Presented at "Short Course V on Conceptual Modelling of Geothermal Systems",
organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, February 24 - March 2, 2013.

UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

RESERVOIR RESPONSE MONITORING DURING PRODUCTION

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ABSTRACT

Comprehensive monitoring and the application of appropriate field management technics must be implemented to achieve sustainable utilization of geothermal resources. Production response monitoring provides some of the most important data on the nature and characteristics of geothermal systems, information which is indispensable for the development of geothermal conceptual models. It is, in particular, essential for the revision of conceptual models previously developed on the basis of exploration and well data. This paper summarizes the main physical parameters to be measured, recorded and interpreted in a continuous manner, as well as their important role in field and resource management. Three examples of response monitoring data, collected during long term exploitation, are presented along with their analysis and significance for the management of the respective fields. The Miravalles geothermal system in Costa Rica, the Momotombo system in Nicaragua and the Berlin system in El Salvador, all have more than 20 years of commercial operation. In spite of some lack of important monitoring data the main effect of long-term utilization on these geothermal resources have been steam discharge decline, both reservoir boiling and reservoir cooling as well as some scaling due to chemical reactions.

1. INTRODUCTION

Hydrothermal geothermal reservoirs are characterized by the presence of a quasi-balance between hot recharge (up-flow) and discharge (out-flow), on a geological time-scale, which creates conditions of high pressure and temperature in the permeable reservoirs where exploitable geothermal resources are located. When large scale (relative to the natural discharge) exploitation commences underbalanced conditions are to be expected, with pressure as well as temperature declining. This depletion, or degradation as several authors have called it, implies the reduction in energy contents of the reservoir. The level of energy reduction depends on how large the energy extraction is, how large the reservoir is as well as how extensive the hot recharge is. The permeability and storage capacity of the geothermal reservoir represent the main parameters controlling the extent of the pressure draw-down and its pace, respectively. In contrast the enthalpy changes depend mainly on inflow from surrounding aquifers (mostly colder), or the relevant boundary conditions, as well as reservoir boiling controlled by permeability effects. Both the hot recharge and the cooler inflow constitute aspects of the renewability of the corresponding geothermal resource.

The sustainability of the utilization of the geothermal system in question depends on the reservoir factors affecting the depletion, or degradation, of the system. This depletion, which can seriously reduce the reservoir conditions, is perhaps the main constraint to resource development while controlling, and minimizing, the degradation is the goal of geothermal field management during utilization. Comprehensive monitoring and the application of appropriate field management technics must be implemented to achieve sustainable utilization of geothermal resources. Production response monitoring provides some of the most important data on the nature and characteristics of geothermal systems, information which is indispensable for the development of geothermal conceptual models. It is, in particular, essential for the revision of conceptual models previously developed on the basis of exploration and well data.

This paper discusses the monitoring of the response of geothermal systems to long-term utilization. It summarizes the main physical parameters to be measured, recorded and interpreted in a continuous manner, as well as their important role in field and resource management. Three examples of response monitoring data, collected during long term exploitation, are presented along with their analysis and significance for the management of the respective fields. The Miravalles geothermal system in Costa Rica, the Momotombo system in Nicaragua and the Berlin system in El Salvador, all have more than 20 years of commercial operation.

2. FIELD MONITORING – ESSENCE OF RESOURCE MANAGEMENT

Management of a geothermal reservoir relies on adequate information on the geothermal system in question (Stefánsson *et al.*, 1995). Data yielding this knowledge through appropriate interpretation is continuously gathered throughout the exploration and exploitation history of a geothermal reservoir (see other presentations at this short course). The initial data come from surface exploration, i.e. geological, chemical and geophysical data. Additional information is provided by exploratory drilling, in particular through logging and well testing. The most important data on a geothermal system's nature and properties, however, are obtained through monitoring of its response to long-term production. These data provide essential input for the development of conceptual models, for the siting of geothermal wells and geothermal reservoir modelling. Conceptual models, and in particular reservoir models, constitute some of the key tools of geothermal resource management (see chapter 3).

