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# BEHAVIOR OF THE GEOTHERMAL RESERVOIR AT THE MIRAVALLES GEOTHERMAL FIELD DURING 1994-2010

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## ABSTRACT

The Miravalles Geothermal Field has been producing electric energy since March 1994. It has provided steam for Unit I (55 MW, installed in 1994), a wellhead unit (5 MW, 1995), Unit 2 (55 MW, 1998) and Unit 3 (29 MW, 2000). A 19 MW "bottoming cycle" plant (Unit 5), completed in January 2004, has brought the total installed capacity in Miravalles to 163 MW. The field has supplied the steam and brine to generate power during more than sixteen years of exploitation (1994-2010). The behavior of production and injection at the Miravalles geothermal field is described, as well as the zone of pressure decline in the reservoir. The micro-seismicity in the field has been increasing since 2001, and even though 2009 has been second in the number of micro-seismic events since 1994, year 2010 seems to be the year of the most micro-seismic events. Until July 2010, there were 165 events registered, with the largest number occurring in May, as was the case in 2009. The events are mainly localized between 1 and 3 km depth and of magnitudes less than 2.9. The micro-seismicity distribution at the Miravalles geothermal field matches the current pressure decline zone.

## INTRODUCTION

Costa Rica is located in the southern part of the Central American isthmus, between Nicaragua and Panama. The country extends over an area of approximately 51,000 km$^2$ and has a population greater than 4.5 million. The most important Costa Rican geothermal area is located on the southwestern slope of the Miravalles volcano. 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 was about 240$^0$C at the beginning of the exploitation. Almost seventeen years later, the temperatures are now around 230$^0$C, due to the process of production-injection in the geothermal reservoir. Fifty-three geothermal wells have been drilled to date. They include observation, production and injection wells, with depths ranging from 900 to 3,000 meters. Individual wells produce enough steam to generate between 3 and 12 MW; injection wells accept between 70 and 450 kg/s of separated geothermal fluids each (Moya and Nietzen, 2010).

Commercial production of electricity using geothermal steam began at Miravalles in early 1994, when Unit 1, a 55 MW single-flash plant, was commissioned. The following year, ICE completed the installation of a 5 MW wellhead unit. This unit was located in the middle of the field for almost 12 years (1995-2006), but in early 2007 it was moved to a new location at the southeastern part of the field.

Two temporary 5 MW wellhead plants came on line as part of an agreement between ICE and the Federal Commission of Electricity of Mexico (CFE) during 1996 and 1997. These two temporary units were disassembled in April 1998 and 1999 (Table 1) and returned to CFE. Unit 2, the second 55 MW plant, started production in August 1998 and in March 2000, Unit 3, a 29 MW single-flash private plant, started delivering electricity to the national grid. Finally, Unit 5, a 19 MW binary plant which extracts additional energy from the separated geothermal brine before it is injected back into the geothermal reservoir, increased the total installed capacity at Miravalles to 163 MW.

The installed geothermal capacity in Costa Rica will be increased in 2011 by 35 MW due to the commissioning of a new unit in Las Pailas geothermal area on the slopes of the Rincón de la Vieja volcano. The history of growth of capacity at the field is shown in Figure 1, and the increase in energy production at the geothermal field is shown in Figure 2.

Currently, the total steam delivered to the power plants is about 330 kg/s. Around 1,235 kg/s of residual (separated) geothermal water is sent to injection wells, which are distributed in four areas of the field (the northern, southern, eastern and southwestern sectors). A total of about 150 MW is generated from these quantities of steam and brine.

*Table 1: Power units at the Miravalles geothermal field. Abbreviations stand for: ICE-Instituto Costarricense de Electriidad; CFE-Comisión Federal de Electricidad (Mexico); WHU-Wellhead Unit; and BOT-build-operate-transfer.*

| Plant Name | Power (MW) | Owner | Start-up (Date) | Shut-down (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 | |

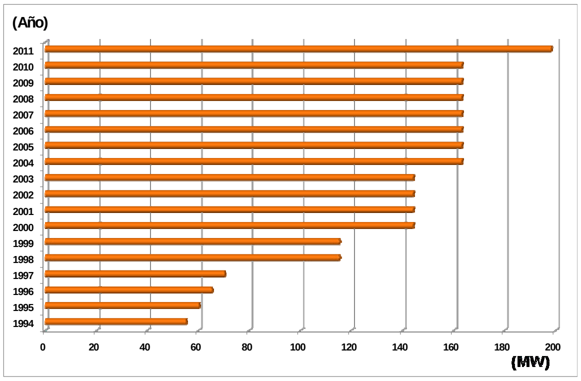

*Figure 1: Geothermal installed capacity (1994-2011).*

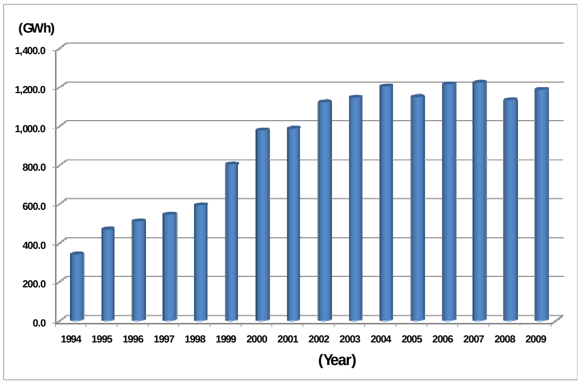

*Figure 2: Energy production (1994-2009).*

Figure 3 shows the location of the geothermal wells at the Miravalles geothermal field.

## PRODUCTION

The two-phase fluids are sent to separation stations, with two to five wells supplying each station. There are seven main separation stations and four minor stations (one at the wellhead unit, the others at the acid wells).

The separation stations are also called satellites, and each is capable of separating a maximum of 60 kg/s of steam (Moya and Nietzen, 2005). The satellites supply the steam and the brine needed by the generating units. A brief description of the history of the separation stations is presented in the following sections. Only the major events for each satellite are described. In the figures showing production to the satellites, the steam rate is represented by the green curve, brine by the blue line and the sum of both by the red curve.

### Separation Station 1

Separation Station 1 is fed by wells PGM-31 and PGM-65. Recently two wells have been sending two-phase flow to Satellite 1; these are PGM-10 (drilled in 1984) and PGM-63 (drilled in 2000). Both wells had been closed because they lost their production, but were reopened during the last semester of year 2010 to be use again as producers. Under current conditions, Satellite 1 separates 28 kg/s of steam and 56 kg/s of brine. Occasionally the flow from well PGM-05 is also separated at this station, but at present it is mainly separated at Station 4. Satellite 1 separated the geothermal fluid for Unit 1 from March 1994 until October 2002. Since November 2002, the steam has been sent to Unit 2, because the latter has a greater capacity to handle the non-condensable gases coming from Satellite 1.

As can be seen in Figure 4, the separated steam rate was almost constant from March 1994 until June 1998; then the flow decreased until September 2001. The decrease in steam and brine occurred because the fluid from PGM-05 was sent to Satellite 4 when Unit 2 started its final tests (March 1998), and the fluid from PGM-11 was sent to Satellite 7 when Unit 3 began generating (March 2000).

