LECTURE 2

PHASED DEVELOPMENT AT AHUACHAPÁN AND BERLÍN
GEOTHERMAL FIELDS

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ABSTRACT

Ahuachapán and Berlin geothermal fields in El Salvador have gone through several phases in their development. In the case of Ahuachapán, the installed capacity has remained constant, but the exploitation strategy has evolved over several years, causing wholesale changes in field management. In Berlin, the exploitation strategy has remained roughly constant, but the installed capacity has grown over time, also causing necessary modifications to field management practice.

1. INTRODUCTION

El Salvador has a decades-old history of exploiting its geothermal resources for the generation of electricity. In fact, considering that the first commercial power came on line in 1975, Ahuachapán was one of the first geothermal resources utilised to produce power for a developing country. Curiously enough, the history of development in both Salvadorian fields currently in production – the other being Berlin – is quite different, owing as much to the geographic location and the characteristics of the resources themselves. Although there are some benefits to standardisation, the differences in the resources and the development periods make it impossible to standardise everything, and each field must be developed in accordance to its own characteristics and the state of the art in the time period when it is developed. In the case of El Salvador, this has meant that work has been done in phases, and that the Salvadorian geothermal projects have been a “work in progress” for a long time.

2. AHUACHAPÁN

2.1 History

The Ahuachapán Geothermal field is located in the Western part of El Salvador, close to the border with Guatemala. Initial exploration efforts started in the early 1960’s when the United Nations Development Programme (UNDP) supported the national electric utility, Comisión Ejecutiva Hidroeléctrica del Río Lempa (CEL), with surface exploration and 3 deep exploratory wells, The first of these, AH-1, in Ahuachapán. This well yielded a commercially viable steam flow rate and with this result CEL decided to continue with the commercial development of geothermal resources.
The Mitsubishi Unit 1 (30 MW, single flash condensing type) came on line in June 1975 and a few months later in July 1976 an additional, identical Mitsubishi 30 MW unit was added. In March 1981 a new Fuji 35 MW Unit 3 (double-flash) came on line using the separated brine to produce low pressure steam (1.4 bar), bringing the total installed capacity in the field to 95 MW.

The initial mass extraction (Witherspoon, 1977) was around 600-700 kg/s and almost 550 kg/s of disposal brine was injected in the centre of the field since 1975. During the first years of commercial exploitation mass injection was implemented and was carried out in wells located at the centre of the field. Brine was injected in the wells AH-17, AH-19, AH-8, AH-29 y AH-2 (see Figure 1), but due to some cooling effects in production wells this procedure was stopped (Campos T, 1985) and in November 1982 a concrete canal was completed to conduct the residual brine to the Pacific Ocean.

At present 50 wells have been drilled in the Ahuachapán-Chipilapa area (Figure 1), 17 of these are currently connected to the power plant for steam production, 5 wells are connected for injection, wells AH-1 and AH-7 are connected but they are not able to produce steam due to low wellhead pressure, wells AH-25 and AH-30 are normally used to monitor the reservoir pressure, well AH-32st and AH-35C are scheduled to be connected later in 2007, and other wells are used to monitor and characterise the systems, or as standby producers. At least 6 wells are abandoned (AH-3, AH-10, AH-11, AH-12, CH-A, CH-A1).

### 2.2 Conceptual model

Several conceptual models have been elaborated for the Ahuachapán field: LBL 1991, Electroconsult 1993, and ENEL-LaGeo 2004. In the last one the main difference with the previous was the consideration of possible expansion of the reservoir to the South-West as presented in Figure 2.
accordance with these conceptual models, the field appears to be dominated by seven major and five minor faults trending SW-NE and SE-NW. Those faults have been identified by lithological logs, aerial photographs, structural mapping, and geophysical data.