Careful monitoring of a geothermal reservoir during exploitation is, therefore, an indispensable part of any successful management program. If the understanding of a geothermal system is adequate, monitoring will enable changes in the reservoir to be seen in advance. Timely warning is thus obtained of undesirable changes such as decreasing generating capacity due to declining reservoir pressure or steam-flow, insufficient injection capacity or possible operational problems such as scaling in wells and surface equipment or corrosion. The importance of a proper monitoring program for any geothermal reservoir being utilised can thus never be over-emphasised.

Monitoring can be divided into physical and chemical monitoring, with the former being discussed in the present paper and the latter in other presentations at the short course. Physical monitoring can, moreover, be divided into direct and indirect monitoring (see below).

Monitoring the physical changes in a geothermal reservoir during exploitation is in principle simple and only involves measuring the (1) mass and heat transport, (2) pressure, and (3) energy content (temperature in most situations). This is complicated in practise, however (Axelsson and Gunnlaugsson, 2000). Measurements must be made at high-temperatures and pressures and reservoir access for measurements is generally limited to a few boreholes, and these parameters cannot be measured directly throughout the remaining reservoir volume.

The parameters that need to be monitored to quantify a reservoirs response to production may, of course, differ somewhat, as well as methods and monitoring frequency, from one geothermal system to another (Kristmannsdóttir *et al.*, 1995; Axelsson and Gunnlaugsson, 2000). Monitoring may also be either direct or indirect, depending on the observation technique adopted. Below is a list of directly observable basic aspects that should be included in conventional geothermal monitoring programs.

(1) Mass discharge histories of production wells (pumping for low-temperature wells).
(2) Temperature or enthalpy (if two-phase) of fluid produced.
(3) Water level or wellhead pressure (reflecting reservoir pressure) of production wells.
(4) Chemical content of water (and steam) produced.
(5) Injection rate histories of injection wells.
(6) Temperature of injected water.
(7) Wellhead pressure (water level) for injection wells.
(8) Reservoir pressure (water level) in observation wells.
(9) Reservoir temperature through temperature logs in observation wells.
(10) Well status through diameter monitoring (calliper logs), injectivity tests and other methods.

Some of the above parameters are monitored through temperature and pressure logging, which is described in detail in other presentations at the present workshop. Monitoring programs have to be specifically designed for each geothermal reservoir, because of their individual characteristics and the distinct differences inherent in the metering methodology adopted. Monitoring programs may also have to be revised as time progresses, and more experience is gained, e.g. monitoring frequency of different parameters. The practical limits to manual monitoring frequency are increasingly being offset by computerised monitoring, which actually presents no upper limit to monitoring frequency, except for that set by the available memory-space in the computer system used. Data transmission through phone networks is also increasingly being used. Axelsson (2012) shows examples of different kinds of direct monitoring data.

Indirect monitoring involves monitoring the changes occurring at depth in geothermal systems through various surface observations and measurements. Such indirect monitoring methods are mainly used in high-temperature fields, but also have a potential for contributing significantly to the understanding of low-temperature systems. These methods are mostly geophysical measurements carried out at the surface; airborne and even satellite measurements have also been attempted. All these methods have in common that a careful baseline survey must be carried out before the start of utilisation, and repeated at regular intervals.

Some of the indirect monitoring methods are well established by now, while others are still in the experimental stage or have met limited success. A review of the geothermal literature reveals that the following methods have been used (Axelsson and Gunnlaugsson, 2000):

(a) Topographic measurements.
(b) Micro-gravity surveys.
(c) Electrical resistivity surveys.
(d) Ground temperature and heat-flow measurements.
(e) Micro-seismic monitoring.
(f) Water level monitoring in ground water systems.
(g) Self-potential surveys.

The reasons why these monitoring methods are seldom used in low-temperature fields are the fact that physical changes in low-temperature systems are generally not as great as in high-temperature systems as well as relatively high costs. A few of the methods are rather widely used in high-temperature fields, such as (a), (b) and (e).

Topographic measurements are carried out to enable detection of ground elevation changes, mostly subsidence. This may occur in all geothermal systems during exploitation because of compaction of the reservoir rocks, following fluid withdrawal. Re-injection may also cause topographic changes (uplift). Recently satellite radar interferometry (INSAR) has been increasingly used for surface deformation studies. Such studies for the Krafla volcanic- and geothermal system in N-Iceland provide a good example (Sturkell *et al.*, 2008).

