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Miravalles Unit 5: Planning and Design

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Keywords

Miravalles Unit 5, Miravalles geothermal field, Costa Rica, geothermal power plant, binary power plant, binary plant design

ABSTRACT

The Miravalles geothermal power station in Costa Rica is described before and after the addition of Unit 5, a bottoming binary power plant. The early planning and design alternatives for Unit 5 are discussed. The bids and the selection criteria are presented. Details of the final design are presented. The unique asymmetrical piping layout is described. During its acceptance tests, Unit 5 demonstrated a net thermal efficiency in excess of 16%.

Overview of Miravalles Field and Plant

The Miravalles field in Costa Rica covers an area greater than 21 km² in the northwestern province of Guanacaste. The 240°C liquid-dominated resource lies on the southwestern slope of the Miravalles volcano, about 250 km from the capital city of San José. Currently, about 16 km² are dedicated to production and 5 km² to injection. Fifty-three geothermal wells, ranging in depth from 900 to 3,000 meters, have been drilled to date (see Figure 1). An average well produces enough steam to generate about 7 MWe; each injection well can absorb between 70 and 450 kg/s of residual (separated) geothermal fluid.

Commercial production of electricity began at Miravalles in early 1994 when the Instituto Costarricense de Electricidad (ICE) commissioned Unit 1, a 55 MW single-flash plant. Table 1 chronicles the history of development at Miravalles. The locations of the present five operating power units are shown in Figure 1. The Miravalles geothermal complex is an important part of the Costa Rican electrical system, both in terms of installed capacity and electricity generation. The installed capacity at Miravalles in 2004 was 8.6% of the country's total,

but it generated more than 15% of the country's electricity. Between 1994 and 2004, the installed capacity at the field grew from 55 to 163 MW (196% increase), while the generation grew from 341 to 1,204.4 GWh (253% increase). The average capacity factor for the entire Miravalles power station was 86.5% in 2004, the highest among all Costa Rican power plants, indicating high availability and reliability.

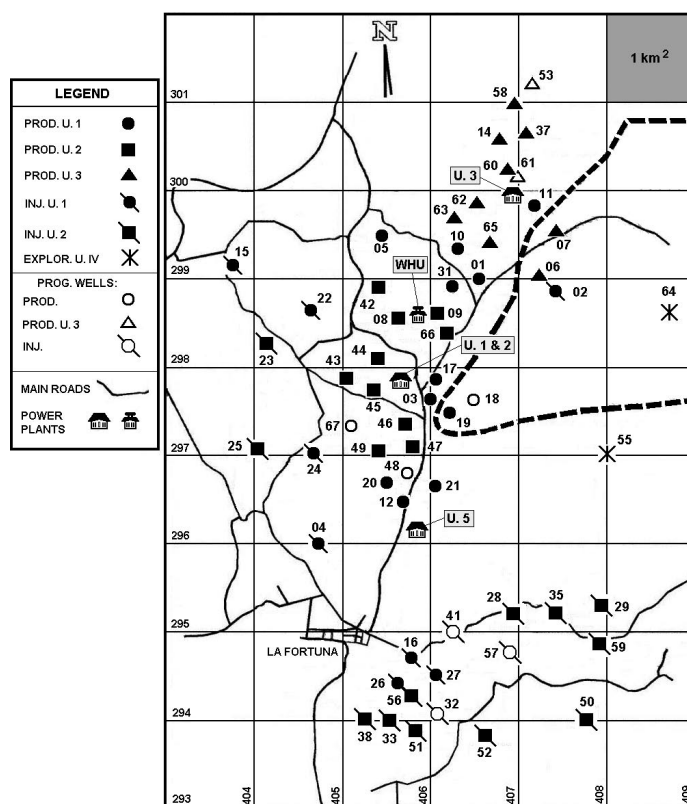


Figure 1. Map of the Miravalles geothermal field and environs. The heavy broken line approximates the current limit of the acid aquifer. Note: All wells have the prefix "PGM-" which was omitted for the sake of clarity.

