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Production-Injection at the Miravalles Geothermal Field, Costa Rica

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ABSTRACT

The Miravalles Geothermal Field has been producing electric energy since March 1994. It has provided steam for Unit 1 (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), that was completed in January 2004, has brought the total installed capacity in Miravalles to 163 MWe.

The field has supplied the steam and brine needed to generate power during fifteen years of exploitation (1994-2009). The performance of the field in terms of its production-injection behavior in response to exploitation is described in the following sections.

1. 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 of about 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 is about 240^{0}C. 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, 2006).

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, increased the total installed capacity at Miravalles to 163 MW (Table 1; Moya and Yock, 2007). 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.

Table 1: Power units at the Miravalles geothermal field Abbreviations stand for: ICE-Instituto Costarricense de Electricidad,; 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	

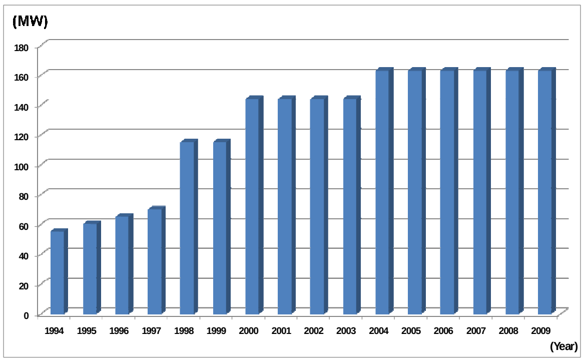

Figure 1: Geothermal installed capacity (1994 – 2009).

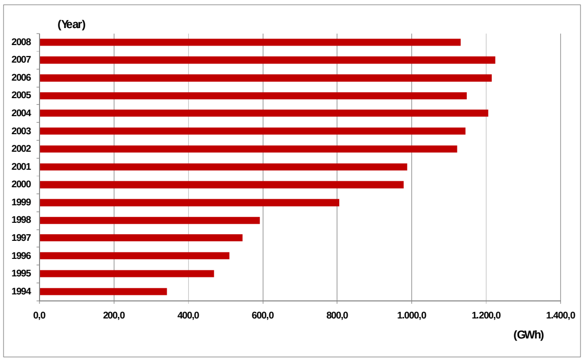

Figure 2: Energy production (1994 – 2008).