Micro-gravity monitoring has been used successfully in a number of geothermal fields (see a separate presentation at this short course). Changes in gravity can provide information on the net mass balance of a geothermal reservoir during exploitation, i.e. the difference between the mass withdrawal from a field and the recharge to the reservoir. The mass-balance effects of enlarging steam-zones may also be seen through gravity monitoring. In addition, the mass-balance effects of re-injection may be detected by gravity monitoring. Methods for analysing gravity changes in geothermal fields are presented by Allis and Hunt (1986). Eysteinsson et al. (2000) present an example of the results of gravity and subsidence monitoring in the Svartsengi high-temperature geothermal field in SW-Iceland. Nishijima *et al.* (2000 and 2005) also provide good examples from Japanese high-temperature fields of the application of repeated micro-gravity monitoring for reservoir monitoring.

Repeated *electrical resistivity surveys* have not been conducted in many geothermal fields, but might help delineate cold, fresh-water inflow into geothermal reservoirs, induced by production. Such surveys may also be helpful in locating reservoir volumes affected by re-injection.

Surface activity and heat flow may either decrease or increase during production from a geothermal field. Monitoring of these changes is, however, more often associated with monitoring of the environmental effects of geothermal exploitation. These may be monitored through repeated (a) ground temperature measurements, (b) airborne infrared measurements, and (c) observations of thermal features (hot springs, fumaroles, mud pools, etc.).

The purpose of *monitoring seismic activity* may be two-fold. Firstly, to monitor changes in seismic activity in an already active area, this may be considered environmental rather than reservoir monitoring. Secondly, to delineate the regions in a geothermal reservoir affected by exploitation or re-injection, because in some cases the pressure and thermal changes associated with geothermal exploitation and re-injection may be sufficient to generate some micro-seismic activity.

Water level changes in shallow ground water systems above geothermal reservoirs are monitored in some geothermal fields. *Self-potential monitoring* has been proposed as a tool to study the changes in geothermal reservoirs due to mass extraction and re-injection.

Finally, it may be pointed out that a combination of indirect monitoring with numerical reservoir simulation should enhance the reliability of such models, as wells as aiding in the correct understanding of the nature of the geothermal system involved.

3. RESOURCE MANAGEMENT AND SUSTAINABLE UTILIZATION

In the broad sense geothermal resource management is an extension of geothermal reservoir engineering. Whereas the former addresses key issues such as heat in place, reservoir performance, well deliverability, heat recovery, water injection and reservoir life, reservoir management aims at optimised exploitation strategies in compliance with technical feasibility and economic viability and environmental safety requirements. Pressure decline and temperature depletion with continued steam and heat production raise the essential problem of the reservoir life, a main concern of geothermal reservoir engineers and managers.

Geothermal resource management is also increasingly incorporating aspects pertaining to sustainable geothermal utilization and more general sustainable development. The longevity of the heat extraction should be through a properly balanced production schedule and designed water injection strategies in order to achieve sustainability. This is indeed a challenging accomplishment in which reservoir/ resource management takes on an important role (Ungemach et al., 2005).

Comprehensive and efficient field management is an essential part of any successful geothermal resource utilisation endeavour. Such management can be highly complicated; however, as the energy production potential of geothermal systems is highly variable. The generating capacity of many geothermal systems is, furthermore, poorly known and they often respond unexpectedly to long term energy extraction. This is because the internal structure, nature and properties of these complex underground systems are poorly known and can only be observed indirectly. Successful field management relies on proper understanding of the geothermal system involve, which in turn relies on adequate information on the system being available (Axelsson, 2008).

**An important element of geothermal resource management involves controlling energy extraction from a geothermal system so as to avoid over-exploitation of the underlying resource. When geothermal systems are over-exploited, production from the system has to be reduced, often drastically. Over-exploitation mostly occurs for two reasons. Firstly, because of inadequate monitoring and data collection, understanding of the systems is poor, and reliable modelling is also not possible. Therefore, the systems respond unexpectedly to long term production. Secondly, when large flow rate and consequently heat is delivery from the reservoir larger than hot recharge and any or limited field management have being undertaken.

