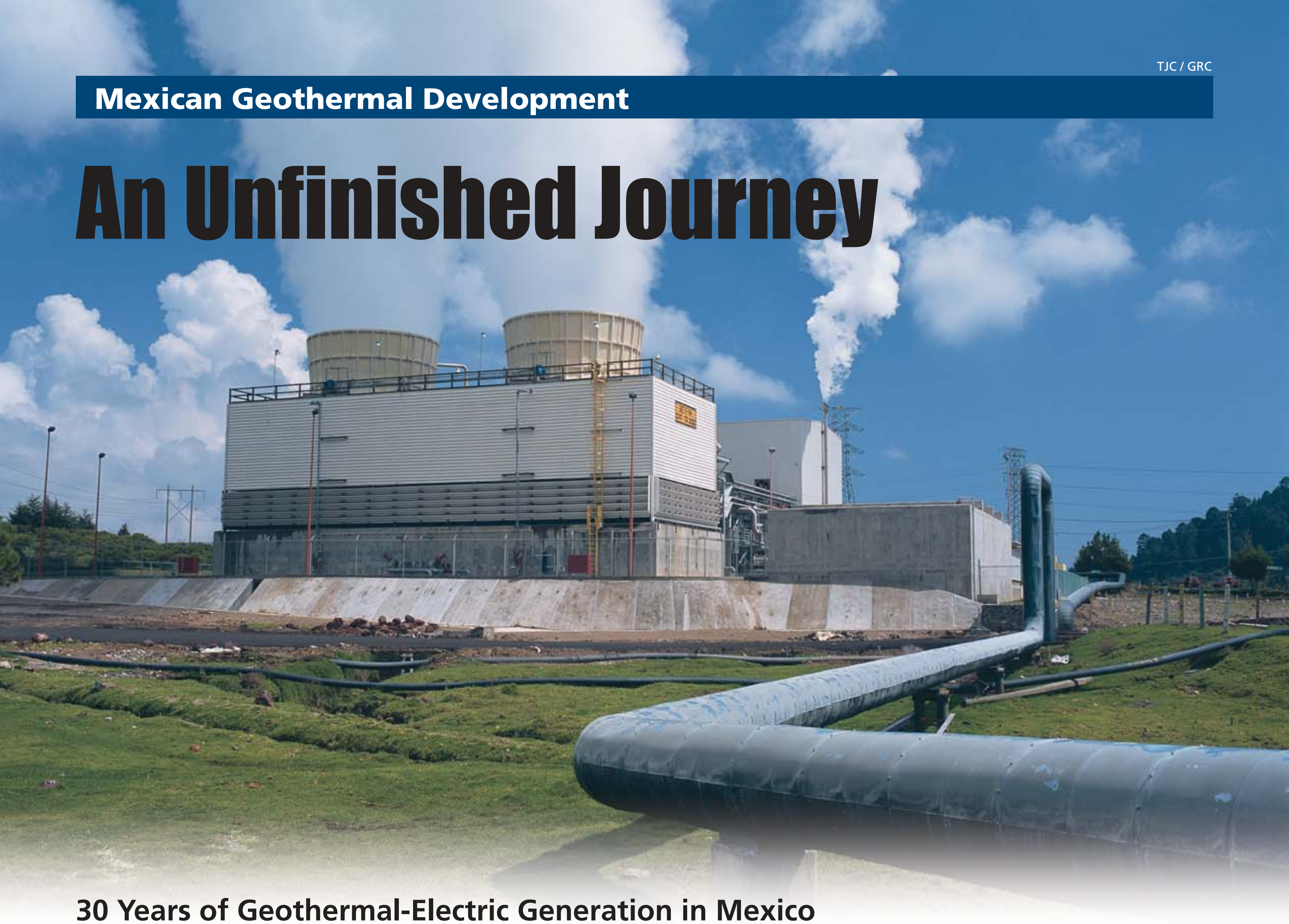
An Unfinished Journey



Comisión Federal de Electricidad's (CFE) Los Azufres II Project recently added 100 megawatts (MW) of new power to Mexico's geothermal capacity, bringing the nation's total to 953 MW. The Los Azufres Geothermal Field is the site of a Geothermal Resources Council (GRC) Geothermal Project Development Workshop and Field Trip in conjunction with the GRC 2003 Annual Meeting in Morelia, Mexico.