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

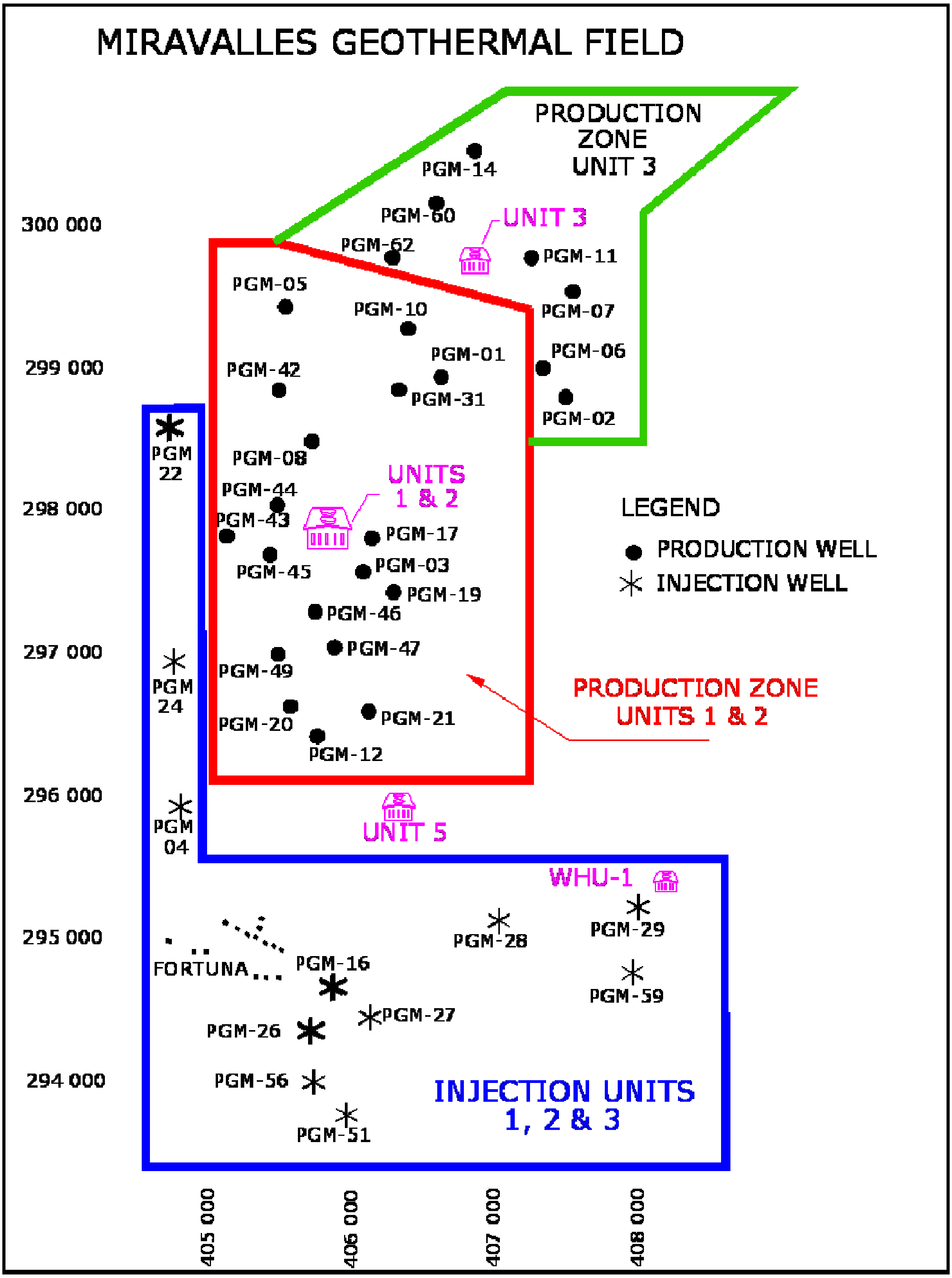

Figure 3: Location of the geothermal wells at the Miravalles geothermal field.

Unit 5 extracts additional energy from the separated geothermal brine before it is injected back into the geothermal reservoir.

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.

2. 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.

2.1 Separation Station 1

Separation Station 1 is fed by wells PGM-31 and PGM-65. Under current conditions, it 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).

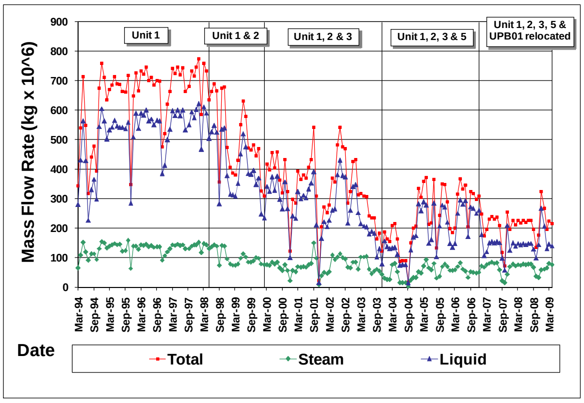

Figure 4: Monthly mass flow rates at Separation Station 1.

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 March 2009 the steam production rate has been kept fairly constant.

2.2 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 April 2009. Some variations in the steam rate are due to instability at well PGM-19.

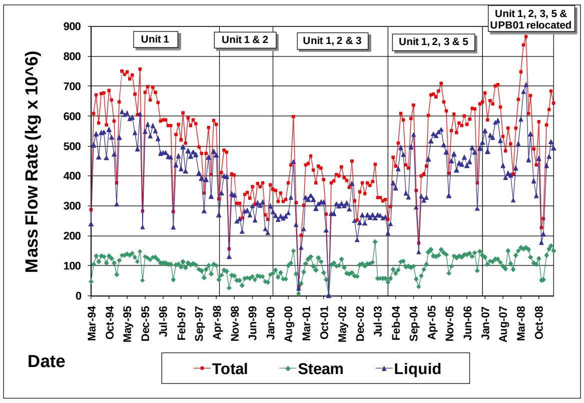

Figure 5: Monthly mass flow rates at Separation Station 2.

2.3 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 has decreased slightly from March 2000 to April 2009.

