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FIRST ELEVEN YEARS OF EXPLOITATION AT THE MIRAVALLES GEOTHERMAL FIELD

Paul Moya and Antonio Yock

Instituto Costarricense de Electricidad, UEN Proyectos y Servicios Asociados
C. S. Recursos Geotérmicos, Apartado Postal 10032-1000
San José, Costa Rica, Centro América
e-mail: pmoya@ice.go.cr , ayock@ice.go.cr

ABSTRACT

The Miravalles Geothermal Field has been producing electric energy since March 1994. It has provided steam for Unit 1 (55 MWe) since 1994, a Wellhead Unit (5 MWe) installed in 1995, Unit 2 (55 MWe) in 1998, Unit 3 (29 MWe) in 2000 and Unit 5 (19 MWe, a binary plant) in year 2004. The total installed capacity in Miravalles is therefore 163 MWe. The reservoir response during the eleven years of exploitation is described in the following sections. So far the field has successfully supplied the steam needed to maintain constant production over the first eleven years of exploitation. Field management policies as well as injection strategies have been implemented to minimize the pressure decline in the reservoir.

INTRODUCTION

The Miravalles geothermal field, located on the southern slope of the Miravalles volcano, is the most important Costa Rican geothermal development. The present field extends over an area of more than $21 km^2$, of which about 16 km^2 are dedicated to production and 5 km^2 to injection. The temperature of the water-dominated geothermal reservoir is about 240°C. Fifty-three geothermal wells have been drilled to date (Figure 1). They include observation, production and injection wells, whose depths range from 900 to 3,000 meters. Individual wells produce enough steam to generate between 3 and 12 MWe; injection wells accept between 70 and 450 kg/s of separated water each (Moya, 2003).

Commercial production of electricity from geothermal steam began at Miravalles in early 1994, when Unit 1, a 55 MWe single-flash plant, was commissioned. The following year, the Costa Rican Electricity Institute (ICE) completed the installation of a 5 MWe wellhead unit. Two temporary 5 MWe wellhead plants then came on line as part of an agreement between ICE and the Comisión Federal de Electricidad of Mexico (CFE). In January and August 1998, the two temporary units were disassembled and returned to CFE.

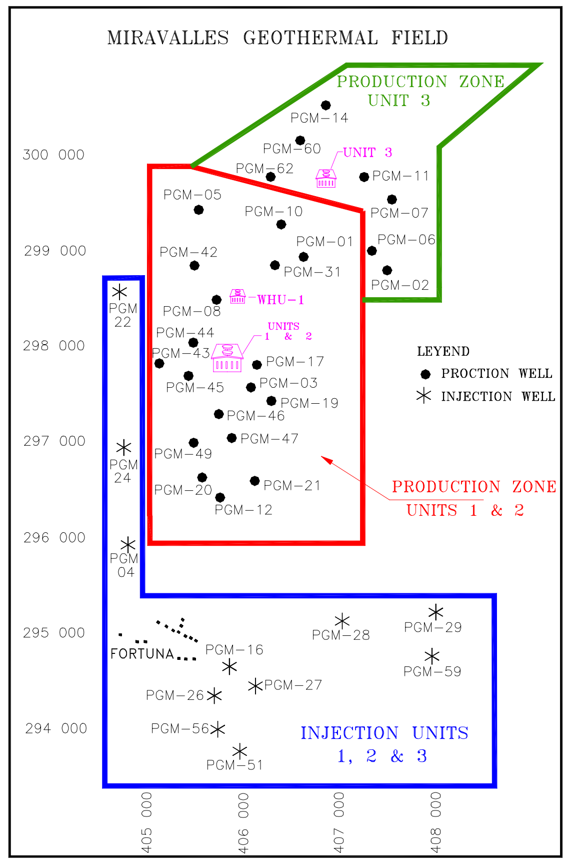

Figure 1. Miravalles Geothermal Field.

Unit 2, the second 55 MWe plant, began production in August 1998. Finally, in March 2000, Unit 3, a privately owned 29 MWe single-flash plant began delivering electricity to the national grid, increasing the installed capacity at Miravalles to 144 MWe. This capacity was increased to 163 MWe when a bottoming-cycle binary plant came online in January of 2004. Table 1 summarizes the units that have been installed at the Miravalles geothermal field.

Plant Name	Power (MW)	Belongs to	Start-up Date	Final Date
Unit 1	55	ICE	3/1994	
WHU-1	5	ICE	1/1995	
WHU-2	5	CFE	9/1996	4/1999
WHU-3	5	CFE	2/1997	4/1998
Unit 2	55	ICE	8/1998	
Unit 3	29	ICE (BOT)	3/2000	
Unit 5	19	ICE	1/2004	

Table 1. Units at the Miravalles Geothermal Field

In Table 1, the abbreviations stand for: ICE - Instituto Costarricense de Electricidad; CFE - Comisión Federal de Electricidad (México); WHU - Wellhead Unit; and BOT – build-operate-transfer.

