The Momotombo Reservoir Performance upon 25 Years of Exploitation

Enrique A. Porras

ORMAT Momotombo Power Company, Managua, Nicaragua

Keywords

Momotombo, chemistry, reinjection, Nicaragua, power output, history

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. By 1999, where the power plant output dropped to 9 MWe 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 wells, implementing a full reinjection and installing a bottoming OEC unit. Since then the plant is producing between 30 and 35 MWe supported by an intensive well maintenance program. Ormat's investment stands at about US$ 45 Million, producing electricity at less than US$5.22 Cents/kWh, making the Momotombo plant the lowest cost electricity producer in Nicaragua.

1. Introduction

There are forty-seven wells in total that have been drilled in an area of about 2 km^2 in Momotombo. Production zone is divided into shallow and deep zones. Separated water has been reinjected since the start of development, but the scheme has been changed in terms of the magnitude of injection amount as well as reinjection water temperature. Currently two reinjection schemes are on going, the so called hot reinjection where brine at about 105ºC from the bottoming OEC unit is pumped to the eastern reinjection wells; and the cold reinjection system where brine collected in lagoons at ambient temperature (30ºC) is currently pumped into wells OM52 (feed zone depth below 2000 m) and MT1 (feed zone depth about 600 m) located at the western and eastern parts of the field respectively (Figure 1).

2. Well Specification and Steam Production History

Figure 1 shows location of the forty-seven wells drilled in Momotombo. Among the 47 wells drilled so far, twenty wells have been connected to the steam gathering system in different periods. A 7 MWe Ormat Electricity Converter (OEC) unit was commissioned in 2002 fed by brine, which was disposed for years to Lake Managua, this brine cools down from 155ºC to 105ºC 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 32 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

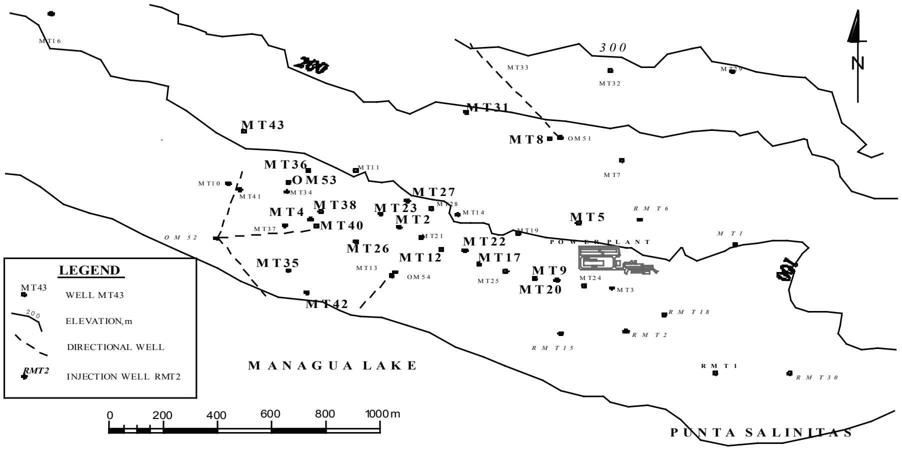

Figure 1. Wells location map.

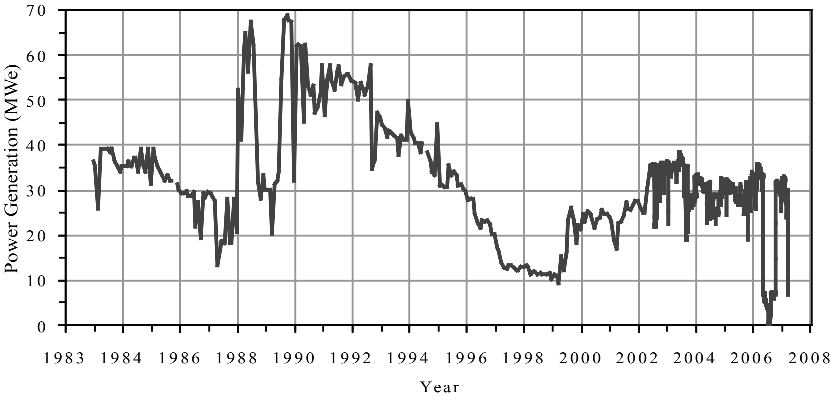

Figure 2. Power output history of Momotombo.

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 the well from dry steam of 2740 kJ/kg at MT43 to saturated water of 260°C at MT40.