30 Years of Geothermal-Electric Generation in Mexico

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In 2003, Mexico proudly celebrates its 30th Anniversary of uninterrupted geothermal-electric generation. Continuous use of geothermal resources to generate electricity in Mexico began in April 1973, when the first power unit at the Cerro Prieto Geothermal Field in northern Baja started operation. The history of geothermal exploration and development hails back to 1937, however, when Luis F. de Anda, a young and enthusiastic engineer, joined the newborn Comisión Federal de Electricidad (CFE).

During the following decade, De Anda continued to promote the use of geothermal energy to Mexican authorities. He published a preliminary study of potential power production at the Ixtlán de Los Hervores Geothermal Area. At that time, José Ísita-Septién carried out geohydrological studies in another geothermal zone, San Bartolomé de los Baños, in Guanajuato (Mañón, 2003). As a portent of a successful future for geothermal energy production, these early beginnings of geothermics in Mexico were accompanied by the ominous birth of the Paricutín Volcano in 1943, not far from Morelia, Michoacán.

The year 1955 is a milestone for geothermics in Mexico, when the Comisión de Energía Geotérmica (CEG) was created by the tenacity of De Anda. CEG employees put their hands to work at once by drilling the first geothermal well in Mexico. Located at the Pathé Geothermal Field, in the State of Hidalgo 300 km north of Mexico City, the Pathé-1 well produced steam in January 1956 (Mañón, 2003).

The first legal provision concerning geothermal energy was issued by the Mexican government in 1956, giving preferential rights to CFE for extraction of hot groundwater and steam for electricity generation. Two years later, the first well drilled in the Ixtlán de Los Hervores Geothermal Field produced steam. The year 1958 was rich in geothermal activities in Mexico, especially with CFE's acquisition of a 3.5-megawatt (MW) geothermal pilot plant from the Larderello Geothermal Field in Italy.

The turbine traveled to Mexico on a ship called Britti. To bring the turbine online, it was necessary to install a 50 to 60 Hz frequency changer from a mine in the Pathé region (Mañón, 2003). The plant started operation on Nov. 20, 1959, making it the first commercial geothermal power plant in the Western Hemisphere. Due to insufficient steam, the power plant never operated at full capacity, but remained online until 1973.

The first aerial and geological reconnaissance in the Cerro Prieto Geothermal Field also occurred in 1958. Nevertheless, geothermal resources in this zone were known since the Colonial Period. The oldest historic reference to geothermal energy dates from 1540, when Spanish explorer Melchor Díaz described his troops' impression of the magnificent fumaroles, hot springs and mud volcanoes they saw in Cerro Prieto's Laguna Volcano: "The land they found trembled like a drum... It was an admirable thing the ash thus boiling in some parts, resembling a truly infernal thing...." (CFE, 1998).