The history of the growth of capacity at the field is shown in Figure 2. Concurrent with growth in installed capacity at Miravalles, there was an even more important increase in the amount of electricity generated (Figure 3). Between 1994 and 2004, the installed capacity at the field grew from 55 to 163 MWe (a 196% increase), while generation grew from 341 to 1,144.3 GWh (a 235% increase).

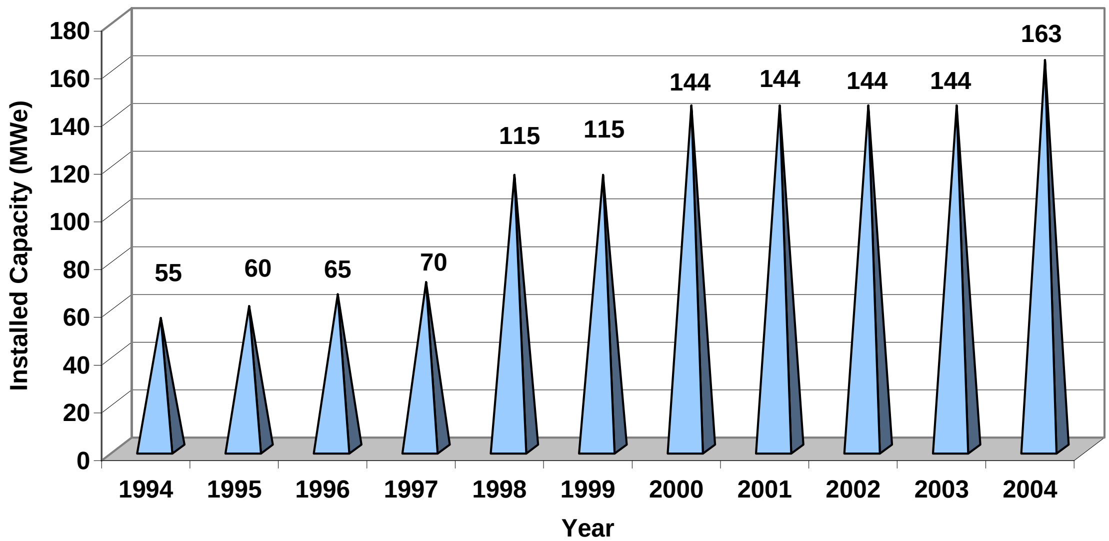

Figure 2. Installed Geothermal Capacity at Miravalles (1994 – 2004)

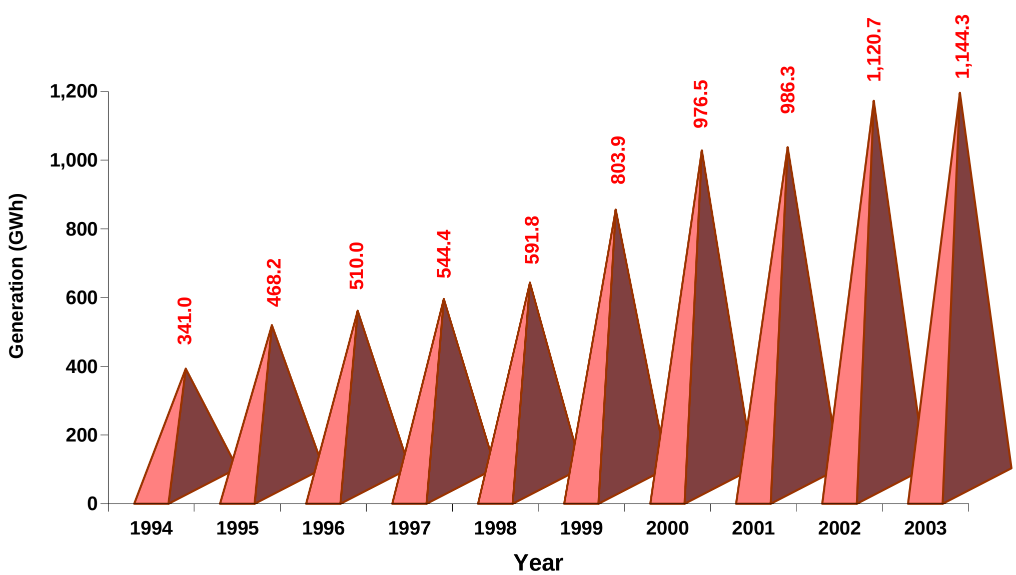

Figure 3. Geothermal Generation at Miravalles (1994 – 2003)

Steam for Units 1-3 and the wellhead unit is separated from the hot water at seven separation stations. Generally, two or three production wells send their two-phase fluids to one of these stations. Separation stations 2, 3 and 4 supply steam mainly to Unit 1; stations 1, 5 and 6 feed Unit 2, and station 7 sends its steam to Unit 3.