Table 1. Power units at the Miravalles geothermal field.

Plant Name	Plant type	Gross Power MW	Owner ⁽¹⁾	Start-up Date	Shut-down date
Unit 1	1-flash	55	ICE	3/1994	
WHU-1	BP steam	5	ICE	1/1995	
WHU-2	BP steam	5	CFE	9/1996	4/1999
WHU-3	BP steam	5	CFE	2/1997	4/1998
Unit 2	1-flash	55	ICE	8/1998	
Unit 3	1-flash	29	ICE (BOT)	3/2000	
Unit 5	binary	19	ICE	1/2004	

(¹) ICE - Instituto Costarricense de Electricidad; CFE - Comisión Federal de Electricidad (México); WHU - Wellhead Unit; BP - Back-pressure; and BOT - build-operate-transfer.

Planning for Unit 5

The objective of the Unit 5 project was to increase the power output of the Miravalles power station without needing to drill additional production or injection wells. This would be accomplished by using the energy remaining in the residual geothermal fluid (brine) from the satellite separator stations. As early as 1997, even before Unit 2 came on-line, ICE began thinking about installing a bottoming unit to supplement the power from the first two single-flash units. Similar units were operating at Cerro Prieto I in México (Canchola, 2005), and at Ahuachapán in El Salvador (DiPippo, 1978). The decision

to employ single-flash units for Units 1 and 2 meant that the residual brine from the separator stations would be at a moderately high temperature, approximately 165°C. If Units 1 and 2 had been double-flash plants, the waste brine would have been at about 110-115°C, and would not have been an attractive target for further energy extraction.

Injection Characteristics

Since the residual brine is the only motive fluid for the bottoming unit, the characteristics of the brine, as well as the location of the brine pipelines to the injection wells, are important to understand. Figure 2 shows, in schematic form, the arrangement of the power units, the satellites and the brine collector pipelines. Currently, about 1,250 kg/s of brine is sent to the injection wells distributed mainly in the western and southern sectors of the field. Also, the southwestern and south areas (PGM-04 and PGM-27) are used for cold injection.

The history of injection at Miravalles may be divided into six periods (see Table 2). From the beginning of Period 1 until the beginning of Period 4, the total rate of injection increased from 579-1350 kg/s. It remained constant at 1447 kg/s until the beginning of Period 5 when it started to decrease, reaching 1254 kg/s by November 2003. This decrease was mainly caused by a loss in production from three wells supplying Satellite 1: PGM-01, -10 and -63, and would have an impact on the output of Unit 5.

Table 2. Injection periods at the Miravalles geothermal field.

Period	Initial/Final Dates	Event
1	March 1994 April 1998	Commissioning of Unit 1; Collector 2; Wells: PGM-02, PGM-22, PGM-24.
2	May 1998 November 1998	Commissioning of Unit 2; Liquid from Satellite 3 changed from Collector 2 to 3; Collectors 1, 2 and 3; Wells: PGM-22 and PGM-24.
3	December 1998 February 2000	PGM-05 & PGM-46 changed from Unit 1 to 2; PGM-05 changed from Satellite 1 to 4; PGM-46 changed from Satellite 2 to 6.
4	March 2000 November 2002	Commissioning of Unit 3; Satellite 7 connected to Collector 1.
5	December 2002 November 2003	Increase in contribution from Satellites 4 and 5 to west injection area to wells PGM-22 and PGM-24.
6	December 2003 February 2006	Commissioning of Unit 5; Last data analyzed

Design Options

Several design options were possible for the Miravalles Unit 5. The first was a double-flash plant similar to Unit 5 at Cerro Prieto I. Since the geofluid from the reservoir had already undergone a primary flash at the main separators, this would render Miravalles Unit 5 effectively a triple-flash plant. There were two problems with this option. First, the optimum flash conditions for a brine at 165°C meant that the lowest-pressure flash vessel would have to operate under a vacuum, at about 0.65 bar, a. By raising the pressure this problem could be