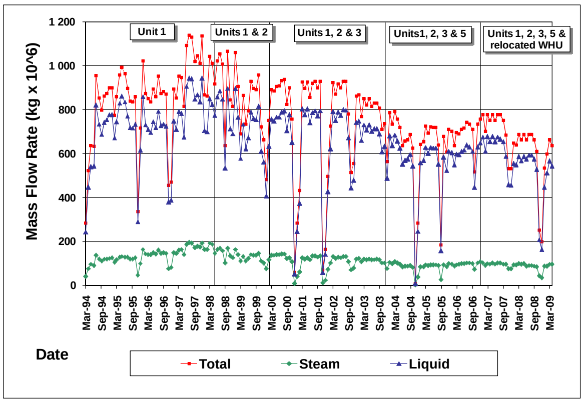

Figure 6: Monthly mass flow rates at Separation Station 3.

2.4 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 April 2009 the steam supply was kept more or less constant, depending on the requirements of the generating units; however, the brine flow has decreased slightly due to an increase in enthalpy.

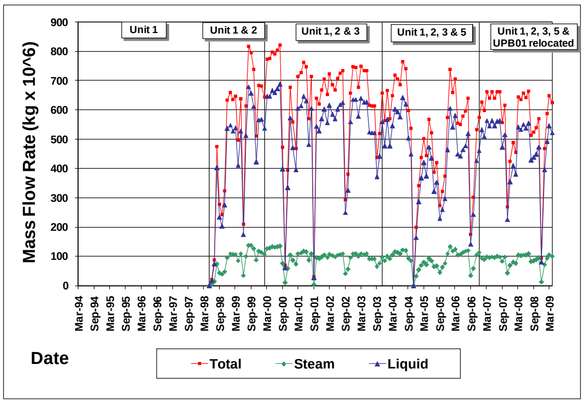

Figure 7: Monthly mass flow rates at Separation Station 4.

2.5 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 April 2009 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 April 2009.

2.6 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 the 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 April 2009.

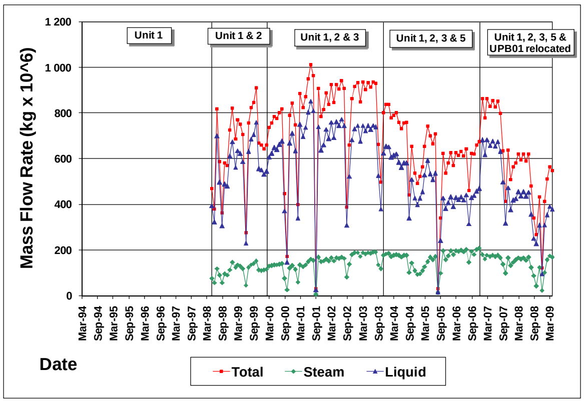

Figure 8: Monthly mass flow rates at Separation Station 5.

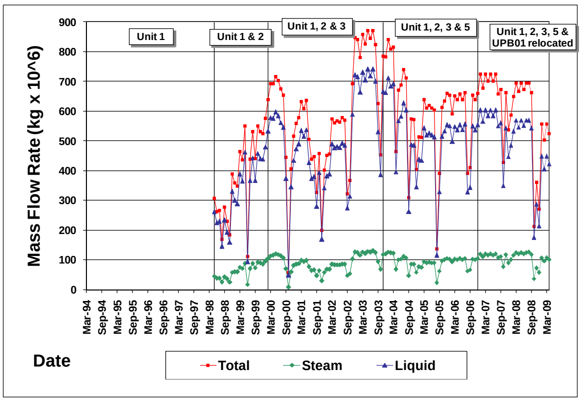

Figure 9: Monthly mass flow rates at Separation Station 6.

2.7 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). 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 September 2007 to April 2009, the steam supply has been fairly stable.

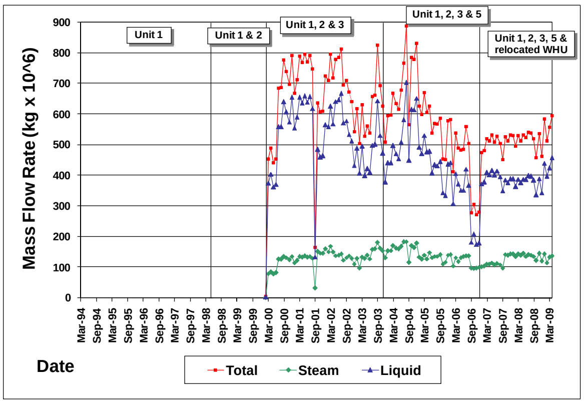

Figure 10: Monthly mass flow rates at Separation Station 7.

