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# First Ten Years of Production at the Miravalles Geothermal Field, Costa Rica

Paul Moya and Federico Nietzen.

Instituto Costarricense de Electricidad, C. S. Recursos Geotérmicos, Apartado Postal 10032-1000, San José, Costa Rica

pmoya@ice.go.cr , fnietzen@ice.go.cr

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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 MWe) since 1994, a Wellhead Unit (5 MWe) installed in 1995, Unit 2 (55 MWe) in 1998, Unit 3 (29 MWe) in 2000, and also Unit 5 (19 MWe, a binary plant) in the year 2004. The steam production and fluid injection during these first 10 years of operation are described in the following sections, as well as the current and future improvements to the gathering system. Changes in strategies for production and injection are also discussed.

## 1. INTRODUCTION

The Miravalles geothermal field is located on the southwestern slope of the Miravalles volcano. The extent of the geothermal field already identified is greater than 21 km$^2$, of which about 16 km$^2$ are dedicated to production and 5 km$^2$ to injection. There are 53 geothermal wells (Figure 1), including observation, production and injection wells, whose depths range from 900 to 3000 meters. The production wells produce between 3 and 12 MW each, and the injection wells each accept between 70 and 450 kg/s. The reservoir has a temperature of about 240 $^oC$ and is water-dominated (Moya and Mainieri, 2002).

The Miravalles geothermal field has been producing since 1994. Seven separation stations now supply the steam needed for Unit 1, Unit 2, Unit 3 and one active Wellhead Unit. At present there is a need to supply enough steam to operate 55 MWe (Unit 1), 5 MWe (Wellhead Unit), 55 MWe (Unit 2) and 29 MWe (Unit 3), for a total of 144 MWe. This capacity was increased to 163 MWe when a bottoming-cycle binary plant came online in January of 2004. As indicated in Table 1, two wellhead units from the Comisión Federal de Electricidad (Mexico) were in operation while Unit 2 was being built, but these have been decommissioned.

Normally, two or three production wells supply two-phase fluid to each separation station. The total steam flow to the plants is now about 280 kg/s, and the residual geothermal water sent to the injection wells is about 1330 kg/s. Most of these fluids are passed through Unit 5 (binary plant) to generate 19 MWe.

In order to analyze the production of the Miravalles geothermal field, the behavior of each separation station (1 to 7) is described below. The injection, on the other hand, is analyzed by describing the different injection sectors (East, West, South, and cold injection) of the field.

**Table 1: Units at the Miravalles geothermal field.**

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

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

## 2. PRODUCTION

The separation stations are also called satellites, and each is capable of separating a maximum of 60 kg/s of steam. The satellites supply the steam needed by the generating units (not necessarily at their maximum separation capacity). They undergo annual maintenance when the main generation units also undergo their annual maintenance program (which takes more than 15 days) during the last quarter of the year.

### 2.1 Separation Station 1

Separation Station 1 is fed by wells PGM-01, PGM-10, PGM-31, PGM-63 and PGM-65. Under current conditions, it separates 5.5 kg/s of steam and 28.7 kg/s of brine. The flow from wells PGM-05 and PGM-11 can also be separated at this station, but nowadays the flow from well PGM-05 is mainly separated at Separation Station 4 and the flow from well PGM-11 is mainly separated at Separation Station 7. 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, since the latter has a larger capacity to handle the non-condensable gases coming from Satellite 1.

As can be seen in Figure 2, the separated steam rate was almost constant from March 1994 until June 1998. After that, the flow decreased and fluctuated until March 2004. The decrease in steam is due to the fact that 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 started its generation (March 2000).