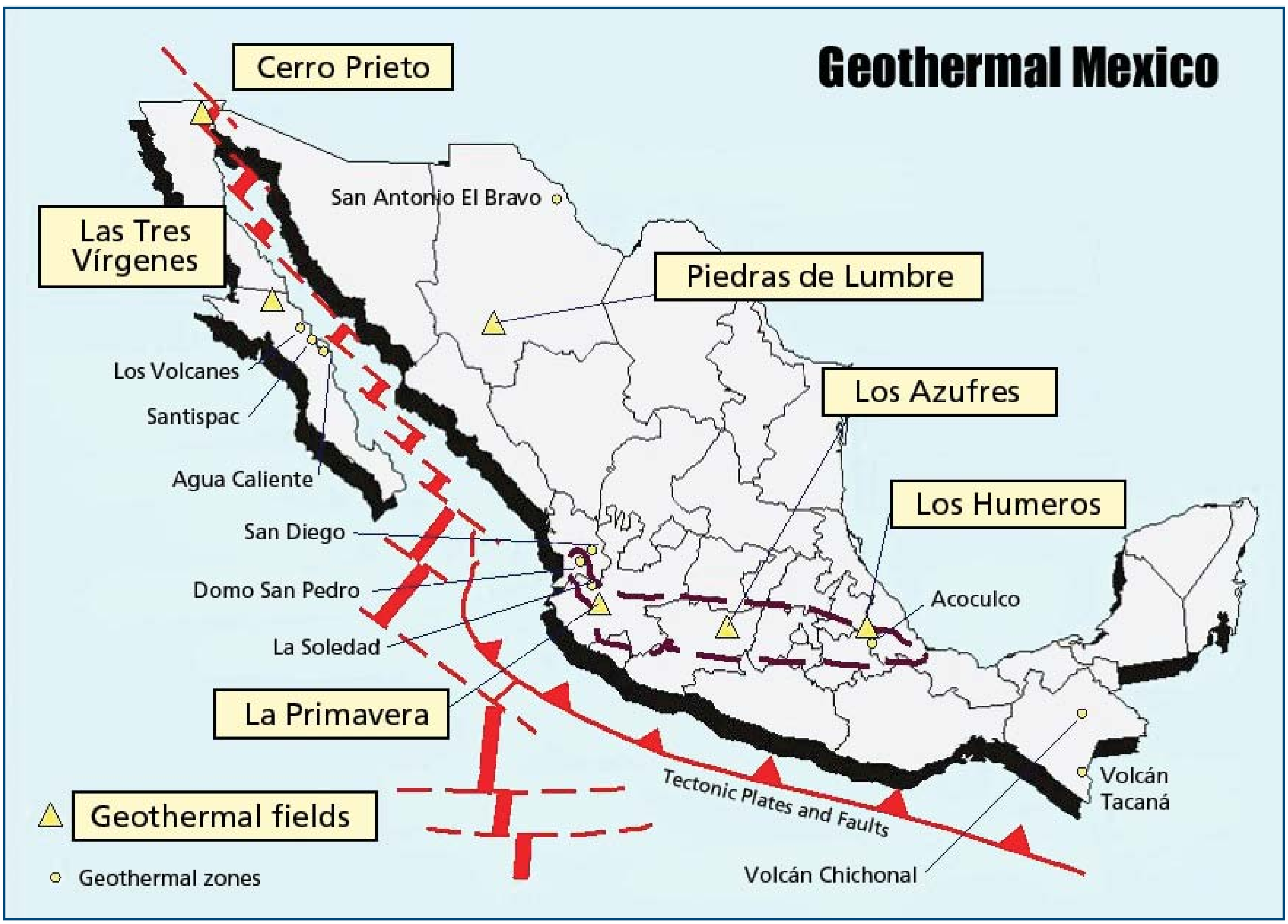
The year 1960 was another important year for the Mexican geothermal community, when the first well at Cerro Prieto was drilled. In 1964, four deep exploration wells were also drilled at the field. Another 14 production wells were drilled during 1967-68, and construction of the first two power generation units totaling 75 MW began in September 1969. At that time, CFE was directly involved with CEG in the field's development, but in 1971 CEG was dissolved and CFE Geothermal took charge of geothermal development in Mexico (Mañón, 2003). In April 1973, the first 37.5-MW unit at Cerro Prieto I was formally commissioned.

During the last 30 years, CFE has scored a number of achievements in developing Mexico's geothermal potential, including bringing online the Los Azufres (1982), Los Humeros (1990) and Las Tres Vírgenes (2001) geothermal fields. Mexico's geothermal-electric capacity grew from 37.5 MW to 853 MW during the period—a figure that jumped to 953 MW when the 100-MW Los Azufres II was commissioned in the summer of 2003. The evolution of Mexican geothermal power development and production is presented in this article.