Geothermal resource management may have different objective, such as (Stefansson et al., 1995):

I. To minimise the operational cost of a given geothermal resource
II. To maximise the energy extraction from a given resource
III. To ensure the security of continuous energy delivery
IV. To minimise environmental effects
V. To avoid operational difficulties like scaling and corrosion
VI. To adhere to the energy policy of the respective country

Real management objectives are often a mixture of several of the objectives listed above. In such cases, the objectives must be placed in an order of importance, since they may in fact be counteractive. One of the more difficult aspects of reservoir management is to determine the most appropriate time span for a given option. There are cases, for example, where depleting a given reservoir in a few year time is more advantageous from a purely financial point of view. This is usually unacceptable from a political and sociological point of view, where a reliable supply of energy for a long time is considered more valuable.

Some of the management options, which are commonly applied in geothermal resource management are:

1) Changed exploitation strategy (increase/reduction production)
2) Implementation of a reliable and effective injection strategy
3) Drilling of make-up and/or stand by wells
4) Changes in well-completion programs (large diameter, changes in casing program, etc.)
5) Search for new production and injection areas
6) Implementation of appropriate scaling control(s) (silica-scaling, calcite-scaling, etc.)

Geothermal utilization involves extracting mass and heat from the geothermal reservoir involved. Mass and heat transfer are, therefore, the dominating processes during the undisturbed natural state, with this transport driven by global pressure variations in the geothermal system. During production, the mass and heat transport forced upon the system causes spatial as well as transient changes in the pressure state of a reservoir. Therefore, it may be stated that pressure is one of the most important parameters involved during exploitation.

Energy content, either represented as internal energy or enthalpy, is the other crucial parameter of during exploitation. In single phase situations, this depends on temperature only, and pressure and temperature define the state of the reservoir. In two phase situations, pressure and temperature are related and an additional parameter is needed, such as water saturation or enthalpy.

The energy production potential of a geothermal system is predominantly determine by pressure decline due to production, but also by the available energy content. The pressure decline is determined by the rate of production, on one hand, and the size of the system, permeability of the rock and hot recharge (i.e. boundary conditions) on the other hand.

The nature of geothermal systems is such that the effect of “small” production is so limited that it can be maintained for a very long time. The effect of “large” production is so great, however, that it cannot be maintained for long. Pressure declines continuously with time, particularly in systems that are closed or with low hot recharge. Production potential is therefore, often limited by lack of water rather than lack of thermal energy.

Water or steam extraction from a geothermal reservoir causes, in all cases, some decline in reservoir pressure. The only exception is when production from a reservoir is less than its natural recharge. Consequently, the pressure decline manifests itself in further changes, which may be summarised in a somewhat simplified manner as follow:

(A) Direct changes caused by lowered reservoir pressure, such as: decreasing well discharge, increase boiling in high enthalpy wells, lowered water level, changes in surface activity.
(B) Indirect changes caused by increase recharge to the reservoir, such as: changes in chemical composition of the reservoir fluid, changes in reservoir temperature conditions, changes in temperature/enthalpy of reservoir fluids

4. LONG TERM RESPONSE MONITORING EXAMPLES

4.1 The Miravalles geothermal field, Costa Rica

The Miravalles geothermal field is located in Costa Rica and went in commercial operation in March 1994, when Unit 1 of 55 MW_e was commissioned. At the moment the installed capacity is 163 MW_e with 5 operating units (2 x 55 MW_e, 1 x 19 MW_e, 1 x 19 MW_e and 1 x 5 MW_e). The annual average electrical production is around 1,200 GW_e. The present steam production field extends over an area of 21 km^2 of which 15 km^2 are dedicated to steam production and 5 km^2 for brine injection. Fifty three geothermal wells have been drilled to date in Miravalles with depths ranging from 900 to 3,000 m; the average production of production wells ranges from 3 to 12 MW_e and injection rates are in the range of 70 – 450 kg/s per well (Moya et al., 2010).

Figure 1 presents the mass extraction history of Miravalles where the beginning of operation of individual units is also indicated.