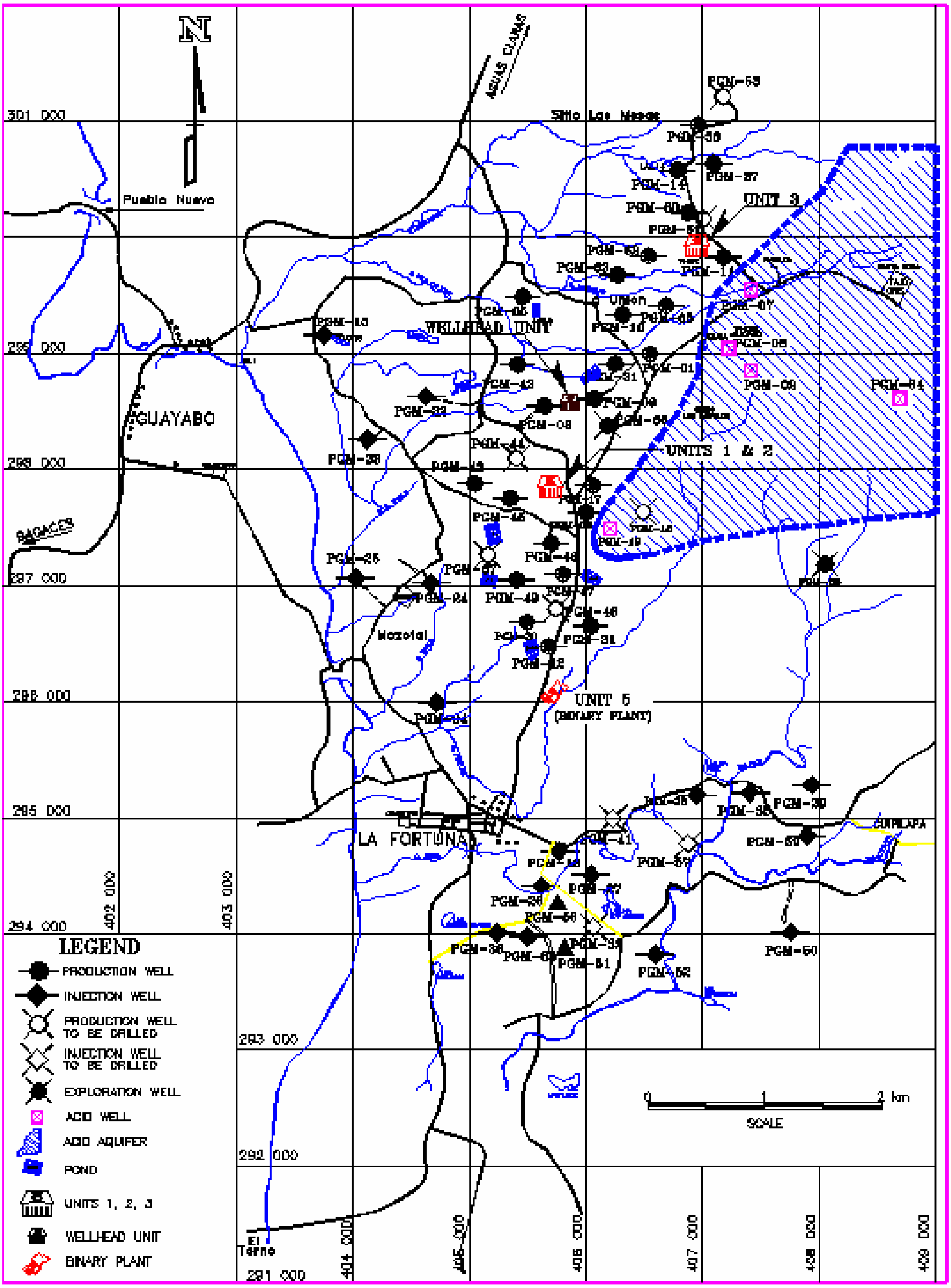


**Figure 1: Location of wells at the Miravalles geothermal field.**

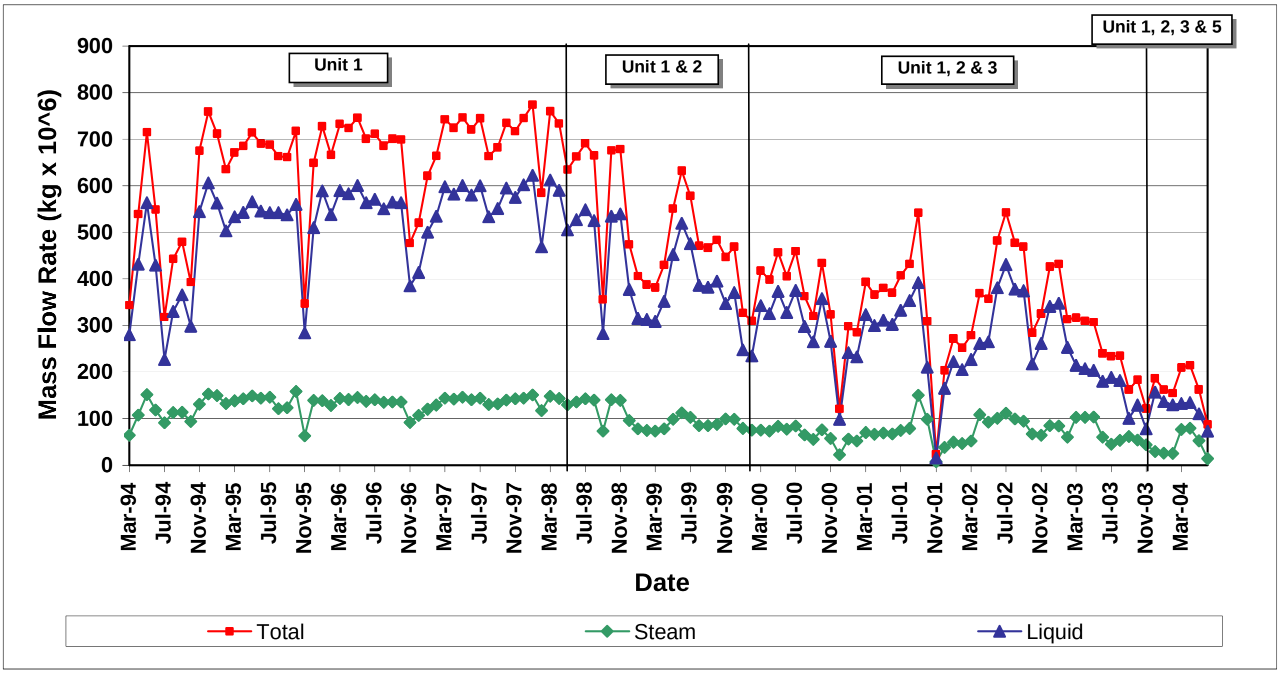


**Figure 2: Separation Station 1.**

Later, the separated steam was kept constant (based on the rate required) from March 2000 until May 2003. After May 2003, some of the wells feeding Satellite 1 lost their production (PGM-01, PGM-10 and PGM-63), which has decreased the steam production until the present time (June 2004).

### 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 35.8 kg/s of steam and 83 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 3 shows that the separated steam rate decreased slightly from March 1994 until March 1988, 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 fluctuated, depending on steam requirements. By July 2001, work had also begun on deepening well PGM-46 because the well had lost part of its production. A new permeable zone was found, and early in the year 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 the year 2004, which explains the increment in steam rate during the first four months of 2004. Early in the year 2003 the geothermal fluid from a new production well (PGM-66) was incorporated in this separation station, which increased its steam production and kept it constant until June 2004.

### 2.3 Separation Station 3

Separation Station 3 is fed by wells PGM-12, PGM-20 and PGM-21. Under current conditions, it separates 33.7 kg/s of steam and 209.5 kg/s of brine. Figure 4 shows that the steam supply from this station increased from March 1994 to March 1998, when Unit 2 came online. From March 1998 to March 2000 the steam supply decreased slightly as a result of commissioning Unit 2 (Satellite 6), mainly because its proximity to the production wells that supply the steam for Satellite 3. With the new production wells that feed Station 6, this sector of the reservoir re-equilibrates to supply the geothermal flow to Separation Stations 3 and 6. The steam supply at Satellite 3 has decreased slightly from March 2000 to June 2004.

### 2.4 Separation Station 4

Separation Station 4 is fed by wells PGM-05, PGM-08, and PGM-42. Under present conditions, it separates 41.7 kg/s of steam and 224 kg/s of brine. The flow from well PGM_05 can also be separated at Separation Station 1. Separation Station 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 5, this separation station began operating with the commissioning of Unit 2 in March 1998. The steam supply increased from March 1998 until August 2001. From October 2001 to June 2004 the steam supply was kept more or less constant depending on the requirements of the generating units.