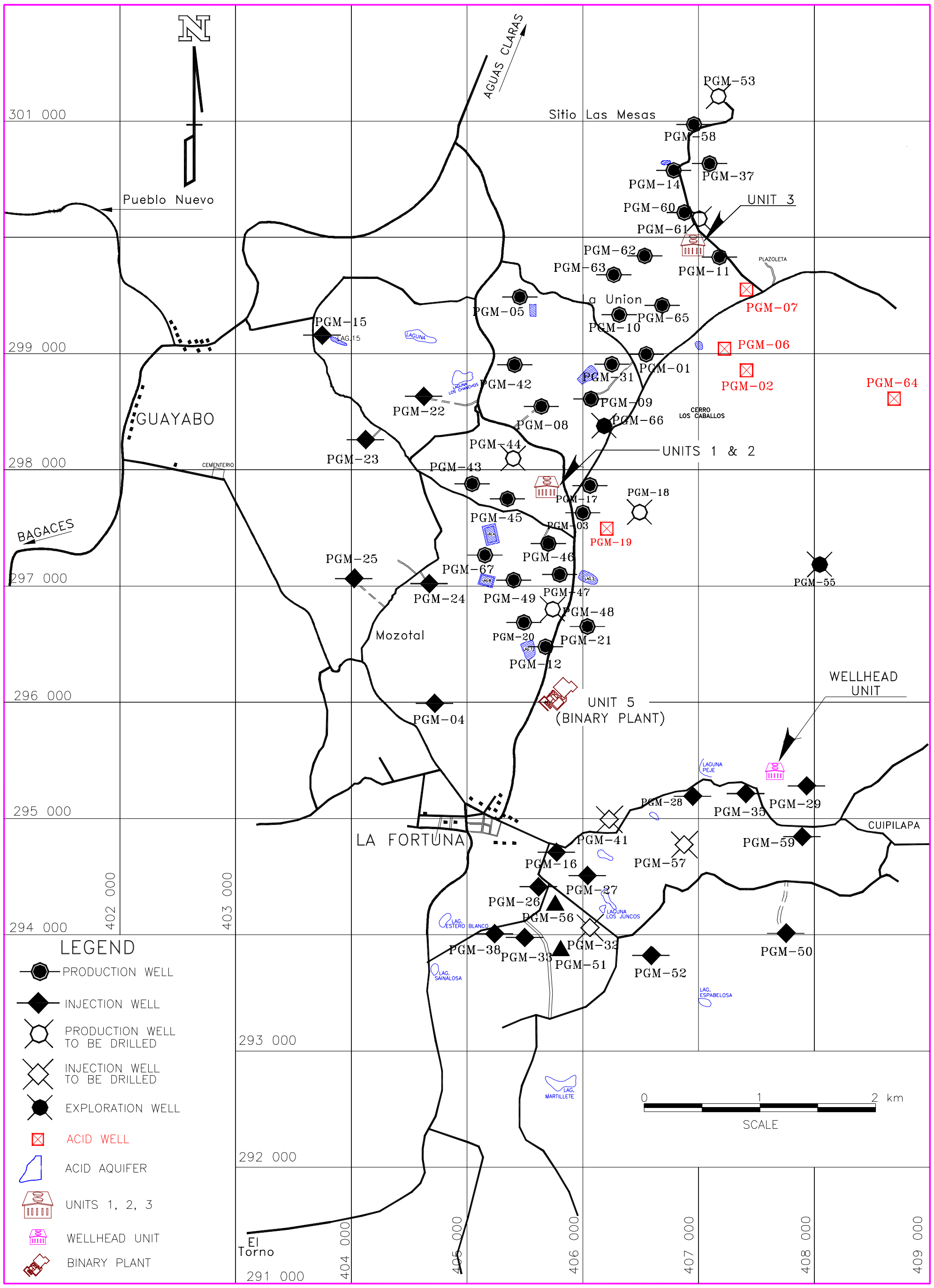

Figure 3: *Location of the geothermal wells at the Miravalles geothermal field.*

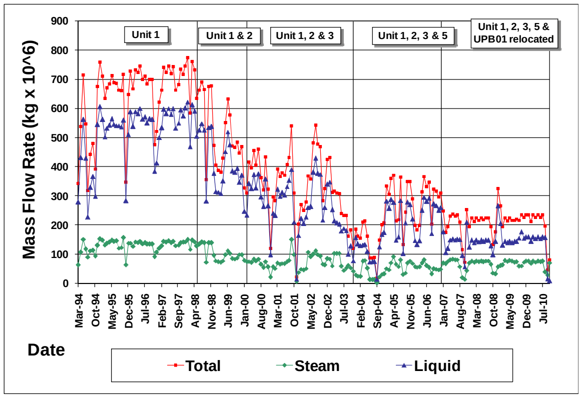

*Figure 4: Monthly mass flow rates at Separation Station 1.*

Later, the separated steam rate was kept more or less constant (based on the rate required by the units) from March 2002 until May 2003. After May 2003, some of the wells feeding Satellite 1 (PGM-01, PGM-10 and PGM-63) lost their production, which decreased the steam production rate until June 2004. From March 2005 to October 2010 the steam production rate has remained fairly constant.

## Separation Station 2

Separation Station 2 is now fed by wells PGM-03, PGM-17, PGM-19 and PGM-66. Under present conditions, it separates 52 kg/s of steam and 160 kg/s of brine. The flow from well PGM-46 was separated at this station until Unit 2 came online; since then the flow from well PGM-46 has been separated mainly at Separation Station 6.

Figure 5 shows that the separated steam rate decreased slightly from March 1994 until March 1998, when only Unit 1 was generating electricity. When Unit 2 came online, the steam rate decreased further, in part because the steam from PGM-46 was sent to Satellite 6. After March 2000, the flow rate varied depending on steam requirements until July 2001, when it was necessary to deepen well PGM-46 because it had lost part of its production. A new deep permeable zone was found, and early in 2002 well PGM-46 was placed back in operation; this kept steam production more or less constant until June 2002. The decrease in steam production from Satellite 2 was also due to the production decline in well PGM-19, which underwent major cleanouts during the last quarter of the years 2000 to 2003. Well PGM-19 went back online early in 2004, which explains the increase in the steam rate during the first four months of that year. Early in 2003 the geothermal fluid from a new production well (PGM-66) was incorporated into this separation station, which increased its steam production rate until October 2010, depending on the requirements of the generating units. Some variations in the steam rate are due to instability at well PGM-19.

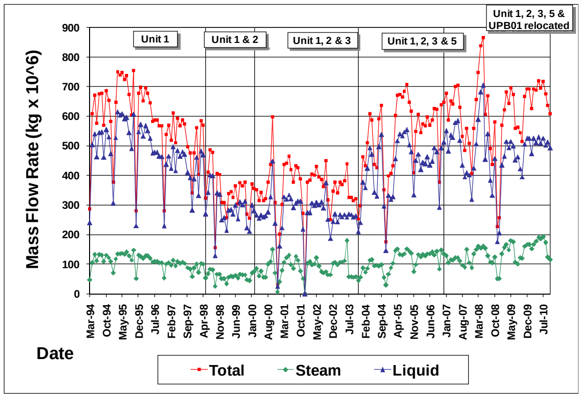

*Figure 5: Monthly mass flow rates at Separation Station 2.*

## Separation Station 3

Separation Station 3 is fed by wells PGM-12, PGM-20 and PGM-21. Under current conditions, it separates 33 kg/s of steam and 190 kg/s of brine. Figure 6 shows that the steam supply from this station increased from March 1994 to March 1998, before Unit 2 came online. From March 1998 to March 2000 the steam supply decreased slightly as a result of the commissioning of Unit 2 (Satellite 6), mainly because of its proximity to the production wells that supply fluid to Satellite 3. Production from the wells feeding Station 6 caused the reservoir to undergo a re-equilibration process to supply the geothermal flow to Separation Stations 3 and 6. The steam supply at Satellite 3 decreased slightly from March 2000 to October 2009, followed by a small increase to December 2009; since then it has remained fairly constant until October 2010.

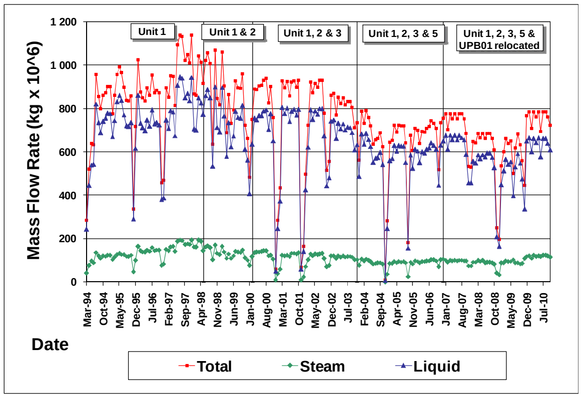

*Figure 6: Monthly mass flow rates at Separation Station 3.*

## Separation Station 4

Separation Station 4 is fed by wells PGM-05, PGM-08, and PGM-42. Under present conditions, it separates 35 kg/s of steam and 200 kg/s of brine. The flow from well PGM-05 can also be separated at Separation Station 1. Satellite 4 separated the geothermal fluid for Unit 2 from March 1994 until October 2002. Since then, the steam from Satellite 4 has been sent to Unit 1, because Unit 1 has a lower capacity to handle non-condensable gases.

As can be seen in Figure 7, this separation station began operation with the commissioning of Unit 2 in March 1998. The steam supply increased from March 1998 until August 2000. From October 2000 to October 2009 the steam supply was kept more or less constant, depending on the requirements of the generating units; however, the brine flow decreased slightly due to an increase in enthalpy during this period. There has been a small increase in the steam supply from October 2009 to October 2010.

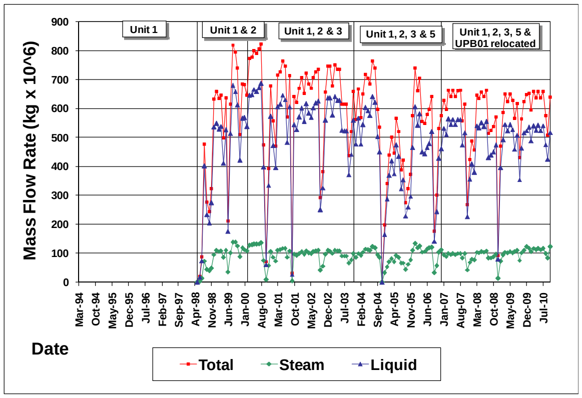

*Figure 7: Monthly mass flow rates at Separation Station 4.*

## Separation Station 5

Separation Station 5 is fed by wells PGM-43, PGM-44, and PGM-45. Under current conditions, it separates 63 kg/s of steam and 145 kg/s of brine. Figure 8 shows that, like Separation Station 4, this station began operation with the commissioning of Unit 2 in March 1998. The steam supply increased slightly from March 1998 to August 2004. Well PGM-44 was not able to supply steam because its wellhead pressure decreased and it was not possible to keep the well connected to the gathering system. Because of this, Satellite 5 decreased its normal steam supply from August 2004 to June 2005. From June 2005 to December 2006 the steam supply was fairly constant, and from December 2006 to October 2010 it has decreased slightly. However, the brine flow (and total flow) at this separation station decreased strongly due to an increase in enthalpy from August 2003 to October 2005. After this period, the brine (and total flow) has been fairly constant, depending on the requirements of the units.

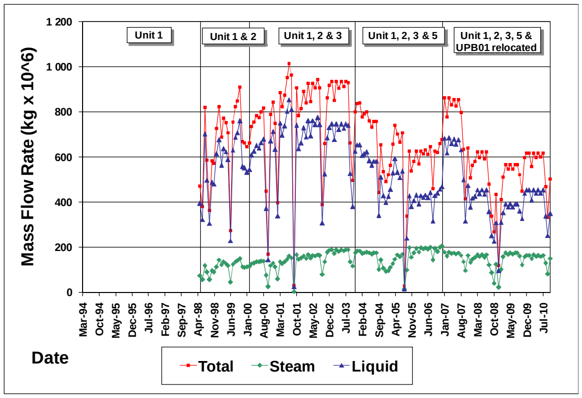

*Figure 8: Monthly mass flow rates at Separation Station 5.*

## Separation Station 6

Separation Station 6 was initially fed by wells PGM-46, PGM-47 and PGM-49. Under the present conditions, only PGM-46 and PGM-49 supply steam to Satellite 6 because PGM-47 was not able to maintain sufficient wellhead pressure to be connected to the gathering system. Currently, Satellite 6 separates 32 kg/s of steam and 155 kg/s of brine. Figure 9 shows that this station began its operation with the commissioning of Unit 2 in March 1998, as did Separation Stations 4 and 5. The steam supply increased from March 1998 to June 2000; after that, the separation station underwent maintenance until October 2000. Early in 2001, well PGM-46 began to slowly decrease its production rate, and therefore it was necessary to deepen the well by July 2001. Fortunately, a new production zone was found in this well, which allowed it to recover its previous steam rate. However, in January 2005, well PGM-47 had to be withdrawn from production because the wellhead pressure was not high enough to connect the well to the gathering system. The steam rate has remained fairly constant from October 2002 to October 2010.

## Separation Station 7

Separation Station 7 is fed by wells PGM-02, PGM-07, PGM-11, PGM-14, PGM-60 and PGM-62. Under current conditions it separates 52 kg/s of steam and 170 kg/s of brine. This separation station began operation in March 2000 with the commissioning of Unit 3, and its steam rate remained constant from March 2000 to June 2000 (Figure 10).