Three aquifers have been identified: the shallow, the regional saturated and the saline “reservoir” aquifers. This classification is based on the chemistry of the fluids, losses of circulation during the drilling operations, and the pressure response of the aquifers to seasonal variations in precipitation. The three aquifers appear to coincide with lithological units. The fluid pressure in the different aquifers reflects limited hydraulic connection between them as their hydraulic potentials are different. The hydraulic potential is lowest in the saline reservoir aquifer and therefore there is a potential for cold water recharge from the overlaying regional saturated aquifer.

The groundwater flow in the shallow aquifer does not seem to be significantly affected by the faults. A study of well circulation losses suggests a rather uniform permeability in these less consolidated materials (alluvial). In the regional saturated aquifer groundwater flow tends to be influenced by the fault pattern, mainly by SW-NE trending faults. The flow in the geothermal reservoir is also controlled by the faults, most notably SW-NE trending. This is evidenced by the temperature distributions. According to MT data interpretations, the Ahuachapán field is represented by three layers sequence (resistor-conductor-resistor), typically, characterizing the andesitic geothermal environment. The reservoir is identified by a conductive layer and its base is marked by the transition zone between a conductive and a deep resistive layer, around the 25 ohm-m.

There is no evidence of the existence of a second deep reservoir. Chemical data and down hole measurements indicate temperatures of no more than 260°C into the deeper geothermal system.

2.3 Well production history

As mentioned above, commercial exploitation started in 1975. Figure 3 gives the reservoir pressure in well AH-25 measured at +200 m asl, and the total mass extracted from the field. Different field management strategies were implemented during 35 years of operation, in order to maximize production, optimize costs, and sustain long-term generation:

I. Start of commercial exploitation 1975-1983, characterized for rapid pressure decline correlated with the mass extracted (more than a 15 bar pressure drop was observed), some injection experiments were carried out with unsuccessful results and were stopped.

II. Stabilization by seasonal operation from 1984-1994. This period was characterized by reducing the declining trend, the power production was greater during dry season and smaller during rainy season to coordinate with hydro generation. No injection was implemented during this period. Pressure decline was around 1.5 bar during this period.
III. Stabilization by “base” well operation 1994-1999. This period was characterized by the continuous use of the high enthalpy wells and reducing the mass extracted. With this strategy the pressure decline was quite low, less than 0.5 bar was observed. No injection was carried out during this period.

IV. Increasing power production with more wells and use of the Chipilapa wells for injection, 2000-2005. 10 new wells were drilled in the centre (AH-4b, AH-16A), to the south west (AH-34’s), to south east (AH-33’s and AH-35’s), new 24” injection line was built to Chipilapa, and later on in order to increase the injection capacity a pumping system was installed. The pressure decline was around 1.5 bar with a 15 MW increase in power production.

![Figure 3: Reservoir pressure and mass extracted at Ahuachapán geothermal field](image)

### TABLE 1: Production wells data for Ahuachapán

<table>
<thead>
<tr>
<th>Well</th>
<th>Wellhead pressure (kg/cm² a)</th>
<th>Liquid flowrate (kg/s)</th>
<th>Steam flowrate (kg/s)</th>
<th>Dryness (%)</th>
<th>Enthalpy (kJ/kg)</th>
<th>Total flowrate (kg/s)</th>
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Increasing the power production at lower reservoir pressure and using the 3 units already installed, 2005-present. The power was increased from 65 to 80 MW and the pressure decline is almost 1 bar. Units 1 and 3 were in commercial operation since the beginning, therefore the maximum power output was 65 MW. Unit 2 was used as stand by or back up unit. In 2005 a large extraction test was carried out (March-June) and Unit 2 was used as “base load”. Since November 2005 the three units are in continuous operation. Figure 4 shows the gross power output at the power plant since 1988.

The behaviour of the wells follows the trend of the reservoir pressure. Figure 5 shows the history of well AH-6. Well AH-6 is a normal well affected by boiling. During exploitation the falling pressure resulted in boiling, the liquid flow rate declined drastically and the enthalpy increased. In the last 10-15 years the reservoir pressure has been almost stable and the conditions in this well have also been stable.