2.8 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.

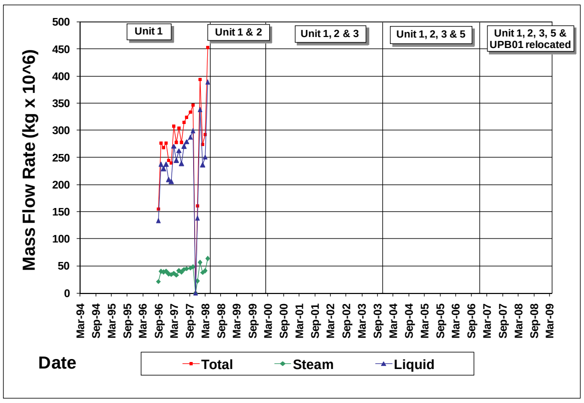

Figure 11: Monthly mass flow rates at Wellhead Unit 2.

2.9 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.

2.10 Wellhead Unit 1 at well PGM-29

From 1995 to 2006, Wellhead Unit 1 was located in the central part of the production zone. In December 2006, it was relocated to the southeastern sector of the field, where it has been fed by well PGM-29 through April 2009. Figure 13 indicates that the steam production rate has been almost constant during this period, but the brine rate has been increasing since December 2006.

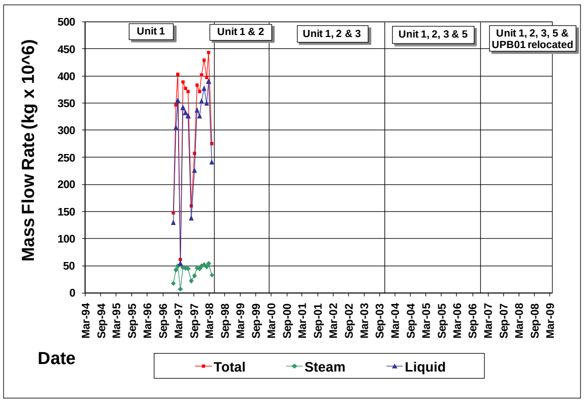

Figure 12: Monthly mass flow rates at Wellhead Unit 3.

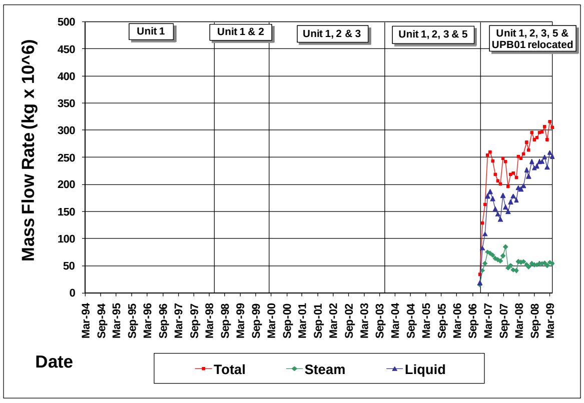

Figure 13: Monthly mass flow rates in Wellhead Unit 1 at PGM-29.

2.11 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 April 2009. The field was capable of supplying the required steam to the generation units until 2008. During 2009 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 gradually from May 1994 (380 686 tons/month) until August 2000 (820 612 tons/month). Then, the steam rate slowly increased from August 2000 to April 2009 (880 559 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 curves from April 1994 to July 2000, and then a slow decrease through April 2009.

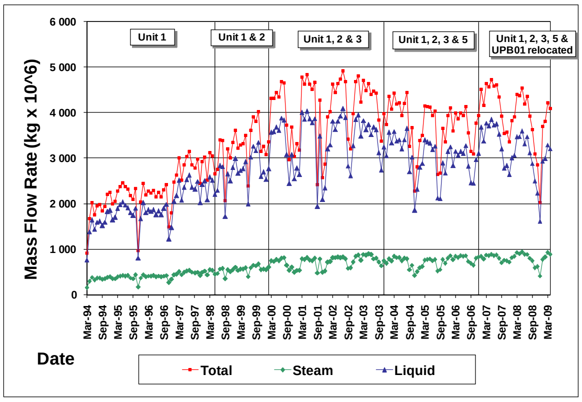

Figure 14: Monthly mass flow rates at the Miravalles geothermal field.