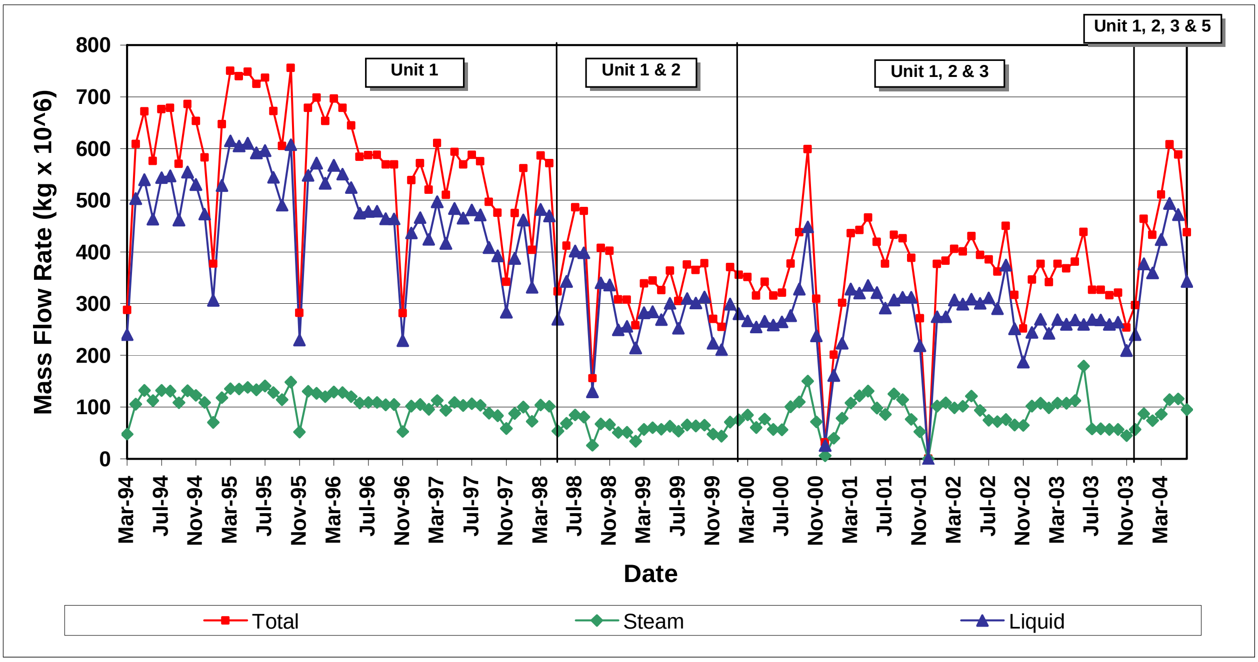


**Figure 3: Separation Station 2.**

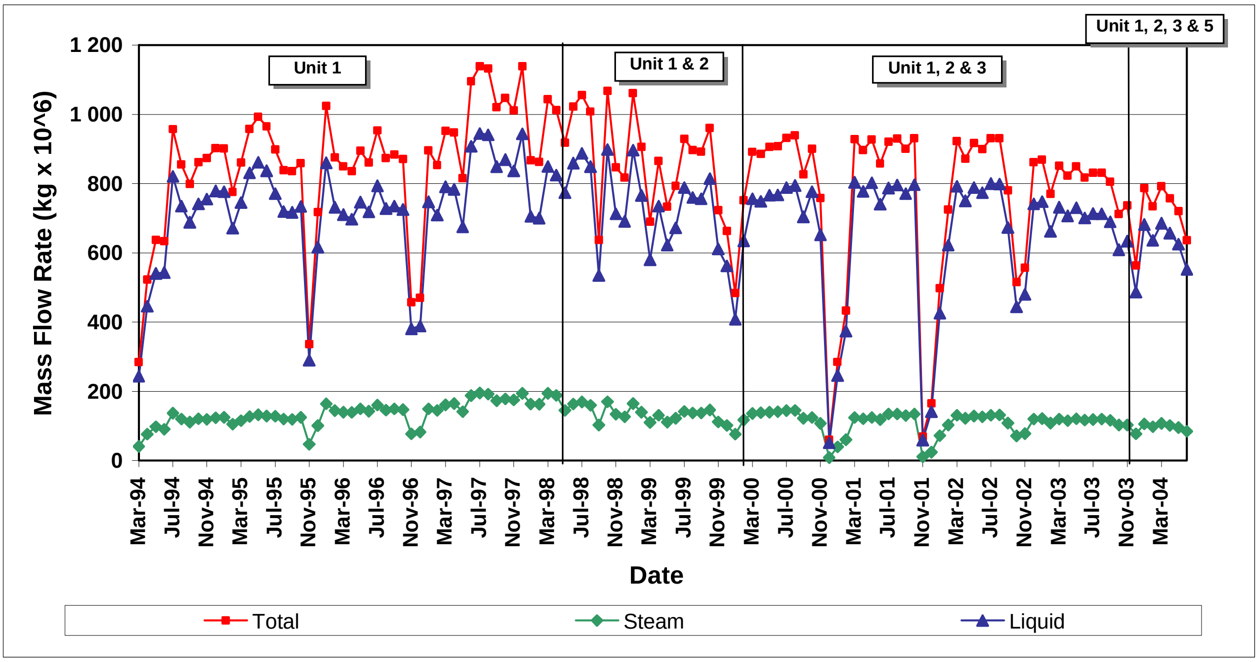


**Figure 4: Separation Station 3.**

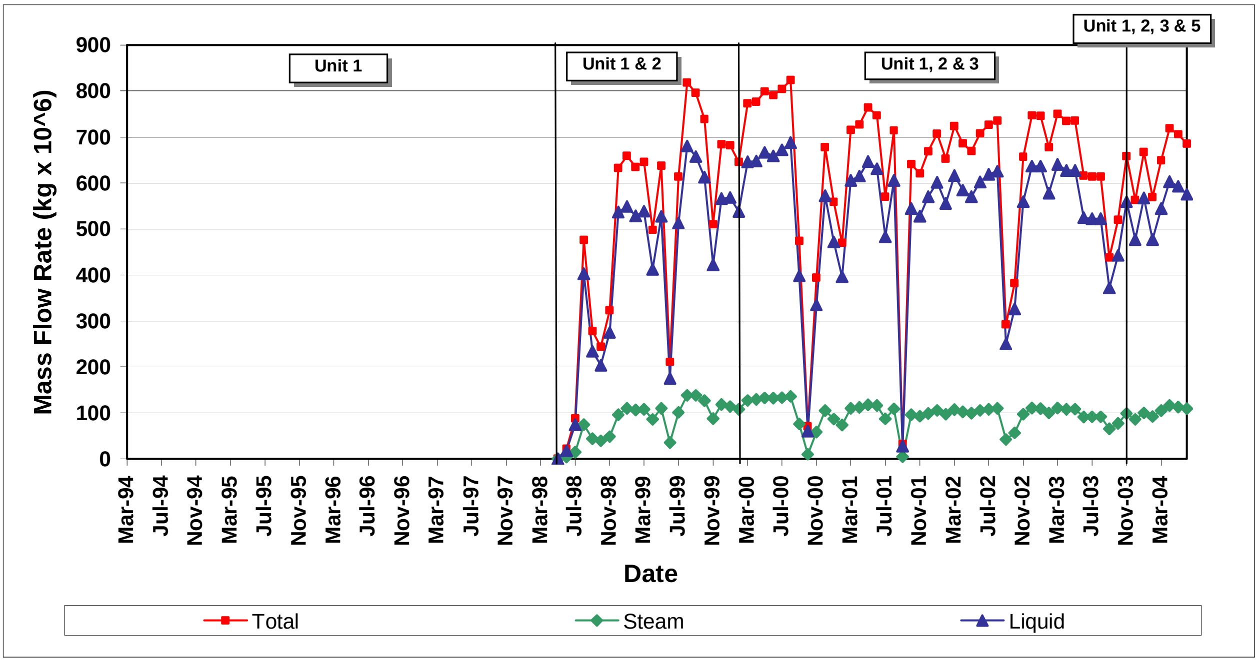


**Figure 5: Separation Station 4.**

### 2.5 Separation Station 5

Separation Station 5 is fed by wells PGM-43, PGM-44, and PGM-45. Under current conditions, it separates 65 kg/s of steam and 216 kg/s of brine. Figure 6 shows that, like Separation Station 4, this station began operation with the commissioning of Unit 2 in March 1998. The steam supply slightly increased from March 1998 to June 2004.

### 2.6 Separation Station 6

Separation Station 6 is fed by wells PGM-46, PGM-47, and PGM-49. Under the present conditions, it separates 43.4 kg/s of steam and 241.2 kg/s of brine. Figure 7 shows that this separation station, like stations 4 and 5, began operating with the commissioning of Unit 2 in March 1998. The steam supply increased from March 1998 to July 2000, but then decreased slightly and was kept fairly constant from December 2000 to May 2001. In July 2001, work began on deepening well PGM-46 and a new production zone is found, which led to a return to the previous rate of steam production from this satellite.

### 2.7 Separation Station 7

Separation Station 7 is fed by wells PGM-07, PGM-11, PGM-14, PGM-60 and PGM-62. Under current conditions, it separates 49.1 kg/s of steam and 136.2 kg/s of brine. The flow from well PGM-11 can also be separated and sent to Satellite 1. As can be seen in Figure 8, this separation station began operation in March 2000 with the commissioning of Unit 3, which receives the separated steam. The steam rate from this station was kept constant from March 2000 to June 2000. After this period, and from July 2000, steam production has increased because well PGM-62 was connected to this separation station. Steam production from this satellite slightly increased from July 2000 to June 2004.

### 2.8 Wellhead Unit 2 at well PGM-45

As indicated in Table 1, two wellhead units from the Comisión Federal de Electricidad (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 9 shows that the produced steam increased slightly during the period in which the unit was generating.

### 2.9 Wellhead Unit 3 at well PGM-29

As indicated in Table 1, the other wellhead unit from the Comisión Federal de Electricidad (México) was Wellhead Unit 3. This unit was fed by well PGM-29 from January 1997 to April 1998. Figure 10 indicates that the produced steam was kept almost constant while the unit was operating.

