease in the total flow rate. Pressure recorded in well MT11 remains constant between 1998 and 2002, in this period shallow production wells with calcite scale within wellbore were shut in. Most of these shallow and calcitic wells were cleaned mechanically between 2000 and 2002 when they were producing for relatively short periods (months) until in 2002 that inhibition systems for calcite scale were installed. It seems that this intermittent production of these wells did not produce any pressure disturbance in the reservoir.

In 2000, the total flow rate jumps from 120 kg/s to 365 kg/s as well as a decrease in the specific enthalpy from 1600 to 1400 kJ/kg. This is because five shallow wells were on line after completion of work over for installing scale inhibition system in 2000. However appreciable change in pressure is not observed as shown in Fig. 3.

High specific enthalpy fluid (2770 kJ/kg) was produced from wells MT12 in 1990 and MT20 between 1991 and 1994, this implies that a steam-water two-phase condition presents in the vicinity of wells or two-phase zone spreads through out the shallow reservoir between 1986 and 1996.

Analysis of the production history data of wells between 1983 and 1991 concluded that the increase in production rate in 1989 resulted in a marked change in the phase conditions of fluid in reservoir (Porras, 1991). Other observed features related to reservoir conditions after 1991 are summarized as follows:

Shallow production wells located in the eastern part of the field, MT17 and 22, suffered enthalpy decline during the history.

Wells MT4, 23, 26, 27, 31 and 36 had scaling problems. Wells MT23, 26 and 27 are however close to each other (Fig. 1) whereas wells MT4 and MT36 are located above the upflow zone.

As of 2003, liquid specific enthalpy (800-1100 kJ/kg) is characterizing wells MT2, 4, 23, 26, 27 and 31. Since 2000, a drop of specific enthalpy can be seen in most of these wells (MT2, 23, 26 and 27).

Deep wells (MT42, 35, 36 and 53) have specific enthalpies slightly higher than what would be expected from the initially liquid saturated feedzone temperature.

5. REINJECTION HISTORY

Location of reinjection wells is shown in Fig. 1 with names that start with R such as RMT15. These wells are located mainly in the eastern part of the well field. Wells have different injection capacity: RMT6 and RMT15 have the highest capacity whereas wells RMT1, 2 and 30 the lowest injection capacity.

A reinjection system has been operating in Momotombo since 1983. The separated water is sent to the wells either as pressurized by pump or as gravitational flow. Before commissioning the 7 MWe OEC unit, temperature of reinjected water was originally 170°C, but it gradually decreased to 150°C in 2002.

Figure 4 shows the reinjection and separated water histories at Momotombo. As can be seen, between 12% and 30% of separated water is reinjected between 1984 and 1996. Reinjection rate has been increased such that more than 90% of the separated water is reinjected after 1999. This difference becomes even smaller in 2003 and 2004 when most of the separated water has been reinjected.

Mechanical failures of the reinjection system frequently occurred for 13 years (1983-1996), and then separated water was discarded into the Managua Lake. In 2002 all production wells were connected to the reinjection system and other two reinjection wells were connected to the system (RMT1 and 30) in early 2003 as reinjection capacity of wells became insufficient.