Figure 15 shows the cumulative production of steam, liquid, and total mass from the geothermal field. All of these masses 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 April 2009). By April 2009, the accumulated production was approximately 114.3 million tons of steam, 507.8 million tons of liquid and 622.2 million tons of total mass.

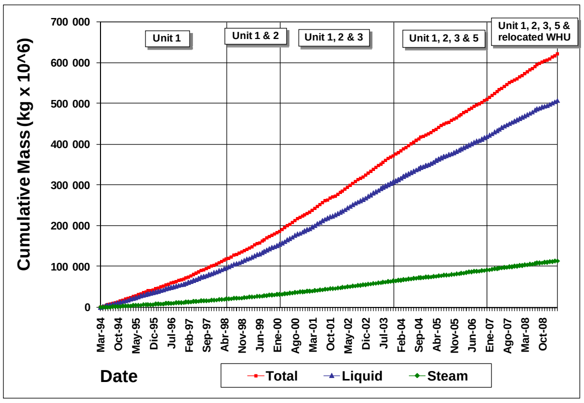

Figure 15: Cumulative mass extraction at the Miravalles geothermal field.

3. INJECTION

Injection at the Miravalles geothermal field can be divided into 6 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.

3.1 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.

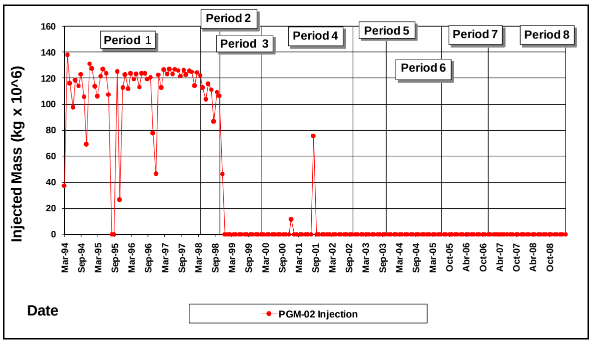

Figure 16: Eastern injection sector at the Miravalles geothermal field.

3.2 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.

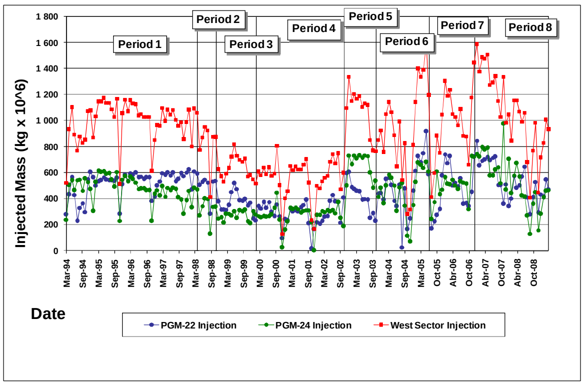

Figure 17: Western injection sector at the Miravalles geothermal field.

Table 2: Injection periods

Period	Initial Date	Final Date
1	**March 1994**	**April 1998**
	Commissioning of Unit 1. Injection line: 2 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. Injection lines: 1, 2 and 3. 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. Injection lines: 1, 2 and 3. 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**	**April 2009**
	Production in well PGM-29	Last data analyzed

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 8 x 10^8 kg per month at the end of Period 5.

3.3 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 periods 1, 2, 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 April 2009 the injection rate in the southern sector has fluctuated with changes in the operating conditions in the field.

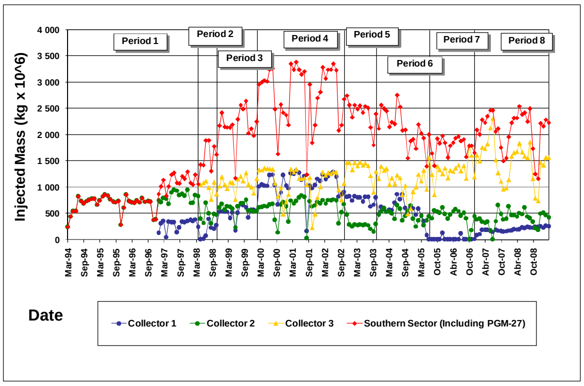

Figure 18: Southern injection sector at the Miravalles geothermal field.