The mass produced from the reservoir since 1994 is shown in Figure 4. Incremental production increases accompanied each of the new units coming on line. The residual (separated) geothermal water is sent to the injection wells, which are distributed in four areas of the field: the northern, southern, eastern and southwestern sectors (Figure 5).

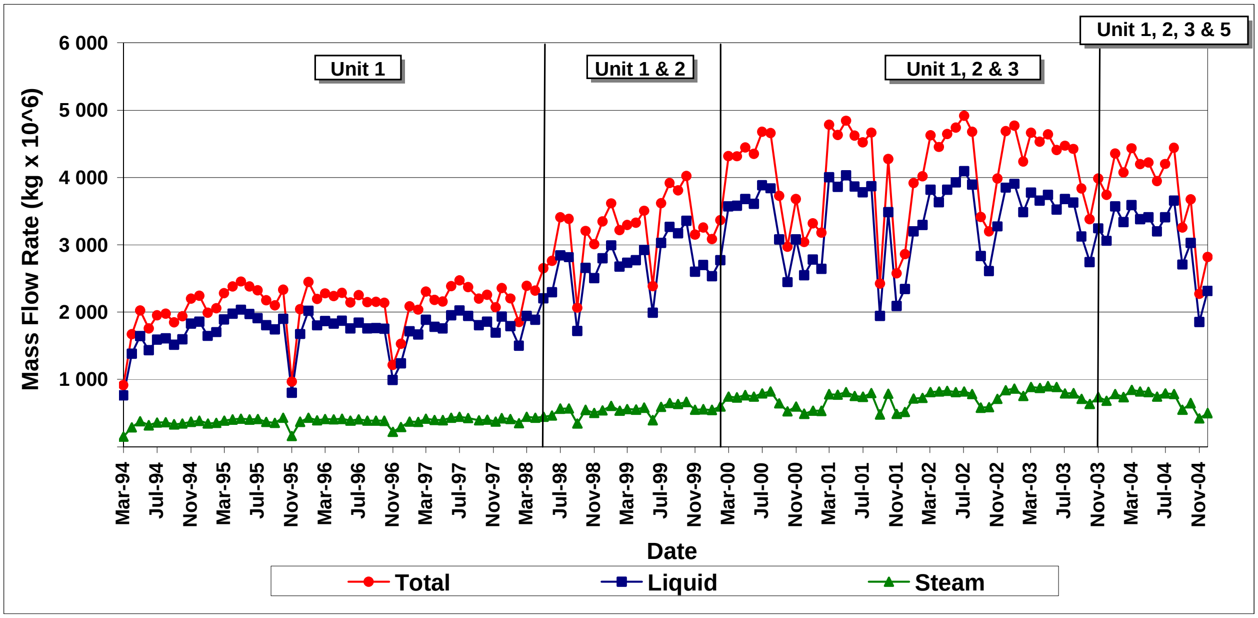

Figure 4. Mass Production at the Miravalles Geothermal Field (March 1994 – December 2004)