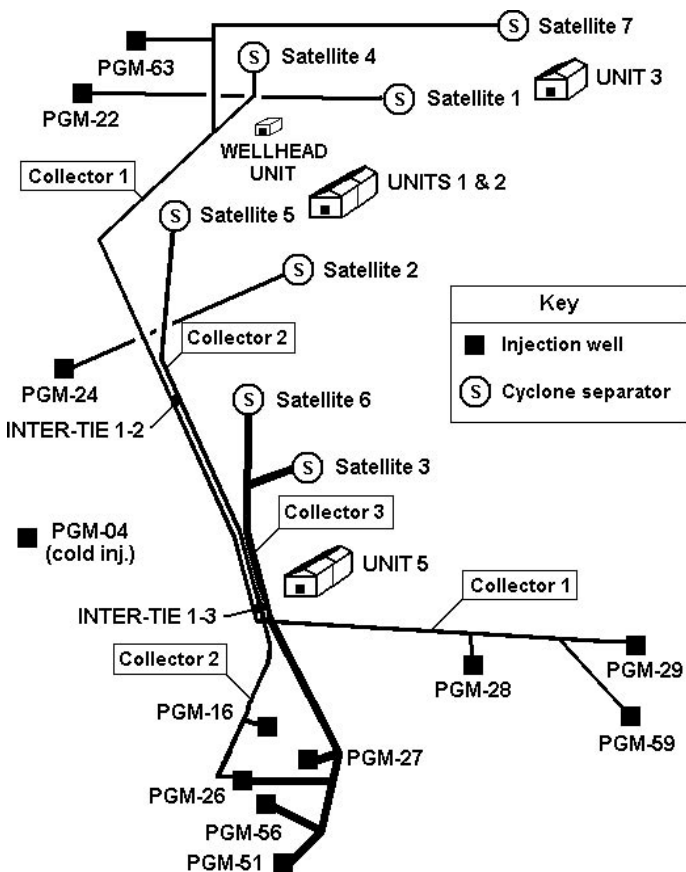


Figure 2. Gathering and disposal system for Unit 5. Note interconnections between brine collectors. Not to scale.

avoided but less power would be generated. Second, supersaturation of silica would occur in the last flash vessel (and in the injection piping and wells), even if subatmospheric conditions were avoided in the flasher. Preliminary calculations indicated that about 39.9 MW might be obtained from the 1,042 kg/s anticipated brine flow if it were flashed at 125°C and 105°C, but the silica supersaturation index in the brine leaving the last flasher would be about 1.55, an unacceptable value.

The next option was to make Unit 5 a single-flash plant. The optimum flash temperature and pressure were roughly 105°C and 1.2 bar a, respectively. The estimated power came to 32.3 MW, while the silica supersaturation index remained at 1.55. Whereas the flasher would operate above atmospheric pressure, the silica supersaturation was still unacceptable. To maintain the silica in equilibrium at the flash vessel (supersaturation index = 1), it would have required raising the flash temperature to 140°C. Under this scenario, the estimated power from the single-flash plant would drop drastically to 21.1 MW.

The last option was a binary-type plant. There were two possible choices in this case: a Kalina-type cycle using a mixture of water and ammonia as the cycle working fluid, or a conventional organic Rankine cycle (ORC). The fact that there were no Kalina cycles operating at any geothermal sites at that time weighed against it in the decision-making process. The brine exit temperature from a bottoming binary unit is a critical parameter for the power output and the silica scaling potential, as well as potential excessive cooling of the reservoir when the relatively “cold” fluid is reinjected. The lower the brine exit temperature, the greater the heat input to the cycle and the greater the power output, others factors being the same. Of course, the lower the exit brine temperature, the greater the potential for reservoir cooling and silica scaling. Preliminary calculations of the power output from a binary plant, based on a conservative thermal efficiency of 10.5%, indicated an estimated power of about 12 MW, based on a brine exit temperature of 138°C. At this temperature the brine would be undersaturated with respect to amorphous silica and no scaling would be expected. The brine could be cooled down to about 133°C before reaching saturation, leaving a 5°C margin of safety.

