Presented at Short Course on Geothermal Development in Central America – Resource Assessment and Environmental Management, organized by UNU-GTP and LaGeo, in San Salvador, El Salvador, 25 November – 1 December, 2007.

UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

GEOTHERMAL RESOURCE ASSESSMENT OF CENTRAL AMERICAN COUNTRIES: EL SALVADOR

Manuel Monterrosa
LaGeo S.A. de C.V.
15 Av. Sur La Libertad
EL SALVADOR
memonterrosa@lageo.com.sv

ABSTRACT

Numerical modelling is usually done several times to calculate the energy potential of the geothermal areas. They are based on a number of physical parameters such as geological and geophysical data, well data (if available), production history, etc.

Four methods of assessment have been discussed: areal estimates, stored heat or volumetric method, lumped parameter model and detailed numerical reservoir simulation.

Geothermal resource assessment has been carried out in Ahuachapan geothermal field using Lumpfit method, and in Berlin geothermal field using TOUGH II. Volumetric assessment was also done in San Vicente geothermal area.

1. INTRODUCTION

The basic principle of geothermal energy utilization is to extract heat stored within the rocks in the subsurface via fluids brought to the surface by wells. This is known as “heat mining”, where heat, typically, is transported by water stored in a permeable zone called the “geothermal reservoir”. The heat stored in the reservoir is divided into the heat contained in the rock and the heat contained in the water. The heat stored in the rocks is transferred by conduction to the water by “water-rock interaction”. A by-product of the “water-rock interaction” is hydrothermal alteration.

Nowadays, when surface exploration begins in geothermal prospecting, a preliminary resource assessment must be carried out, mainly, due to financial requirements. The resource assessment includes standard and preliminary assessment estimates or calculations of the thermal energy content in the proposed area. At this stage, the heat stored in the rock is not yet considered, only the heat content in the water. This method of assessment is commonly known as volumetric assessment; assuming that the heat content in the water is later transformed into electricity through the turbine-generator.

Geothermal exploitation involves energy extraction from highly complex anisotropic volcanic systems, and the geothermal resource management involves controlling this energy extraction in order to maximize the resulting benefits, without over-exploiting the resource. The generating capacity is often poorly known and usually responds unexpectedly to long term exploitation.

In a developed geothermal reservoir, 3D numerical modelling can be carried out based on abundant production data, necessary for the model input. The confidence level of the model is based on reliable information.

2. METHODOLOGY

The general assessment for geothermal resource can be done by six methods depending on the information, and time available:

1- Areal estimates, power density, surface heat flow, Wisian et al (2001)
2- Stored heat, or volumetric method, Mufler and Cataldi (1979,1979), White and Williams (1975), Williams (2004,2007)
3- Planar fracture
4- Magmatic heat
5- Lumped parameter model
6- Detailed numerical reservoir simulation

In this report, we will discuss only (1), (2), (5) and (6).

2.1 Areal estimates

The areal estimates are usually expressed as an allowable flow unit per surface area, or an allowable well density. Often the estimates are based upon a simple reservoir model in a drainage area, where flow unit per well and calculated rundown are dependent on the drainage area.

An alternative is expressed as power density, number or megawatt generated per area of a reservoir. Usually 10-20 MW/km2 is used in the early stages of exploration, to give preliminary estimates of the field capacity. The amount of heat in the reservoir is proportional to the temperature; hence, this estimate is dependent on the reservoir temperature.

2.2 Stored heat or volumetric method

The stored heat or volumetric assessment method is the oldest, easiest, and most popular method. Its theoretical basis is simple, and for that reason is considered a standard approach for preliminary assessment of the geothermal reservoir. This method estimates the total amount of heat stored in the rock and the water, where heat is transferred from the rocks to the water and moves with the water to the surface. The fraction of heat that can be recovered is estimated. However, this method has significant defects. There is little experimental evidence to validate the recovery factor used. Typically, the field capacity is overestimated.