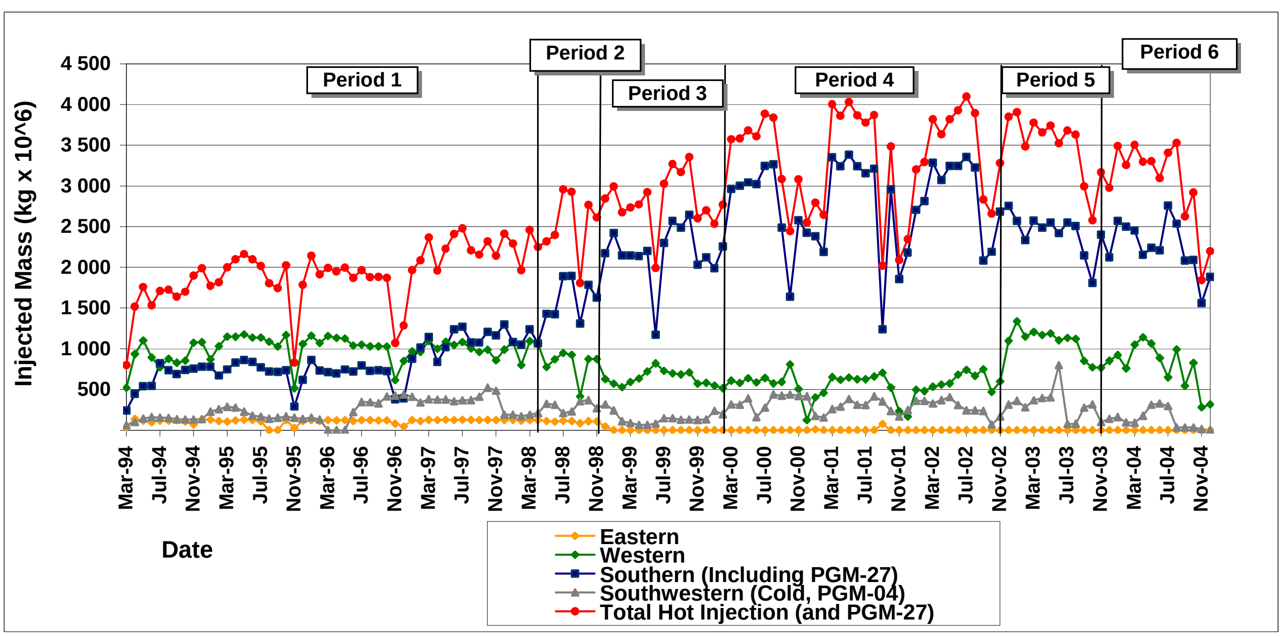

Figure 5. Injection at the Miravalles Geothermal Field (March 1994 – December 2004)

CHEMICAL AND THERMODYNAMIC CHANGES WITH TIME

Several parameters have been monitored at each production well to evaluate the behavior of the reservoir over the first eleven years of its exploitation. These parameters are: enthalpy, temperature, pressure, flow rate, wellhead pressure, and certain chemical species such as chloride, sulfate, bicarbonate, sodium, potassium, calcium, magnesium, silica and non-condensable gases (Yock, 1998).

The production zone at the Miravalles geothermal field has been divided into six different sectors: northern-1, northern-2, western-central, central, central-southern and southern (Figure 6). Each production sector contains a group of wells and, for each well, the non-condensable gases, enthalpy and chloride concentration parameters have been graphed versus time (figures 7 to 12).