Proposed Systems

ICE initiated a bidding process to select the best alternative for utilizing the residual water. Based on the preliminary scoping studies, quotes were solicited for both single-flash and binary plants. **Table 3** shows the type and net power output of the units proposed by each of the three qualified bidders (ICE, 2001).

Table 3. Bidding companies and type of plant.

Company	Type of plant	Net output, MWe
A	Binary	15.5
B	Single-flash	17.0
C	Single-flash	16.5

In the bidding process, each company was evaluated in several areas, including technical experience, legal aspects,

and final cost to generate a kWh of electricity. The option providing the lowest cost per kWh on a net-present-value basis would be the one selected. The economic analysis considered the investment that ICE would have to make in order to buy and commission the necessary equipment, as well as the associated maintenance for a 20-year period. The annual discount rate was 12% at the date of formal adjudication. The comparative value of the alternatives was determined by the following equations:

$$CV = \frac{NPV(cost, dr; fad)}{NPV(generation, dr; fad)} \quad (1)$$

$$CV = \frac{NPV(debt) + NPV(O \& M) + NPV(EM \& civil works)}{NPV(generation)} \quad (2)$$

where

- CV = comparative value
- NPV = net present value
- dr = discount rate = 12%
- fad = formal adjudication date
- O&M = operation & maintenance
- EM = electromechanical equipment.

The result was that the lowest cost per kWh at net-present-value would be obtained utilizing a binary plant. Although the flash option would be more efficient from an energy conversion point of view, it would incur a higher cost per kWh (UEN PySA, 2001). Table 4 shows some of the parameters that were taken into account to make the final decision.

Table 4. Parameters used in making the final decision on Unit 5.

Item	Company >>>	A	B	C
Type of unit	Binary	Single- flash	Single- flash	
Nominal output, MW	15.5	17.0	16.5	
Legal aspects	OK	OK	OK	
Financial condition of firm	OK	OK	OK	
Experience (design, construction, supply)	OK	OK	OK	
Technical evaluation, % ⁽¹⁾	91.50	87.70	88.33	
Initial maintenance cost (covered by bidder until first major plant maintenance), \$	60,000	193,180	80,500	
Maintenance interval, years	4	2	3	
Maintenance period duration, days	5	30	10	
Debt amount (cost of engineering and procurement), million \$	X	X + 7.7	X + 18.8	
Total cost for civil works and equipment erection by ICE, million \$	2.86	4.33	3.83	
Cost of electricity, \$/kWh	0.01637	0.01968	0.02804	

⁽¹⁾ Note: To qualify as a bidder each company must have a technical evaluation score of at least 86%.

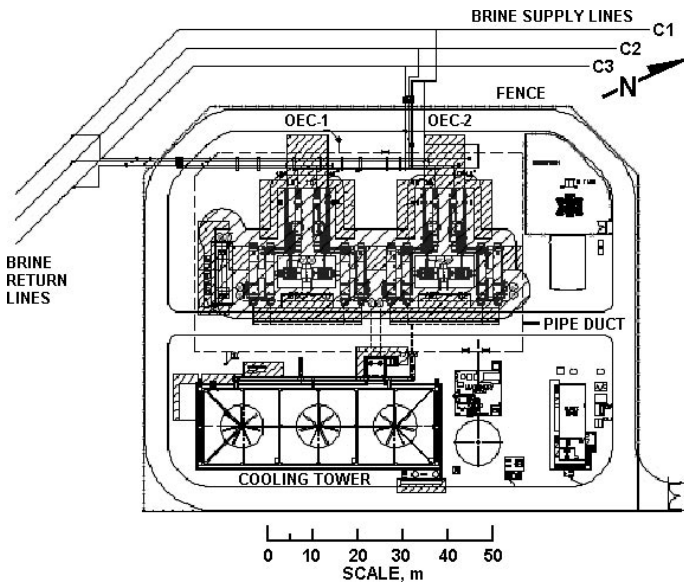


Figure 3. Site layout of Unit 5.

