CONTRIBUTIONS FROM IIE, MEXICO, TO THE DEEP GEOTHERMAL RESOURCES TASK OF THE IEA GEOTHERMAL IMPLEMENTING AGREEMENT

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ABSTRACT

The Instituto de Investigaciones Electricas, México, through its Geothermal Unit, has submitted three projects to the International Energy Agency's "Implementing Agreement for a Cooperative Programme on Geothermal Energy Research and Technology". Two of them, *Borehole Logging Based on Optical Fiber Technology* and *Development of an Expert System for Assessment and Management of Geothermal Fields Under Production* correspond to the Agreement's Task IV *Deep Geothermal Resources.* In this paper we summarize these projects. The first project aims to develop a borehole logging system capable of simultaneously measuring distributed temperature and pressure along geothermal wells. This system will be rated to 450°C and 500 bar at depths to 4,000 m, with spatial resolution of 0.25 m and aquisition time of ~ 4 minutes. We will apply the high-quality data obtained with this logging system to develop techniques for better assessment of geothermal reservoirs and wells.The goal of the second project is to develop a sophisticated and powerful expert system for assessment and management of exploited geothermal reservoirs. From analysis of production histories corresponding to groups of wells, this system will infer the mechanisms that control reservoir production at the present time, in different areas of the field. Then, it will warn about likely consequences for future production.

INTRODUCTION

The Instituto de Investigaciones Electricas, México, through its Geothermal Unit, has submitted three projects to the International Energy Agency's "Implementing Agreement for a Cooperative Programme on Geothermal Energy Research and Technology". Two of them, *"Borehole Logging Based on Optical Fiber Technology"* and *"Development of an Expert System for Analysis of Geothermal production data"* correspond to the Agreement's Task IV *Deep Geothermal Resources.* The other one, *"Natural Levels of Contaminants in Prospect Geothermal Areas"* belongs to Task I *Environmental Impacts of Geothermal Energy Development*.

In this paper we summarize the projects mentioned in the first place.

BOREHOLE LOGGING BASED ON OPTICAL FIBER TECHNOLOGY

This project is in the context of Subtask B "Drilling and Logging Technologies". The objectives of this Subtask include " ... interpretation of logging data and development of logging tools." (IEA, 1996*a*).

In what follows we describe how this project will contribute to Subtask's B objectives and probably enlarge them. Enlargement would come about by generating new and more accurate techniques for assessment of geothermal reservoirs and wellbores.

BACKGROUND

Geothermal heat is mined through wells that intercept hot-water and steam reservoirs. One main tool to evaluate geothermal mass- and energy- reserves and their deliverability is well logging (e.g., Grant *et al.*, 1982). This is the only way to obtain direct measurements of reservoir and well pressures and temperatures. Furthermore, it provides crucial information about reservoir transmissivity and storativity, permeability type, the existence, type and location of reservoir boundaries, whether and to what extent the formation closest to the well is damaged or fractured, formation temperature above the reservoir, etc.

Well logging is also the major tool to evaluate the wells, this most important link to the reservoir. Geothermal wells must be evaluated to locate their feed zones and their relative strenghts, the existence and importance of thief zones, the mechanical conditions of the well, etc.

Deep-geothermal-well logging presents unique difficulties, due to the associated high temperatures (which may exceed 400°C), substantial pressures and agressive chemical environment. The first tools used for geothermal well logging were of the Amerada type. These gages, first developed for the oil industry, were standard fare for many years in the geothermal industry and are still used in some places. They typically use Bourdon tubes and bimetals or gass-filled Bourdon tubes, as pressure and temperature sensors respectively. Their data acquisition system consists of a stylus, driven by the sensor, that scratches a blackened card, which is driven, in turn, by a mechanical clock. Operators then read the data from the card by means of a microscope and record them by hand. Pressures and temperatures must be recorded with different gages. The gages are lowered inside the wells and retrieved by means of steel wirelines. Profiling of a well requires emplacing the gage(s) at a given depth, waiting for the sensor to equilibrate with the environment, recording the time and depth, moving to the next station and repeating the same procedure. Because this is laborious and time-consuming, the spatial resolution achieved this way is usually low: several tens of meters to hundreds of meters. Also, the accuracies and resolutions of these gages are low by today's standards.