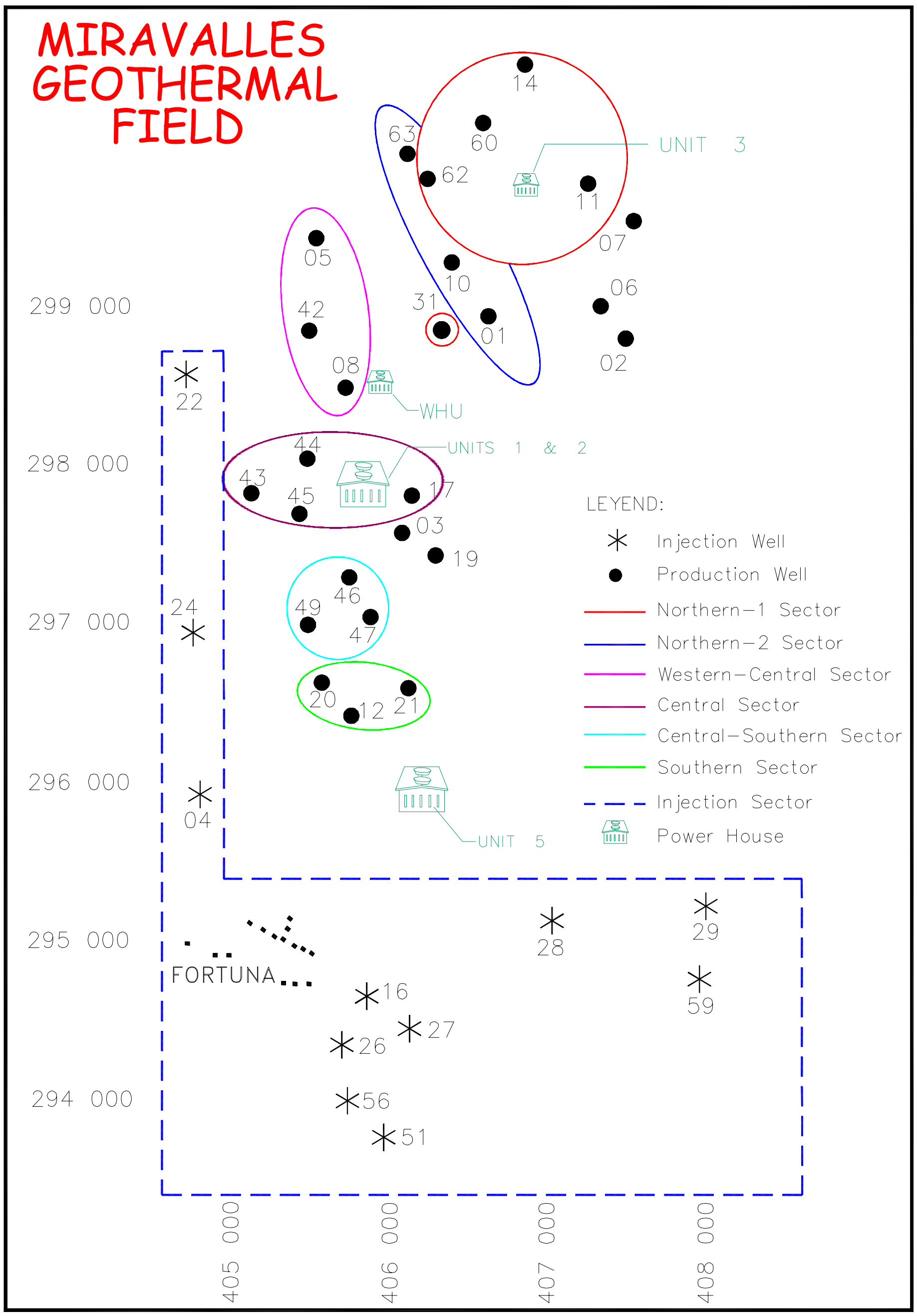

Figure 6. Production Sectors at the Miravalles Geothermal Field

Fluid injection at the Miravalles geothermal field has taken place mainly in two areas: the west and south of the production zone (Figure 6).
The vertical lines in figures 7 to 12 indicate the commissioning of Unit 1 (U-1), Unit 2 (U-2), Unit 3 (U-3) and Unit 5 (U-5). "IC" in these figures stands for "injection change".
Early in the year 2003, the injection rate in the western zone was increased by diverting some of the fluids that initially were sent to the southern zone.

Northern-1 Sector

The wells that belong to this sector are PGM-11, PGM-14, PGM-60, PGM-62 and PGM-31. Wells PGM-11 and PGM-31 began their production in 1994 with the commissioning of Unit 1. Wells PGM-14, PGM-60 and PGM-62 began producing when Unit 3 came online. The chloride concentration in all of these wells has been almost constant (around 4,100 ppm), with the exception of PGM-31, where the chlorides increased slightly until the year 2000 (Figure 7). After the commissioning of Unit 3, the chloride content in PGM-31 began to decrease slightly, reaching values close to 4,100 ppm. The enthalpy values for these wells are close to 1050 kJ/kg, and their non-condensable gases increased after the commissioning of Unit 3 in the year 2000.

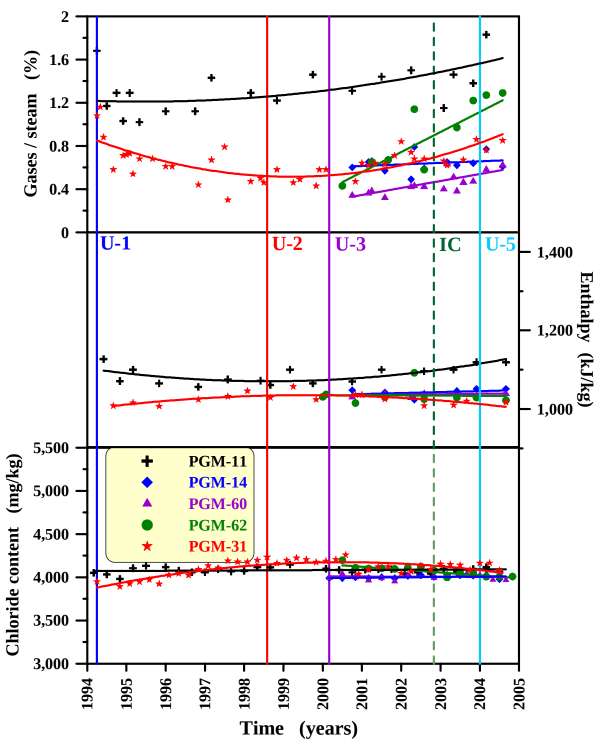

Figure 7. Monitoring results, Northern-1 Sector wells

Northern-2 Sector

The wells associated with this sector are PGM-01, PGM-10 and PGM-63. At present, all of these wells are non-productive. Wells PGM-01 and PGM-10 were in production from March 1994 to February 2003. Well PGM-63 produced from July 2002 to August 2003 (Figure 8).
For wells PGM-01 and PGM-10, the chloride concentration increased until Unit 2 came online in August 1998; thereafter, it decreased to values between 3,750 to 4,000 ppm. The enthalpy at PGM-01 remained constant until the end of 2002, but then it increased rapidly from 1,000 kJ/kg (end of 2002) to 1,200 kJ/kg (end of 2003). The enthalpy at PGM-10 has increased steadily since the middle of 1997. The non-condensable gas concentration began to increase in both wells (PGM-01 and PGM-10) after the commissioning of Unit 2.
At PGM-63 the chloride content decreased while the well was producing, but both the enthalpy and the non-condensable gases increased during the same period.