FIGURE 4: Gross power at Ahuachapán power plant

FIGURE 5: Production history of well AH-6
Another historic well is AH-21. This well is affected by dilution, and for that reason the enthalpy and steam flow rate are decreasing, as shown in Figure 6.

**FIGURE 6: AH-21 production history**

Figures 7 and 8 present the current flow rate and the dryness of the fluid.

**FIGURE 7: Flow rate by well**
A special case is well AH-4bis, which is affected by the reservoir pressure and the hot injection in the south (AH-33A). Figure 9 presents the reservoir pressure at well AH-25 and the steam flow rate of well AH-4bis. Well AH-4bis produces relatively high enthalpy fluid. Its main feed zone is from the shallow part of the reservoir and therefore is affected by boiling. From March 2005 the well operated with two separators and the steam flow increased from 19 to 32 kg/s. Normally, when the injection into AH-33A is more than 30 kg/s the steam flow rate from AH-4bis decreases and if the reservoir pressure declines the steam flow increases.
3. BERLÍN

3.1 History

The Berlín geothermal field is located in the Eastern part of El Salvador, 110 km from the capital, close to the town of Berlín (named by German immigrants in the late 19th century). Exploration started in 1965, with assistance from the UNDP. One deep well, TR-1, was drilled to a depth of 1,500 m, but during discharge tests low steam and well head pressure was observed. Development efforts were then concentrated in Ahuachapán.

During the period 1975-1981 four additional wells were drilled in Berlín (TR-2, TR-3, TR-4 and TR-5) (Figure 10). In order to decide about the commercial development of the field, CEL ordered a complete evaluation of the field, but all development was soon stopped due to the start of the civil conflict that affected the area from 1980 to 1992.

In 1992, 2 x 5 MW back pressure units (ACEC/ABB) went on line using a doublet configuration of TR-2 as producer and TR-9 as an injector. During a failed drilling operation there was a blow-out at TR-6 at 115 m depth and the well was never completed. The intention was for TR-6 to be an injection well that would allow TR-9 to produce.

To complete injection capacity TR-8 and TR-14 were drilled in 1993-1994, TR-14 was connected in April 1994 and TR-8 in December 1994. TR-9 recovered temperature and went on line as a producer in February 1995. Power production during this period was around 6-7 MW. The production conditions from 1995-1999 were stable.

CEL contracted Electroconsult Spa to perform a new feasibility study from 1993-1995 (Electroconsult, Estudio de Factibilidad Primer Desarrollo a Condensacion Campo Berlín, 1994), and its main conclusions were:

![FIGURE 10: Well locations at the Berlín field](image-url)
1. The proven field potential according to numerical models was at least 50-60 MW and could achieve 100 MW with high level of probability (95%).
2. The design of the future power plant and general installation could be done taking into account this possible field development.
3. The first condensing power plant could be size 2 x 25 MW.

The new power plant came on line in 1999 when 2 x 28 MW Fuji condensing type units were commissioned. 18 new additional wells were drilled, 6 for production (TR-5A/B/C, TR-4A/B/C) and 12 for injection (TR-11,61/A/B/C, TR-1A/B/C, TR-12/A, TR-8A, TR-7). The Figure 10 shows the well location in the Berlin field.

In 2003 a new revised reservoir assessment was carried out as a joint effort between Enel and LaGeo. The main conclusion was that it was possible to increase the power production by at least 44 MW. Between 2004-2006, 9 new additional wells were drilled (TR-17/A/B, TR-18/A, TR-19/A/B/C) to complete the production and injection capacity for the new power unit (GE-Nuovo Pignone), which came on line in December 2005.