In time, more convenient, sophisticated and accurate logging tools were developed. Currently, the most popular geothermal logging tools use platinum resistances, thermocouples or thermistors as temperature transducers, and strain gages, capacitors or quartz cristal oscillators as pressure transducers. Typically, they are able to measure pressure and temperature simultaneously. Thus tey are termed *PT* tools.Their data acquisition systems are computer based, and many are capable of automatically recording real-time data at the surface.There are two main groups: tools that do not include downhole electronics and tools that do. The first group typically relies on multi-conductor electromechanical cables (e.g., Adorni et al., 1985; Dennis et al., 1985; Dennis, 1990; Arisi *et al.*, 1995) or more complex combinations of multiconductor cable and steel tubing (e.g., Pruett, 1992) to deliver the transducer's signals to the surface. Their temperature rating depends mostly on the temperature rating of the insulation of the conductor cable. Due to their complexity, these cables are bulky and expensive; also, they require heavy and costly equipment for their deployment.

The second group deploys electronic circuits together with the transducers, downhole. The electronics are heat-shielded by a dewar flask. They usually relie on monoconductor (e.g., Davarzani and Sloan, 1988) or multiple conductor (e.g., Itoh et al., 1985) armored cables to deploy the tools and to transmit the information to the surface . A variant of this type uses electronic (e.g., RAM) memory and steel wireline or cable for deployment. In this case the data are read at the surface after retrieving the tool.

During the last several years our group at I.I.E. developed, demonstrated and applyed the *METRE* System, a geothermal, electronic, simultaneos pressure-temperature-flow logging tool (e.g., Iglesias et al., 1995). Our system may operate in two modes: real-time data aquisition in the surface for temperatures of up to 320°C and electronic memory for higher temperatures. It can also log continuos PTS profiles with a spatial resolution of up to 0.25 m, depending on logging speed (Fig. 1).

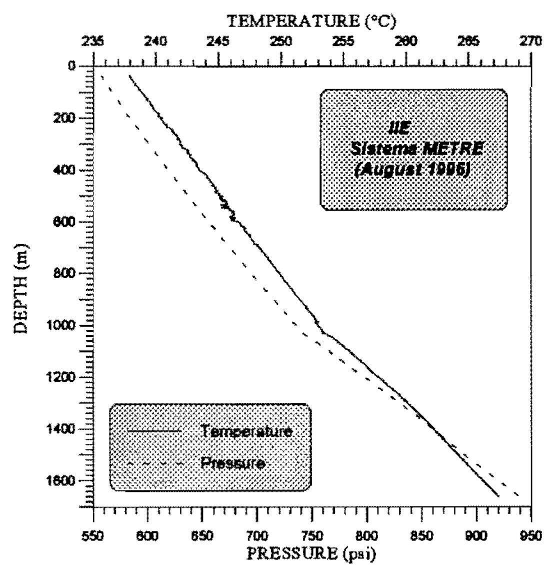

Fig. 1. An example of continuous, simultaneous pressure and temperature profiles recently obtained with IIE's METRE System.

As a result of having successfully completed this sophisticated technological development, our group amassed substantial expertise and know-how on geothermal well logging equipment, transducers, sealing systems, high-temperature materials and devices, high-temperature electronics, computer systems and software development. Furthermore, we have built a considerable infrastructure, which includes a fully equiped logging truck with its data aquisition system and winch, 4.5 km of armored monoconductor cable, 4.5 km of swab line, a hydraulic-crane auxiliary truck, wellhead lubricator, diesel and gasoline generators, calibration facilities, high-temperature testing facilities, in-house cappability for reeling cables under prescribed tension, computers and peripherals, software to aid interpretation of the data, etc.