According to Muffler and Cataldi, the electric power generation potential from an identified geothermal system depends on the thermal energy (q_r) present in the reservoir, the amount of thermal energy that can be extracted from the reservoir at the wellhead (q_{wh}), and the efficiency with which that wellhead's thermal energy can be converted to power. The challenge in the resource assessment lies in understanding the size and thermal energy of a reservoir as well as the constraints on extracting the thermal energy. This is done by:

$$q_r = \rho C V (T_r - T_{ref})$$

, where ρC is the volumetric specific heat of the reservoir rock, V is the volume of the reservoir, T_r is the reservoir temperature, and T_{ref} is a reference temperature. The thermal energy that can be extracted at the wellhead is given by:

$$q_{wh} = m_{wh} (h_{wh} - h_{ref})$$

, where m_{wh} is the extracted mass, h_{wh} is the enthalpy of the produced fluid, and h_{ref} is the enthalpy of a reference temperature (25 ºC). The wellhead thermal energy is then related to the reservoir thermal energy by the recovery factor, which is normally defined by.

$$Rf = q_{wh} / q_r \cong 0.25$$

Other authors use the simple relationship:

$$Rf = 1.25\ \phi$$

The value for the recovery factor is normally complicated to estimate. Nathenson (1975) did an analysis regarding the factors influencing the extraction of heat from a geothermal reservoir through a "cold sweep" process, in which the hot reservoir fluid is gradually replaced by colder water through natural or artificial injection. According to this analysis, the previous equations are determined by a geometrical concept of the "reservoir" that allows calculation of a volume and an estimate of the ability to extract hot fluid of that volume. With this calculation, the recovery factor is equal to 0.25. More recent analyses of data from fractured reservoirs indicate that the recovery factor is close to 0.1, with a range of approximately 0.05 to 0.2 (Williams, 2007, Monterrosa, 1993).

In the actual implementation of this approach, the average value for the input variable is replaced with a range of values corresponding to estimated uncertainties and these values are then used in Monte Carlo simulations to define the most likely reservoir properties and productivity along with the associated uncertainties. Typically, the classification used is *proved*, *probable*, and *possible*, with regards to improve the approach.

2.3 Lumped Parameters model

There are reservoir models using simple box or "lump" to represent the reservoir. They are the simplest case of reservoir simulation and were extensively used before reliable simulation codes became available. Nowadays, they are used for short term field predictions.

Such simple models, generally implemented on spread sheets, can provide good estimations over a period of few years, and are often, by far, the best method in making short term incremental decisions about field management. In the long term, they cannot predict the behaviour of a field with the same accuracy as a detailed simulation.

One good lumped simulator tool came from Axelsson (1986, 1989) and Axelsson and Arason (1992). This automatic computer code named Lumpfit has been used since 1986 in most modelling studies carried out. The method tackles the simulation as an inverse problem and automatically fits the analytical response functions of the lumped model to the observed data by using a non-linear iterative last –square technique for estimating the model parameters. Being automatic, it requires very little time compared to other forward modelling approach.

In the Lumpfit code, the lumped model consists of a few tanks and flow resistors. The water level or pressure in the tank simulates the water level or the pressure in different parts of the geothermal system. The resistor simulates the flow resistance in the reservoir, controlled by the permeability of its rocks. Lumped models can either be open or closed, corresponding to constant pressure or no-flow boundary conditions. An open model may be considered optimistic, since equilibrium between production and recharge is eventually reached during long term production, causing the water level drawdown to stabilize. In contrast, a closed model may be considered pessimistic, since no recharge is allowed for such model and the water level declines steadily with time, during long term production. In most cases, models composed of two or three tanks are sufficient for accurate simulations.

2.4 Detailed numerical reservoir simulation

The process of reservoir simulation is the construction of a detailed numerical model of a reservoir and calculations of the past and future flows of geothermal fluid, using a standard simulation code. The structure is specified on the basis of known geological and geophysical structures, and upon the results of drilling. Those results include geological logging, downhole pressure and temperature logging, and permeability indicated by well tests.

The form of the model is then validated by either one or two steps:

a. Natural state matching
b. Production history matching

These two matching processes constrain the reservoir model. Natural state matching should always be done, and production history matching may also be done, if there is much history to match. Because it is more constrained, a model is better when there is a history matching; however, even the natural match alone provides significant definition of the reservoir.