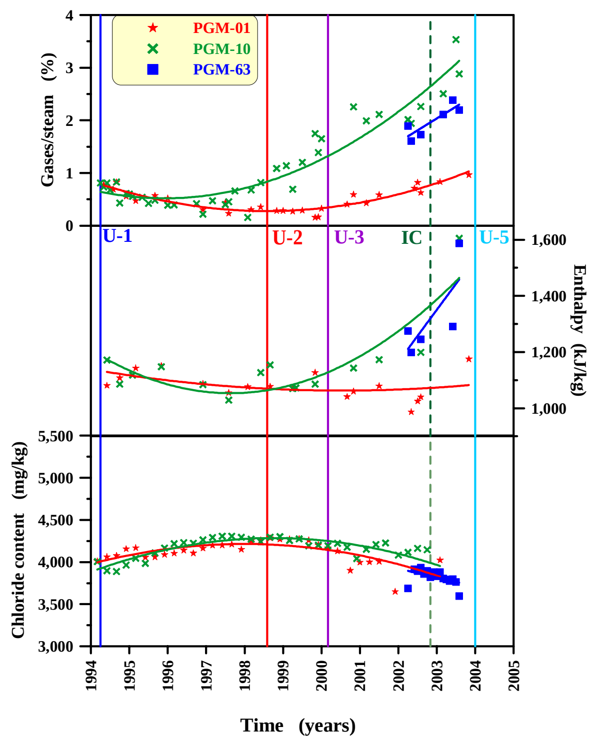

Figure 8. Monitoring results, Northern-2 Sector wells

Western-Central Sector

The wells that are part of this sector are PGM-05, PGM-08 and PGM-42. PGM-05 started producing in 1994, when Unit 1 came online. Wells PGM-08 and PGM-42 began production in 1998, when Unit 2 came online. The chloride concentration at PGM-05 increased from 1994 to the middle of 1998, then remained almost constant until the end of 2004. Since the commissioning of Unit 2, all the wells in this sector have maintained a constant chloride content of about 4,250 ppm (Figure 9). Enthalpy decreased at wells PGM-05 and PGM-42 during their production period, and remained constant at well PGM-08. Non-condensable gases have decreased in well PGM-05 ever since 1994, and stayed constant in wells PGM-08 and PGM-42 from the start of their production until the middle of 2001. After mid-2001, the non-condensable gases in all three wells have shown a slight tendency to increase.

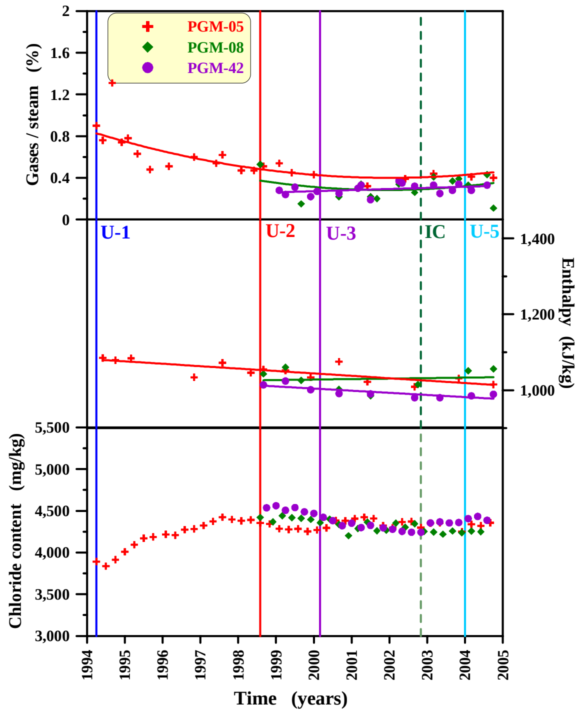

Figure 9. Monitoring results, Westhern-Central Sector wells

Central Sector

The wells that belong to this sector are PGM-17, PGM-43, PGM-44 and PGM-45. These wells are close to injection wells PGM-22 and PGM-24. PGM-17 started its production in 1994, PGM-45 in 1996, PGM-43 in 1998 and PGM-44 at the end of 1999. Even though all these wells were in operation in different years, all of them have experienced an increase in chloride content since their production began. The enthalpy slightly decreased or remained constant (at around 1,000 kJ/kg) in all the wells, with the exception of PGM-45, which has presented an anomalously high enthalpy from the middle of 2001 to the present (Figure 10). The non-condensable gases have remained constant in PGM-44, decreased in PGM-43, and increased PGM-45. In PGM-17 the non-condensable gases have fluctuated and have tended to decrease since early 2003 (when injection into wells PGM-22 and PGM-24 was increased).