Cerro Prieto Geothermal Field

Cerro Prieto ("black-mount" in English) is the name of a Quaternary, isolated and monogenetic volcano northwest of the Cerro Prieto Geothermal Field. The volcano rises 260 m above sea level. Since it is the most prominent topographic feature in the area, the mountain has given its name to the whole field, even though it has no relationship with its geothermal system.

The Cerro Prieto Geothermal Field is located in the State of Baja California, in northwestern Mexico close to its border with the United States (Fig. 1). The field lies at only 6 to 7 m above sea level in the alluvial plain of the Mexicali Valley, an arid region



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with extreme ambient temperatures ranging from –2°C in winter to 47°C during the summer.

The geothermal field covers an area of approximately 15 km^2. From a tectonic viewpoint, it lies in a “pull-apart” basin of the San Andreas Fault system, limited by two important right strike-slip faults, the Imperial and the Cerro Prieto. These NW-SE oriented faults are interlaid by several NE-SW faults that act as collectors of geothermal fluids. The heat source is a regional thermal anomaly resulting from the thinning of the continental crust at the bottom of the basin. The heat—along with hydrothermal fluids—is transferred through Late Cretaceous, granitic basement rocks to deep aquifers within Tertiary sandstones and shales.

The granitic basement outcrops toward the west of the field, forming the Cucapá and El Mayor ranges that are part of the California Batholith. Toward the central part of the Cerro Prieto Geothermal Field, the basement deepens to 4,000 m depth or more. A sequence of gray shales and sandstones, with an average thickness of 2,400 m, overly the basement and host the field’s geothermal fluids. The sandstones are hydrothermally altered by interaction with these fluids. Several secondary minerals have replaced the original cement of the rocks, giving place to chlorites, calcite, silica, epidote, amphiboles and prehnite, among others.

As noted above, the first Cerro Prieto geothermal power unit was commissioned in 1973. Presently, there are 13 power units in operation, grouped into four powerhouses (CPI through IV) with a total installed capacity of 720 MW. The power units have distinct capacities, ranging between 25 and 110 MW. The last four 25-MW units at CP IV were commissioned in July 2000. The geothermal field has more than 120 km of steam pipe; 40 km of pipe and 60 kilometers of channels to channel brine, and 10 km of pipe to conduct non-separated fluids (mixing).

During 2002, there were 138 production and 13 injection wells in operation at Cerro Prieto. The wells produced 47.6 million metric tonnes of steam at an annual average rate of 5,430 metric tonnes per hour (t/h). This represents the highest annual production of steam in the last 10 years. In addition, 72.3 million metric tonnes of geothermal brine were produced (Residencia General de Cerro Prieto, 2003) and disposed of by injection and evaporation. Evaporation takes place in a solar pond with a surface area of 18 km^2.

Total electricity generated at Cerro Prieto in 2002 was 4,934 gigawatt-hours (GWh) (Subdirección de Generación, 2003). This output is lower than the previous year’s 5,013 GWh, despite high steam-production in 2002. This electrical generation supplied more than 50 percent of total demand for all of Baja California, which has a power transmission system that is isolated from the national electric grid.

During the last three decades, more than 870 million metric tonnes of steam and 1,300 million metric tonnes of brine have been extracted from Cerro Prieto geothermal system, totaling approximately 2.5 km^3 of fluids. This volume is greater than the total of geothermal fluids (>250°C) estimated in the reservoir by some older and more more conservative studies (1.6 km^3 - Gutiérrez-Negrín, 1983). More than 90,000 GWh of electricity had been generated at the Cerro Prieto Geothermal Field through the end of 2002.

Los Azufres Geothermal Field

Los Azufres, the first volcanic field exploited in Mexico for its geothermal energy, owes its name to small and scarce deposits of native sulphur around some of its hot springs and fumaroles. The landscape is quite different from desert of Cerro Prieto. Los Azufres lies at 2,800 m above sea level, surrounded by a pine forest.