Selected System

The winning bidder, Ormat, Inc., provided the design specifications and layout of the selected binary plant (see Figure 3), as well as the characteristics of the residual and working fluids (see Table 5). The plant was built by ICE personnel using the equipment supplied by Ormat. Construction of the binary plant started in November 2002 and was finished by January 2004; the acceptance tests were conducted in early February 2004.

Table 5. Characteristics of the residual brine, working fluid and binary plant.

System	Item	Value
Residual brine	Mass flow rate, kg/s	885
	Pressure range, bar, a	8.04 – 7.25 (in); 5 (out)
	Temperature range, °C	167.6 – 163.1 (in); 136 (out)
Working fluid: pentane C_5H_{12}	Normal boiling point, °C	36.1
	Flash point, °C	-49
	Mass flow rate, kg/s	242.4
	Pressure range, bar, a	16.4-1.25
	Temperature range, °C	147.4-38
	Losses, kg/day	29
Binary plant	Total power, MWe	18.07
	Net power, MWe	15.5
	Internal service, MWe	2.57
	Construction period, months	17

Unit 5 Description

The Unit 5 consists of two very nearly identical binary modules, OEC-1 and OEC-2. Each module is comprised of two trains of equipment served by a single electrical generator.

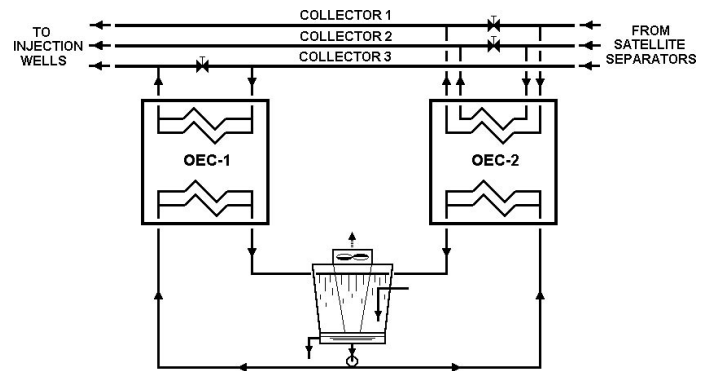


Figure 4. General schematic layout of Unit 5.

Flow Diagram and Brine Supply

With reference to Figure 2, the flow to Unit 5 comes from brine Collectors 1 & 2 (OEC-2) and Collector 3 (OEC-1); see simplified flow diagram Figure 4. The design calls for Collector 1 to supply 229 kg/s of brine, Collector 2 to supply 238 kg/s, and Collector 3 to supply 418 kg/s.

