CONF-791016--8

Presented at the Second Symposium on the Cerro Prieto Geothermal Field, Mexicali, Mexico, October 17-19,1979, and to be published in the Proceedings

LBL-9591

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HIGH TEMPERATURE GEOTHERMAL RESERVOIR ENGINEERING

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February 1980

Prepared for the U.S. Department of Energy
under Contract W-7405-ENG-48

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Submitted to the Proceedings of the
Second Symposium on the Cerro Prieto
Geothermal Field, Baja California, Mexico
October 17-19, 1979

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ABSTRACT

A review of high-temperature geothermal reservoir engineering is presented. High-temperature downhole conditions encountered during field activities are reviewed with data from Cerro Prieto as the primary example. The types of measurements required for estimation of formation parameter values and how they depend on other geoscience data are reviewed. The analysis techniques that are currently used to evaluate field data are discussed and their limitations, applicability, and associated difficulties are described using data from Cerro Prieto as an example. Downhole tools that are needed for high-temperature measurements are discussed with a review of the current state of the art. The use of measured data in reservoir engineering simulation calculations is summarized, and different numerical models are reviewed. Data from Cerro Prieto are used as an example to show how reserves and reservoir depletion calculations can be used to aid the field developer in choosing operational field strategies.

INTRODUCTION

We have reached a point in the Cerro Prieto cooperative research project where we have a large amount of resource data and a relatively refined interpretation of that data. For that reason it is now appropriate to review the purpose and current status of high-temperature geothermal (HTG) reservoir engineering, keeping in mind that one of the reasons for the research at Cerro Prieto is to produce techniques and tools that can be applied to other geothermal fields. Using Cerro Prieto as an example, we will review briefly the type of work that is important in HTG reservoir engineering. We will discuss how we go about it and what the data requirements are from geologists, geophysicists, and others. We will also review the measurements and tools that are needed, discuss their availability, and relate these items to the determination of the reservoir reserves and depletion.

Reservoir engineering activities include coordinating and supervising drilling and completion operations, obtaining well test measurements, and performing analyses and computer modeling. These activities begin during exploration and continue through the field development stage, at which time improved estimates of reserves and depletion are determined. All of these detailed activities relate to the three major aims associated with the evaluation of a subsurface resource, which are as follows:

1. Estimation of reservoir reserves
2. Estimation of reservoir depletion
3. Optimization of reservoir utilization

The first two estimates are made initially during exploratory drilling operations. During the development phase of an HTG resource, the well locations and production strategy are chosen to optimize the resource use. Finally, all of these activities continue during the production phase to ensure that the field management is consistent with use optimization, and to improve continually the estimates of reserves and lifetime.

Traditionally petroleum engineers have coordinated activities from the exploration phase to the production phase of hydrocarbon resources. Petroleum engineers often specialize in some particular aspect of hydrocarbon production, whereas reservoir engineering deals mainly with the transfer of fluids (oil, gas, and water) to, from, or within the reservoir and wellbore.

There is no counterpart to the petroleum engineer in the high temperature geothermal industry. There are no educational programs that turn out a geothermal equivalent of a petroleum engineer. There are also no formal programs for geothermal reservoir engineering, although the Stanford Petroleum Engineering Department includes geothermal course work in their program. For this reason it has become the task of geothermal reservoir engineers to assume the responsibility for resource development in HTG projects. In addition to coordinating field projects from the exploratory drilling phase through the production phase, it is also the specific responsibility of the HTG reservoir engineer to deal with the transfer of heat and fluids (brine, steam, and gases) to, from, and within the reservoir.

Before proceeding with a review of the methodology and tools available to the HTG reservoir engineer, a brief review of the fundamentals of HTG reservoirs will be presented. These fundamentals are paraphrased in Table 1 from the petroleum engineering text on Reservoir Engineering by Calhoun (1976).