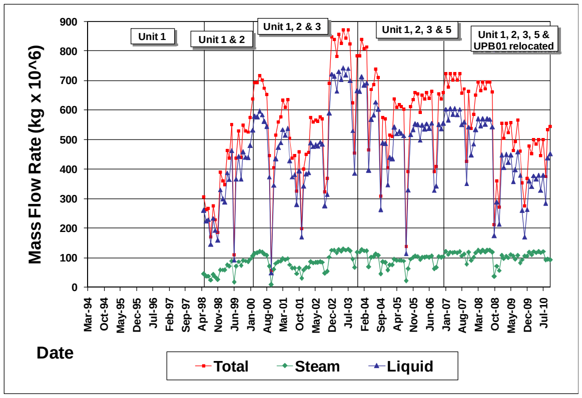

*Figure 9: Monthly mass flow rates at Separation Station 6.*

After this period, steam production increased because well PGM-62 was connected to the separation station.

Steam production from this satellite increased slightly from July 2000 to August 2004 and decreased strongly from December 2004 to August 2006. Well PGM-62 has been closed since May 2006 because of the high non-condensable gas content of its steam, but well PGM-02 was connected in the same month to supply the steam lost from PGM-62. From October 2007 to October 2010, the steam supply has been fairly stable.

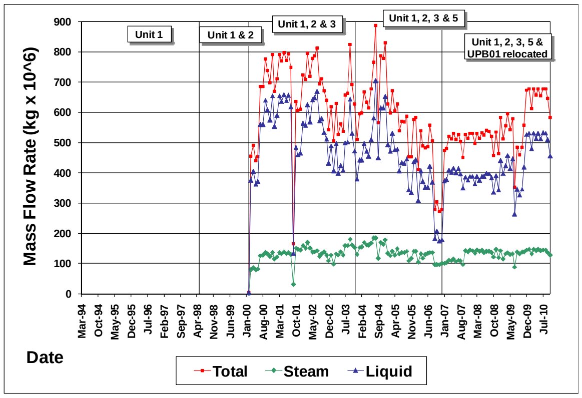

*Figure 10: Monthly mass flow rates at Separation Station 7.*

## Wellhead Unit 2 at well PGM-45

As indicated in Table 1, two wellhead units from the Federal Commission of Electricity of México were in operation while Unit 2 was being built. Wellhead Unit 2 was fed by well PGM-45 from September 1996 to April 1998. Figure 11 shows that the steam production rate increased slightly while the unit was generating.

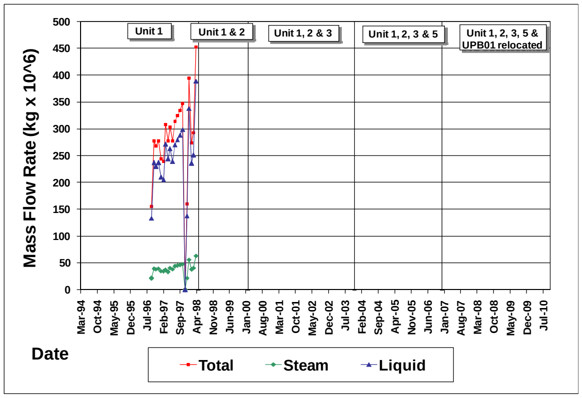

*Figure 11: Monthly mass flow rates at Wellhead Unit 2.*

## Wellhead Unit 3 at well PGM-29

Wellhead Unit 3 was the other wellhead unit from the Federal Commission of Electricity of México (Table 1). This unit was fed by well PGM-29 from January 1997 to April 1998. Figure 12 indicates that the steam rate was kept almost constant while the unit was operating.

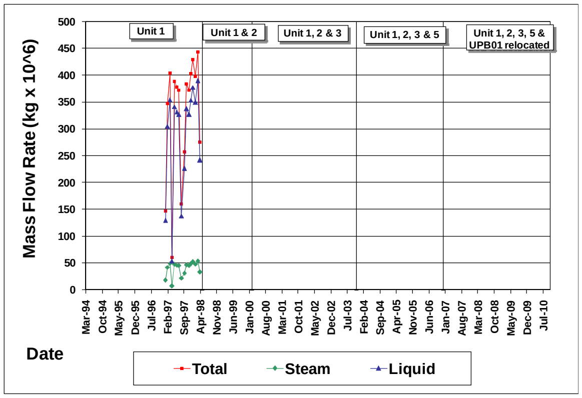

*Figure 12: Monthly mass flow rates at Wellhead Unit 3.*

## Wellhead Unit 1 at well PGM-29

From 1995 to 2006, Wellhead Unit 1 was located in the central part of the production zone. At this location, the Wellhead Unit took advantage of the steam of two spare wells (first PGM-31, and later PGM-65) and also of the separated steam coming from Satellite 1 and going to steam Collector Pipeline No.1, to produce 5 MW. This location was very convenient to the geothermal development in Miravalles while there was enough steam to supply the main units (Units 1 and 2) and also the Wellhead Unit.

At this location, ICE benefitted from the Wellhead Unit between 1995 and 2006, even when the unit only produced energy for half of the year (i.e., only during the dry season). The amount of excess steam available began to decrease over time, and it was thought best to change the location of the Wellhead Unit in order to obtain generation from it all year long.

The facts that: a) the Wellhead Unit was operating only during the dry season (from January to June), b) there was no spare steam in the center of the field, and c) the available steam could be better utilized if it was sent to the main units motivated the thought to move the Wellhead Unit to a new location.

Since in the past, there had been a Wellhead Unit at the PGM-29 site and well PGM-29 had the necessary conditions to supply steam to a Wellhead Unit, ICE decided to move it to this new location during the second half of 2006. The geothermal reservoir conditions around PGM-29 seem to be somewhat different from the rest of the field; namely, the noncondensable gases are higher than the average value in the rest of the field (Moya, DiPippo 2010)

In December 2006, it was relocated to the southeastern sector of the field, where it has been fed by well PGM-29 through July 2010. Then, the wellhead unit underwent a major maintenance. Figure 13 indicates that the steam production rate was almost constant from December 2006 to June 2009, then increased slightly in August 2009 and remained constant until July 2010. On the other hand, the brine rate has been increasing basically since December 2006.

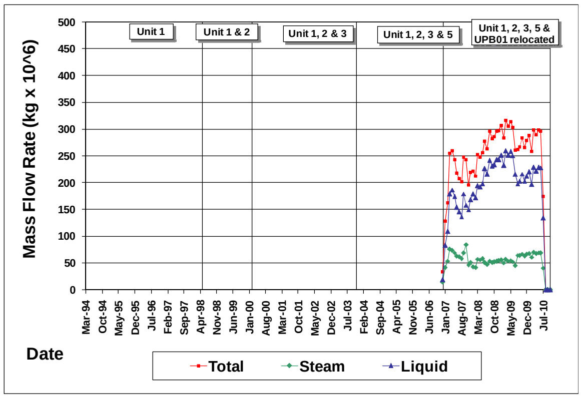

*Figure 13: Monthly mass flow rates at the Wellhead Unit 1.*

## Field Production

Figure 14 shows monthly mass flow rates since production began at the Miravalles geothermal field. It can be seen that the steam supply slowly increased from March 1994 to May 2009. The field was capable of supplying the required steam to the generation units until 2008. During 2009 and 2010, the total generation has decreased by about 13 MW, mainly because of: a) the current gas extraction capacity of Units 1, 2 and 3, and b) a decrease of the total discharge rate of some of the production wells, which has affected the steam as well as the brine supply to the generation units.

The steam extraction rate increased steadily from May 1994 (380 686 tons/month) until August 2000 (820 612 tons/month), then more slowly from August 2000 to July 2010 (982 417 tons/month). The steam production rate has decreased every year from September to December, mainly as a consequence of the maintenance program on Units 1, 2 and 3. The liquid mass and total mass curves have behaved in basically the same way: there was an increase in both from April 1994 to July 2000, and then a slow decrease through October 2010.

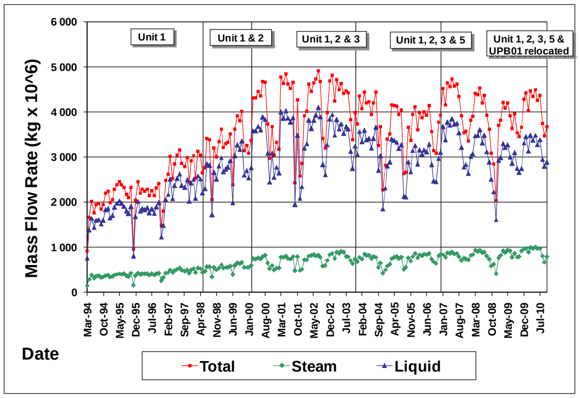

*Figure 14: Monthly mass flow rates at the Miravalles geothermal field.*

Figure 15 shows the cumulative production of steam, liquid, and total mass from the geothermal field. All three increased almost linearly from March 1994 until May 1998. When Units 2 and 3 began operation the slope of the curves became steeper, but the increases were still nearly linear over those periods (from April 1998 to March 2000 and from April 2000 to October 2010). By October 2010, the cumulative production was approximately 130.3 million tons of steam, 563.8 million tons of liquid and 694.1 million tons of total mass.

## INJECTION

Injection at the Miravalles geothermal field can be divided into 8 periods, which are described in Table 2.

There are three sectors of the Miravalles geothermal field that have been used for hot-water injection (designated as the eastern, western and southern sectors), as well as one cold-injection sector, located in the southern part of the field. These sectors are described in the following sections.

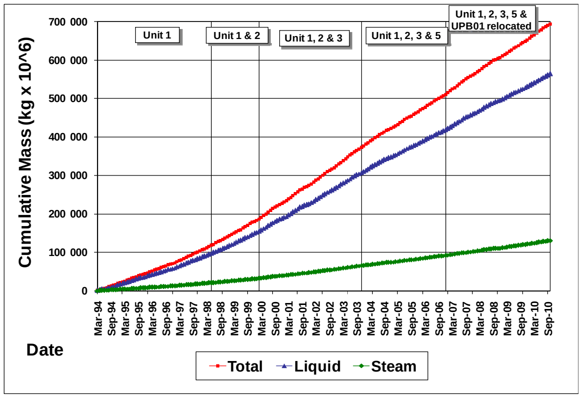

*Figure 15: Cumulative mass extraction at the Miravalles geothermal field.*

## Eastern Injection Sector

In 1994, well PGM-11 sent its two-phase flow to an additional separation station called the "Plazoleta". The steam was sent to Separation Station 1 and the brine to well PGM-02, located in the eastern sector of the field.

The Plazoleta separation station was very important when Unit 1 came online, because it allowed the steam coming from well PGM-11 to be used for generation at Unit 1.

During injection Period 1, the injection rate remained more or less constant at about 1.2 x $10^8$ kg per month (Figure 16). Injection in this sector began to decrease in Period 2, for several reasons: valve repairs, changes in deliverability curves of some wells, and several activities in the wells such as changes of their down-hole capillary tubing strings.