The Los Azufres Geothermal Field is located in the State of Michoacán, in central Mexico, 90 km east of Morelia. It is part of the Mexican Volcanic Belt, a region covered by Pliocene-Quaternary volcanoes (some active) crossing the country from coast to coast (Fig. 1). Geothermal exploration at Los Azufres started in 1975 with geological, geophysical and geochemical surveys. The first exploration well was drilled in 1976, and the first geothermal power units were commissioned at Los Azufres in 1982.

Following the first geophysical surveys, the Los Azufres Geothermal Field was divided into two zones: north and south. Both zones appeare to join each other at depth to form a single reservoir, but between them the geothermal reservoir seems to deepen. In both zones, production rocks are of volcanic origin (Miocene-Pliocene andesites), belonging to the calc-alkaline series, typical of the Mexican Volcanic Belt. The andesitic series are hydrothermally altered, presenting calcite, quartz, chlorite, clay minerals, epidote and amphiboles, among other secondary minerals. There are also Quaternary rhyolites covering the andesites in the south zone.

The Los Azufres heat source appears to be related to the San Andrés volcano, located at the southern end of the reservoir. The field’s geothermal fluids are contained


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Cerro Prieto Geothermal Field.

in andesites. At depth, production zones are located where wells intersect E-W trend faults, and at a depth interval defined between the first appearance of epidote and the amphibole top. According to pressure and temperature profiles, the Los Azufres geothermal reservoir is vertically comprised of three thermodynamic zones: steam-dominant, liquid-dominant, and compressed-liquid (Pérez-Esquivias, 2000). Because of structural conditions and high enthalpy of rising fluids, vapor domes were formed in the subsurface of the south zone, where CFE wells produce dry steam (Quijano *et al.*, 1987).

CFE currently operates 10 geothermal power units at Los Azufres, including one 50-MW condensing unit (#7), seven 5-MW back-pressure units (#2, 3, 4, 5, 6, 9 and 10), and two 1.5-MW binary cycle units (#11 and 12), for a total capacity of 88 MW. Unit 1 was recently sold to Guatemala's Instituto Nacional de Electrificación, and Unit 8 was moved to the Los Humeros Geothermal Field. Four new, 25-MW condensing power plants (#13, 14, 15 and 16) were recently installed and commissioned as the Los Azufres II Project (see article on pg. 208). With these units, installed electrical capacity at the field now totals 188 MW.


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Los Humeros Geothermal Field.

On average, 15 production and 6 injection wells were in operation at Los Azufres during 2002. Total steam production was 6.21 million metric tonnes at an annual average rate of 709 t/h—the lowest production since 1995. Production of separated geothermal brine reached 3.34 million metric tonnes, which was injected back to the reservoir (Residencia de Los Azufres, 2003).

Electricity generation at Los Azufres totaled 299 GWh during 2001 (Subdirección de Distribución, 2003), the lowest in the past 10 years, and far from the record of 752 GWh set in 1996. The reason for this low production was an outage of the field's original 50-MW unit for most of the year.

Los Humeros Geothermal Field

The Los Humeros Geothermal Field is also located in central Mexico, which reaches eastward into the Mexican Volcanic Belt (Fig. 1). Its name comes from white clouds of steam released by fumaroles at the field, which were mistakenly identified as smoke by inhabitants of nearby villages. Geothermal exploration surveys began in 1968, and the first exploration well (H-1) was drilled in 1981. CFE started commercial generation of electricity at Los Humeros in May 1990.

The Los Humeros Geothermal Field is located inside the Quaternary age Los Humeros Caldera, which formed a half-million years ago with the sudden eruption of almost 100 km^2 of magma. The blast caused a collapse in surface strata 21 km in diameter. A smaller caldera was formed inside the first (Los Potreros Caldera) 100,000 years ago. The last volcanic activity in the area occurred 20,000 years ago (mainly basaltic flows and cone formation).