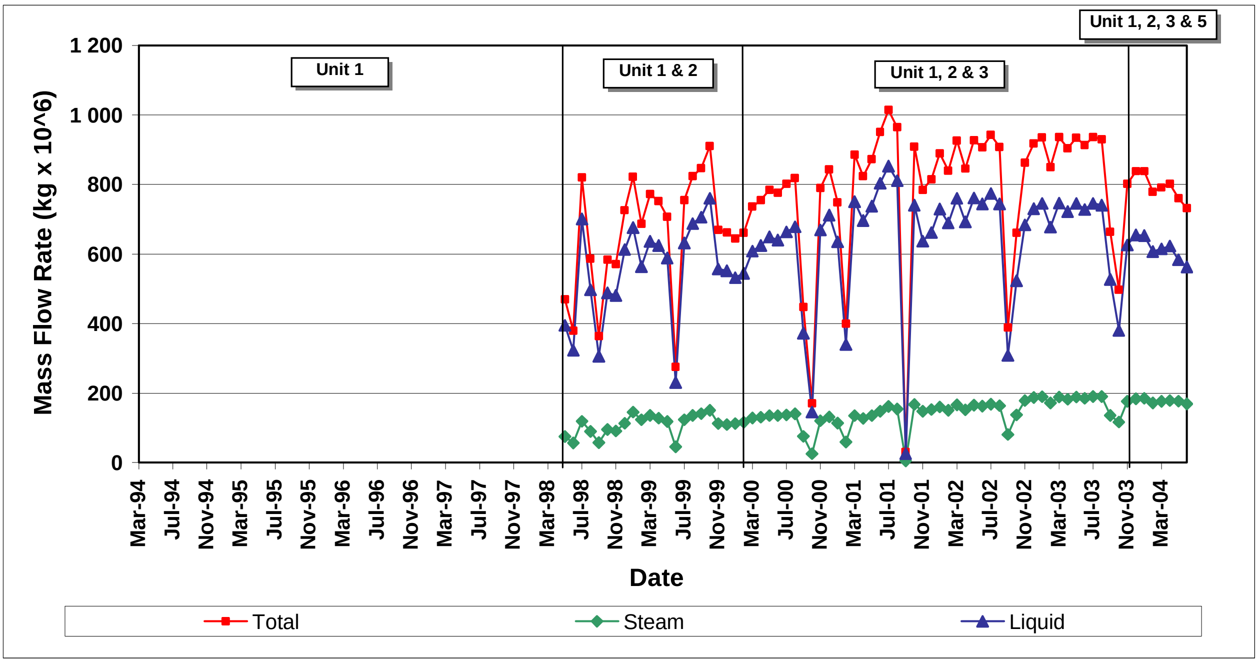


**Figure 6: Separation Station 5.**

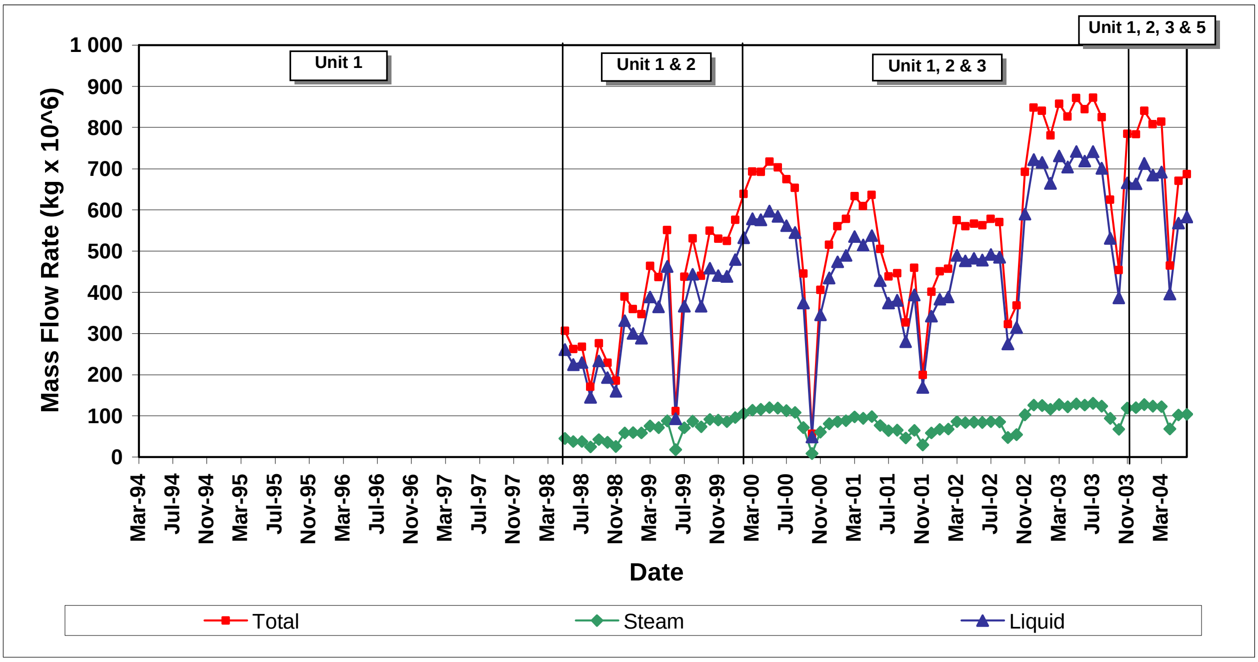


**Figure 7: Separation Station 6.**

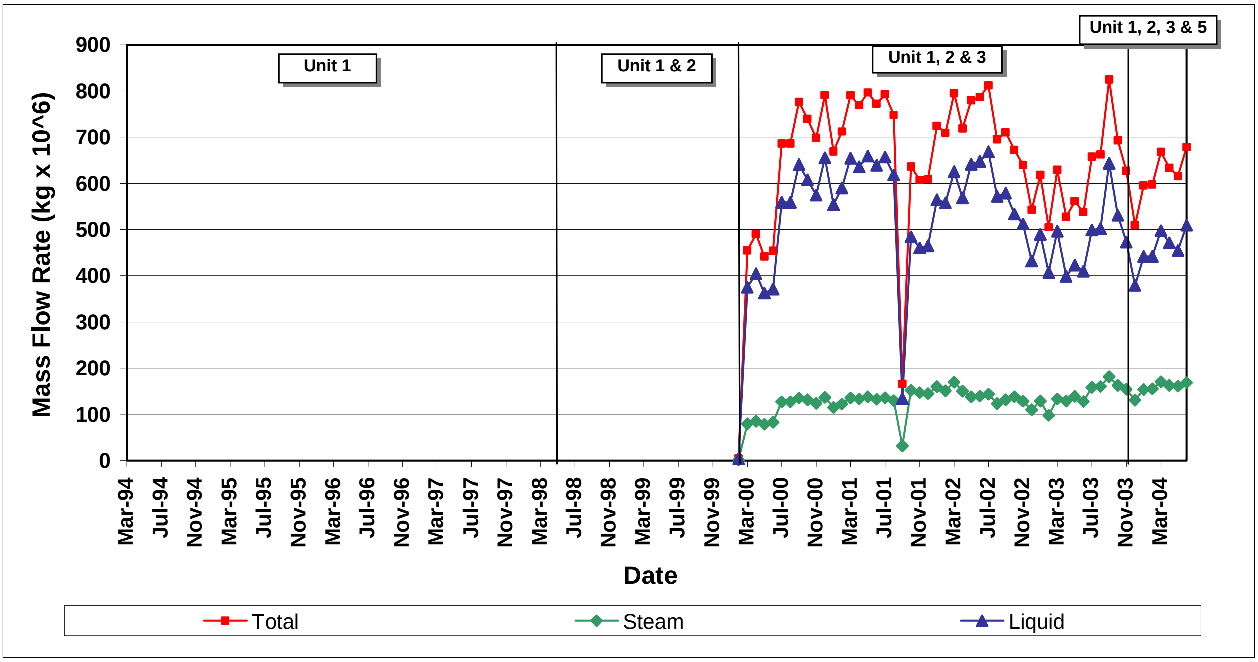


**Figure 8: Separation Station 7.**

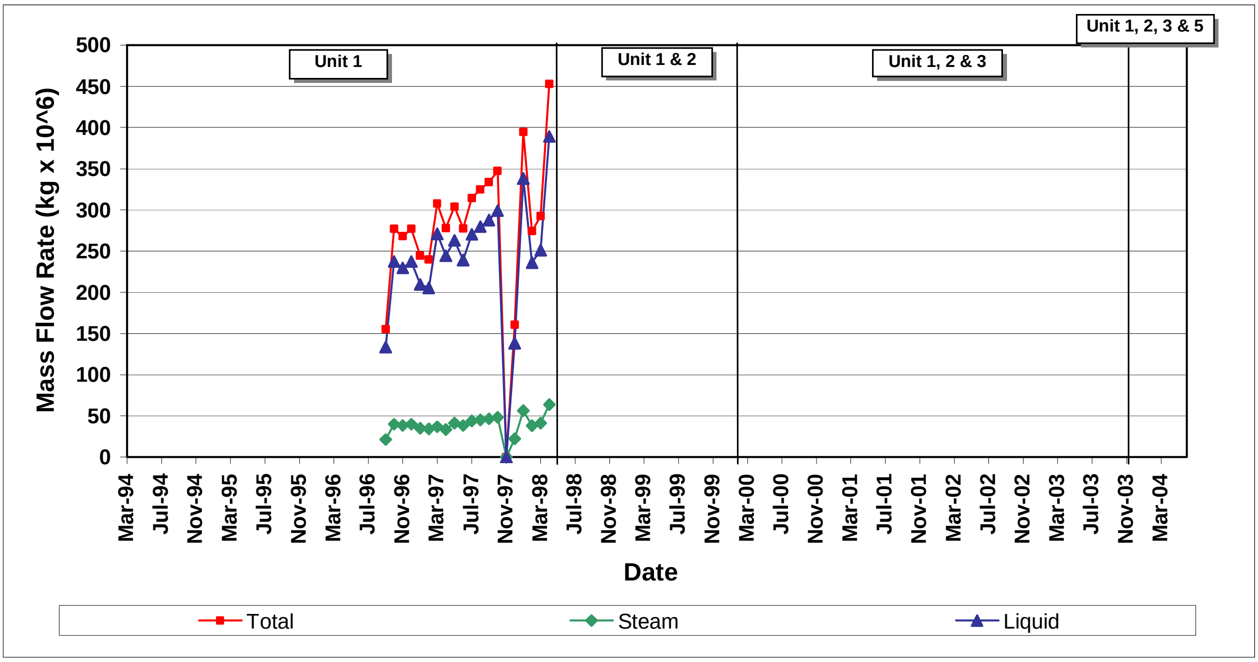


**Figure 9: Wellhead Unit-2 at well PGM-45.**

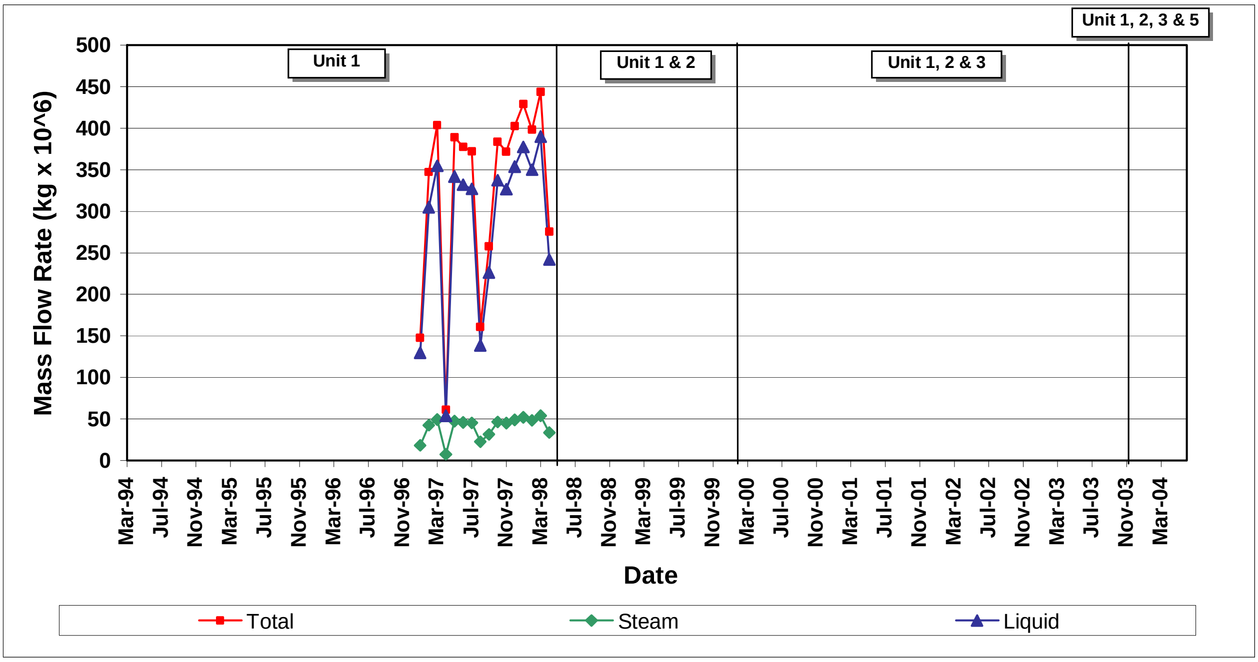


**Figure 10: Wellhead Unit 3 at well PGM-29.**

### 2.10 Field-Wide Production

Figure 11 shows the rate of mass extraction from the Miravalles geothermal field since production began. The steam extraction rate increased gradually from May 1994 (380,000 tons/month) until August 2000 (820,000 tons/month). Since April 2000, steam production has increased from 745,000 to 844,000 tons/month, with the exception of maintenance periods. The production rate has decreased every year during September-December, mainly as a consequence of maintenance work on Units 1, 2 and 3. Liquid mass and total mass extraction have behaved in basically the same way: there was an increase from April 1994 (1.4 million tons of liquid per month) to May 1995 (2 million tons/month); they then fluctuated within a range of 1.7 to 2.5 million tons/month until April 1998. Thereafter, the total mass extraction increased from 2.7 to 4.9 million tons/month and the liquid mass increased from 2.3 to 4.1 million tons/month. This last increment is the result of the start-up of Units 2 and 3. From March 2001 to June 2004, total mass extraction stabilized at around 4.5 million tons/month and liquid mass extraction stabilized at around 3.5 million tons/month. The behavior of the extraction curves coincides quite well with the increases in generation over these years as the different new units were commissioned.

Figure 12 shows the cumulative production of liquid, steam and total masses from the geothermal field. All of these masses increased linearly from March 1994 up 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 June 2004). By June 2004, the accumulated production was approximately 70.3 million tons of steam, 330.9 million tons of liquid and 401.3 million tons of total mass.

## 3. INJECTION

Injection at the Miravalles geothermal field has been divided into 6 periods. These periods as well as their initial and final dates are indicated in Table 2.

There are three sectors of the Miravalles geothermal field that have been used for hot-water injection (these are designated East, West and South), 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 East Injection Sector

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

The Plazoleta separation station was very important when time Unit 1 came online, because it allowed us to add the steam coming from well PGM-11 to the generation of Unit 1. During Injection Period 1, the injection rate remained more or less constant at about 120,000 tons per month (Figure 13). Injection in this sector began to decrease in Period 2, for several reasons: valve repairs, changes in deliverability curves, change of the capillary tubing (thus reducing the flow), etc. Injection in well PGM-02 ended in December 1998, when there was no longer a need to supply more steam from well PGM-11, the emergency valve had to be repaired and PGM-02 had to be 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 dispose of liquid while Satellite 7 was undergoing maintenance.