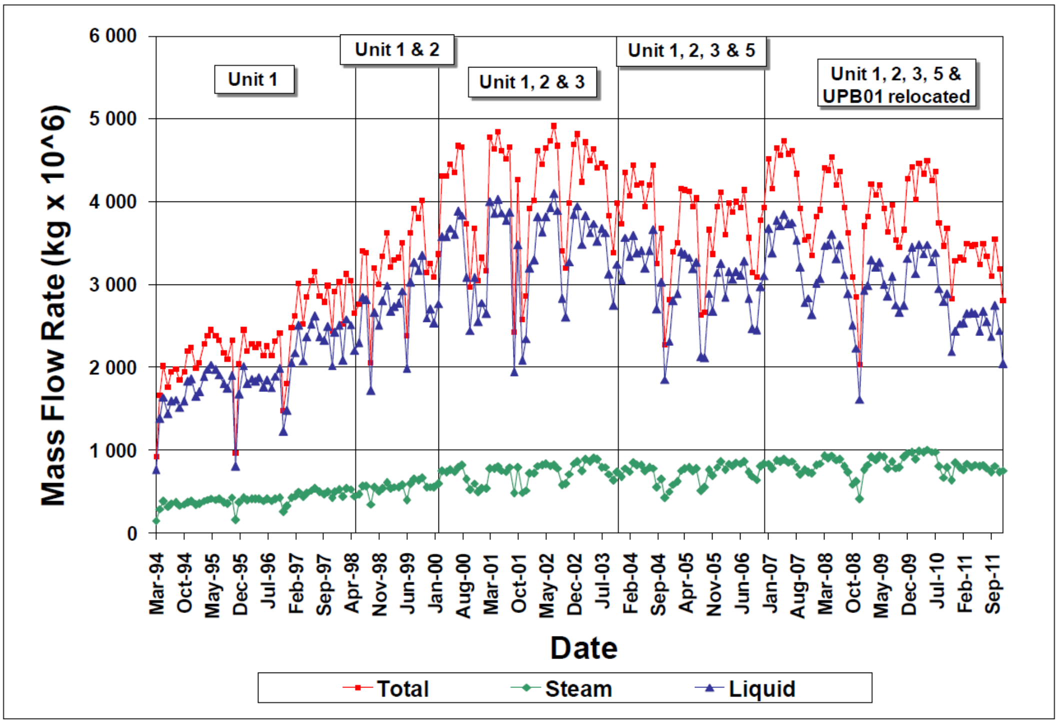

FIGURE 1: Production history of the Miravalles geothermal field in Costa Rica (from Moya et al., 2012)

The main effects observed in the Miravalles field, through monitoring, after 16 years of commercial exploitation, may be summarised as follow:

a) The reservoir temperature has decrease from 240 to 230°C, most evidently in the centre of the main steam production field.
b) The pressure draw-down observed in the reservoir has been of the order of 1.7 bar/year (1.7, 2.0, 1.8, and 1.3 for the respective production periods, see Figure 2).
c) The steam flow delivered from producer wells has declined during the whole exploitation period.
d) Increasing non-condensable gases content in steam, from 0.4 to 1.6%.
e) No data are available regarding calcite scaling due to boiling in the reservoir.
f) The main process affecting the whole reservoir appears to be increased boiling, mainly in the centre of steam field.
g) There is no data available regarding silica scaling in injection wells and pipelines.
h) The possible effects of production and reinjection on micro-seismic activity is being observed in the field.

4.2 The Momotombo geothermal field, Nicaragua

The Momotombo geothermal field is located in Nicaragua and went in commercial operation in 1983 when a condensing type unit of 33 MW_e was commissioned; the presently installed capacity is 77 MW_e while the running capacity has not exceeded 32 MW_e in recent years. Figure 3 presents the production history of the Momotombo power plant.