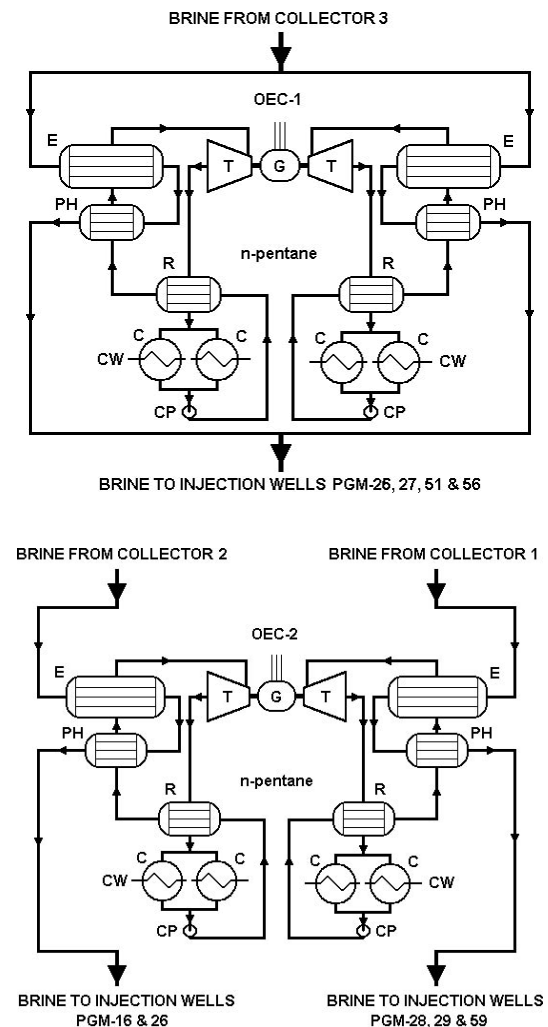


Figure 5. Schematic flow diagrams for Unit 5. Key: E=evaporator, PH=preheater, R=recuperator, C=condenser, CP=condensate feed pump, CW=cooling water, T=turbine, G=generator.

Owing to the asymmetrical arrangement, i.e., three brine supply pipelines and two binary power modules, the piping layouts for the two units are different. These are shown in Figure 5: OEC-2 on the top and OEC-1 on the bottom.

To allow for flexibility during operation, there are bypasses installed in the collector lines, as shown in the typical arrangement in Figure 6. The bypass valve at station 5 allows excess brine to pass directly to the injection wells during normal operation and allows the full flow to bypass a module during maintenance periods. The bypass at station 4 (not part of the original design) is activated periodically to purge the line of sand that would affect the readings on the flow meter (an Annubar[®] instrument).

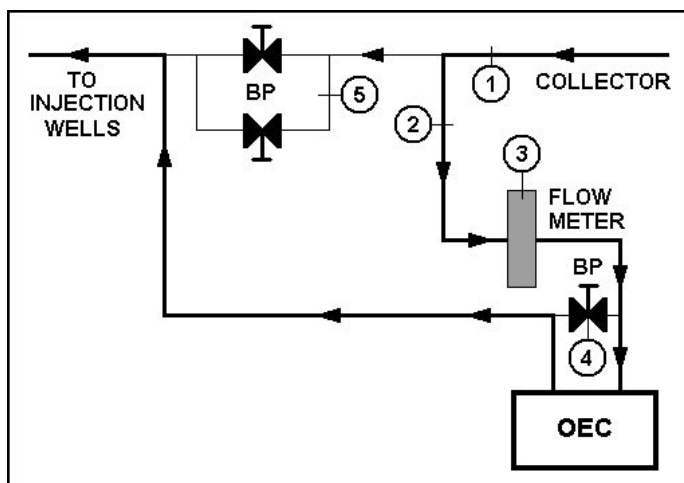


Figure 6. General schematic of bypass piping between collectors and OEC modules.

Component Descriptions

The power house consists of two OEC modules each with a rated net capacity of 7.75 MWe. The thermodynamic cycle used by the modules is the Rankine cycle. Each module is mounted on its own skid and is composed of two turbines

and a generator (primary equipment), and the following pieces of auxiliary equipment: two preheaters, two vaporizers, two separators, two recuperators, four condensers, and two cycle feed pumps. The layout of the equipment for one module is shown in the perspective drawing in Figure 7.

The main components of the power plant are described below.

- **Preheaters:** These are horizontal shell-and-tube heat exchangers, two per module, each one having a total of 743 19.45-mm diameter tubes, 11.48-m long, fabricated from 316L stainless steel, with a welded tube-to-tube-sheet connection, within a 13.87-m long, 0.78-m diameter shell made of carbon steel. The brine flows through the tubes and the pentane flows within the shell. The tube bundle is fixed.

- **Vaporizers:** These heat exchangers are similar to the preheaters, but larger. There are two per module, each having a total of 1,744 19.45-mm diameter, 10.86-m long tubes fabricated from 316L stainless steel, within a 14.2-m long, 1.42-m diameter shell. The tube bundle is fixed.