The heat source for Los Humeros is the magma chamber that created the caldera. Some studies indicate that the chamber appears to be partially solidified, with present temperatures between 600° and 650° C at a depth of 7 to 8 km (Verma, 2000).

Geothermal fluids at Los Humeros are contained in Tertiary andesites, covered by a series of Quaternary ignimbrites with low permeability that act as cap rock for the geothermal reservoir. Andesites are intensely altered by hydrothermal minerals like calcite, quartz, chlorite, epidote and garnet, and are underlain by a basement of Cretaceous-Jurassic limestones partially metamophosed to marble and skarns by granite intrusions.

The andesites of the geothermal production zone present a lower permeability than those at Los Azufres, but fluid temperatures are higher. Indeed, temperatures of 400° C have been measured in wells at Los Humeros, the highest in Mexico. These fluids have a sodium chloride to sodium bicarbonate composition. Fluids from the deepest portions of the reservoir in the central part of the field are high in acidity.

By December 2002, six 5-MW backpressure power units were in operation at the Los Humeros Geothermal Field, and an additional unit of the same capacity from the Los Azufres Geothermal Field was to be installed. Because they were under repair, two of the field's original six units were operated only a few months during the year. Total installed capacity at Los Humeros was 35 MW in 2002.

Though 40 wells have been drilled at Los Humeros, only an average 11 production wells were in operation during 2002 because of low steam demand by the power units. Two injection wells were used throughout the year. Total steam produced in 2002 was 2.43 million metric tonnes, at an annual average rate of 277 t/h. Geothermal brine extraction totaled 0.86 million metric tonnes (153 t/h) (Residencia de Los Humeros, 2003).

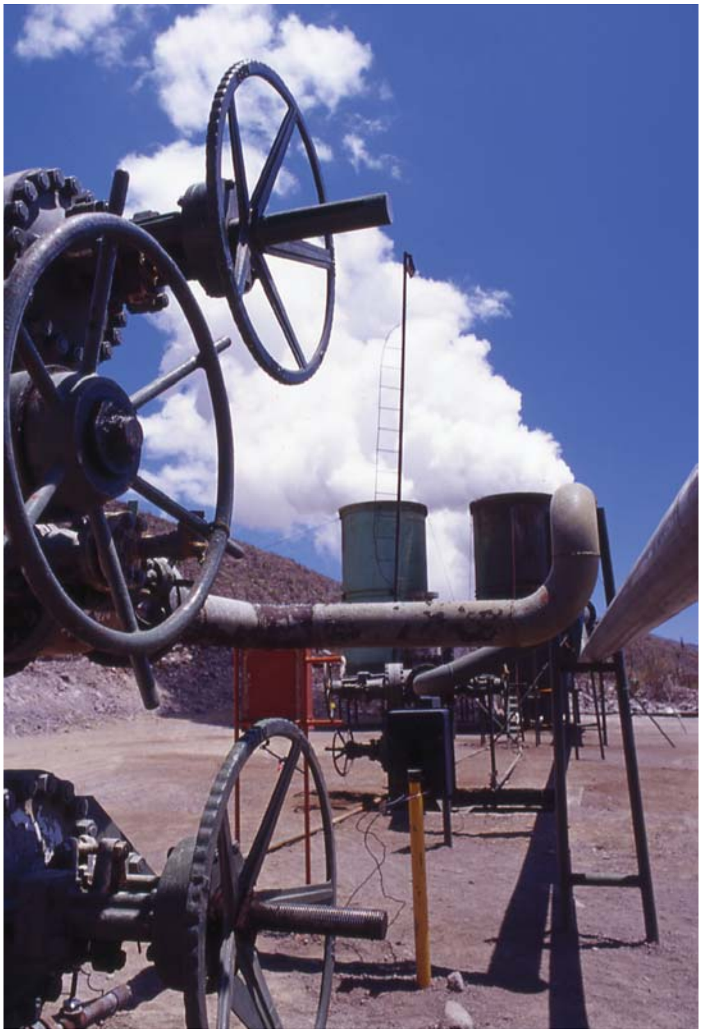
Because only four of the seven power units were in continuous operation during the year at Los Humeros, total electricity generated during 2002 was 146 GWh (Subdirección de Distribución, 2003). This is about 42 percent of 1999 production (351 GWh), but slightly higher than the 127 GWh generated in 2001, when only three units were in operation.