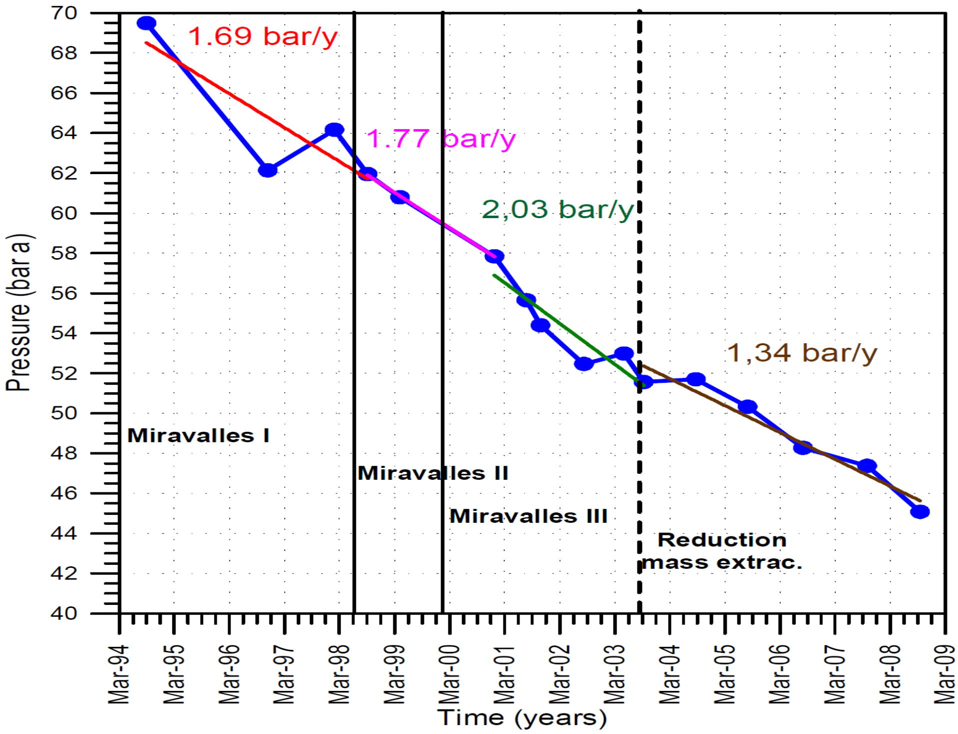

FIGURE 2: Observed pressure decline (monitored in well PGM-31) in the Miravalles geothermal reservoir (Castro, 2010)

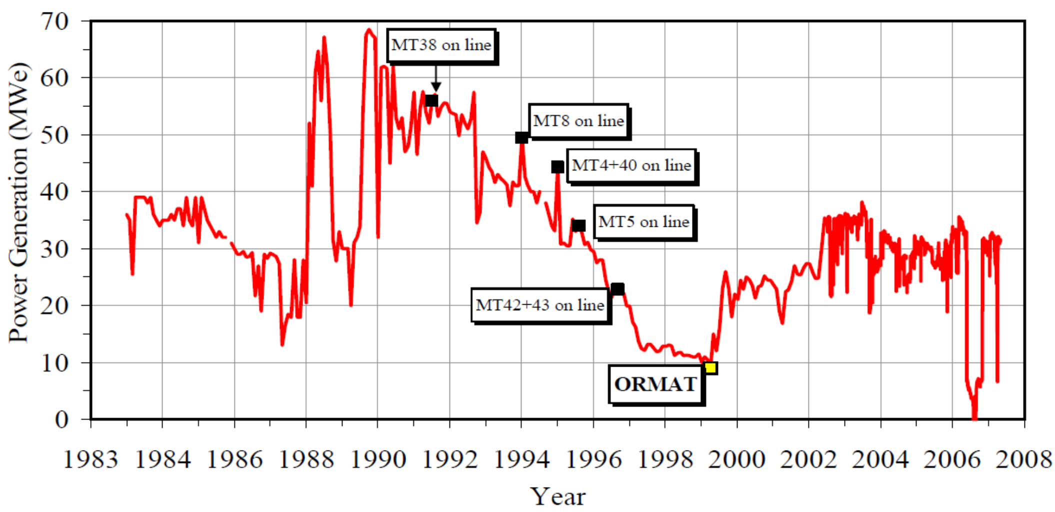

FIGURE 3: Production history of the Momotombo geothermal field in Nicaragua (Porras, 2008)

The main effects observed during long term exploitation of the Momotombo geothermal system can be summarized as follows:

a) Fast decline of steam delivered to the power plant after exploitation started with a corresponding decrease in observed discharge enthalpy, as shown in Figure 4.
b) Cooling effects have been observed in a shallow part of the reservoir since beginning of utilization.
c) Some boiling has also been observed in the shallow reservoir, in spite of the cold water inflow into the system.

d) There are no data available regarding average pressure and temperature drawdown.
e) Some calcite scaling due to boiling appears to be affecting some production wells.
f) There are no data available regarding seismicity related to the exploitation.