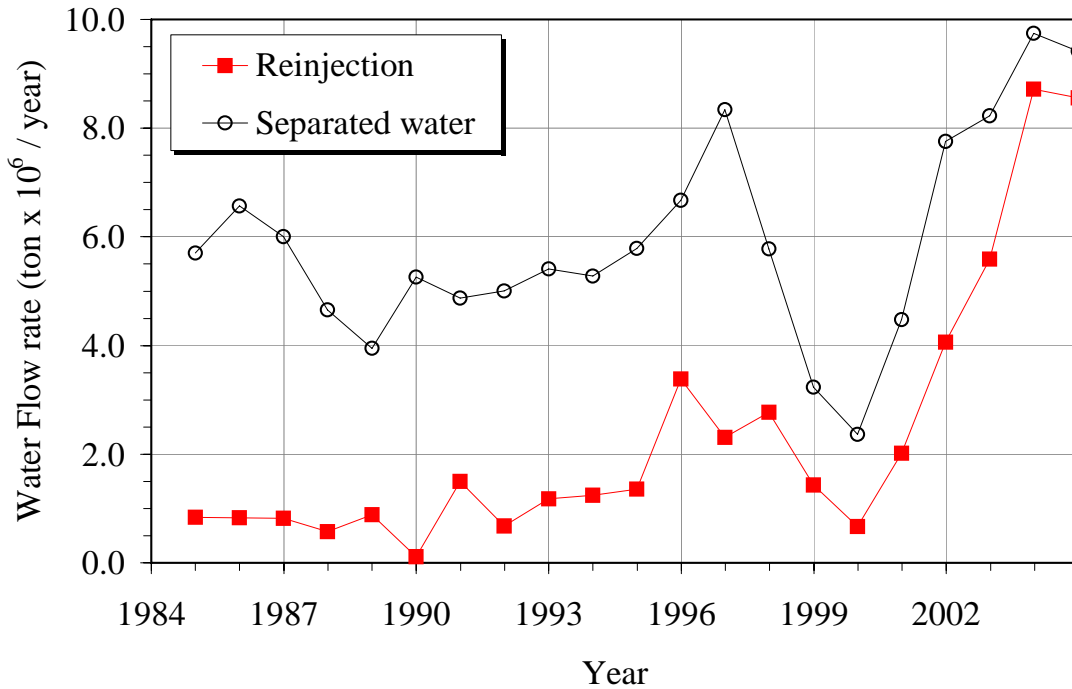


FIGURE 4: Rejected and separated water history

A tracer test analysis reveals that flow channels connect reinjection well RMT15 and probably RMT6 to the main production zone (Kaplan, 2004). The geological model of the field supports the results of the tracer test. Such a model suggests a south-north boundary separating wells RMT2 and RMT18 and the rest of the wells (Kaplan, 2004). This model explains the slow returns of the tracers while maintaining the pressure support. As a result of the tracer test a new injection strategy has been adopted since installation of the binary unit began in 2003 with limited injection into well RMT15, maximizing the injection into wells RMT2, RMT18 and RMT30.

Figure 4 shows that as result of the new injection strategy, near 100% has been reached as for 2005. Currently, wells RMT18 and 30 were stimulated with acid injection resulting in an increase on injection capacity by more than double of their original injectivity. As a result of the colder water injection (100°C) it has been noticed that injectivity has been improved in some wells, such phenomenon has been reported in other fields (Kazuharu Arika and Kazuyoshi Hatakeyama, 1998). In several geothermal fields the brine is cooled in open ponds prior to being injected into the reservoir at a temperature close to atmospheric. Reports from Cerro-Prieto Geothermal field in Mexico indicate improving the productivity of some production wells and reduction in pressure decline in other wells (Truesdell et al, 1999). This behavior of enhanced injection definitely relates to higher density of colder fluids and, hence, higher pressures bottomhole. Other factors may also influence, such as thermal contraction of rock surrounding feedzones, resulting in increased fracture aperture.

6. CHANGES IN FLUID CHEMISTRY

Mixing of the ground water with deep recharge fluid can be detected by examining chloride (Cl) concentration with time as the ground water has low Cl concentration (Truesdell and Mañón, 1977).

Chloride (Cl) concentration history of produced fluid

Figure 5(a) presents Cl concentrations with time for waters sampled at weir box of shallow production wells that are located at the edge of the shallow reservoir. Figure 5(b) is for shallow and deep production wells located in the western part of the wellfield near the upflow zone.

As shown in Fig. 5, Cl concentrations quickly decrease with time from the early times, notably the shallowest wells in the eastern part of the field (MT2, 12, 17, 20 and 22 in Fig. 1). Another shallow well (MT31) indicates a fast decrease in concentration between 1989 and 1997.