Current technological trends in this field indicate that the next generation of logging tools will be based on optical fiber technology. Early attempts to apply optical fiber technology for temperature logging in wellbores were published starting seven years ago (e.g., Angel *et al.*, 1989; Sharma *et al.*, 1990). Shortly after that Bjornstad *et al.* (1991) discussed ongoing development of a pressure/temperature well logging system based on optical fiber technology, intended for oil wells. Two years later Kluth *et al.* (1993) reported on another pressure/temperature optical fiber sytem based on a different technique, also intended for oil wells. A common characteristic of this earlier developments, in addition to being based on optical fiber technolgy, is that their measurements are point-like. That is to say, pressures or temperatures are measured at a particular depth in the well. If one is interested in the values of these variables elsewhere in the well, one must relocate the tool accordingly.This is also the way most earlier devices discused in previous paragraphs, based on mechanical, electrical and electronic sensors, work.

More recently, Hurtig et al. (1994, 1995) reported on a new technique, based on optical time-domain reflectometry, to measure *distributed* temperature in wellbores. This technique provides a "snapshot" of the temperature distribution along the optical fiber. Nearly at the same time, Osato *et al.*(1995) reported field testing of another logging system that profiles temperature using the same technique, and measures bottomhole pressure by means of a conventional capillary tube/chamber device.

This technique for measuring distributed temperature along optical fibers constitutes a technological breakthtrough in well logging. For the first time ever we are able to obtain a nearly-instant (few minutes) temperature profile of a whole well. The space resolution of this device is rated ar about 1 m. These characteristics open exciting possibilities for enhancing the asessment of geothermal wells and reservoirs.

PROJECT'S OBJECTIVES

- To develop a borehole logging system based on optical fiber technology for simultaneously measuring distributed temperature and pressure.
- To apply the high-quality data obtained with this logging system to develop techniques for better assessment of geothermal reservoirs and wells.

FINAL PRODUCT

- A geothermal borehole logging system capable of simultaneously measuring distributed temperature and pressure along the well. The system will be rated to 450°C and 500 bar at depths to 4,000 m, with spatial resolution of 0.25 m. Suitable optical fibers, conveniently protected in armored cable, will act as the downhole temperature, pressure and depth sensors. An optoelectronic data acquisition subsystem, linked to a personal computer for control and display, will complement the sensors. Critical components will be protected by built-in redundance. Ad-hoc software will facilitate tabular and graphical display of the data as well as calibration, unit conversion, routine checks on the system, etc. The system will be mounted on a logging truck.
- Techniques for better assessment of geothermal reservoirs and wells.

SPECIFICATIONS OF THE PROPOSED LOGGING SYSTEM

Temperature:

Sensor: optical fiber
Range: 0 to 450 °C
Accuracy: 0.5 °C
Resolution: 0.1 °C
Spatial resolution: 0.25 m

Pressure:

Sensor: optical fiber
Range: to 500 bar
Accuracy: 0.1 bar
Resolution: 0.01 bar
Spatial resolution: 0.25 m

General system:

Logging depth: to 4,000 m

Maximum sampling rate: 10 Gigasamples/s

Sampling window:
Minimum lag: 1 ns
Maximum lag: 100 μs

Acquisition time: ~ 4 min.

Control and display: Pentium personal computer.

JUSTIFICATION

The proposed system will make three main contributions to borehole logging:

(i) simultaneous measurement of *distributed* pressure and temperature;

(ii) very short (compared to typical time scales of most reservoir and wellbore phenomena) aquisition time;

(ii) high spatial resolution .

These characteristics, plus the good pressure and temperature accuracies attainable with fiber optic technology, will open exciting opportunities for improving the current techniques for interpretation of pressure and temperature logs. For example, simultaneous pressure-temperature profiles of newly drilled or recently repaired wells undergoing their heating stages, will reveal, in minute detail, the locations and relative strenghts of their feeding and thief zones. Another interesting possibility is to use time sequences of temperature profiles while cementing tubular goods in wells, to aid in diagnosing the results of this all-important operation, with high spatial resolution.