3.4 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 June 2004. 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.

3.5 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 3.25 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).

3.6 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.

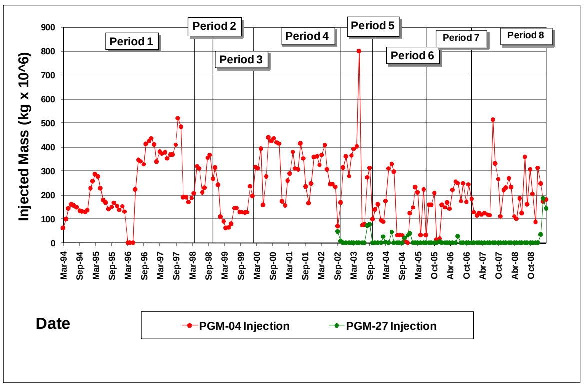

Figure 19: Cold injection, Southwestern sector at the Miravalles geothermal field.

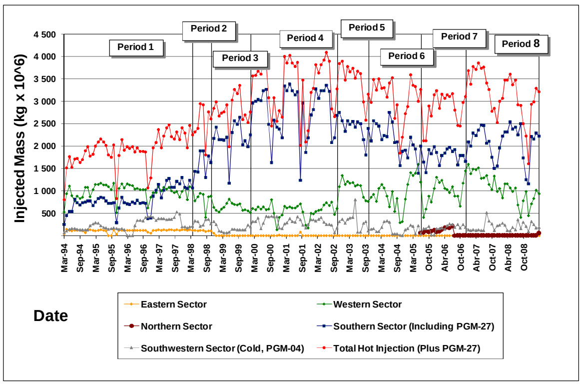

Figure 20: Field- Wide Injection at the Miravalles geothermal field.

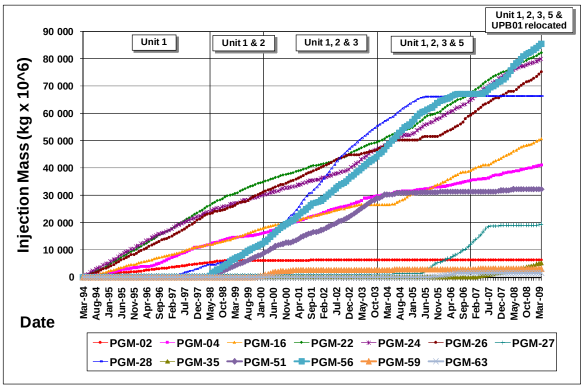

Figure 21: Cumulative Injection by Well at the Miravalles geothermal field.

4. PRESSURE RESPONSE

Reservoir pressure has been monitored routinely at the Miravalles geothermal field since production began in 1994. Static water levels (hydraulic levels) have also been recorded in many geothermal wells, providing an indirect indication of the reservoir pressure. With these measurements, it has been possible to evaluate the changes in reservoir pressure 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) from September 2003 to December 2008 for all units in the field.

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. Figures 22, 23, 24 and 25 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).

4.1 Period 1: March 1994 to July 1998

As indicated in Table 1, 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.

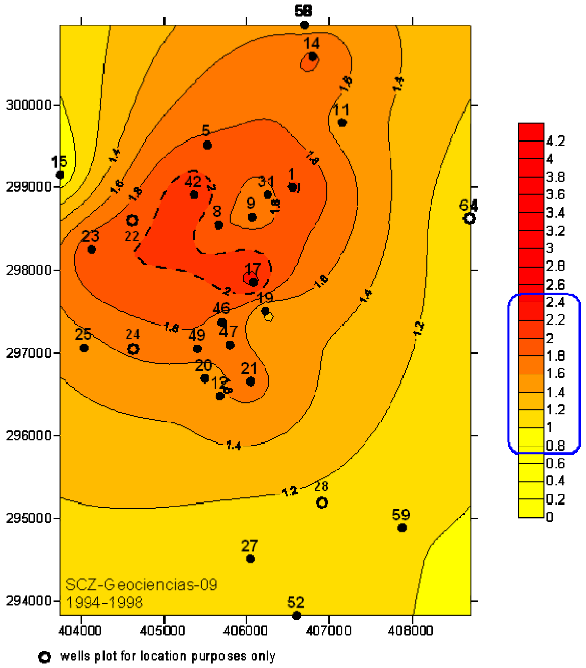

Figure 22: Pressure Decline during March 1994-July 1998. (Castro, 2009)

4.2 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 23 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 is in agreement with the inferred main production zone.