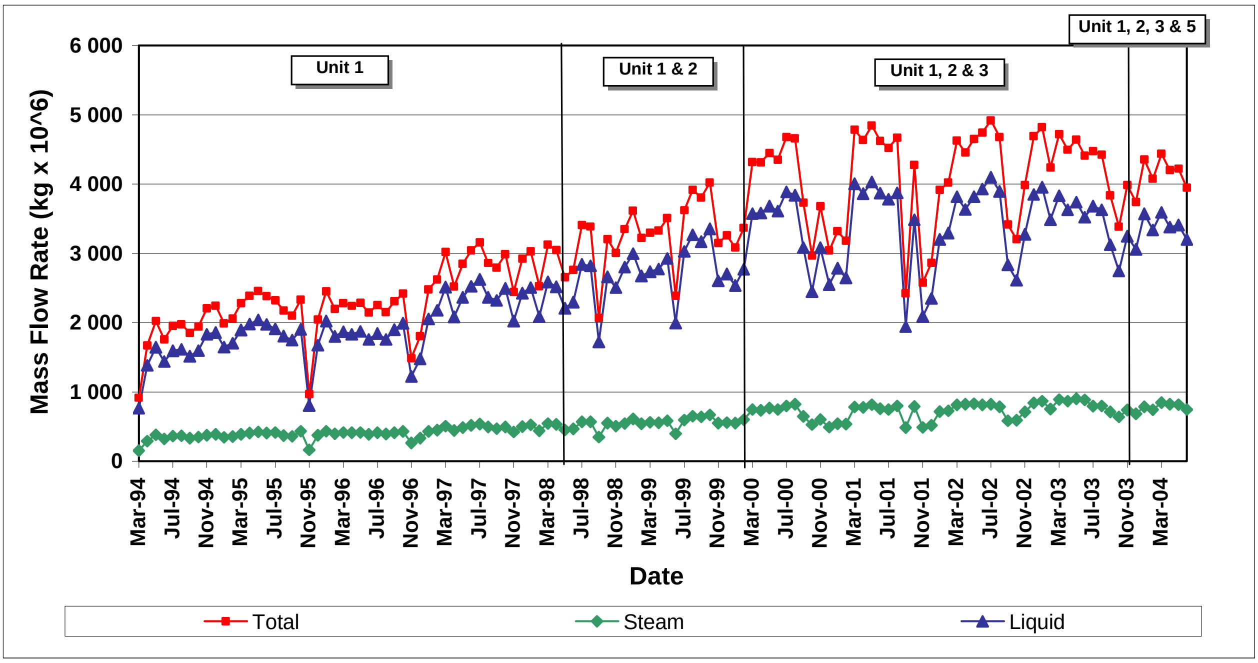


**Figure 11: Field-Wide Extracted mass.**

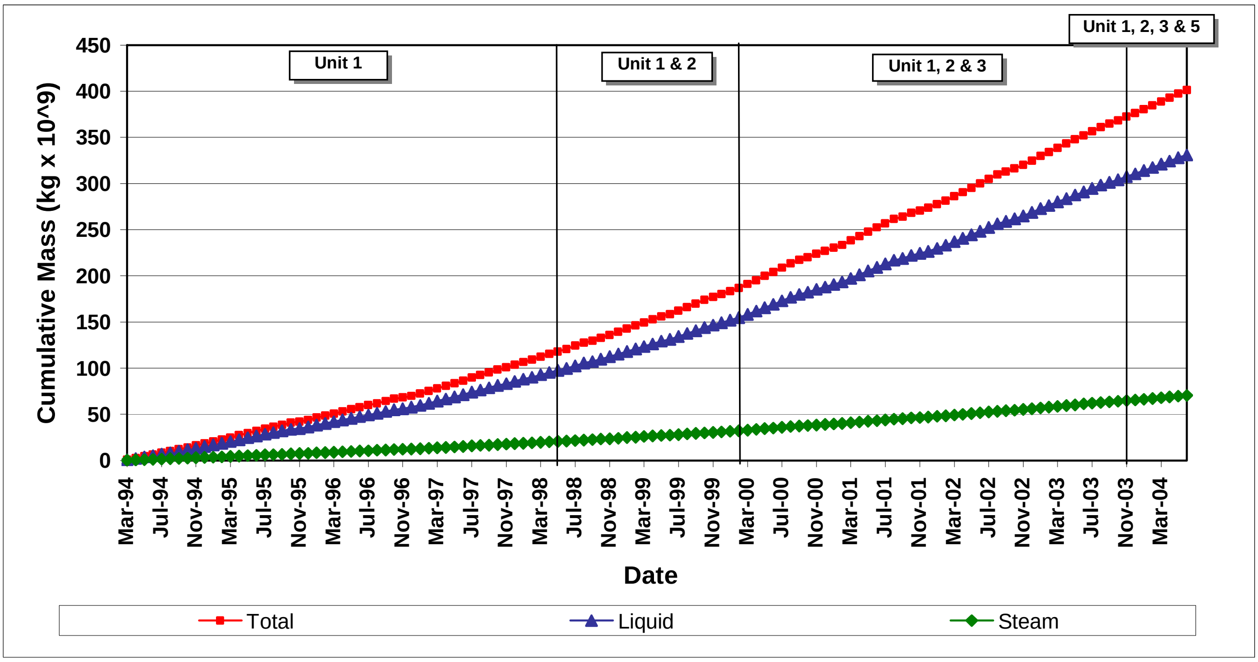


**Figure 12: Cumulative extracted mass.**

**Table 2: Injection periods**

| Period | Initial Date | Final Date |
|---|---|---|
| 1 | March 1994 | April 1998 |
| | Commissioning of Unit 1.<br><br>Injection line: 2<br><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><br>Injection lines: 1, 2 and 3.<br><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><br>Injection lines: 1, 2 and 3.<br><br>Wells: PGM-22 and PGM-24 | The flow from PGM-05 had been separated at Satellite 1, but was changed to Satellite 4. The flow from PGM-46 had been separated at Satellite 2, but 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. | Increment in the contribution from Satellites 4 and 5 to the West Injection Sector, wells PGM-22 and PGM-24. |
| 5 | December 2002 | November 2003 |
| | Increment in the contribution from Satellites 4 and 5 to the West Injection Sector, wells PGM-22 and PGM-24. | Commissioning of Unit 5 |
| 6 | December 2003 | June 2004 |
| | Commissioning of Unit 5 | Last data analyzed. |

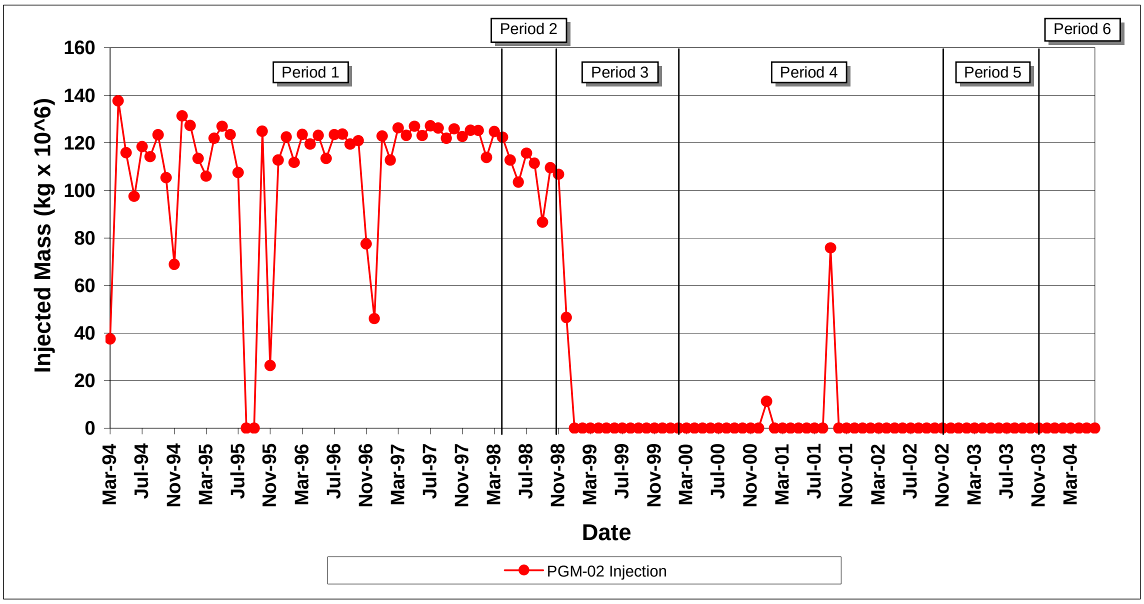


**Figure 13: East Injection Sector, well PGM-02.**

### 3.2 West Injection Sector

The wells that contribute to injection in the west sector are PGM-22 (Satellite 1) and PGM-24 (Satellite 2). This injection sector has been utilized since the first plant was commissioned. There have been several activities that explain the behavior of the curves. To summarize, injection in the west sector was kept constant during Period 1 (1,100,000 tons per month, Figure 14). During Period 2, production from well PGM-05 was partially diverted to Satellite 4, decreasing the injection rate. Well PGM-05's production was completely diverted to Satellite 4 at the end of Period 3, at which time injection decreased to 600,000 tons per month and remained constant at this value during Period 4.

During Period 5 there was an increment in the liquid 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 support for the pressure decline 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 1,300,000 tons per month to about 800,000 tons/month at the end of Period 5, coincident with annual maintenance work on generating units at the end of this period.

### 3.3 South Injection Sector

Injection in the southern sector is distributed over three injection pipelines called collectors 1, 2 and 3. The behavior of each collector is shown in Figure 15. The liquid injected through these collectors has depended on the operating conditions of the field. In this section, we describe only the total injection in the southern sector. Figure 15 indicates that injection was constant until October 1996, after which it increased (end of Period 1, Period 2, Period 3, and the beginning of Period 4) up until August 2000, when annual maintenance took place on the generating units. Leaving aside the annual maintenance periods of the plants, injection was kept constant around 3,250,000 tons per month during Period 4.