We also envision several applications to improve the interpretation of transient pressure tests in geothermal wells. One such application would be to exploit the knowledge of the time variations of the pressure and temperature profiles in the well during testing, to deconvolve the wellbore storage effects from the transient pressure (and temperature?) effects generated by the reservoir.We also envision several other exciting possibilities in this context.

DEVELOPMENT OF AN EXPERT SYSTEM FOR ASSESSMENT AND MANAGEMENT OF GEOTHERMAL FIELDS UNDER PRODUCTION.

This project is in the context of Subtask A "Exploration Technology and Reservoir Engineering". "This Subtask will involve collaborative research on ... reservoir engineering, including reservoir characterization and reservoir modelling" (IEA, 1996*b*).

In what follows we describe how this project will contribute to Subtask's A objectives.

BACKGROUND

Energy production is the ultimate goal of any geothermal development. Energy production is accomplished through wells that intersect the reservoir (or reservoirs).

Production of geothermal wells varies with time. This may be due to "normal" or to "pathological" causes. Normally, well production diminishes with time due, mainly, to exploitation-induced reservoir pressure drawdown. On the "pathological" side, several causes may impair the capacity of a well as a conduit. For example, mechanical damage of its internal casing (piping), scaling by minerals precipitated from the produced fluid, partial occlusion by measuring or drilling equipment accidentally left in the well, etc. Production may also be influenced by many "pathological" causes affecting the reservoir (or reservoirs) intersected by the well. These include invasion by colder waters from neighboring aquifers or from injection of spent brines, permeability reduction near the well by mineral deposition triggered by boiling or by mixing of different fluids, production from two or more reservoirs having fluids with different enthalpies or chemical compositions, etc., and combinations of these. Often some of these causes affect production not only at the reservoir level, but also by impairing the capacity of the well as a conduit (e.g., scaling of the well piping induced by the arrival of a cold front).

From a practical point of view, production problems can be classified into those that affect only one well, and those that affect some or all the wells in a certain area. In economic terms, the latter are obviously more important. In general, production problems with the capacity to affect a significant area, or even a whole field, can be detected early in one or a few wells, before much damage is done. Early detection allows, in many cases, implementation of remedial actions to correct the causes of the problem, or to delay as much as possible their effects on production. Though usually less important, diagnostic of individual well production problems is also economically significant. For these reasons, diagnostic of production problems in wells is a crucial capability to have, for successfully managing geothermal fields.

Wells act as conduits for production of fluid and heat from the reservoir. Because of the serial nature of the flow, the production histories of fluid and heat (e.g., pressure, enthalpy, chemical composition, etc.) corresponding to each well in the field, provide information about processes ocurring in the area of the reservoir (or reservoirs) they intersect. Thus, in principle, from the analysis of production histories of a well one can infer the processes controlling its production. And, from analysis of production of a number of wells, it is possible to infer processes affecting their production area or even the whole field.

This approach has been followed by several authors (e.g., Truesdell *et al*, 1989; Lippmann and Truesdell, 1990; Arellano *et al*, 1991; Truesdell *et al*, 1992; Truesdell *et a*l, 1995, Iglesias *et al*, 1996). From their collective experience it is fair to conclude that diagnostic of production problems in geothermal wells is a complex inferential task, which requires processing great amounts of data, considerable knowledge of its possible causes, careful assessment of multidisciplinary evidence, and enough experience. These characteristics make this task a good candidate for a computerized expert system.

In 1992 our group published the first version of WELL_DR, an expert system for production diagnostics of geothermal wells (Arellano *et al*, 1992). Not long after that, our group's experience in production analysis was considerably incremented by comprehensive studies of several tens of wells from the Cerro Prieto Field (Iglesias et al, 1996). This experience evidenced that WELL_DR necessitated a major upgrade. That is the main goal of the present project.

PROJECT'S OBJECTIVES

- ▶ To develop an expert system for assessment and management of geothermal fields under production.

FINAL PRODUCT

- ▶ A user-friendly expert system with the cappability to analyze production histories of the wellfield to infer the mechanisms that control reservoir production at the present time, and to warn about likely consequences for future production.