Injection in well PGM-02 ended in December 1998, when there was no longer the need to supply more steam from well PGM-11 to Unit 1. Instead, PGM-02 was tested as a potential production well. In Period 4, well PGM-02 was used for injection twice (in January and September 2001), in order to inject the liquid from PGM-11 while Satellite 7 was undergoing maintenance.

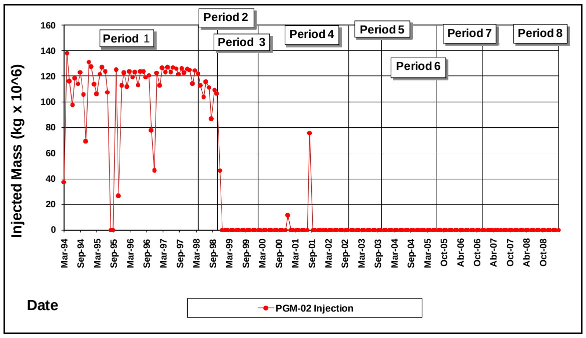

*Figure 16: Eastern injection sector at the Miravalles geothermal field.*

## Western Injection Sector

The wells that contribute to the injection in the western sector are PGM-22 (Satellite 1) and PGM-24 (Satellite 2). This injection sector has been utilized since the first plant was commissioned. Injection in the western sector was kept constant during Period 1 (1.1 x $10^9$ kg per month, see Figure 17). Production from well PGM-05 was partially diverted in Period 2 and totally diverted in Period 3 to Satellite 4, decreasing the injection rate in this sector. Then, due to well PGM-05, the injection rate decreased further and was kept constant at 6 x $10^8$ kg per month during Period 4.

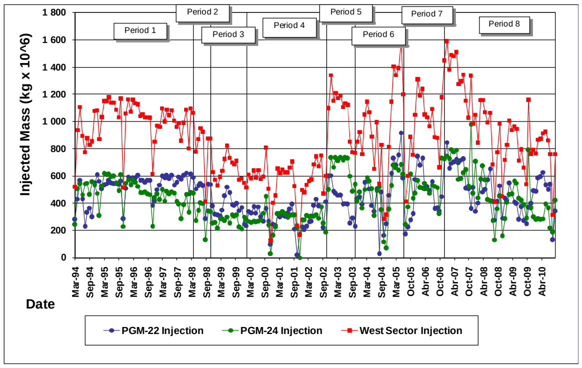

*Figure 17: Western injection sector at the Miravalles geothermal field.*

During Period 5 there was an increase in the brine injected in the western sector because part of the liquid coming from Satellites 1 and 4 was diverted to wells PGM-22 and PGM-24, as recommended by ICE's consultant, GeothermEx, Inc., in order to provide better pressure support in the reservoir. Unfortunately, wells PGM-01, PGM-10 and PGM-63 lost their productivity (Moya and Yock, 2004), and injection during Period 5 decreased from 1.3 x $10^9$ kg per month to about 7.6 x $10^8$ kg per month at the end of Period 5. During Period 6, the total injection increased from 7.6 x $10^8$ kg per month to 1.6 x $10^9$ kg per month at the end of Period 6. During Period 7 the total injection increased at first from 4.1 x $10^8$ kg per month to about 1.3 x $10^9$ kg per month, then decreased to 6.6 x $10^8$ kg per month. During Period 8, the total injection in this sector decreased from 1.5 x $10^9$ to 7.5 x $10^8$ kg per month by October 2010.

*Table 2: Injection Periods.*

| Period | Initial Date | Final Date |
|---|---|---|
| **1** | **March 1994** | **April 1998** |
| | Commissioning of Unit 1.<br>Injection line: 2<br>Wells: PGM-02, PGM-22, PGM-24. | Injection of liquid coming from Satellite 3 was changed from injection line 2 to injection line 3, due to the commissioning of Unit 2.<br>Injection lines: 1, 2 and 3.<br>Wells: PGM-22 and PGM-24. |
| **2** | **May 1998** | **November 1998** |
| | Injection of liquid from Satellite 3 was changed from injection line 2 to injection line 3, due to the commissioning of Unit 2.<br>Injection lines: 1, 2 and 3.<br>Wells: PGM-22 and PGM-24 | The flow from PGM-05 had been separated at Satellite 1, but it was changed to Satellite 4. The flow from PGM-46 had been separated at Satellite 2, but it was changed to Satellite 6. |
| **3** | **December 1998** | **February 2000** |
| | Wells PGM-05 and PGM-46 were changed from Unit 1 to Unit 2. | Commissioning of Unit 3. Satellite 7 sends its liquid to injection line 1. |
| **4** | **March 2000** | **November 2002** |
| | Commissioning of Unit 3. Satellite 7 sends its liquid to injection line 1. | Increase in the contribution from Satellites 4 and 5 to the Western Injection Sector, wells PGM-22 and PGM-24. |
| **5** | **December 2002** | **November 2003** |
| | Increase in the contribution from Satellites 4 and 5 to the Western Injection Sector, wells PGM-22 and PGM-24. | Commissioning of Unit 5 |
| **6** | **December 2003** | **July 2005** |
| | Commissioning of Unit 5 | Injection begins in well PGM-63 |
| **7** | **August 2005** | **December 2006** |
| | Injection in well PGM-63 until August 2006 | Production begins in well PGM-29 |
| **8** | **January 2007** | **October 2010** |
| | Production in well PGM-29 | Last data analyzed |

## Southern Injection Sector

Injection in the southern sector is distributed over three injection pipelines, called injection collectors 1, 2 and 3. The history for each collector is shown in Figure 18. The brine rate injected through these collectors has depended on the operating conditions of the field. In Figure 18, the red curve (total injection in the southern sector) corresponds to the sum of the injection of the three collectors, and shows that injection rate was fairly constant from July 1994 until September 1996, then increased during the rest of Period 1 and during Periods 2 and 3, and the beginning of period 4 until August 2000, when a new annual maintenance took place on the generation units. Aside from the annual maintenance periods of the plants, the injection was kept fairly constant at around 3.25 x $10^9$ kg per month during Period 4.

At the beginning of Period 5, part of the fluid injected in the southern sector was switched to the western sector (following the advice of GeothermEx). As a consequence of this decision, injection in the southern sector decreased and remained constant at about 2.5 x $10^9$ kg per month during all of Period 5 and half of Period 6 (September 2004). From September 2004 to early 2007 the injection rate was basically constant at around 1.8 x $10^9$ kg per month. From January 2007 to October 2010 the injection rate in the southern sector has fluctuated with changes in the operating conditions in the field.

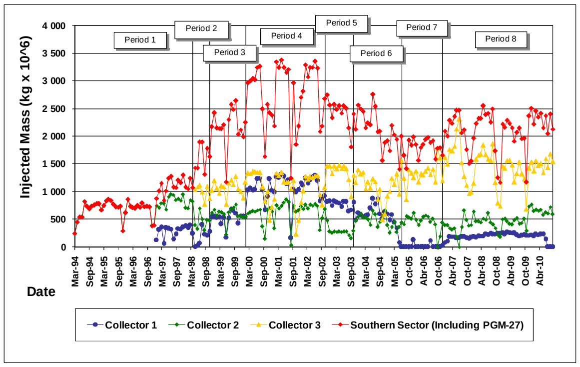

*Figure 18:Southern injection sector at the Miravalles geothermal field.*

## Cold Injection, Southwestern Sector

The condensed steam from the generating units, the separated brine from the acid wells (PGM-02, PGM-07 and PGM-19), and the brine separated when measuring deliverability curves (which is done periodically on the production wells) is all injected into the reservoir using the cold injection system. This system consists of concrete pipelines running from each production well to five different ponds. Also, there are concrete pipelines between the ponds, to carry the brine from higher-elevation ponds to the lower ones. From the lowest-elevation pond, the brine is sent to PGM-04, which is the cold-injection well. Figure 19 shows the amount of separated brine that has been injected in this well between March 1994 and October 2010. The injection rate depends on the operating conditions of the field, and therefore has varied substantially.

In October 2002, the cold-injection capacity was increased by adding a new injection line and connecting an additional cold injection well (PGM-27). As can be seen in Figure 19, the injection rate in PGM-27 (green curve) has been very low because this well, which has recently been added to the system, is used only as a back-up cold injection well.

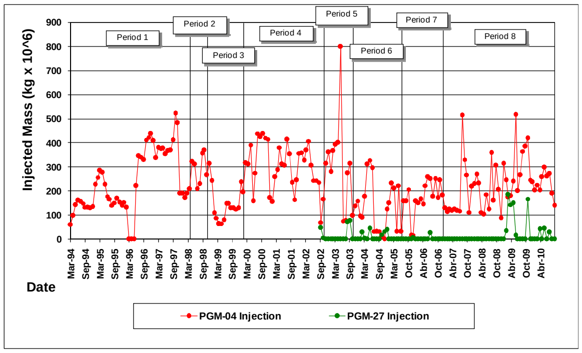

*Figure 19:Cold injection, Southwestern sector at the Miravalles geothermal field.*

## Field-Wide Injection

Figure 20 shows the overall history of injection at the Miravalles geothermal field. The total hot injection rate (red curve) increased from 1.5 x $10^9$ kg per month (beginning of period 1) to 3.5 x $10^9$ kg per month (beginning of Period 4), and was kept fairly constant (3.75 x $10^9$ kg per month) until the beginning of Period 5. Then the injection rate began to decrease, reaching 3.1 x $10^9$ kg per month by November 2003. The decrease is mainly the result of production loss in wells supplying two-phase flow to Satellite 1 (PGM-01, PGM-10, PGM-63). From Period 6 until October 2010, the field-wide injection has fluctuated depending on operating conditions.

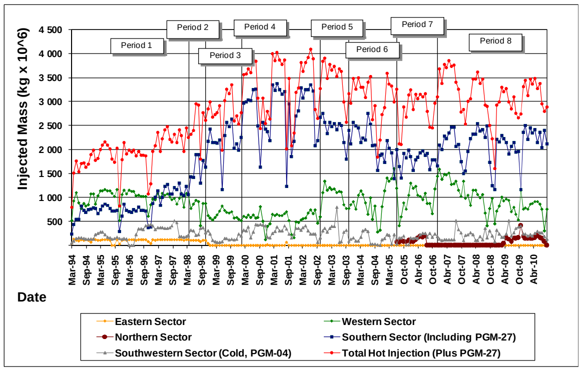

*Figure 20:Field-Wide Injection at the Miravalles geothermal field.*

## Cumulative Injection by Well

The cumulative injection per well can be seen in Figure 21. The majority of the brine produced at the Miravalles geothermal field has been injected in the western (PGM-22, PGM-24) and southern (PGM-04, PGM-16, PGM- 26 and PGM-56) sectors of the field. The effect on the reservoir pressure due to extraction and injection is addressed in the next section.