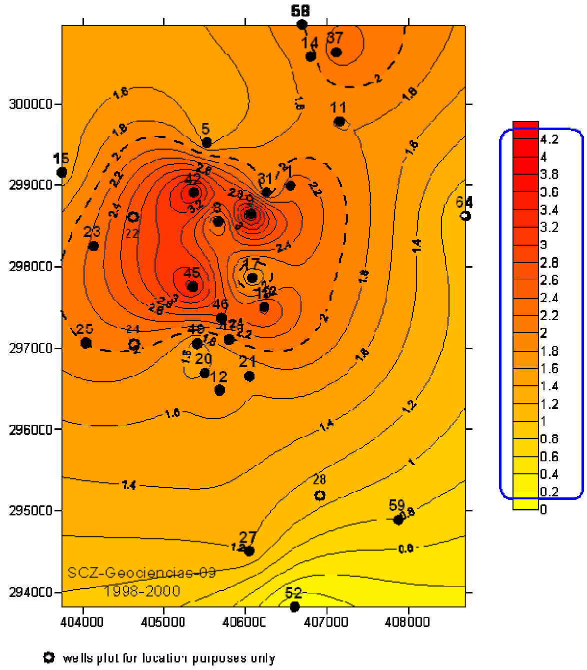

Figure 23: Pressure Decline during August 1998-February 2000. (Castro, 2009)

4.3 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 24, 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 less for this period than the previous one, but 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.

4.4 Period 4: September 2003 to December 2008

During this 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 25 it can be seen that the entire eastern area shows greater pressure declines than the western area.

5. 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.

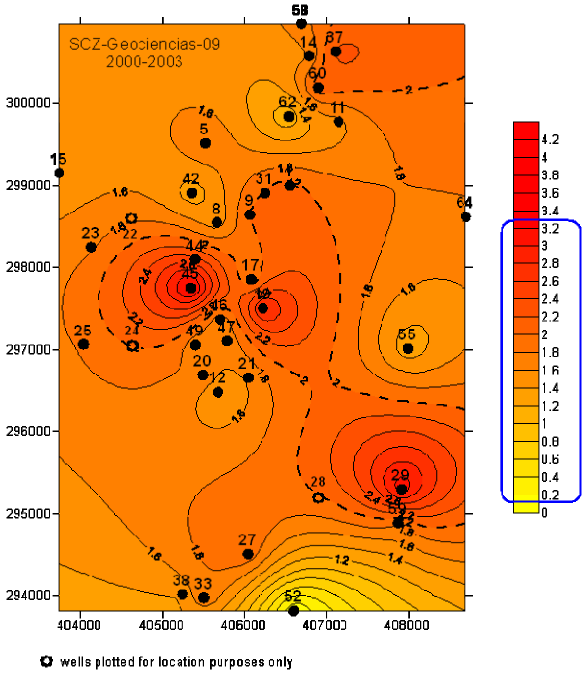

Figure 24: Pressure Decline during March 2000-August 2003. (Castro 2009)

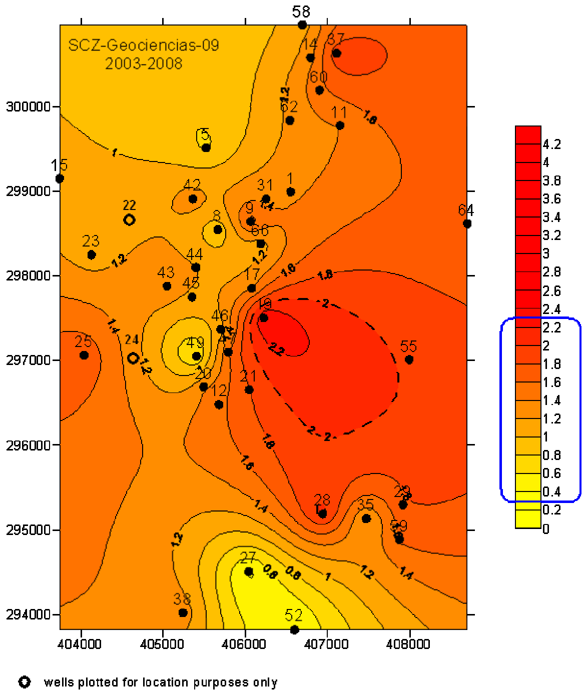

Figure 25: Pressure Decline during September 2003-December 2008. (Castro, 2009)

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 make production larger at 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 26 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-20, PGM-12 and PGM-08) they have been increasing.