At the beginning of Period 5, part of the fluid injected in the southern sector was moved to the western sector (following the advice of GeothermEx as mentioned above). As a consequence, injection in the southern sector decreased and remained constant at about 2,500,000 tons per month during Period 5.

### 3.4 Cold Injection, Southwestern Sector

The condensed vapor from the generating units, the separated fluids from the acidic wells (PGM-07 and PGM-19) and the separated water from deliverability tests (conducted periodically on the production wells) are all injected into the reservoir by means of the cold injection system. This system consists of concrete pipelines running from each production well to five different ponds. There are concrete pipelines between the ponds, to carry liquid from higher-elevation ponds to a lower ones. From the lowest elevation pond, the liquid is sent to PGM-04, the cold-injection well. Figure 16 shows the amount of separated liquid that has been injected in this well between March 1994 and June 2004. The injection rates depend on the operating conditions of the field, and therefore have varied substantially as a consequence of adjusting to particular operation conditions.

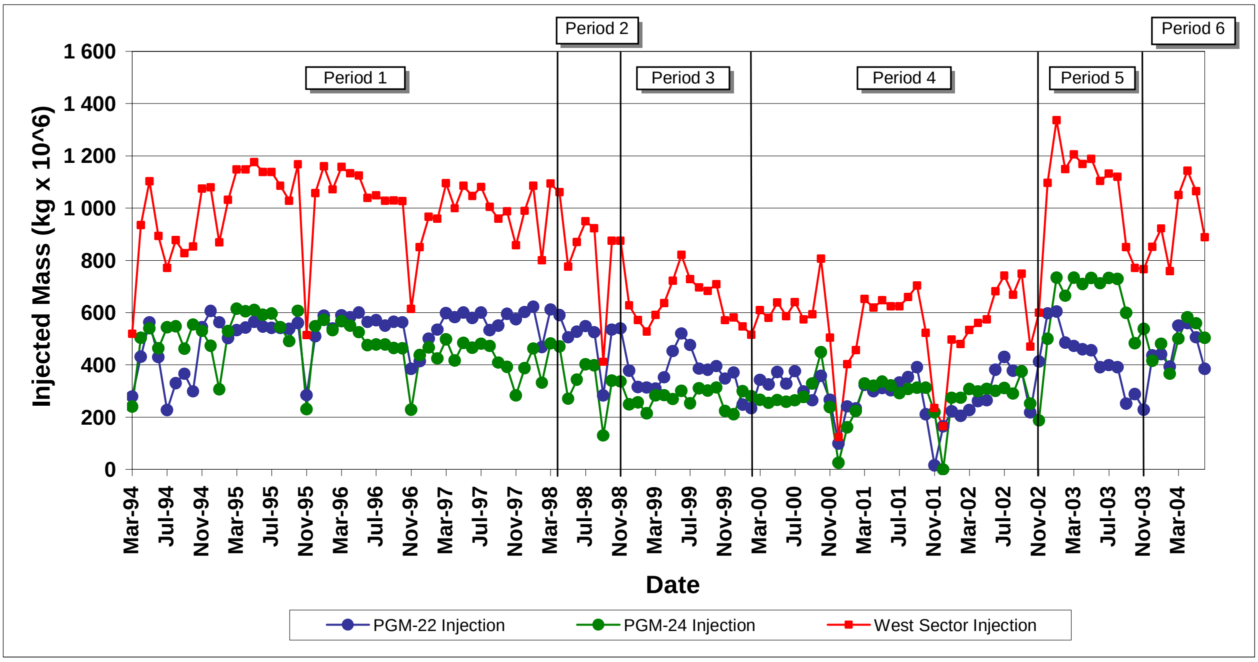


**Figure 14: West Injection Sector, Wells, PGM-22 and PGM-24.**

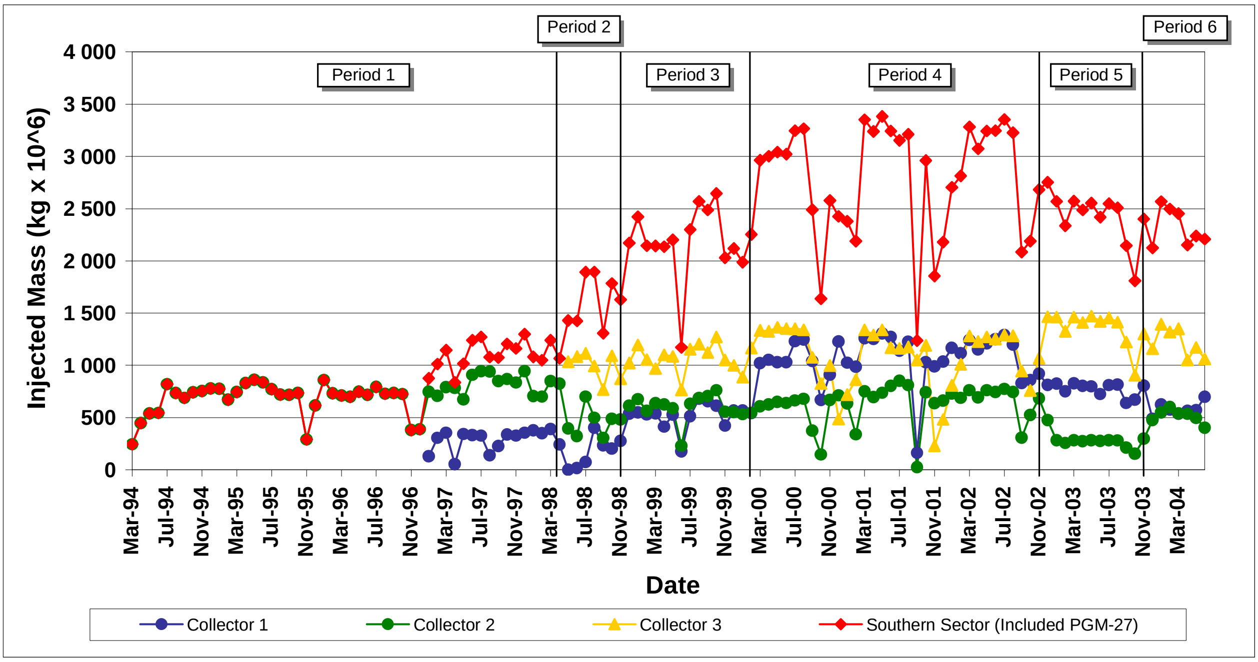


**Figure 15: South Injection Sector, wells PGM-16, PGM-26, PGM-27, PGM-28, PGM-51 and PGM-56.**

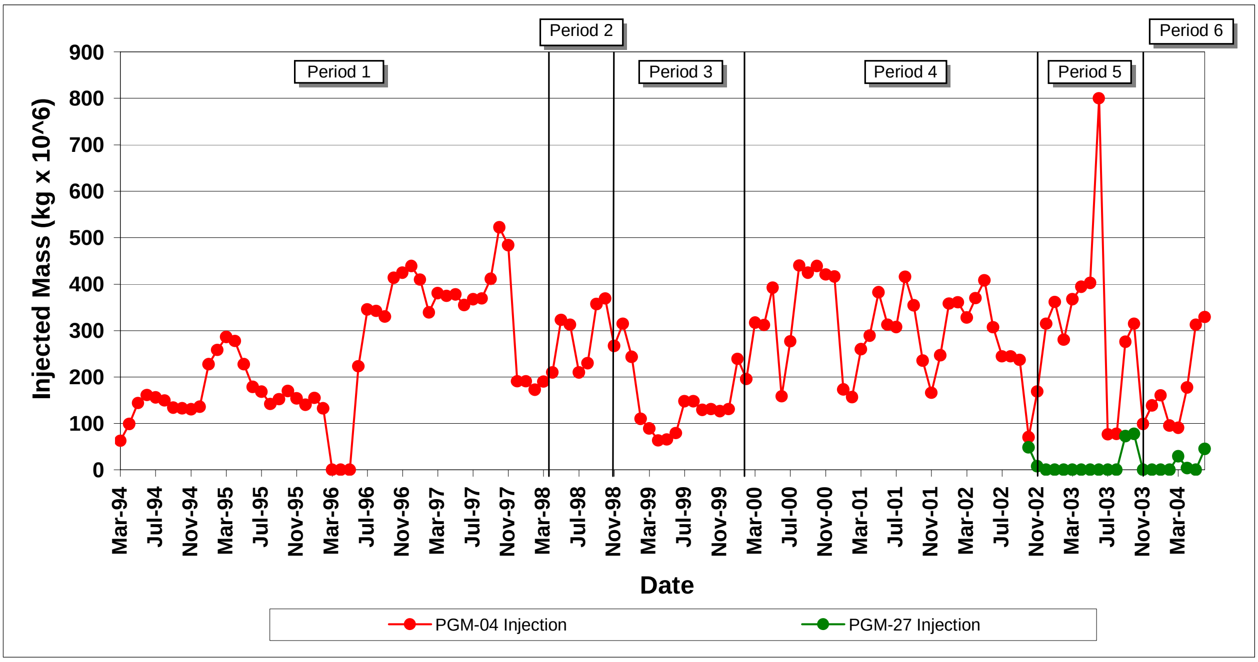


**Figure 16: Cold Injection, Southwestern Sector, wells PGM-04 and PGM-27.**

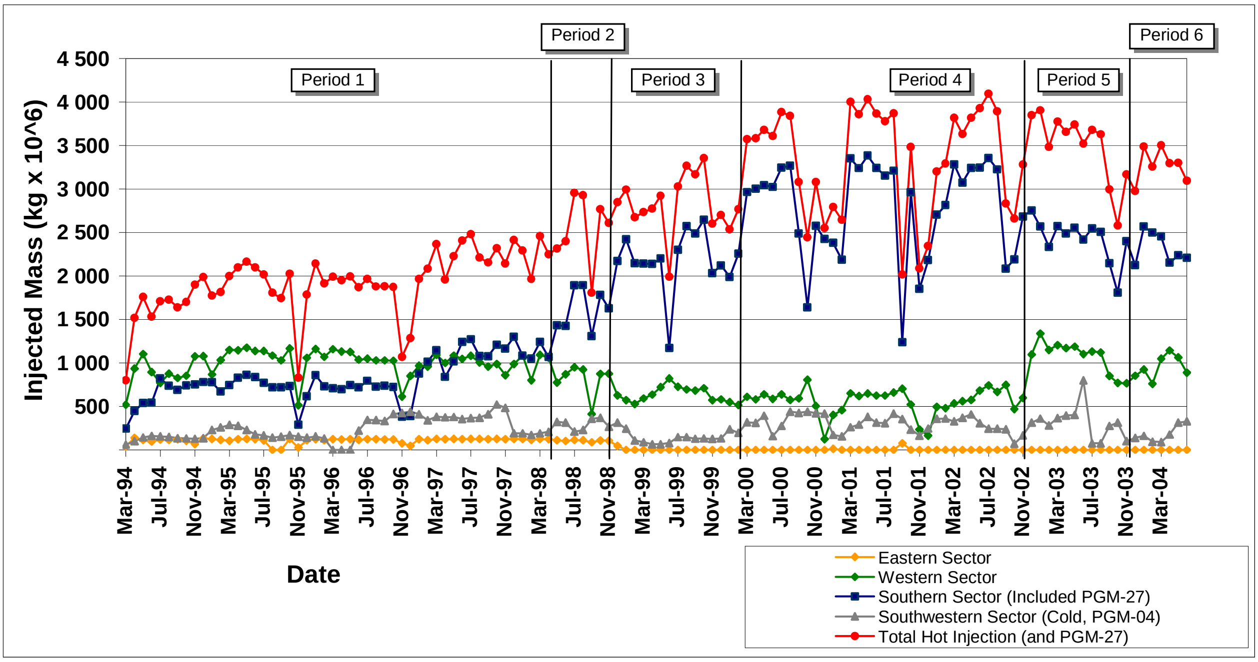


**Figure 17: Total injection.**

In October 2002, a new cold-injection line was constructed in order to have a spare and additional cold injection well (PGM-27), and also to improve the capacity of this system. As can be seen in Figure 16, the injection rate in PGM-27 is very low because this well has recently been added to the cold injection system and is only used as a back-up cold injection well.

### 3.5 Field-Wide Injection

Figure 17 shows the trend of total injection at the Miravalles geothermal field. Total injection increased from 1,500,000 tons/month (beginning of Period 1) to 3,500,000 tons/month (beginning of Period 4), and was kept constant (3,750,000 tons/month) until the beginning of Period 5, when it started to decrease, reaching 3,250,000 tons/month by November 2003. This decrease is mainly the result of a loss in production from the wells supplying Satellite 1 (PGM-01, PGM-10, PGM-63).

## 4. SYSTEM FLEXIBILITY

There is some flexibility built into the gathering system, allowing fluid from some of the wells to be sent to different separation stations, depending on operating conditions. As mentioned above, PGM-05 can send its two-phase fluid to either Satellite 4 or Satellite 1. PGM-11 can send its fluid to Satellite 7 or Satellite 1, and, finally, PGM-46 can send its fluid to Satellite 6 or Satellite 2.

There is also a line dedicated to supplying steam to Unit 3, in case there is a shortfall of steam from the wells feeding Satellite 7. This line has been used as a spare line to supply the steam needed by Unit 3, which operates under a Build, Operate and Transfer (BOT) contract.

The steam collectors at Units 1 and 2 are interconnected, which means that the steam available can be shared between the two plants. When one of the plants is under maintenance the steam flow can thus be diverted to the other plant in order to increase generation.