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, 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 condensing type unit was commissioned when an additional six shallow wells were online for this unit. The output increased to about 68 MWe for a short period, and then it drops down to 30 MWe because of a generator-turbine failure. 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 six makeup wells from 1992 until 1997. In spite of these additional wells, decrease of output remains because of productivity decline of other wells. Wellbore surveys 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 suffered from cooling. In 1999, the output dropped down to about 8 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. In 1999 seven wells were producing steam for a power output of 8 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 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. As the 4 wells drilled didn't increase the output sufficiently, ORMAT decided to invest in a 7 MWeOEC 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.
4. To implement 100% re-injection for environmental reasons and mitigating cooling effect of re-injection. Currently ORMAT is in process of connecting well MT1 to the reinjection gathering system for increasing the injection capacity of the field. Improvements on pumping capacity of the reinjection system are also taking place as well as enhancement of the cold injection system.

As a result of this program, the power generation reached a peak power of 37.5 MWe between July 2003 and August 2004. However, the power output started to decline in 2003 due probably to decrease both in enthalpy and flow rate of four shallow production wells. On the other hand, scale was formed again at feed zone of wells MT42 and MT35. By intensive well maintenance including chemical treatment and mechanical cleaning, power output was stabilized around 32 MWe after a second acid stimulation and work over campaign carried out during 2006.

A drop in generation can be seen in 2007 when the 35 MWe condensing units stopped due to mechanical failures in the turbine. Turbine of Unit II stopped functioning in September 2006 and Turbine of Unit I in March 2007. In October 2007 Unit II was back on line. By January 2008 a six months silica inhibition test started at the heat exchangers of the bottoming OEC unit. The test has been successful avoiding formation on silica scale in heat exchangers (pre-heaters and vaporizers) by pumping GEOSPERSE 5110, a chemical product distributed by PowerChem, into the brine line at the inlet of the bottoming OEC unit.

3. Analysis of the Production Data

Relationship between downhole pressure in well MT11 and total flow rate of the wells is shown in Figure 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 a quick decline in 1987 corresponding to stopping 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 feed zone temperature and scaling in wellbore as well.

In March 1996 the total flow rate reaches a peak 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.

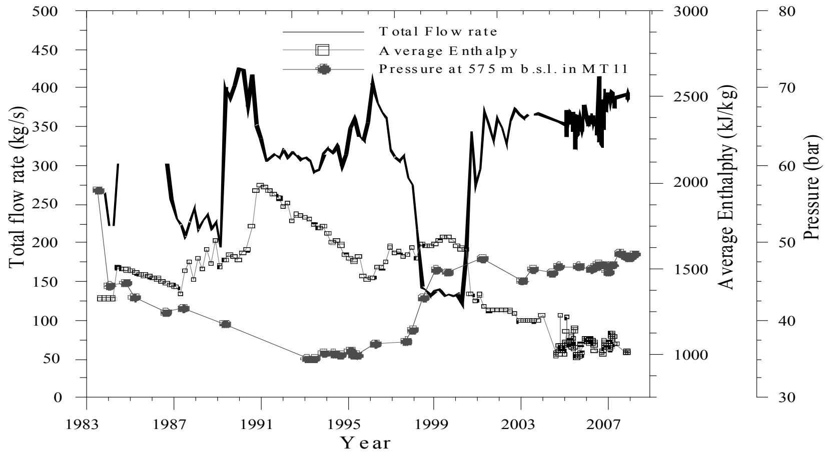

Figure 3. Pressure in MT11, total flow rate and average specific enthalpy.

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 produced steam for the power plant 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 in the 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 2002 when 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 workovers for installing scale inhibition system in 2000. However appreciable change in pressure is not observed as shown in Figure 3 until 2006 when it starts increasing with time due to full injection and increase of injection rate. Total flow rate from reservoir increases from 2006 as a result of the second work over and acid stimulation campaign carried out during this year. By 2007 a peak value on total mass flow rate was reached that is compared with the peak reached in 1989-1990 when the second condensing type unit was started up. The difference between these two peaks on total flow rates, is that in 2007 average specific enthalpy is about 1000 kJ/kg lower than for 1989-1990. Therefore, although we are currently extracting the same mass rate from the reservoir as for 1989-1990, we have now a much lower power output than in 1989-1990.

High specific enthalpy fluid (2770 kJ/kg) was produced from wells MT12 in 1990 and MT20 between 1990 and 1994, this implies that a steam-water two-phase condition exists in the vicinity of the wells or a two-phase zone spreads throughout the shallow reservoir between 1986 and 1996. Currently, low specific enthalpy fluid (1000 kJ/kg) is being produced.

4. Reinjection History

Location of reinjection wells is shown in Figure 1 with names that start with R such as RMT15 (except for well MT1 that will be connected to the reinjection gathering system middle 2008). 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 155°C in 2002.