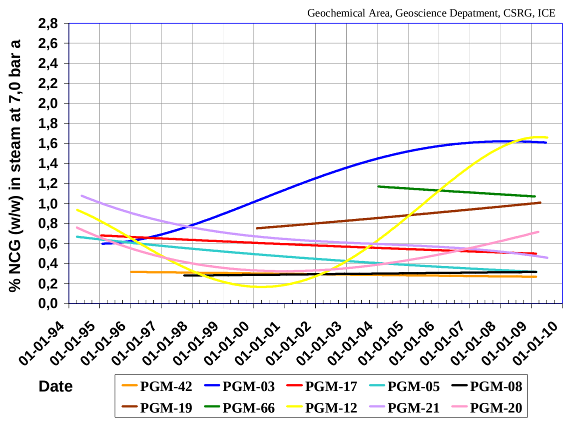

Figure 26: Non-condensable gases in wells feeding Unit 1. (Sánchez, 2009)

Figure 27 shows the wells that are feeding Unit 2 at the Miravalles geothermal field. The non-condensable gases have only decreased in well PGM-43, but they have increased in the rest of the wells (PGM-65, PGM-45, PGM-05, PGM-31, PGM-46, PGM-49 and PGM-44).

Figure 28 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. On the contrary, wells PGM-60, PGM-62 and PGM-07 have shown a trend of increasing non-condensable gases.

As can be seen from Figures 26, 27 and 28, only a few wells have decreased their non-condensable gas contents, whereas most of the wells have experienced substantial increases in gas concentrations, which has forced the generating units to exceed their capability to handle the extraction of the non-condensable gases.

6. 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.

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. 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 pressure declines were recorded. During the next two periods (March 2000 to August 2003 and September 2003 to December 2008), even though the pressure decline spread throughout the entire reservoir, the magnitude of the decline at each well was smaller than in the previous periods.

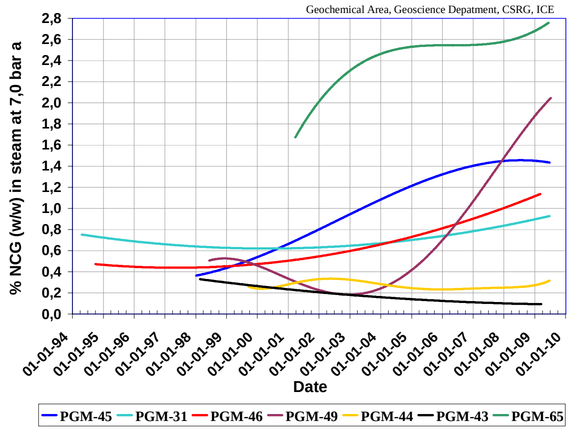

Figure 27: Non-condensable gases in wells feeding Unit 2. (Sánchez, 2009)

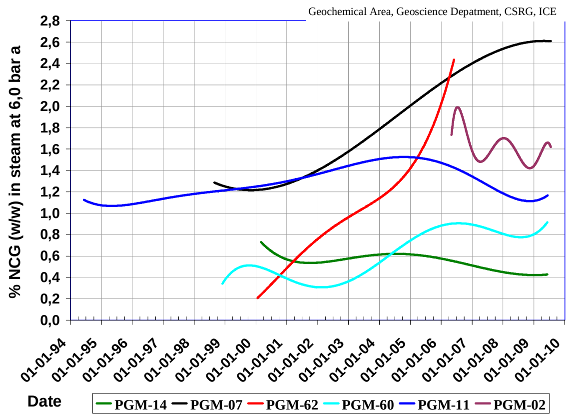

Figure 28: Non-condensable gases in wells feeding Unit 3. (Sánchez, 2009)

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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