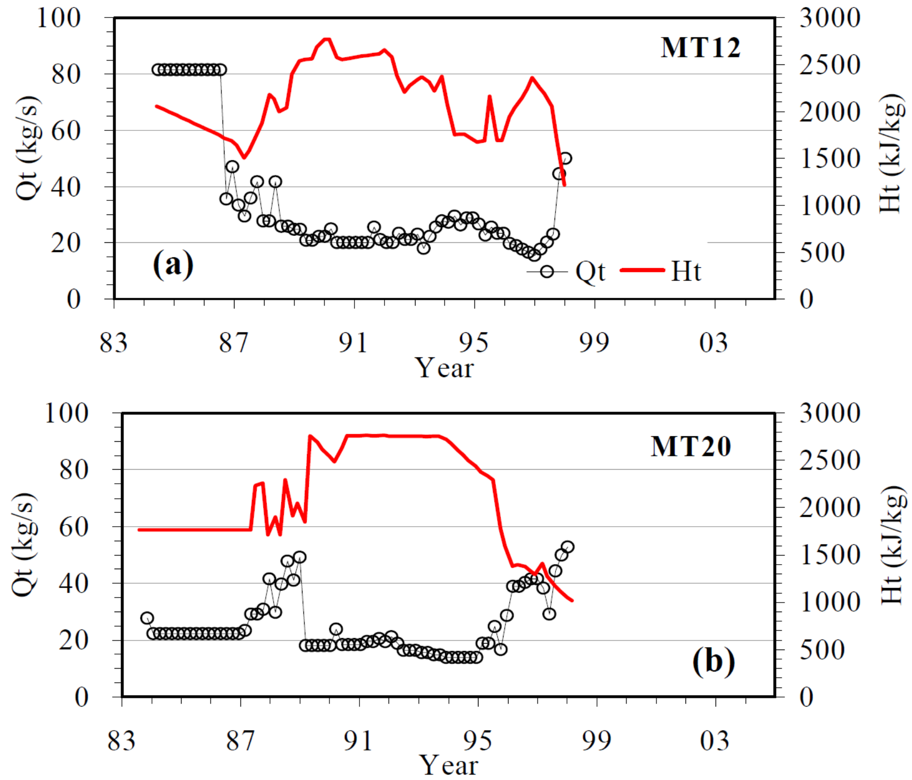

FIGURE 4: Steam flow rate and enthalpy changes monitored in selected wells in the Momotombo field (Porras, 2008)

4.3 The Berlin geothermal field, El Salvador

The Berlin geothermal field is located in El Salvador and went into commercial operation in 1992 when 5 MW_e back-pressure well-head units went on line. Later on the same year two 28.6 MW_e condensing type units were commissioned. In 2007 another condensing type unit of 44 MW was additionally commissioned, and later a 9.2 MW_e bottoming binary unit completed the current total installed capacity of 109.2 MW_e.

At present 38 wells have been drilling in the Berlin field, 14 of them are used as producers and 20 are injectors (4 wells in addition have been abandoned). Figure 5 presents the total mass extraction history of the Berlin system. The total mass extraction has ranged up to 870 kg/s; the steam delivered to the power plant is approximately 220 kg/s at full capacity and the injected brine is 650 kg/s, which is partially injected using a high pressure pumping system located at the site of well TR-1 (Monterrosa 2012).

The total pressure drawdown in the geothermal system is approximately 18 bar, however over the last 12 years the decline has been less than 10 bar, the discharging enthalpy has been fairly constant in most production wells and no evidence of cooling due to injection has been observed in the field. Some boiling is perhaps the main process affecting the reservoir, however.

Some aspects affecting sustainable utilization of the Berlin geothermal system are related to calcite scaling in well TR-18, weakening steam cap in the southern part of the steam field, high concentration of non-condensable gases in well TR-18A and silica plugging of injection wells and pipe-lines, in-particular those connected to the binary unit. As part of the field management several actions have been initiated to reduce the impact of these issues.