## 5. SYSTEM IMPROVEMENTS

The non-condensable gas extraction capacity of Unit 2 is higher than that of Unit 1. Because of the high percentage of non-condensable gases coming from Satellite 1 (which initially sent steam to Unit 1), it was decided to exchange Satellites 1 and 4, in order to obtain a better distribution of the non-condensable gases at those generating units. The exchange was implemented and a better utilization of the steam was effectively achieved. At present, Satellite 1 sends its steam to Unit 2 and Satellite 4 to Unit 1, which has allowed us to exploit the total non-condensable gas extraction capacity and at the same time improve generation in the units.

As mentioned above, there are three main reinjection lines, called Collectors 1, 2 and 3. Some of these collectors are going to be interconnected to improve the performance of Unit 5. In the future, it will be possible to exchange separated fluid between Collectors 1 and 2 a couple of kilometers upstream of Unit 5. This will allow us to use either of these collectors as a spare in this section of the injection lines. Also, downstream of Unit 5, Collector 1 will be connected to Collector 3, so that Collector 3 could be used to transport the liquid from this point on.

The specific steam consumption of the wellhead units is greater than that of the condensing units. At present the operating wellhead unit is located in the center of the field but it will be relocated (probably during year 2006) to the southern part of the field (PGM-29), where one of the wellhead units of the Comisión Federal de Electricidad was previously installed. By relocating the wellhead unit, the steam from the center of the field will be utilized to feed the condensing units (1 and 2), thus making more efficient use of the steam from the center of the field. The new location will also allow us to extract geothermal fluids from the southern sector of the field. Well PGM-29 will be the production well, and well PGM-28 (or PGM-35) will become the injection well.

The numerical model of the Miravalles geothermal field prepared by ICE and GeothermEx (Mainieri et al, 2002) was utilized to simulate these new operating conditions, obtaining good results. It is foreseen that the wellhead unit will operate in this new location and that the redistribution of the injected fluids will help to support pressure in this sector of the field.

## 6. FINAL REMARKS

The installed geothermal generation capacity at the Miravalles geothermal field has increased from 55 MW to 163 MW in ten years (1994 - 2004).

The reservoir has been able to supply the steam needed for all the generating units installed in the field during the first ten years of production. Fluid extraction has increased as new units have come online.

Injection of the separated fluids has been taking place mainly in the western and southern sectors of the field. This distribution of the injected fluids has provided pressure support to the reservoir.

The current flexibility of the gathering system has allowed us to divert some of the fluid from the production wells to different generating units, making it possible to meet the steam-supply requirements.

Improvements have and will be made in the gathering system to maximize generation and increase flexibility of the system.

## ACKNOWLEDGEMENTS

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