Prior to exploitation, the reservoir is in natural state with a certain fluid, pressure, and temperature distribution, where a natural flow of fluid from the reservoir discharges to the surface. The natural state matching uses the model, run to quasi-steady state, to reproduce the pressure, and temperature distribution. The natural influx is specified at the base of the model, and the quasi-steady state must match the surface discharge, pressure, and temperature distribution, all around the wellbore, known from drilling. The model structure with primary permeability is adjusted until a match is obtained.

If there is any history of discharge from the wells, then this history must also be matched. This matching provides additional constraints, as there is now a non-steady flow in the reservoir, and pressure drawdown draws fluid in directions different from the natural flow. Even if there is only a short history of well testing, it can be valuable to match this. If nothing else, it will test how the chosen structure matches individual well performance.

The most common simulator codes which have been used to construct complex 3D numerical models are STAR, TETRAD and TOUGH II, the most popular is TOUGH II which was developed by Lawrence Berkeley Lab (Pruess 1998) and is part of the MULKOM family codes. A simplified version PETRASIM could be used on a normal PC Windows based.

3. AHUACHAPAN GEOTHERMAL FIELD ASSESSMENT

At the Ahuachapan geothermal field, several simulation studies are already available. In this paper, only the lumped parameter model is considered. This model is available and has been used to estimate the reservoir pressure trend during large scale extraction in order to evaluate the reservoir condition over a total mass extraction of 900 kg/s.

The Lumped model was constructed by two open tanks connected by two conducters and was calibrated according to the methodology described earlier. Because the Lumpfit did not reproduce the effect of the mass injected, it was necessary to estimate mass returned to the reservoir as part of the total mass extracted.

Figure 1 presents the model matching results.

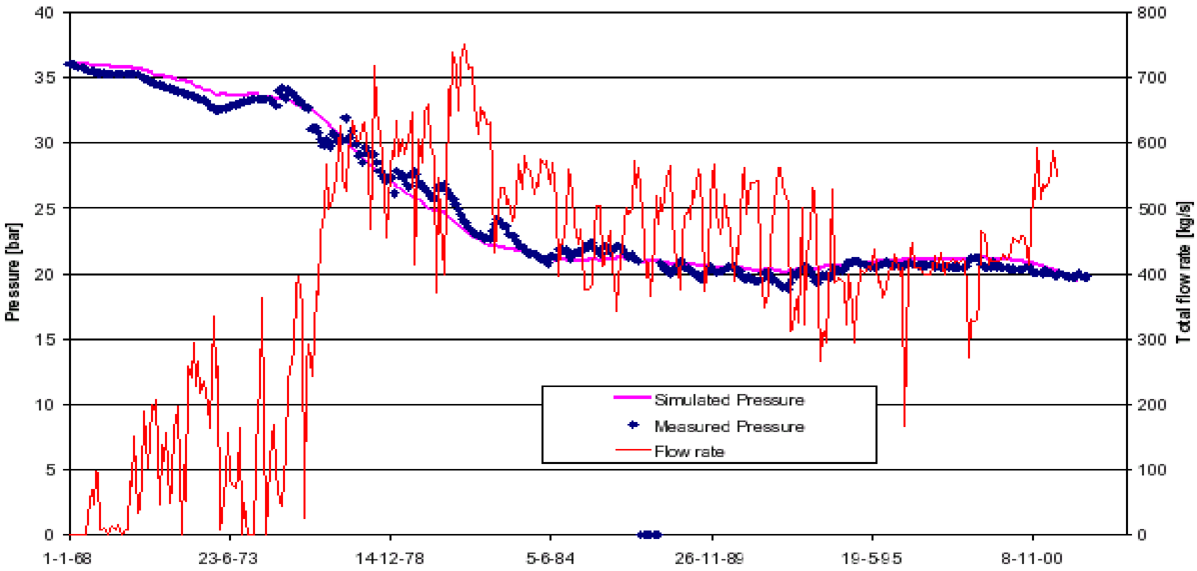

FIGURE 1: Lumped parameter model matching for the Ahuachapan geothermal field.