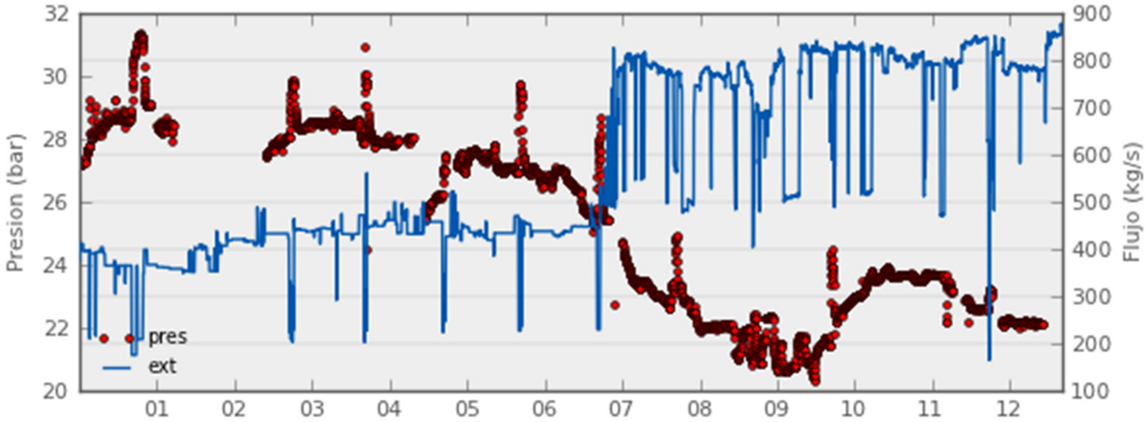

FIGURE 5: Mass extraction and reservoir pressure histories of the Berlin geothermal system (Monterrosa, 2012)

The main effects observed during long term exploitation of the Berlin system can be summarized as follows:

a) The pressure draw-down has reached almost 18 bar and temperature has declined an average 5 – 10°C.
b) The main process affecting the reservoir is increased boiling.
c) There is no evidence of large scale cooling due to injection or due to cooler inflow from surrounding aquifers.
d) The steam delivered to the power plant has declined due to reservoir pressure and temperature decrease, but also due to scaling in the formation around wells.
e) Calcite and silica scaling has been observed in production and injection wells and chemical treatment and/or mechanical cleaning is being used for resource management operations.
f) After 10 years of seismic monitoring no conclusive evidence of micro seismicity related with the exploitation has been observed.
g) High precision topographic level monitoring doesn't indicating any significant effect due to mass extraction from the field.

4.4 Other case histories

Numerous other long-term physical monitoring histories are available, with some published in the geothermal literature. The histories presented above are for high-temperature, volcanic geothermal systems while some histories are available for low-temperature systems as well. The histories of the convective, facture-controlled, low-temperature systems discussed by Axelsson (2011) can e.g. be pointed out as well the history of the Paris sedimentary, low-temperature system (Lopez et al., 2010). The high-temperature case histories of the Ahuachapan geothermal system in El Salvador and Olkaria in Kenya presented by Monterrosa and Montalvo (2010) and Ofwona (2008), respectively, are also noteworthy.

5. CONCLUSIONS

Geothermal reservoirs are affected by mass and energy extraction, mainly causing some decline or degradation of thermodynamic reservoir parameters, steam flow decrease, reservoir cooling, increased boiling and/or chemical scaling in pipelines, wells and/or reservoir formations. Production response monitoring aims at evaluating these changes, but concurrently the monitoring provides some of the most important data on the nature and characteristics of geothermal systems, information which is indispensable for the development of geothermal conceptual models. It is, in particular, essential for the revision of conceptual models previously developed on the basis of exploration and well data.

Reservoir response monitoring is an essential by providing the basis for future predictions and consequently to prevent severe degradation and extensive depletion of the corresponding resource. The main parameter to be monitored are down-hole pressure and temperature for all relevant wells, mass-flow rate and enthalpy of discharging wells, indications of reservoir temperature changes, due to cold recharge or reinjection, and the chemical content of produced fluid. Indirect monitoring, repeated at regular intervals in time, such as accurate monitoring of gravity changes and monitoring of micro-seismic activity, can also be extremely valuable.

A sufficiently high, yet site-specific, monitoring frequency must be implemented to ensure a sufficiently comprehensive data collection. The overall field and resource management, the monitoring is part of, must also be implemented as soon as the energy extraction commences. Changes in operational strategies must be also implemented to attain sustainable utilization.

Similarities can be seen in the production responses of the three geothermal systems, with long production histories presented above. All show indications of some degradation/depletion, yet to a varying degree. Field management programs can be implemented in those fields, however, which will permit their continued operation.

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