- **Separators:** Each vaporizer is fitted with an upper horizontal cylinder that serves to separate liquid droplets from the 2-phase mixture of pentane as it rises out of the vaporizer. The vessel utilizes mesh inserts and produces essentially saturated vapor, i.e., a dryness fraction of nearly 1.0.

- **Turbines:** There are two single-flow, 3-stage, 1800 rpm, axial-flow turbines per module, each fed by one preheater-vaporizer set. The exhaust leaves the turbines in a horizontally-opposed direction and is ducted up to the recuperators. Each turbine has a rated power capacity of 4.7 MW and a maximum capability of 6.5 MW. The two turbines for OEC-1 and the turbine on the right-side of OEC-2 (fed from Collector 1) are all identical. The left-side turbine for OEC-2 (fed from Collector 2) is of the same type but was designed for the particular flow associated with that train. All turbines were designed to produce equal cycle thermal efficiency.

- **Generator:** A common generator serves the two turbines in a tandem-compound arrangement. The generator is totally-enclosed-water-to-air cooled (TEWAC) and has a rating of 10.5 MVA, a maximum capability of 11.67 MVA, and a power factor of 0.9.

- **Power House:** Each module has a power house that encloses the turbines and generator and their immediate auxiliaries; all other components are outside. Each power house measures 13-m long x 7.3-m wide x 7.3-m high and is made of corrugated metal.

- **Recuperators:** There are two horizontal, shell-and-tube recuperators per module. The hot turbine exhaust passes over tubes in which flows the pentane discharged from the feed pumps. In each recuperator, there are a total of 544 tubes, 25.7-mm in diameter, 9.80 m long; the vessel is 1.625 m in diameter and is 11.72-m long.

- **Condensers:** These are also shell-and-tube heat exchangers, four per module. Cooling water flows through the tubes and condenses the pentane that passes through the shell. Each condenser has a total of 2,750 tubes, 19.3-mm in diameter and

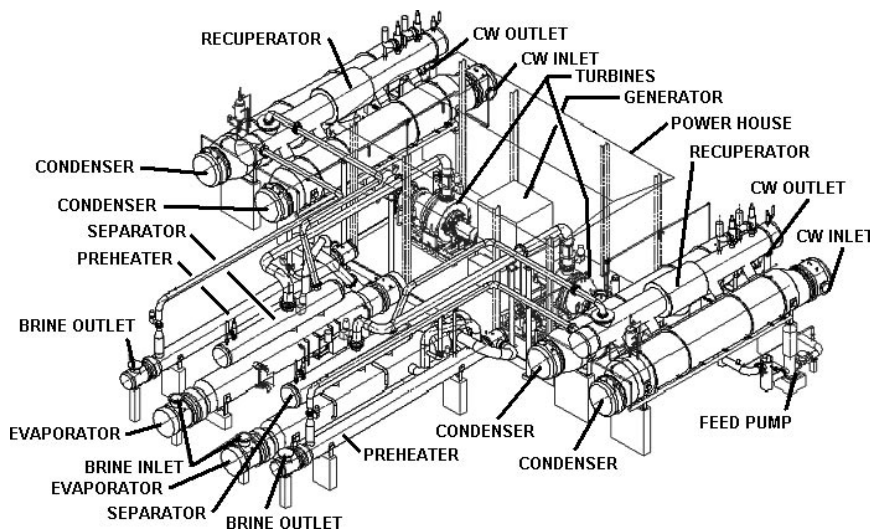


Figure 7. Unit 5 energy conversion module: one of two identical OECs.

10.97-m long; the overall diameter of the vessel is 1.97 m and it is 13.5-m long.

- **Feed Pumps:** There are two centrifugal, motor-driven pumps per module, with each pair of condensers draining to a single pump. The comment made about the turbines for the various sides of the modules applies to the feed pumps as well.