Figure 2 shows the results of the forecasting for different scenarios and 50% of the effect in pressure recharge from Chipilapa to Ahuachapan:

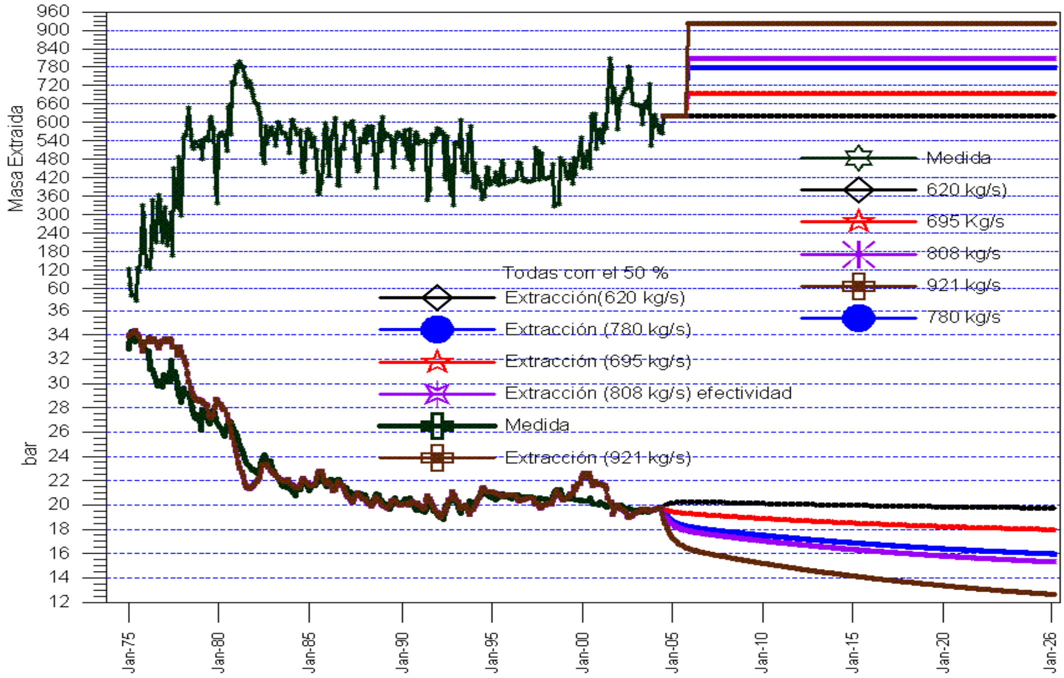

FIGURE 2: Lumped model forecast for the Ahuachapan field.

4. BERLIN GEOTHERMAL FIELD ASSESSMENT

Several simulation models have been available at the Berlin geothermal field. The last detailed 3D numerical model is presented here. To construct a detailed 3D model, it is necessary to determine the geometry and the characteristics of the geothermal system in order to define the input conditions of the TOUGH II code. Figure 3 presents the geometry of the Berlin Field model.

Normally, this model is acceptable and includes all the features of the conceptual model (recharge, fluid pattern, feed zone, boundary conditions, etc.).