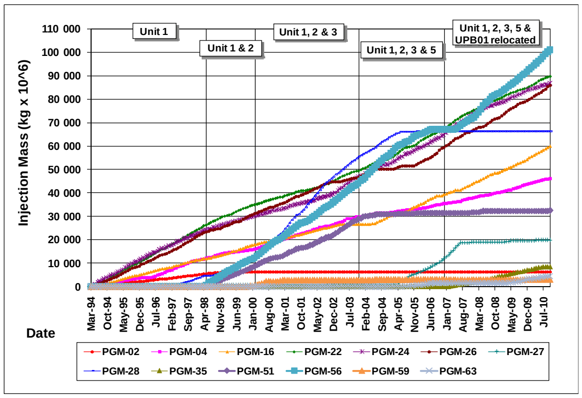

*Figure 21:Cumulative Injection by Well at the Miravalles geothermal field.*

## PRESSURE RESPONSE

Reservoir pressure has been monitored routinely at the Miravalles geothermal field since production began in 1994. Three methods have been used to obtain the reservoir pressure data: a) direct measurement: pressure is measured in observation wells using electronic equipment, including a quartz pressure transducer, data logger and pressure chamber. These measurements were carried out in eleven wells during different periods until January 2008, when the equipment malfunctioned; b) static water levels (hydraulic levels) have been recorded in observation and inactive wells once a month from August 1994 to July 2010; and c) static pressure and temperature measurements in the available production wells during the programmed maintenance shutdowns of the power plants, as well as measurements done once a year in observation and inactive wells from September 1994 to July 2010. All these measurements have provided an indication of the reservoir pressure, which can be used to evaluate the changes that have occurred since the first power plant began production.

To interpret the reservoir pressure response as new generation units have come online, four periods were defined: 1) from March 1994 to July 1998 for Unit 1, 2) from August 1998 to February 2000 for Units 1 and 2, 3) from March 2000 to August 2003 for Units 1, 2 and 3 and 4), and from September 2003 to July 2010 for all units in the field. (Moya, Castro 2001)

## Pressure Data

Table 3 shows the pressure decline values obtained by the three methods described above. Also shown in Table 3 is the use of the well (production, injection or monitoring) and the average pressure decline for each period. For several wells it was not possible to determine the average pressure decline, due to insufficient or questionable data. There were differences in the calculated pressure decline depending on the method used. These differences indicate that it is better to use more than one method to estimate the pressure decline, to reduce or eliminate the uncertainty in the average pressure decline values.

In order to evaluate the behavior of the pressure decline in the reservoir, the average pressure decline rates observed in the wells during each of the four periods were contoured using the computer software SURFER. Figures 22, 24, 25 and 27 show the patterns of pressure decline for the different periods. In each figure, the yellow color represents the minimum pressure decline and the red color indicates the maximum decline (within the particular time frame). All figures (22, 24, 25 and 27) include the 2 bar/year decline contour (dotted line) in order to more easily visualize the trend of pressure decrease. Also, in the legend of each figure, the pressure decline range is shown by the blue rectangle for each period.

There have been reports (e.g. Barquero, 2001a, 2001b; Taylor, 2002, 2003, 2004, 2005, 2007 and 2009) that indicate that the base micro-seismicity at the Miravalles geothermal field is low and it has increased over time in response to the exploitation of the field.

## Period 1: March 1994 to July 1998

As indicated in Table 3, Unit 1 and the wellhead units (WHUs-1, 2 and 3) began generating during March 1994 and July 1998, respectively. The mass extraction for these four units created the pressure decline shown in Figure 22. The greatest pressure decline took place mainly around wells PGM-08, PGM-17, PGM-42 and PGM-14. The shape of the zone of pressure decline coincides with the inferred main production zone of the field.

The injection zone located in the southern part of the field showed a small pressure decline (PGM-27, PGM-52 and PGM-59). The lowest estimated decline was in well PGM-15. The pressure drop for this period varies between 0.8 and 2.5 bar/year.

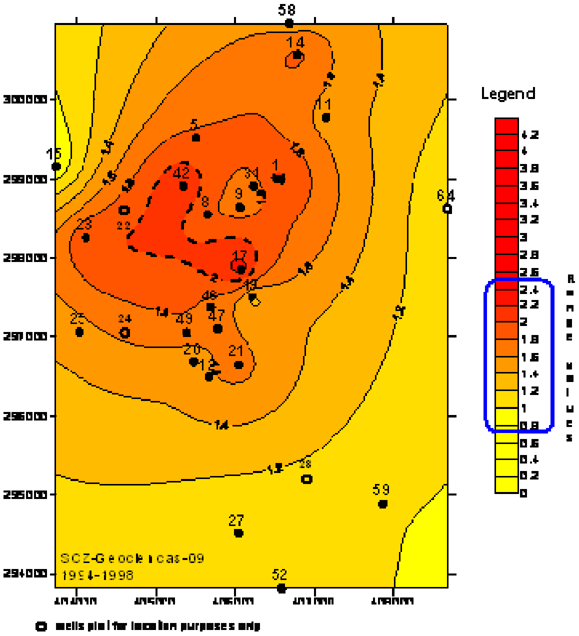

*Figure 22: Pressure Decline during March 1994-July1998. (Castro, 2010).*

*Table 3: Pressure Decline Values in geothermal wells at the Miravalles geothermal field*

| | | I Period (Mar94-Jun98)<br>OD (0-1565)<br>Miravalles Unit I | | | | II Period (Jul98-Feb00)<br>OD (1565-2173)<br>Miravalles Units I y II | | | | III Period (Mar00-Aug03)<br>OD (2173-3420)<br>Miravalles Units I, II y III | | | | IV Period (Sep03-Jul10)<br>OD (3420-5960)<br>Extracted mass reduct.<br>Miravalles Units I, II y III | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Well | Use | CPM | HL | SPP | *Average* | CPM | HL | SPP | *Average* | CPM | HL | SPP | *Average* | CPM | HL | SPP | *Average* |
| PGM-01 | Prod-Out | | | 2,06 | ***2,06*** | | | 2,38 | ***2,38*** | | | 2,09 | ***2,09*** | | | | |
| PGM-05 | Prod | | | 1,84 | ***1,84*** | | | 1,51 | ***1,51*** | | | 1,79 | ***1,79*** | | | 0,93 | ***0,93*** |
| PGM-08 | Prod | 1,91 | 1,83 | 1,70 | ***1,81*** | | | 2,05 | ***2,05*** | | | 1,47 | ***1,47*** | | | 0,85 | ***0,85*** |
| PGM-09 | Monit | 1,43 | 1,93 | 1,75 | ***1,70*** | 4,04 | | | ***4,04*** | 1,55 | | 2,48 | ***2,03*** | | | 0,78 | ***0,78*** |
| PGM-11 | Prod | | | 1,49 | ***1,49*** | | | 1,78 | ***1,78*** | | | 1,53 | ***1,53*** | | | 1,38 | ***1,38*** |
| PGM-12 | Prod | | | 1,58 | ***1,58*** | | | 1,73 | ***1,73*** | | | 1,38 | ***1,38*** | | | 1,25 | ***1,25*** |
| PGM-14 | Prod | | 1,70 | 2,00 | ***1,85*** | 2,18 | | 1,61 | ***1,90*** | | | 1,59 | ***1,59*** | | | 1,36 | ***1,36*** |
| PGM-15 | Monit | | 1,02 | 0,60 | ***0,81*** | 1,33 | 1,58 | | ***1,46*** | | 1,23 | 1,71 | ***1,47*** | | 0,65 | 1,36 | ***1,01*** |
| PGM-17 | Prod | | | 2,31 | ***2,31*** | | | 1,43 | ***1,43*** | | | 1,84 | ***1,84*** | | | 1,34 | ***1,34*** |
| PGM-19 | Prod | | 1,41 | 1,30 | ***1,36*** | | 2,63 | 2,81 | ***2,72*** | | | 2,91 | ***2,91*** | | | | |
| PGM-20 | Prod | | | 1,41 | ***1,41*** | | | 1,60 | ***1,60*** | | | 1,82 | ***1,82*** | | | 1,77 | ***1,77*** |
| PGM-21 | Prod | | | 1,71 | ***1,71*** | | | 1,61 | ***1,61*** | | | 1,63 | ***1,63*** | | | 2,03 | ***2,03*** |
| PGM-23 | Monit | | 2,00 | | ***2,00*** | | 2,25 | | ***2,25*** | | 1,34 | 2,20 | ***1,77*** | | 1,15 | 1,23 | ***1,19*** |
| PGM-25 | Monit | | 1,63 | 1,38 | ***1,51*** | | 1,73 | 2,28 | ***2,01*** | 1,69 | 2,00 | 1,80 | ***1,83*** | | 1,30 | 1,21 | ***1,26*** |
| PGM-27 | Injec | | 1,13 | 0,87 | ***1,00*** | | 1,51 | 0,88 | ***1,20*** | | 1,67 | 2,25 | ***1,96*** | | | | |
| PGM-28 | Injec | | | | | | | | | | | | | | 0,84 | 1,48 | ***1,16*** |
| PGM-29 | Prod | | | | | | | | | 4,44 | | 1,88 | ***3,16*** | | | 1,80 | ***1,80*** |
| PGM-31 | Prod | | | 1,69 | ***1,69*** | | | 1,77 | ***1,77*** | | | 2,03 | ***2,03*** | | | 1,04 | ***1,04*** |
| PGM-33 | Monit | | | | | | | | | | 1,77 | | ***1,77*** | | | | |
| PGM-37 | Monit | | | | | | | 2,36 | ***2,36*** | | | 2,24 | ***2,24*** | | | 1,55 | ***1,55*** |
| PGM-38 | Monit | | | | | | | | | | 1,07 | 1,77 | ***1,42*** | | 0,87 | 1,20 | ***1,04*** |
| PGM-42 | Prod | | 1,23 | 3,16 | ***2,20*** | | | 3,76 | ***3,76*** | | | 1,29 | ***1,29*** | | | 1,69 | ***1,69*** |
| PGM-43 | Prod | | | | | | | | | | | | | | | 1,29 | ***1,29*** |
| PGM-44 | Prod | | | | | | | | | | | 2,44 | ***2,44*** | | | 1,09 | ***1,09*** |
| PGM-45 | Prod | | | 3,65 | ***3,65*** | | | 3,54 | ***3,54*** | | | 3,38 | ***3,38*** | | | | |
| PGM-46 | Prod | | | 1,71 | ***1,71*** | | | 2,61 | ***2,61*** | | | 1,63 | ***1,63*** | | | 1,13 | ***1,13*** |
| PGM-47 | Prod-Out | 1,90 | 1,52 | 1,73 | ***1,72*** | | 1,63 | 2,22 | ***1,93*** | | | 1,65 | ***1,65*** | | | 1,31 | ***1,31*** |
| PGM-49 | Prod | | 1,42 | 2,08 | ***1,75*** | | | 1,47 | ***1,47*** | | | 1,65 | ***1,65*** | | | 0,88 | ***0,88*** |
| PGM-51 | Injec | | | | | | | | | | | | | | 0,43 | 1,39 | ***0,91*** |
| PGM-52 | Monit | 1,52 | | 0,65 | ***1,09*** | | | -0,61 | ***-0,61*** | | | -0,77 | ***-0,77*** | | | 0,59 | ***0,59*** |
| PGM-55 | Monit | | | | | | | | | 2,30 | 0,22 | | ***1,26*** | | | 1,61 | ***1,61*** |
| PGM-58 | Monit | | | | | | 2,12 | 1,86 | ***1,99*** | | 1,53 | 1,88 | ***1,71*** | | | | |
| PGM-59 | Injec | 1,02 | | | ***1,02*** | | 0,79 | | ***0,79*** | 1,81 | 1,84 | | ***1,83*** | | | 1,49 | ***1,49*** |
| PGM-60 | Prod | | | | | | | | | | | 2,16 | ***2,16*** | | | 1,50 | ***1,50*** |
| PGM-62 | Prod-Out | | | | | | | | | | | 1,03 | ***1,03*** | | | | |
| PGM-64 | Monit | | | | | | | | | | 1,57 | 1,97 | ***1,77*** | | 1,10 | 1,48 | ***1,29*** |
| PGM-66 | Prod | | | | | | | | | | | | | | | 1,37 | ***1,37*** |
| Total | | 1,56 | 1,53 | 1,75 | ***1,71*** | 2,52 | 1,78 | 1,94 | ***1,97*** | 2,36 | 1,42 | 1,82 | ***1,78*** | *ND* | 0,91 | 1,31 | ***1,26*** |