Las Tres Vírgenes Geothermal Field

The Las Tres Vírgenes Geothermal Field is located on the Baja peninsula, in the northern part of the State of Baja California Sur (Fig. 1). Its name comes from three N-S aligned volcanoes known by the same name ("three virgins" in English). The geothermal field lies within a volcanic complex composed of three volcanoes—La Virgen, El Azufre and El Viejo—inside a buffer zone for the El Vizcaíno Biosphere Reserve. The field extends over a 57-km^2 area at an average elevation of 720 m above sea level.

From a structural viewpoint, the Las Tres Vírgenes Geothermal Field is located within a NW-SE trending Pliocene to Quaternary depression (Santa Rosalía Basin) that constitutes the western limit of a deformation zone related to the opening of the Gulf of California. In Baja California, a Pliocene-Quaternary extensional tectonic regime with NE-SW and NW-SE structural trends triggered the formation of three important volcanic centers: La Reforma, El Aguajito, and Las Tres Vírgenes. This deformation formed a regional NW-SE striking fault system, that extends to the Gulf of California coast, with structural blocks tilted to the SW (López *et al.*, 1981).

The geothermal field's heat source appears to be related to the magma chamber of the La Virgen Volcano, the youngest and most southern of the complex at Las Tres Vírgenes. Geothermal fluids are contained in intrusive rocks (granodiorites) with low secondary permeability. These rocks are part of the regional intrusive basement of the California Batholith, a post-Cretaceous granodioritic intrusion dated at 91 to 84 Ma, at depths of 900 to 1,000 m (López *et al.*, 1993). Volcanic-sedimentary rocks overlie the basement.



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Las Tres Vírgenes Geothermal Field.

At depth, secondary minerals occur as a replacement of primary phases. Veining, or direct deposition, does not seem to have been abundant. There are some veins of quartz and calcite, but these are narrow and few in number. Vein minerals in the subsurface rocks include quartz, calcite, and chlorite, with varying proportions of adularia, illite, sphene (titanite), pyrite, hematite, wairakite, and anhydrite (Viggiano and Gutiérrez-Negrín, 2000).

CFE started geothermal surveys at Las Tres Vírgenes in 1982, and drilled the first exploration well there in 1986. To date, four production wells and two injection wells have been drilled at the field. By July 2001, the first power units—two 5-MW condensing turbines—were installed at Las Tres Vírgenes. Steam production during 2002 was 0.28 million metric tonnes, at an average annual rate of 37 t/h. On average during the year, three production and two injection wells were in operation. Only one power unit operated between January and the first days of November, with a total generation of 19 GWh (Residencia de Las Tres Vírgenes, 2003). Electricity produced at the field was distributed to nearby towns, which are isolated from Mexico's national electrical grid.

La Primavera and Piedras de Lumbre Fields and Other Geothermal Zones

Besides the four geothermal fields currently generating electricity in Mexico, CFE has identified and assessed the La Primavera Geothermal Field, in central Mexico near Guadalajara, Jalisco (Fig. 1). La Primavera lies in the western portion of the Mexican Volcanic Belt, within a Quaternary caldera of the same name.

The field's heat source is related to the La Primavera Caldera's magma chamber, where an eruption occurred 20,000 years ago that formed a rhyolitic dome. Geothermal fluids are contained in Tertiary andesites, covered by ignimbrites and lacustrine sediments, and underlain by a granitic basement. Interaction between these fluids and host rocks has left hydrothermal mineral assemblages of medium temperatures, including calcite, quartz, clay minerals, chlorites, pyrite and some relatively scarce epidote.