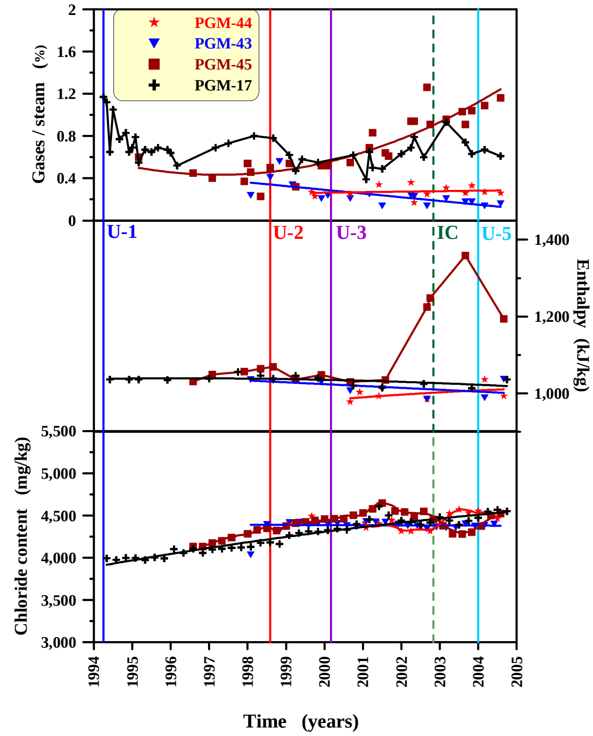

Figure 10. Monitoring results, Central Sector wells

Central-Southern Sector

The wells associated with this sector are PGM-46, PGM-47 and PGM-49. All of these wells are close to injection well PGM-24. PGM-46 started its production in 1994 and was deepened at the end of the year 2001. Wells PGM-47 and PGM-49 began their production in the middle of 1998 when Unit 2 came online.

The chloride content in all these wells has tended to increase, indicating that injected geothermal fluid is arriving in this sector. There was a decrease in the chloride concentration at PGM-49 by the middle of 2003, right after the rate of fluid injection in the western part of the production zone (PGM-22 and PGM-24) was increased. The chloride concentration at PGM-46 has remained constant since the well was deepened, and has also stayed constant at PGM-47 (Figure 11). The enthalpy at PGM-46 increased from 1994 to 2001, but after the well was deepened the enthalpy became constant. A similar behavior (constant enthalpy, around 1,000 kJ/kg) was seen at wells PGM-47 and PGM-49. The non-condensable gases in PGM-46 decreased until the year 2000, then increased until the well was deepened during 2001, and have kept increasing until the present. In contrast, in PGM-47 the non-condensable gases have shown a tendency to decrease slightly, while in

PGM-49 they have stayed constant (close to 0.4% w/w).

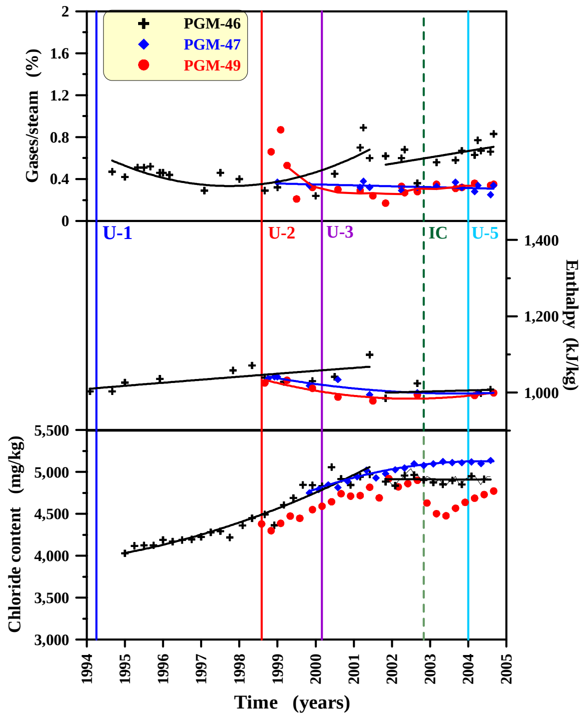

Figure 11. Monitoring results, Central-Southern Sector wells

Southern Sector

The wells that are part of this sector are PGM-12, PGM-20 and PGM-21. All of these wells began their production in 1994, when Unit 1 came online. The chloride concentration in all of the wells has increased since 1994 (Figure 12).

The enthalpy in PGM-20 and PGM-21 has been constant from 1994 to the present, but in well PGM-12 it has decreased slightly, to less than 1,000 kJ/kg. The non-condensable gases in wells PGM-20 and PGM-21 have decreased slightly, but in PGM-12 they decreased from 1994 to 2001, then have increased until the present.

DATA ANALYSIS

Analyzing the northern part of the production zone (northern-1 and northern-2 sectors, figures 7 and 8), it can be observed that the majority of the wells (producing since 1994) were receiving a small fraction of the injected fluids until Unit 2 came online (middle of 1998). After that, the chloride content at the wells started to decrease and their non-condensable gases began to increase.

Wells PGM-01, PGM-10 and PGM-63 became non-productive, probably because fluid withdrawal rapidly lowered the flashing depth in these wells due to low permeability in this part of the reservoir. Lowering the flashing depth causes calcium carbonate deposition to take place, initially inside the production casing and then in formation fractures, reducing the permeability that allows the wells to produce.