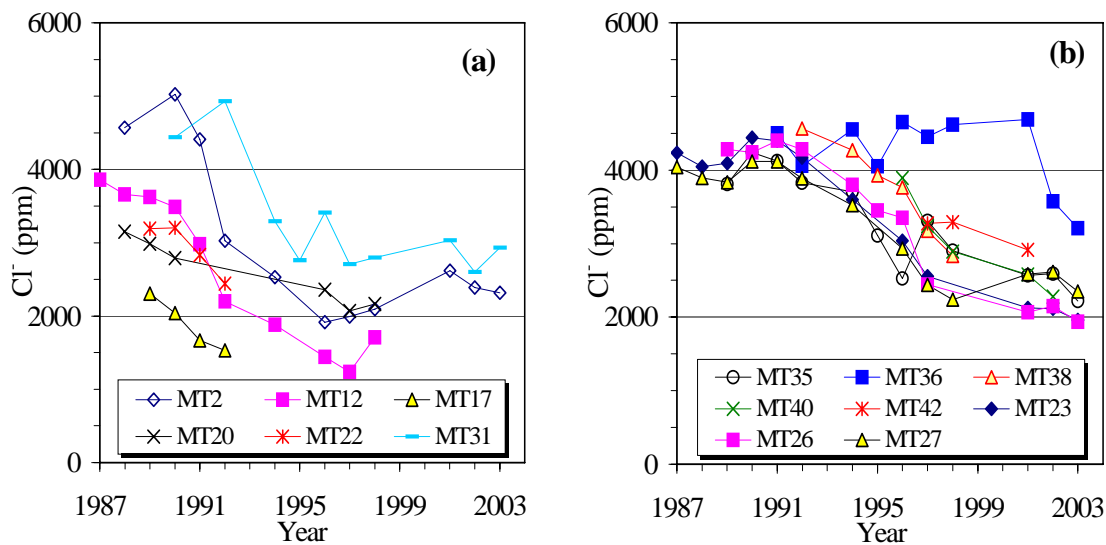


FIGURE 5: Cl concentrations in water from weir box

Wells near the upflow zone MT23, 26, 27, 35 and 38, show relatively stable values of about 4000 ppm during the early times followed by a significant decline after 1992.

Well MT36 shows constant Cl between 1991 until 2001. This well is located near the upflow zone with a main feed zone at about 789 m b.s.l. There is a slight increase in Cl followed by a quick drop in 1998. This increase may be due to mixing of reinjected water that has high Cl concentration. The deep production wells MT40 and 42 show slight decline in Cl indicating a mixing of low temperature ground water. Figure also shows that these deep wells have higher Cl (>4000 ppm) between 1987 and 1992 than the shallow ones (<4000 ppm) except shallow wells MT2 and MT31.

Decreasing behavior of Cl, concentration with time is found in most of the production wells irrespective to depths. This suggests a progressive inflow or intrusion of low temperature ground water of low salinity occurs in the whole reservoir. In particular, wells located in the eastern part of the field are seriously affected of this intrusion. Consequently, four shallow wells have lost their productivity because of excessive cooling.

Decrease of Cl, however, has been moderated in wells that suffered from calcite scaling in wellbore (MT2, 27 and 31). These wells also show an increase of Cl in 2000 when reinjection rate was increased as shown in Fig. 4. Thus, these wells could be affected by mixing of reinjected water of high concentration of Cl (2800 ppm as of January 2004).

7. FUTURE POTENTIAL

In 1995, the Italian consultant company DAL SpA proposed that Momotombo was able to generate up to 90 MWe by deep drilling (DAL, 1995). At that time four wells were drilled having as depth target 2500 m or deeper, however due to rig limitations, only wells MT39 reached 2019 m (without success since drilling tool stuck) and MT43 that reached only 2500 m.

In 2000, we, as Ormat, drilled 4 wells keeping in mind a target depth of 2500-3000 m. Unfortunately none of the wells found deep permeability. In addition when we were close to the target depth, drilling tools got stuck except for OM53 (OM51_2396 m, OM52_2815 m, OM53_2090 m, OM54_1838 m) which resulted to be the only production well.

Except for OM53, there were not found significant circulation losses during drilling, but we still believe that a deep source may exist in Momotombo and that we were not able to confirm it by the drilling campaign in 2000-2002. This believe is based on temperature distribution of the reservoir and geophysics suggesting that the hot fluid moves upward ($>320^{\circ}\text{C}$) at the northwestern part of the field from depth deeper than 3000 m. However, the low permeability found so far in the deep wells is a concern and the only well producing from more than 2000 m depth (MT43) produces about 20 t/h of steam.