3.2 Conceptual model

The Berlin geothermal field is located on the northern slope of the Tecapa volcanic chain, inside a system of faults to the South of the Central American graben (Figure 11). The caldera rim geometry observed in the field suggest a collapse at the same time that trending faults NW-SE (Guallinac, El Hoyon, Las Curcitas) were also activated leading to the formation of NW-SE Berlin graben. This volcanic complex is composed of a series of volcanic cones that have erupted lava and scoria which emerge around the craters in the southeast part of the old Berlin volcano caldera. The more recent volcanic activity was the freatomagmatic explosion named El Hoyon 700 years ago.

Berlin field is controlled by NW-SE trending fault system. It is considered the most recent, active and important because it permits the ascent of the fluids from depth to surface.

From geophysical data, the reservoir top seems to be identified by the combination of the gravimetric high and the top of a medium resistive anomaly (30-100 ohm-m). The resistivity of the andesitic rocks of the reservoir could be lowered by the saline geothermal fluids.

In correspondence to the El Hoyon fault area, a deep vertical conductor (resistivity 15-20 ohm-m) has been located; it is likely to be the channel through which primary geothermal fluids flow from depth to the reservoir. The chemical compositions of the fluids sampled in the wells corroborate this assumption.
Boiling phenomena, if any, are negligible. The circulation seems to originate in the deep vertical conductor, then flow towards NE and beyond the northern boundary of the field, with increasingly degraded thermal characteristics.

The reservoir is generally located in the lithological Unit IV (Unit III composes the cap rock), a layer of fairly high permeability perhaps fractured or fissured, and its mean porosity is around 7% and the primary permeability is 60 mD.

The top of the reservoir is located on average at –1000 masl, while the base is still not known. The known minimum extension of the high enthalpy surface (bounded by 290ºC isotherm) is 3x3 km, but it might spread further to the South.

Figure 12 shows the updated conceptual model of the Berlín field (Enel, 2003).

### 3.3 Power production

Power production started in February 1992 when 2x5 MW back pressure units went on line. In 1999 2x28 MW condensing units were commissioned and the previous units were disconnected. In December 2006 an additional 44 MW was installed, bringing the total current installed capacity to 100 MW. Figure 13 shows how the gross power has been delivered to the national electric grid, versus reservoir pressure. The total daily production is around 2,300 MWh and the net injected power is 2,100 MWh. During maintenance (every two years for each unit) low values of generation are observed.

### 3.4 Production history

To date 39 wells have been drilled at the Berlin field, 14 producers wells and 19 injectors, 6 wells are abandoned (TR-1, TR-6, TR-11/B/C, TR-10A). The total steam flow rate is 215-220 kg/s and the injected brine is around 550-560 kg/s, therefore the total mass extracted is around 775 kg/s.

The steam field area is located to the South of the power house and the injection area is located to the North, however, some injection wells are located in the centre of the field (TR-7, TR-12/A) and due to the lack of injection capacity some producer wells are still used for injection.
In Berlin, it was found that acid stimulation with a mixture of HF/HCl improves the well permeability, and hence production. Figure 15 shows the behaviour of well TR-5C where acid jobs were used. This result has been observed, even in wells that do not have skin effect due to drilling, although the reasons are still not well understood.
FIGURE 14: Total mass and pressure trend at the Berlín Field

FIGURE 15: Production history of well TR-5C

An expected drilling result was TR-18A, which produces dry steam at high pressure, probably because it intersected the steam cap of the reservoir. Figure 16 shows the short term production history of the well which started exploitation in December 2006.
4. CONCLUSIONS

Geothermal fields in El Salvador have long been a “work in progress”. In Ahuachapán, the installed capacity has not changed, but the exploitation policy has evolved significantly over the years, and now exploitation is done over a larger area and coupled with reinjection in Chipilapa. In Berlin, on the contrary, the exploitation strategy has remained more or less constant, but the installed capacity has been growing over the years. In both cases, the evolution has led to a greater power output as the field is better understood.

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