CFE drilled its first exploration well at La Primavera in 1980 (well PR-1), followed by another 11 wells between 1980 and 1988. Six have been assessed as producers, with a combined mass flow rate measured at 221 t/h of steam, and 434 t/h of brine at 8 bars separation pressure (Gutiérrez-Negrín *et al.*, 2002).

At the request of the local government, CFE suspended its activities at the La Primavera Geothermal Field from 1989 to 1994, and carried out a complete program of environmental restoration to the area affected by its drilling and other activities. CFE planned to install three 25-MW condensing units at La Primavera, following assessment modeling that shows potential electrical output of 75 MW+ from the known reservoir (Gutiérrez-Negrín *et al.*, 2002).

CFE has also carried out exploration studies and drilled exploration wells in other geothermal zones in Mexico, including: Acoculco, La Soledad, the San Pedro Dome, San Antonio El Bravo, Agua Caliente, Los Volcanes, Santispac, San Diego-El Naranjo, and the Tacaná and El Chichonal volcanoes. Most are located inside the Mexican Volcanic Belt, while others lie near the borders of major tectonic plates (Fig. 1).

Of particular note is the Piedras de Lumbre geothermal zone, in Chihuahua State (Fig. 1). Located in the high country of the Sierra Tarahumara within the Basin and Range tectonic province, the area's geothermal manifestations include fumaroles, hot springs of sodium-chloride composition and wide alteration zones (kaolin). Nearby Maguarichic, a small village of around 600 inhabitants, is located 75 km from the nearest electric-transmission lines. Before geothermal development, the village produced electricity using a diesel generator, from 7 p.m. to 10 p.m. daily, at very high cost.

CFE decided to drill one shallow exploration well after a series of geological, geochemical and geophysical studies showed positive results. The 300-m well produced approximately 35 t/h of water at 120° C. A fully automatic, factory assembled ORMAT 300-kW binary-cycle turbine-generator set was installed. The unit includes a modular cooling tower with integrated basin and 8 fans, and a 480-volt synchronous generator. The unit's heat exchanger uses isopentane as working fluid. A 6-km transmission line was constructed from Piedras de Lumbre to Maguarichic, which already had a local distribution grid in place (Mendoza *et al.*, 2002).

The Maguarichic power plant was commissioned in April 2001. CFE trained people from the village to start-up, reset the alarms, check main readings, and re-start the power plant if it shuts down. When a major problem occurs, CFE engineers visit the geothermal field and the power plant.


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La Primavera Geothermal Field.

Conclusions

During the last three decades, geothermal development in Mexico has grown from a single 37.5-MW power plant to 37 units of various types (backpressure, condensing, binary) and output (0.3 to 110 MW), for a total installed capacity of 953 MW. This equates to an increase of 2,500 percent. Geothermal-electric generation in Mexico has grown from 193 GWh in 1973 to 5,400 GWh (with a maximum 5,900 GWh in 2000), for an increase of 3,000 percent. Mexican technicians at CFE and the former CEG have accomplished all of this development. Geothermal-electric generation during 2002 was 5,398 GWh, constituting 3 percent of total public service power generation in Mexico (178,510 GWh).

Though this figure may seem small compared to total electricity generation in Mexico, it must be remembered that geothermal power development plays an important local role for the country. For instance, power produced at Cerro Prieto during the last three decades has supplied an average of 65 percent of regional demand in Baja California. During 10 of those 30 years, approximately 30 percent of the geothermal power produced at Cerro Prieto was exported to California through a long-term contract. And geothermal power generated at Piedras de Lumbre is changing the way of life for the isolated and marginal economic community of Maguarichic.

Thirty years ago, Mexico started the long journey of developing its geothermal resources to produce electricity. Today it ranks third in the world for geothermal power production, behind only the United States and the Philippines. Certainly, many achievements have been gained, but more must be secured. The journey is far from finished! ■

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