Provided that Ormat is able to extend its Concession rights, a first step in raising generating capacity of the reservoir should consist of analyzing existing geophysical data and geology of the field, together with application of new geophysical methods. Based on this, we will be able to reassess the geothermal resource of Momotombo and adopt new exploitation strategies based on production sustainability. Deep drilling projects have given excellent results in other geothermal fields such as Larderello – Travale/Radicondolu in Italy (Cappetti, 2006), where high temperature resource ($300^{\circ}\text{C} - 350^{\circ}\text{C}$) was found at depth between 3000 m and 4379 m.

8. CONCLUSIONS

1. The Momotombo reservoir changed its phase conditions from the initially liquid single phase to the liquid-steam two-phase soon after fluid production started for the first unit in 1983. This two-phase zone developed mainly in the shallow reservoir, and was enlarged when more fluid produced from 1989 for the second unit of the plant.
2. Decreases in specific enthalpy and chloride concentration for shallow wells implied intrusion of low temperature and low salinity ground water into the reservoir.
3. Intrusion of low temperature ground water into the reservoir and the extensive boiling in the shallow reservoir due pressure drawdown induced cooling in the reservoir.
4. Utilization of the separated hot brine for generation of electrical energy resulted in increased capacity of the flash-type geothermal power plant from the limited fluid supply.
5. In spite of the results of the disappointing drilling campaigns in 1996-1997 and 2000-2002, we still believe that using better drilling equipment, the deeper resource of Momotombo can be reached. We are awaiting the extension of the Concession rights to carry out a new

geophysical and geological exploration campaign in order to identify deep targets for deeper drilling.

6. In parallel with deep drilling campaign using better drilling equipment we plan to implement some power equipment upgrade to utilize the flash plants still unused capacity and remain the lowest cost electricity producer in Nicaragua.

REFERENCES

- Ariki, K. and Hatakeyama, K. 1998: Effects of Injection Temperature on the Injectivity of a Geothermal Well. *Geothermal Resources Council Transactions*. vol. 22, pp.539-545.
- DAL SpA. 1995: Estudios de evaluación del potencial energético: Factibilidad de la estabilización y de la tercera unidad geotermoeléctrica del campo geotérmico de Momotombo, Fase IA: Investigaciones científicas; Informe de síntesis. *Internal report, ENEL (Empresa Nicaragüense de Electricidad), Managua, Nicaragua. DAL SpA, Milano, Italia.*
- Grant, M. A., Truesdell, A. H. and Mañón, A. 1984: Production induced boiling and cold water entry in The Cerro Prieto Geothermal Reservoir indicated by chemical and physical measurements. *Geothermics*, vol. 13, No. ½. 117-140.
- Cappetti, G. 2006. Geothermal Power Generation in Italy, Update Report. *IEA-GIA ExCo Meeting, September 7-8, 2006, San Diego, CA, USA.*
- Kaplan, U. 2004: Geothermal cold brine injection two years experience in the Momotombo Field, Nicaragua. *Geothermal Resources Council Transactions*, vol. 28. 59-64.
- Porras, E. A. 1991: Production characteristics of the Momotombo geothermal field, Nicaragua. *Report 10. UNU Geothermal Training Programme, Reykjavik, Iceland.* 54 pp.
- Truesdell, A. H., Mañón, M. A., Jiminez, M., Sanchez, A., and Fausto, J. 1977: Geochemical evidence of drawdown in the Cerro Prieto geothermal field, Baja California, Mexico. *Proceedings 1st Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico, San Diego. Rep. LBL-7098, Lawrence Berkeley Lab., Berkeley, Calif.*. 130-138.
- Truesdell, A.H., Lippman, M.J., de León, J., and Rodríguez, M.H. (1999). Cerro Prieto Cold Water Injection: Effects on Nearby Production Wells. *Geothermal Resources Council Transactions*, vol. 23, 17-20.