- **Cooling Tower:** One three-cell, concrete, counter-flow cooling tower serves the two binary modules. The tower measures 52-m long x 17.5-m wide x 10.5-m high. Each cell has a motor-driven fan inside a fiberglass fan cylinder. There are two circulating water pumps.

A water cooling tower (WCT) was chosen over an air-cooled condenser (ACC) primarily out of concern for the noise produced by the fans of the ACC, given the close proximity of the plant to the town of La Fortuna (see Figure 1). Additional factors favoring the WCT included: the ACC would cost more than three times as much, would weigh more than two and a half times as much, would cover about three times as much surface area, and would consume about three times more fan power than a WCT. The excess water from the cooling tower that serves the main central plant Units 1 and 2 is used as make-up water for the Unit 5 cooling tower. This novel approach eliminates the need for a separate supply of fresh water. The excess water from the Unit 5 cooling tower is sent to the holding pond next to Satellite 3 and is eventually injected into wells PGM-04 and/or PGM-27.

The completed power plant is shown in Figure 8.

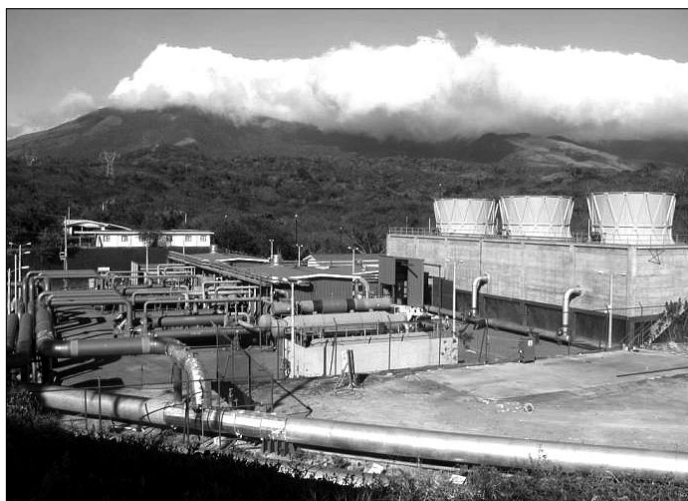


Figure 8. Miravalles Unit 5 with Miravalles volcano in the background. One of the brine return collectors is seen in the foreground.

Conclusions and Discussion

The bottoming binary plant, Unit 5, was constructed and installed in 14 months from November 2002 to December 2003; it began producing electricity in January 2004. This was faster than the 17 months anticipated in the successful bid, and eight months faster than the alternative flash plant bids. The plant has added 15.5 MW of net electricity to the existing 136 MW-net, without requiring any additional wells.

The plant is environmentally benign, having no emissions to the atmosphere except for water vapor from the cooling towers and a tiny loss of pentane, roughly equal to 0.0001% of the circulating flow rate in the plant. The plant is also visually unobtrusive, being located in a hollow beneath the level of the main road that passes close to it.

The performance of the plant during its acceptance test in February 2004 was excellent, with the plant achieving a net thermal efficiency in excess of 16%. A paper is in progress that will present a detailed analysis of the performance of the plant (DiPippo and Moya, 2006).

Although the addition of a bottoming cycle to an existing plant is simple in concept, there have been some effects created by its existence that have caused some inconvenience in the operation of the whole Miravalles power station and the reservoir. Since the plant is close to the main injection area at the south end of the field, the cooled brine passes directly from the plant to the injection wells that are less than 2 km distant. While this aspect is efficient from an injection point of view, it imposes a constraint of sorts on the management of the reservoir. Whenever it is desired to inject more fluid to the western side of the field to support the reservoir pressure in the central production area, the amount of brine that reaches Unit 5 is reduced, as is its power output. Alternative means of handling the residual brine are being studied to minimize the impact on Unit 5 while still achieving a flexible and effective injection strategy.

Other impacts on the performance of the Miravalles system, including the effect of pressure changes on the fluid gathering system and the effect of lower brine injection temperatures, are more fully discussed in our companion paper (DiPippo and Moya, 2006).

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