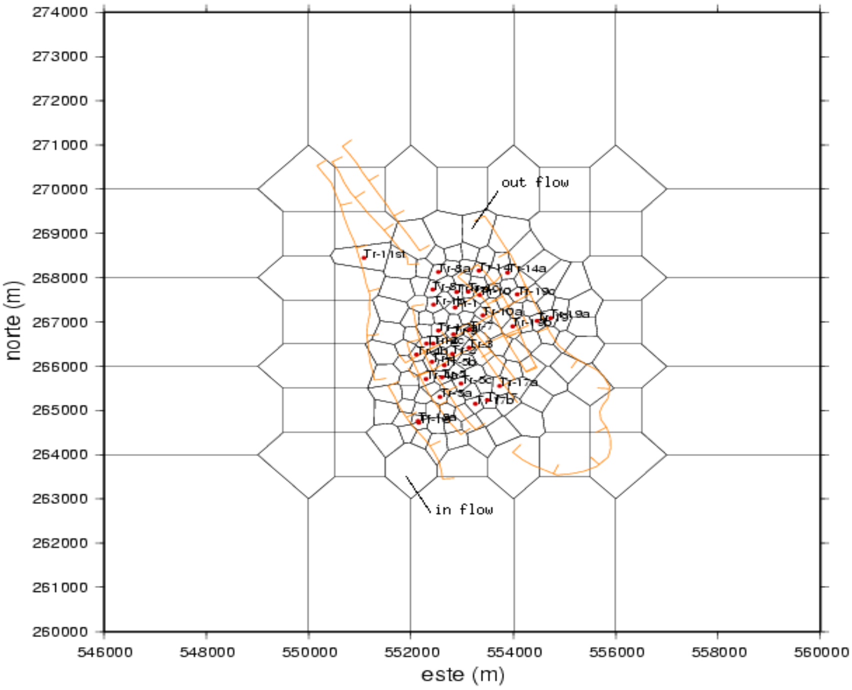

FIGURE 3: Model geometry of the Berlin Field.

A Natural state matching was done and due to abundant available data for the production history, a production history matching was carried out. Figure 4 presents this matching.

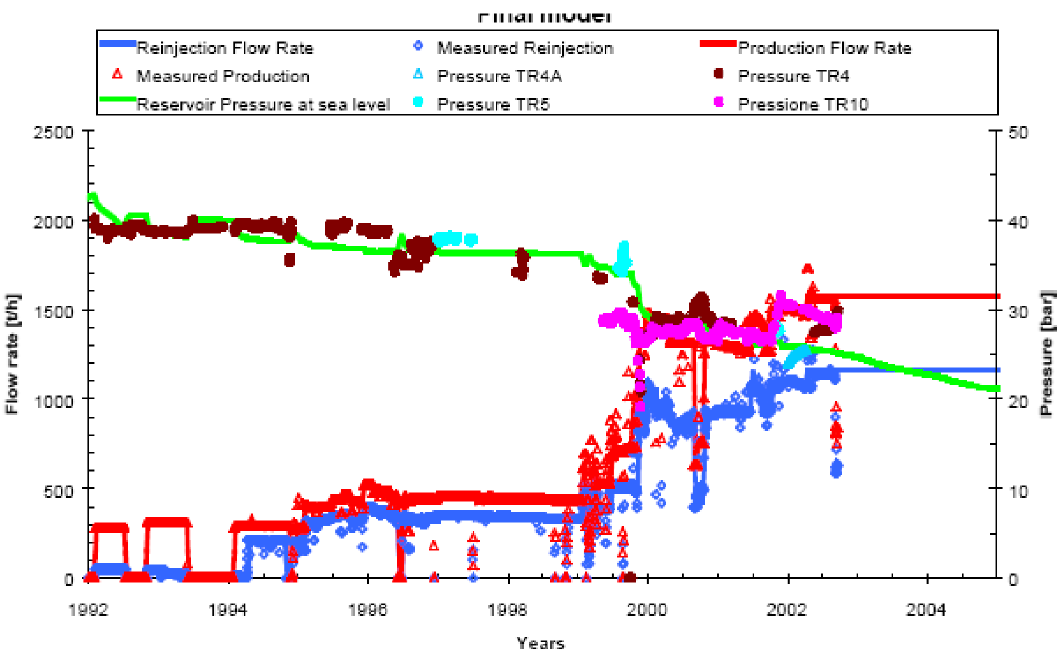

FIGURE 4: Production history matching for the Berlin Field.

After calibration of the model, the next step is the forecasting. Figure 5 presents the forecast of reservoir pressure at 1,800 t/h of mass extraction for 25 years.