We would like to review these fundamental ideas of reservoir engineering in more detail. One of the major important items is that each geothermal reservoir is unique. For example, in the Salton Trough and the Mexicali-Imperial Valley we notice that Cerro Prieto is a high-temperature, relatively low-salinity silica system, East Mesa is a moderate-temperature high-carbonate system, Niland or Salton Sea is a high-temperature high-silica system. Even within this relatively contiguous region,

Table 1. HTG RESERVOIR FUNDAMENTALS

1. Each reservoir is unique.
2. The well system is considered to be part of the reservoir.
3. The underground (in situ) state of the rock and fluid is different from its state after being transported to the wellhead.
4. Brine, gas, and (at times) steam coexist in most reservoirs.
5. Heat and fluid cannot be produced from the containing rock without the presence of some displacing energy.
6. HTG reservoirs are generally heterogeneous in their rock, fluid, and energy displacing properties.
7. Reservoir management is accomplished by controlling the transfer of heat and fluid from, to, or within the reservoir.

each of these geothermal systems is unique in its major characteristics. The second important point is that the well is part of the reservoir system. This is particularly important when there is flashing in the wellbore, and eventually flashing in the formation. The behavior of the system must always include the wells as part of the system to be analyzed. Another obvious consideration is that the underground state is different from the wellhead state. This is particularly true when there is flashing in the reservoir. In the latter case there is gas and sometimes steam coexisting at the reservoir conditions. The heat and fluid in the reservoir cannot be produced without some displacing energy, and in the case of geothermal (as in the oil industry) that displacing energy takes the form of a pressure gradient. We understand that we cannot produce geothermal energy using temperature gradients because of the low conductivity of the rock. It is necessary to move fluid through fractures or interconnected pores, i.e. the displacing energy has to be a pressure gradient. High-temperature reservoirs are almost always heterogeneous both vertically and areally.

The reservoir management is dependent upon the properties of the reservoir, the mode of injection and production, and the economics associated with the project. Each of these factors must be considered in determining how many wells are used and how many are kept as back up, what flow rates are optimum, and so on.

Taking note of these seven fundamental HTG reservoir engineering concepts in Table 1, it becomes clear why HTG resource development projects should be coordinated by reservoir engineers. No other discipline has the responsibility for evaluating and applying all of these resource related items.

METHODOLOGY

To evaluate a subsurface system, data must be collected and interpreted. These include geology, mineralogy, geochemical, and geophysical data. The first and most important step in accomplishing the three major goals of HTG reservoir evaluation is to gather (synthesize) all of the available data for the subsurface system of interest. Since, in general, these HTG subsurface systems are related to the sub-regional and regional hydrology and to the thermal features, data must be gathered on a regional scale, although the emphasis will be on the localized (subregional) thermal anomaly of interest. Clearly this requires close working relationships between the HTG reservoir engineer and the specialists (experts) who gather and interpret the data. Some of the data are acquired by the HTG reservoir engineer during well tests and static well profile measurements. In general, the approach taken in accomplishing the goals is:

1. Review all geological, geophysical, geochemical and mineralogical data and interpretations.
2. Review the regional hydrology.
3. Review all existing well completions and all drilling data.
4. Review the well logging correlations and well test interpretations.
5. Plan and coordinate drilling and well testing, as needed.
6. From a synthesis of these data, choose a consensus geological model. From the synthesis of thermal and hydrological data construct a representative subsurface hydrothermal model. From the well logs, core and drill cutting data, and the well test data, construct a distribution of material parameters in the reservoir.
7. Use these models with available production data to make zero-order estimates of the energy in situ (reserves).
8. Use the geological and hydrothermal models with the material property distributions as the basis for a numerically computed match of the available, measured production data.
9. Use the detailed history match as a basis to study future reservoir production behavior, effects of injection, well patterns, etc.

Clearly, tasks 1 through 4 above can be accomplished with sufficient help from the specialists. It is equally clear that to accomplish tasks 5 through 9, specialized reservoir engineering "tools" are required. These include downhole and wellhead measuring devices for well testing, physical models and computer programs for the analysis of hydrothermal well tests, models for the computation of hydrothermal production and injection, and so on.