CPM: continous pressure monitoring
HL: hydraulic levels
SPP: static pressure profiles
OD: operation days

During this first period, a total of 12 production wells (PGM-01, PGM-03, PGM-05, PGM-10, PGM-11, PGM-12, PGM-17, PGM-20, PGM-21, PGM-31, PGM-45, PGM-46) and six injectors (PGM-02, PGM-04, PGM-16, PGM-22, PGM-24, PGM-26) were utilized to supply the two phase fluid to the generation units and to inject the brine (Moya and Yock, 2001). During this period, 24 recorded micro-earthquakes indicated a low level of micro-seismicity, distributed in the center and northeast of the geothermal field. (Figure 23)

The black circles with a cross in Figure 23 correspond to injection wells, the blue circles with a cross represent the producers, the black lines (continuous and dashed) are fractures, and the dashed lines with triangles represent the caldera border. The most recent lava flow is also indicated in gray in this figure.

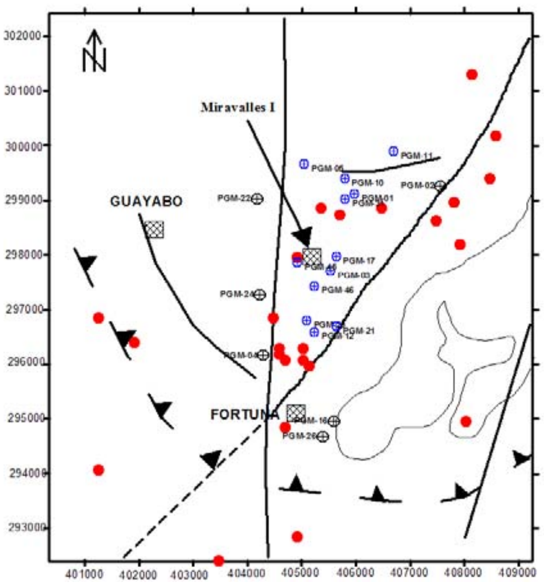

*Figure 23: Location of micro-earthquakes (red dots) during the first period (Unit 1) at the Miravalles geothermal field.*

## Period 2: August 1998 to February 2000

During this period, the two temporary 5 MW wellhead plants from the Federal Commission of Electricity of Mexico (CFE) were disassembled in April 1998 and 1999 (Table 1) and returned to CFE. Unit 2, the second 55 MW plant, started production in August 1998. This period ends before the commissioning of Unit 3.

Figure 24 shows that the zone where the pressure decline takes place is basically the same as in the previous period; the major difference is that the pressure decline is greater for Period 2. Wells PGM-09, PGM-42, PGM-45 and PGM-37 show the greatest pressure declines during this period. Again, the shape of the zone of pressure decline coincides with the inferred main production zone. In the western part of the field an increment in the pressure decline took place, which is probably related to the reduction in the injection discharge in this sector during this period. In the main injection zone, located in the southern sector of the field, the pressure decline continued, in spite of the important increase in the rate of injection in this zone. The lowest decline is located in the southeast part of the field, where PGM-52 and PGM-59 are located. The pressure drop varied between 0.2 and 4.2 bar /year.

In this second period, four producers were added to the exploitation of the field (PGM-08, PGM-42, PGM-43, and PGM-49) as well as three new injectors (PGM-28, PGM-51 and PGM-56). For this period, brine injection was concentrated in the southern sector of the field, around wells PGM-51, PGM-56 and PGM-28, (Moya and Castro, 2001, 2004; Moya and Yock, 2001).

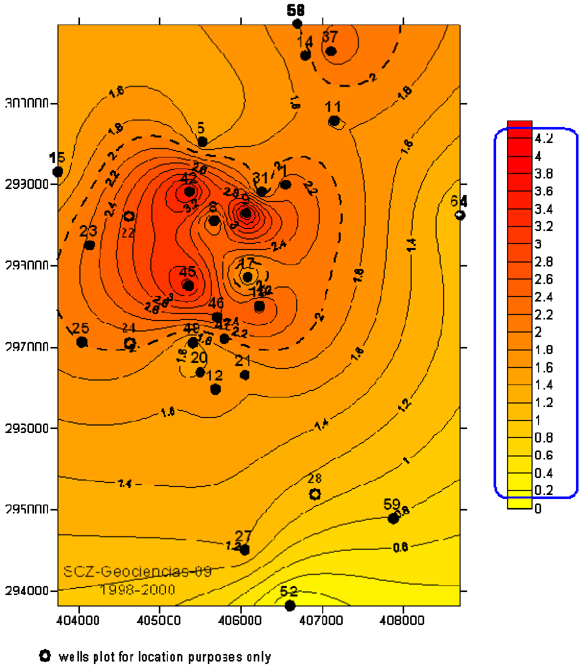

*Figure 24: Pressure Decline during August 1998-February 2000 (Castro, 2010).*

In spite of the increase in the quantity of fluids extracted and injected during this second period at the Miravalles geothermal field, the micro-seismicity of the field remained very low, with only one additional micro-earthquake occurring during this period. This is probably because: a) the injection took place in the southern part of the field; and b) a seismic swarm that took place on the southeastern flank of the Miravalles volcano in 1997 (outside the boundaries of the Miravalles geothermal field) generated a quiet period that lasted 16 months, from November 1998 to April 2000.

## Period 3: March 2000 to August 2003

This period begins with the commissioning of Unit 3 during March 2000, and lasts until the commissioning of Unit 5. As shown in Figure 25, during this period the pressure decline changed drastically in comparison to the two previous periods: the pressure declines are not limited to the initial production zone but have spread to the southeast. The magnitude of the pressure decline is smaller for this period than for the previous one, but is greater than in the first period, and it has spread through the entire geothermal zone. In this period, the major pressure decline occurs around wells PGM-37, PGM-45, PGM-19 and PGM-29. The lowest pressure declines were observed in some peripheral wells such as PGM-52, PGM-55 and PGM-15. The pressure drop varies from 0.1 to 3.3 bar/year.

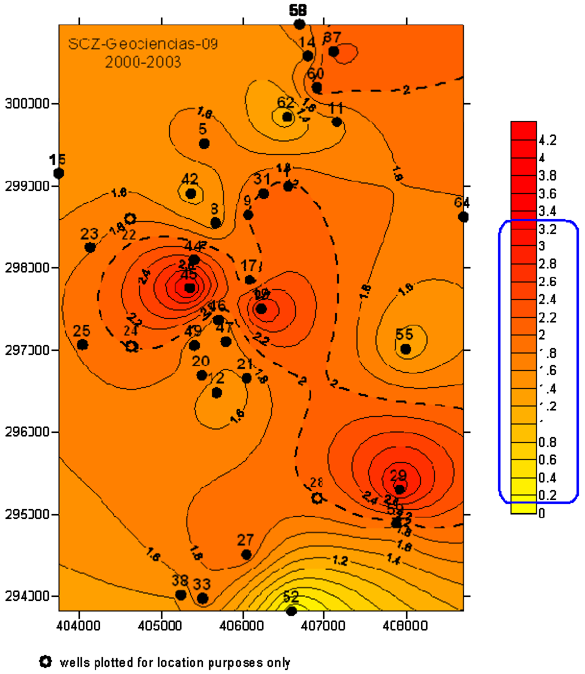

*Figure 25: Pressure Decline during March 2000-August 2003 (Castro, 2010).*

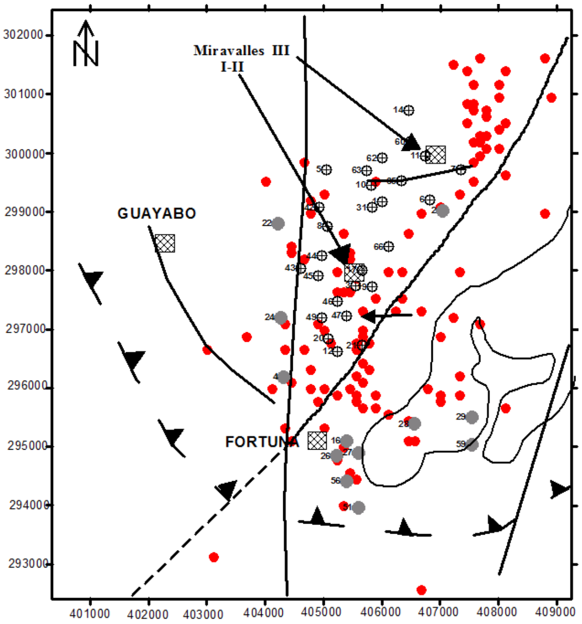

*Figure 26: Location of micro-earthquakes (red dots) during the third period (Unit 1, 2 and 3) at the Miravalles geothermal field. Black circles with a cross represent production and gray dots represent injectors.*

During this third period, five new producers (PGM-14, PGM-60, PGM-62, PGM-63, and PGM-65) were utilized to supply the geothermal fluids to the generation units. No extra injection wells were required for this period. The injection in this period was concentrated in wells PGM-28 and PGM-56 (Moya and Castro, 2001, 2004; Moya and Yock, 2001).