SPECIFICATIONS OF THE PROPOSED EXPERT SYSTEM

To facilitate its use at the Institutional/departmental level, the system will be installed in a network server. We have chosen the *Windows NT* platform to implement this aspect of the project.

The system will be composed of the following main moduli:

ANPROD, the actual expert system, will analyze the production histories of individual wells. From this it will generate diagnostics about the causes of production behavior in different stages of the well history and will alert about likely future consequences. At user's request, ths system will be able to pool the information corresponding to a number of wells from related areas of the field and make inferences about the processes affecting the reservoir in the covered area. The necessary data will be automatically retrieved from the database in the NUCLEO module, which will also provide visualization cappability. Part of the original data must be pre-processed for ANPROD. Pre-processing will be tackled by the COMGEO and SIMFLU moduli.

NUCLEO will consist of a relational database, developed specifically for assessment and management of geothermal fields, with visualization cappability. Our relational database BDGEO (e.g., Iglesias *et al*, 1994), developed and installed in the *Unix* platform will be ported to the *Windows NT* platform. This will be accomplished by means of *MS Access*, a powerful and flexible database management system native of *Windows*.

The visualization cappability of NUCLEO will be based on *MATLAB*. This well-known, high-performance numeric computation and visualization software package will be linked to the database by means of *MS Visual Basic*. Visualization will include displaying specialized plots correlating different production histories, field maps and sections, well's tubular goods, etc., at user's request.

COMGEO will integrate a variety of standar geochemical computations. For instance, it will automatically perform the charge balance analysis of the chemical composition of the produced fluids, compute temperatures from several chemical geothermometers, infer concentrations of chemicals at reservoir level, etc. This module will automatically retrieve the necessary data from NUCLEO and will use MATLAB's numerical computation cappabilities. It will also automatically transfer its results to ANPROD.

SIMFLU will compute bottomhole parameters, such as pressure, enthalpy, saturation, temperature, from standard wellhead data. These data and the necessary information about the geometrical parameters of the well, its feed zones, etc, will be automatically retrieved from NUCLEO. SIMFLU's results will be automatically fed to ANPROD, for its use. This module will be based on a reliable, well proven, wellbore flow numerical simulator developed in-house several years ago.

JUSTIFICATION

This system will make three main contributions to geothermal reservoir characterization:

i) to capture and code extensive experts' knowledge about the complex relationships existing between geothermal reservoir thermophysical, chemical and hydrodynamic mechanisms, and field production;

ii) to automatically apply this knowledge to infer the current reservoir mechanisms controlling production and warn about likely consequences for future production; and

iii) to automatically retrieve and process the (usually) huge datasets necessary to make these inferences.

We conceive this expert system mainly as a tool to considerably alleviate the work of the human experts who, in the end, will take responsibility for the diagnostics related to field production assessment and related recommendations. As a byproduct, the system could be used to train selected personnel in modern reservoir assessment.

CONCLUSIONS

The Instituto de Investigaciones Eléctricas, México, will contribute two projects to Task IV *DEEP GEOTHERMAL RESOURCES* of the International Energy Agency's "Implementing Agreement for a Cooperative Programme on Geothermal Energy Research and Technology".

One project, *Borehole Logging Based on Optical Fiber Technology*, is in the context of Subtask B "Drilling and Logging Technologies". Its aim is to develop a borehole logging system capable of simultaneously measuring distributed temperature and pressure along geothermal wells. This system will be rated to 450°C and 500 bar at depths to 4,000 m, with spatial resolution of 0.25 m and aquisition time of ~ 4 minutes. We will apply the high-quality data obtained with this logging system to develop techniques for better assessment of geothermal reservoirs and wells.

The other project, *Development of an Expert System for Assessment and Management of Geothermal Fields Under Production*, is in the context of Subtask A "Exploration Technology and Reservoir Engineering". From analysis of production histories corresponding to groups of wells, this system will infer the mechanisms that control reservoir production at the present time, in different areas of the field. Then, it will warn about likely consequences for future production.

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