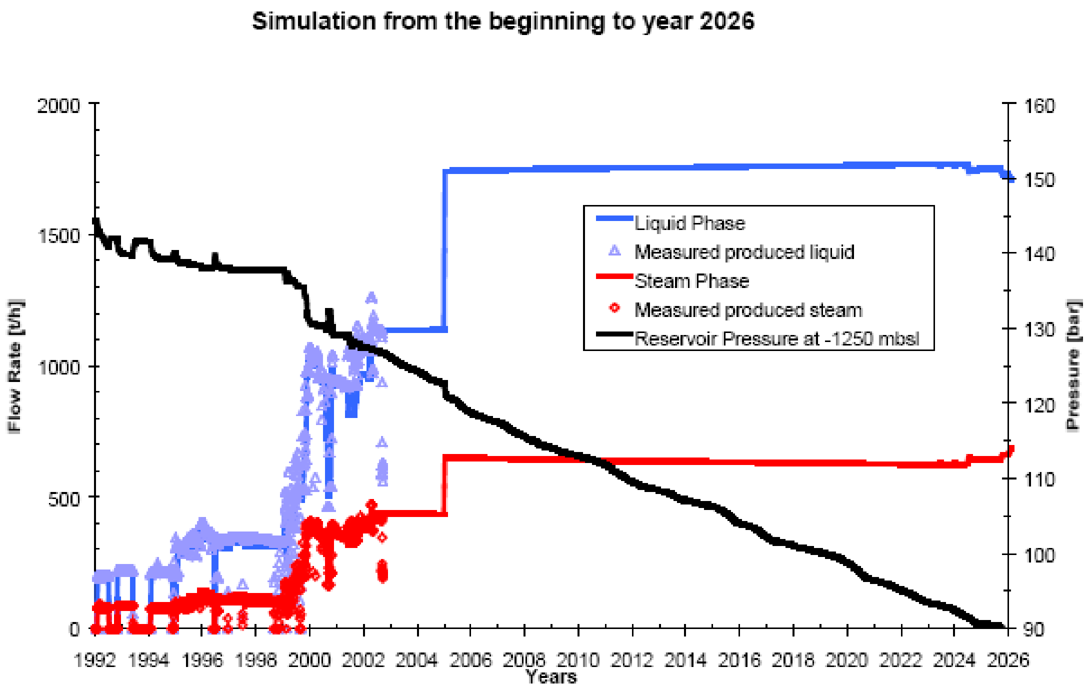

FIGURE 5: Numerical modeling forecast for the Berlin Field.

5. SAN VICENTE GEOTHERMAL AREA ASSESSMENT

In a green-field, where there are no well data, the only way to do an assessment is by volumetric heat stored calculation. In the volumetric assessment, a preliminary conceptual model must be constructed. The following information must be obtained:

1- The area of the reservoir can be classified as a possible or a probable area. If there is well data it can be classified as probable area. A geological or geophysical anomaly can be used.
2- Thickness of the reservoir is more difficult to estimate than the area. If there is available well data, the thickness can be estimated by the feed zone or permeable zone from well measurements, or if not, a geological cross section can be helpful.
3- Reservoir temperature is obtained from geothermometers (water or gas chemistry), and also by well measurements (if available).
4- Effective porosity of the reservoir rocks has large uncertainty and it is carefully used. In volcanic rocks, the rock porosity is quite small (5-10%).
5- The conversion factor depend on the resource applications.
6- The recovery factor is another constraint parameter.

Due to the fact that several parameters have large uncertainties, the use of Monte Carlo simulation has been popular; using software available like Crystal Ball, Easy Risk, etc., due to its ability to run in a standard worksheet with statistics and graphics tools.

The volumetric assessment for the San Vicente geothermal area is shown in the Figure 6:

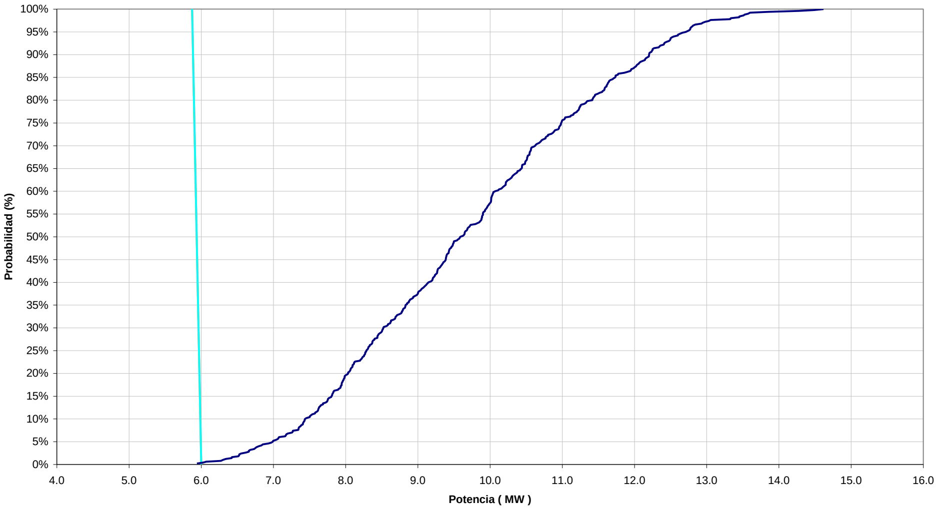

FIGURE 6: Probability distribution curve for the San Vicente Field.

The results of the modelling indicate a 95% probability of more than 7 MW electric power capacity in this geothermal area.

6. CONCLUSIONS

1. When surface exploration begins in geothermal prospecting, a preliminary resource assessment must be carried out, mainly due to financial requirements, including standard and preliminary assessment estimates or calculations of the thermal energy content in the proposed area.

2. At the Ahuachapan geothermal field, only the lumped parameter model was considered, which is available and used to estimate the reservoir pressure trend during large scale extraction in order to evaluate the reservoir condition over a total mass extraction of 900 kg/s.

3. The latest detailed 3D numerical model is presented for the Berlin geothermal field. To construct a detailed 3D model, is it necessary to determine the geometry and the characteristics of the geothermal system in order to define the input conditions of the TOUGH II code.

4. In San Vicente geothermal field, where there was no well data at the time of assessment, only the volumetric heat stored calculation was possible. A preliminary conceptual model was constructed and several factors were considered, such as, area of the reservoir, thickness of the reservoir, reservoir temperature, and porosity of the reservoir rocks.

7. REFERENCES

Axelsson G., 2003: *The Essence of the Reservoir Management*, United Nations University, IGC 2003 Short Course, Page 129-151

Axelsson G., Arason P., 1992: LUMPFIT *Automated simulation of pressure changes in hydrogeological reservoir*, Version 3.1 User`s guide. Orkustofnun, Iceland

Grant M., 2000: *Geothermal Resource Proving Criteria*. Proceedings of the World Geothermal Congress Kiushu, Japan

Mercer J. and Faust C., 1979: A Review of numerical simulation of hydrothermal system. *Bulletin-des Sciences Hydrologiques.*

Muffler P. and Cataldi R., 1977: *Methods of regional assessment of geothermal resources*. ENEL-ERDA Agreement, Part 1, p 131-207

Muffler P., 1978: 1978 *USGS Geothermal Resource Assessment.* Workshop on Geothermal Reservoir Engineering Stanford University.

Monterrosa M., 1993: A 3D Natural state modelling and reservoir assessment for the Berlin Geothermal field El Salvador. United Nation University Geothermal Programme, Iceland Report 11.

Nathenson M. and Muffler P., 1975: Geothermal resources in hydrothermal convection systems and conduction dominated areas. *Assessment of geothermal resources of the United States,* USGS, Circular 726, 104-121.

O`Sullivan M., Pruess K. and Lippmann M., 2000: *Geothermal Resource simulation: The state-of-practice and emerging trends*. Proceedings of the World Geothermal Congress Kiushu, Japan

Parini M., 2000: *Combining Probabilistic Volumetric and Numerical Simulation Approaches to Improve Estimates of Geothermal Resource Capacity*. Proceedings of the World Geothermal Congress Kiushu, Japan.

Pruess K, 1987,: *TOUGH II User`s Guide*, Lawrence Berkeley Laboratory, Report LBL- 20700.

Williams C., 2007: *Updated Methods for Estimating Recovery Factors for Geothermal Resources*. Thirty second Workshop on Geothermal Reservoir Engineering, Stanford University.

Williams C., 2004: Development of Revised Techniques for Assessing Geothermal Resources. Twenty Ninth Workshop on Geothermal Reservoir Engineering Stanford University.