The quiet period mentioned above ended in May 2000, only three months after the commissioning of Unit 3, together with full operation of Units 1 and 2. As can be seen in Figure 26, the micro-earthquakes were concentrated in the middle of the field, mainly inside the area delimited by the main fractures trending N-S and NE-SO, indicating that there is a structural control due to these fractures. In total, 99 shallow micro-earthquakes were registered, with an average depth of 1.8 km and maximum local magnitudes of 3.8 during 2003 (in general they all were less than M 2.1).

## **Period 4: September 2003 to July 2010**

During this fourth period, the reservoir re-equilibrates and the major pressure declines are now found around wells PGM-37 (north), PGM-19 (center) and well PGM-25 (west). Fortunately, the pressure declines were smaller during this last period than in the previous period. The shape of the zone of pressure decline does not coincide with any of the patterns of the previous periods. In Figure 27 it can be seen that the entire eastern area shows greater pressure declines than the western area.

The new pattern could be related to several changes that have occurred during the last seven years: a) the total mass extracted in the reservoir was drastically reduced since 2003 due to the loss of four producers in the north-center part of the field, b) many wells have shown an increase in production enthalpy, causing a reduction in the total mass extracted from the reservoir, c) to improve the hydrodynamic movement in the reservoir, some changes in the injection strategy were implemented. The main change was to use the wells located near PGM-27 to inject and at the same time, stop injection in PGM-28, d) less fluid was injected in wells PGM-22 and PGM-24 (western sector) because Unit 5 went online early 2004.

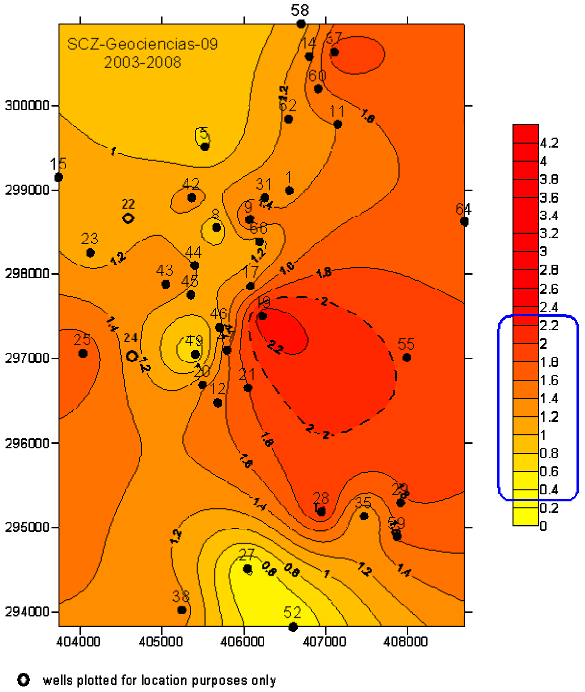

*Figure 27: Pressure Decline during September 2003-December 2010 (Castro, 2010).*

The micro-seismicity inside the geothermal field has increased in recent years. Figure 28 shows the distribution of the 529 micro-earthquakes recorded during this last period, the majority having local magnitudes of less than 2.

As seen in Figure 28, the micro-seismicity has increased over the entire area, and at least two important seismic zones can be identified, one in the central and southern part of the geothermal field and the other to the northeast of the field.

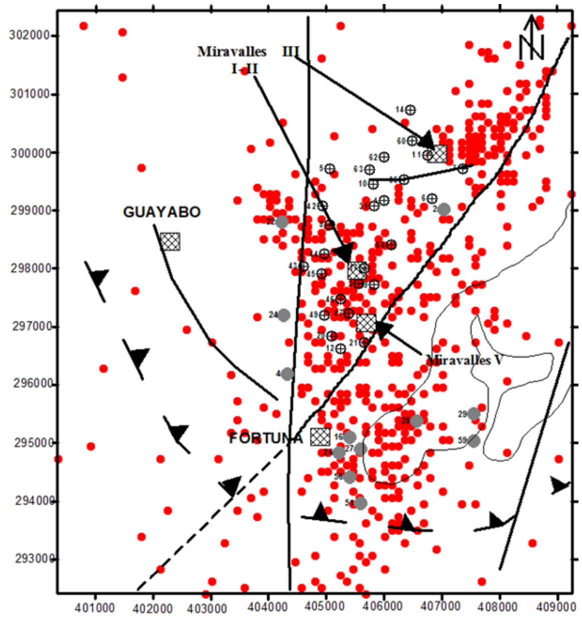

*Figure 28: Location of micro-earthquakes (red dots) during the fourth period (Unit 1, 2,3 and 5) at the Miravalles geothermal field. Black circles with a cross represent production and gray dots represent injectors.*

A possible explanation of the behavior of the four periods may be related to the major change that took place when Unit 2 came online in 1998, representing an increase of about 40% of the mass extraction in the reservoir. In year 2000, the change could be explained by the presence of several wells producing in two phases, mainly in the north part of the reservoir, causing a reduction in the extracted liquid phase.

Finally, in 2003, a reduction in the mass-extraction rate occurred as a result of the sustainable management of the reservoir. For this period there was an increase in the fluid enthalpy, together with implemented changes in injection strategy, which helped to reduce the rate of pressure decline.

## RELATIONSIP BETWEEN MICRO-SEISMICITY AND THE BOUNDARIES OF THE GEOTHERMAL FIELD

The exploitation of a geothermal field produces changes in the stress of the geological formations, which can cause micro-earthquakes to occur. The induced micro-earthquakes will be located inside the affected region, and consequently, they represent a good (though indirect) indicator of the extent of the geothermal field. The micro-seismicity associated with the Miravalles geothermal field seems to indicate that the field has an "L" shape, with the major axis trending NNW, 2 km wide, 7 km long, with 2 km thickness, while the minor axis trends NE and is 2 km wide, 5 km long and 2 km thick (see Figures 29, 31 and 32).

Figures 31 and 32 shows respectively the NW and NE micro-seismicity views in 3D for the Miravalles geothermal field. These figures provide an idea of the real boundaries of the geothermal system. Also, these figures reveal the presence of two micro-seismicity nuclei, one in the central-southern sector and the other one in the northeast sector. The separation of the two sectors represents a strong indicator of the existence of a geological or structural barrier between them, related to the fractures that trend NE-SW.

Within the known boundaries of the geothermal field (approximately 90 km$^2$), several micro-earthquakes have been felt since 2001, in particular on March 26th, 2005 when there was a micro-earthquake of $M_L$= 3.7 and it was felt with an intensity III on the Modified Mercalli Scale in Guayabo and La Fortuna de Bagaces (the towns nearest to the geothermal field). In total, in the period from September 2003 until July 2010, there were 1,117 recorded events with depths between 0.5 and 13.2 km (90% with depths less or equal than 4.0 km) and magnitudes smaller than 3.2. Figure 30 indicates that, excepting years 2003 and 2004, there have been more than 137 micro-seismic events annually, and that a large increase occurred in 2006 and 2009. From the data observed so far, it appears that 2010 will see the most micro-seismic activity during the period of monitoring (Barquero, R, 2001; Taylor, W, 2002, 2003, 2004, 2005, 2007 and 2009).

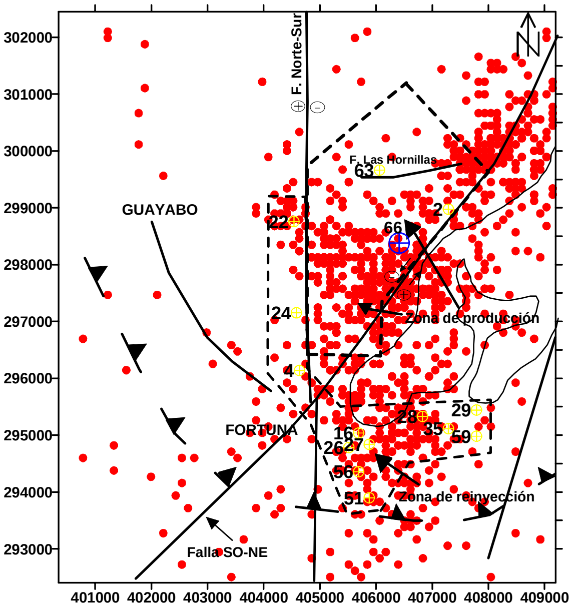

*Figure 29: Location of the micro-earthquakes within the Miravalles geothermal filed during 1994-2010.The main production and injection areas are indicated as well as the location of the injectors (in yellow) and the producer PGM-66 (in blue).*

Table 4 shows the number of micro-earthquakes recorded monthly from 2003 to 2010. The events normally occur in seismic swarms which take place over short periods of time, generally in less than an hour. The months of greatest activity are May and October, which coincide with the beginning of the rainy season and the month of highest precipitation, respectively.

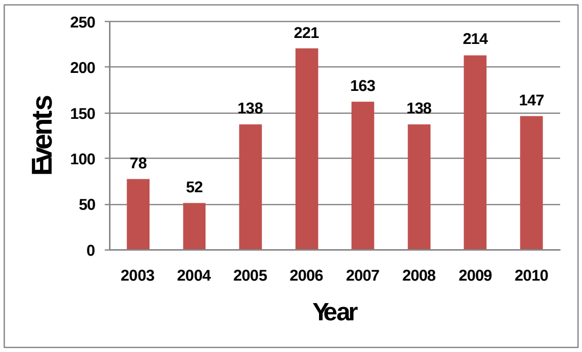

*Figure 30: Recorded annual seismicity at the Miravalles geothermal field 1994-2010.*

During 2004 and 2005, it was observed that there were two principal clusters of micro-earthquakes, the first one towards the northeast, out of the production zone, and the second one in the center of the field where the main production zone is located. Nevertheless, beginning in 2006, the micro-seismicity appears more uniform along the production and injection zones and has expanded outside these zones.