Figure 4 shows the reinjection and separated water histories at Momotombo. As it can be seen, between 12% and 30% of separated water is reinjected between 1984 and 1996 when separated water was discarded into the Managua Lake. In 2002 all production wells were connected to the reinjection system and another two reinjection wells were connected to the system (RMT1 and 30) in early 2003. Reinjection rate has been increased such that more than 90% of the separated water is reinjected after 1999. This difference becomes zero in 2008 when all of the separated water is reinjected as a result of a new cold injection system that injects cold brine stored in four lagoons into wells OM52 and MT1. This cold injection allows us to manage over-flow of produced brine at the weir boxes of all production wells.

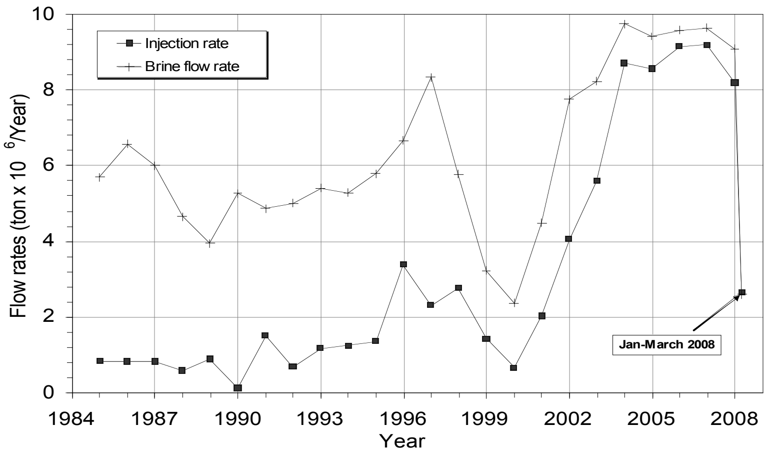

Figure 4. Reinjected and separated water history.

Figure 4 shows that as a result of the new injection strategy, more than 100% injection has been reached in 2008. 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.

5. 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). 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 Figure 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 Figure 1). Another shallow well (MT31) indicates a fast decrease in concentration between 1989 and 1997.

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.

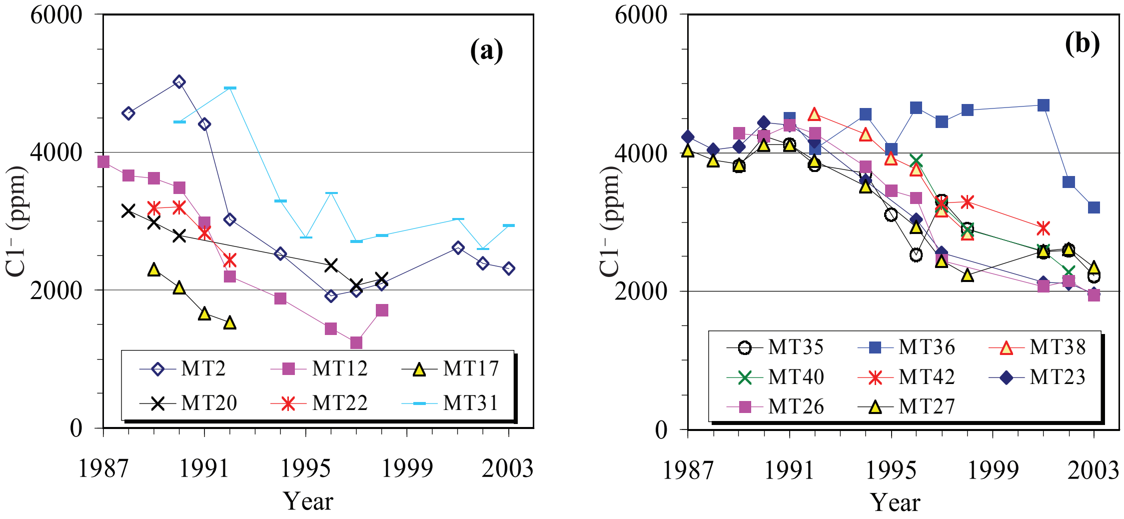

Figure 5. Cl concentrations in water from weir box.

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.. 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 by this intrusion. Consequently, four shallow wells have lost 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).

6. Future Potential

In 1995, four wells were drilled having as depth target of 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, 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 was the only successful production well. Except for OM53, there were not 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 belief is based on temperature distribution of the reservoir and geophysics suggesting that the hot fluid moves upward (>320ºC) 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.

7. 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 concentrationfor 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 to 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 drilling campaigns in 1996-1997 and 2000-2002, we still believe that the deeper resource of Momotombo can be reached by using better drilling equipment. 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 power equipment upgraded to utilize the flash plants still unused capacity and remain the lowest cost electricity producer in Nicaragua.

References

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.

Truesdell A.H., M.A. Mañón, M. Jimenez, A. Sanchez, and J. Fausto, 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*, v. 23, p. 17-20.