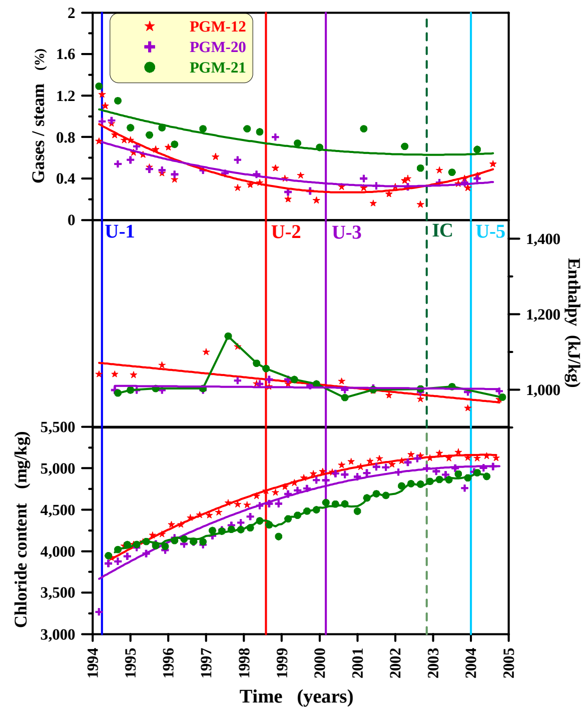

Figure 12. Monitoring results, Southern Sector wells

While calcium carbonate deposition is taking place, CO_2 moves from the liquid to the steam phase, following the reaction indicated by Equation 1:

$$2HCO_3^- + Ca^{+2} \leftrightarrow CaCO_3\downarrow + CO_2\uparrow + H_2O \qquad (1)$$

When lowering the flashing depth, this reaction causes the precipitation of calcium carbonate and some shallow productive fractures may be affected.

In the central part of the production zone (Western-Central and Central Sectors) it can be observed that the chloride concentration has increased or stayed constant in all the wells (Figures 9 and 10). The enthalpies in all the wells have decreased slightly, to values close to 1,000 kJ/kg, with the exception of well PGM-45, which presents a high-enthalpy anomaly due to a shallow steam zone. This steam zone was initially observed also in nearby well PGM-46, but it disappeared as the well produced. It was necessary to deepen well PGM-46 to recover its productivity.

The non-condensable gases have decreased in the majority of the wells that belong to the central sectors. In PGM-17 the non-condensable gases fluctuated from 1994 to 2003, but began decreasing right after the western fluid injection was increased, and have continued to do so until the present. Of all the wells that are part of the Western-Central and

Central Sectors, the only one that has shown an increase (since 1997) in non-condensable gases is PGM-45.

In the Central-Southern and Southern Sectors of the field, the chloride concentration has increased in all the wells since they began production (Figures 11 and 12). In all of these wells it is noticed that, due to the increase in the western fluid injection (with a corresponding decrease in the southern injection), less injected fluid is reaching these wells, causing the chloride content to stop increasing and be fairly constant. The enthalpies in the wells of these two sectors have decreased or stayed constant at values around 1,000 kJ/kg.

The non-condensable gases decreased in the majority of these wells, except for PGM-12 and PGM-46. The non-condensable gases have been increasing in PGM-12 since the middle of 2001, and in PGM-46 since late 1997. The deepening of PGM-46 caused the rate of increase to lessen, but it has continued nonetheless.

FINAL REMARKS

On March 25, 2005, the Miravalles geothermal field will complete 11 years of continuous exploitation. During all these years, the field has been able to supply the steam and the separated brine required by the generating units, even though the installed capacity and the generation have increased ever since 1994.

At present, wells PGM-01, PGM-10 and PGM-63 are non-productive. It is probable that the natural low permeability in that part of the reservoir, combined with some calcium carbonate deposition in the reservoir fractures, has caused these wells to stop producing.

In the near future, injection into PGM-63 will be performed in order to evaluate the possibility of recovering the production within the northern sector of the field.

Chloride concentrations increased in wells PGM-01, PGM-10 and PGM-31 until Unit 2 came online, then decreased and remained constant. On the other hand, the chloride content has shown a tendency to increase in the central and southern part of the field. The northern sector of the reservoir benefits the least from return of injected fluids. The increase in the western fluid injection has had an impact mainly on the central and southern parts of the production zone. At present, no cool front has been detected, and therefore effect of the arrival of the injected fluids at some wells has been positive so far.

Enthalpies have tended to decrease slightly in the northern, central and southern parts of the field ever since production began.

The non-condensable gases have increased in the northern sectors and in some wells of the central part of the production zone. In the southern part of the field, the non-condensable gases have been decreasing.

Since the northern sector of the reservoir has experienced the strongest productivity declines, the wellhead unit should be relocated to well PGM-29. By doing so, the steam requirements will decrease in the northern and central sectors of the production zone.

The generating units should be kept at their nominal capacities. Extra generation from these units will tend to over-exploit the reservoir, and might not be sustainable over the long term.

The current detailed program of monitoring the main reservoir parameters should be continued in order to detect any future negative impacts.

ACKNOWLEDGEMENTS

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