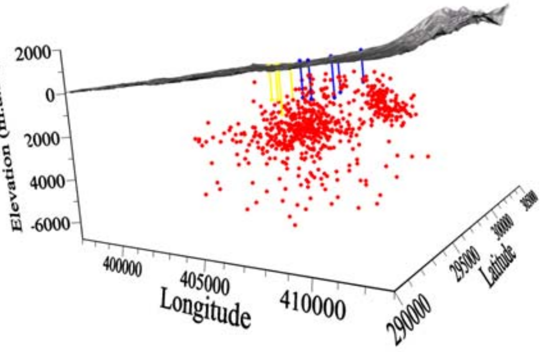

*Figure 31: NW Micro-seismicity view in 3D of the Miravalles geothermal field, where the extension of the field can be observed (red dots). Yellow lines represent injection wells, blue lines represent producers.*

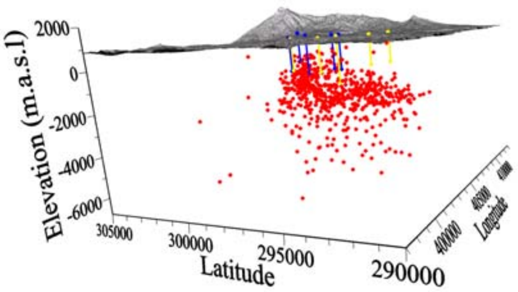

*Figure 32: NE Micro-seismicity view in 3D of the Miravalles geothermal field, where the extension of the field can be observed (red dots). Yellow lines represent injection wells, blue lines represent producers.*

*Table 4: Monthly seismic events during 2003 to July 2010 at the Miravalles geothermal field.*

| Month | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | Total |
|---|---|---|---|---|---|---|---|---|---|
| **Jan.** | 0 | 7 | 14 | 32 | 15 | 7 | 4 | 20 | 99 |
| **Feb.** | 12 | 0 | 10 | 4 | 5 | 7 | 7 | 21 | 66 |
| **Mar.** | 4 | 2 | 19 | 6 | 10 | 22 | 10 | 28 | 101 |
| **Abr.** | 13 | 5 | 10 | 11 | 8 | 12 | 2 | 11 | 72 |
| **May** | 2 | 1 | 9 | 25 | 44 | 9 | 47 | 51 | 188 |
| **June** | 5 | 4 | 12 | 38 | 12 | 1 | 9 | 16 | 97 |
| **July** | 3 | 14 | 3 | 28 | 8 | 12 | 19 | 18 | 105 |
| **Aug.** | 13 | 8 | 11 | 6 | 11 | 11 | 10 |  | 70 |
| **Sep.** | 14 | 3 | 17 | 6 | 15 | 10 | 36 |  | 101 |
| **Oct.** | 3 | 5 | 10 | 48 | 8 | 31 | 22 |  | 127 |
| **Nov.** | 7 | 2 | 12 | 3 | 18 | 4 | 34 |  | 80 |
| **Dec.** | 2 | 1 | 11 | 14 | 9 | 12 | 14 |  | 63 |
| **Total** | 78 | 52 | 138 | 221 | 163 | 138 | 214 | 165 | 1169 |

## NON-CONDENSABLE GASES

The behavior of the non-condensable gases in the steam has changed as mass has been extracted from the geothermal field. At first, the non-condensable gas levels were slightly above initial estimates, because the geothermal wells were drilled using air to protect permeable fractures once they were found. Some of the air used for drilling was captured and stored in the formation, and, as soon as the wells began production, the captured air began to come out of the formation, increasing the non-condensable gas levels above their expected initial values. This effect took place mainly during the drilling campaign for production and injection wells for Units 1 and 2. Once the majority of the wells were drilled, the non-condensable gases decreased and stabilized at values near those estimated initially.

Units 1, 2 and 3 were able to handle the non-condensable gases for several years, but the gases kept increasing as the mass extraction continued in order to supply steam to the generation units at their nominal capacity. By 2003, the maximum capacity of the non-condensable gas extraction equipment was reached, and therefore it was not possible to increase production to the generation units.

Some actions were taken (such as switching Satellites 1 and 4, injecting into well PGM-63 after the well stopped producing, decreasing production from some wells, and adding some other production wells) which allowed production to be kept constant until 2005. Despite the actions taken, the non-condensable gas levels began to increase again from 2005 to 2007, and then stabilized in 2008.

Figure 33 shows the history of gas concentrations of the wells feeding Unit 1. In some of the wells (such as PGM 66, PGM-21, PGM-05, PGM-17, and PGM-42) the non-condensable gases have been decreasing over time, while in others (such as PGM-03, PGM-19, PGM-12 and PGM-08) they have been increasing.

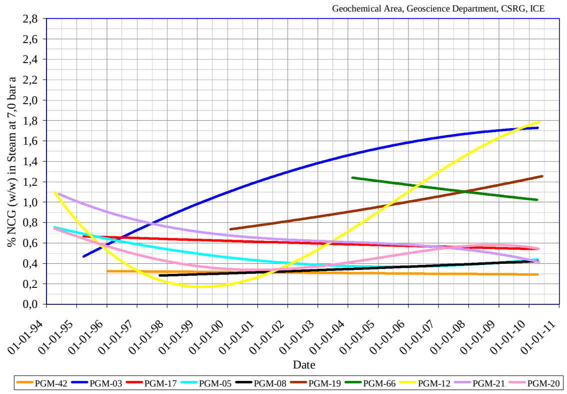

*Figure 33: Non-condensable gases in wells feeding Unit 1 (Sánchez, 2010).*

Figure 34 shows the wells that are feeding Unit 2 at the Miravalles geothermal field. The non-condensable gases have decreased in well PGM-43, but have increased in all other wells (PGM-65, PGM-45, PGM-31, PGM-46, PGM-49 and PGM-44).

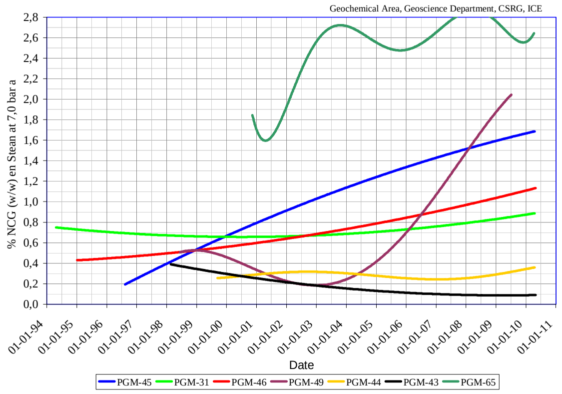

*Figure 34: Non-condensable gases in wells feeding Unit 2 (Sánchez, 2010).*

Figure 35 shows the wells that are connected to Unit 3. Gases in wells PGM-02, PGM-11 and PGM-14 have tended to decrease from early 2005 until now. Conversely, wells PGM-60, PGM-62 and PGM-07 have shown a trend of increasing non-condensable gases.

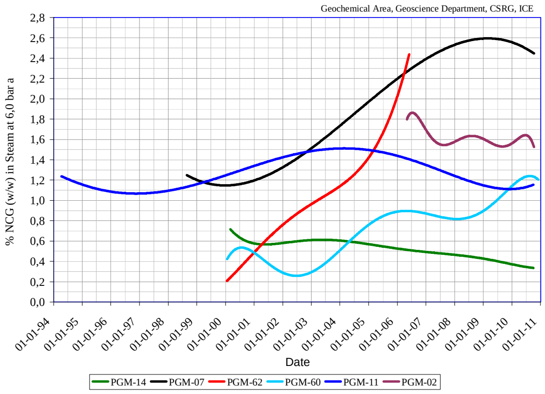

*Figure 35: Non-condensable gases in wells feeding Unit 3 (Sánchez, 2010).*

As can be seen from Figures 33, 34 and 35, only a few wells have decreased their non-condensable gas contents, whereas most of the wells have experienced substantial increases in gas concentrations; this has forced the generating units to exceed their capability to handle the extraction of the non-condensable gases.

## FINAL REMARKS

The behavior of all the separation stations at the Miravalles geothermal field since exploitation began has been presented in this document. The main events occurring at each separation station have been described in order to understand the behavior of each particular station.

All the reinjection sectors that have been used at the Miravalles geothermal field and their behavior were also described in this document, as well as the amount of brine injected in each injection well.

Data gathered from continuous pressure monitoring, hydraulic levels and static pressure profiles showed, in some cases, significant differences in the value of the calculated pressure decline, which suggest the need to estimate the pressure drop using all available methods.

The pressure decline at the Miravalles geothermal field was analyzed for 4 different periods, in order to understand the behavior of the pressure response as the generating units came on line. During the first period, the average pressure decline was near 1.71 bar/year. The production area was well defined when only Units 1 and 2 were producing. During the second period (from August 1998 to February 2000), greater average pressure declines were recorded (about 1.97 bar/year). During the next two periods (March 2000 to August 2003 and September 2003 to July 2010), even though the pressure decline spread throughout the entire reservoir, the magnitude of the average decline at each well was smaller than in the previous periods. The average pressure drop during the third period was close to 1.78 bar/year, and finally, since 2003, the mass extraction was reduced and the average pressure drop was also reduced to 1.26 bar/year.

Before the commissioning of Unit 1, micro-seismicity in the Miravalles area did not have a defined pattern related to geological structures or the extent of the geothermal reservoir. Micro-seismicity was low during the first stage of field operation, while in the second stage, after a seismic swarm in October 1997, there was a 16-month period of seismic quiescence. Until year 2000, the micro-seismicity in the geothermal field was very low (less the 30 micro-earthquakes per year). Since 2001, the micro-seismicity has increased each year, with a major increase in 2005. It is believed that 2010 will be the year with the greatest number of micro-earthquakes inside the Miravalles geothermal area. Through July 2010 there were 165 recorded events, with the largest number occurring in May, as was the case in 2009. The majority of the micro-earthquakes are concentrated between 1 and 3 km depth, in particular within the area between the fault that trends NE-SW through the field.

Most of the wells associated with each of the generation units have experienced an increase in the non-condensable gas content of their produced steam. This increase has exceeded the gas extraction capacities of Units 1, 2 and 3 at the Miravalles geothermal field. Modifications to the non-condensable gas extraction equipment are planned to be made within the next two years.

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