The first step in this procedure is to synthesize all these data and to construct a consensus model. Currently at Cerro Prieto there are detailed geological models, but we do not have a consensus model that can be used as the basis for our reservoir simulation. As an example consider an approach that was taken a couple of years ago for the Serrazzano zone of the Larderello field in Italy (Marconcini et al., 1977). Figure 1 shows contours of the altitude of the basement rock. Figure 2 shows typical cross sections from that reservoir model. A computational grid was generated from these cross sections, and formed the basis for the history match and depletion studies. A similar simplified reservoir model is needed for Cerro Prieto in the region of the production. Then

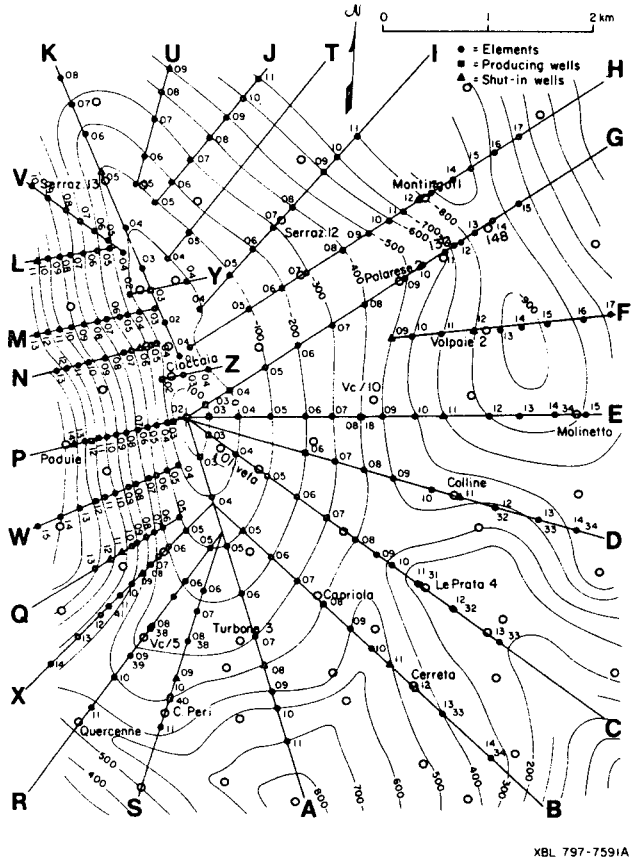

Figure 1. Caprock elevations and geologic cross sections for Serrazzano.

a computational grid can be generated that will accurately represent the significant geological features relative to the flow of fluids in the reservoir.

Reservoir engineering "tools" have been extensively developed in the oil and gas and groundwater industries for isothermal systems. The development of the reservoir engineering hardware and methodology for deep wells was accomplished through research and development in the oil and gas industry over a period of more than 50 years. Recently, the development of tertiary methods of oil recovery, the deep hot gas well technology, and the initial development of hydrothermal resources has helped to provide a few basic "tools" for use in HTG reservoir engineering activities.

Most of the major problems of measurements and analysis of hydrocarbon resources have been solved, and gas and oil production is accomplished by well-trained engineering personnel. This is not the case in HTG resource utilization. In general, the personnel associated with hydrothermal development are experts from related oil and gas disciplines. Most of the major problems of measurements and analysis of hydrothermal

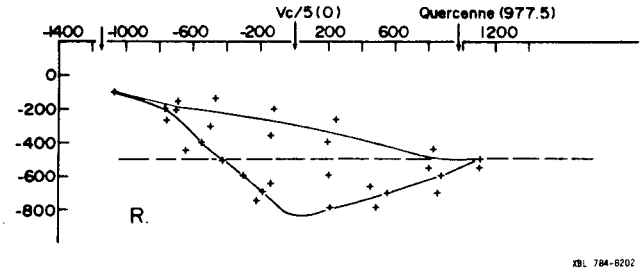

Figure 2. Cross section R from the Serrazzano field.

resources have not been solved. Although HTG resources are being developed in several areas around the world, the HTG situation is absolutely analogous to the oil industry 75 years ago. The technology at that time was in its infancy, but there were places where oil was bubbling out of the earth. No high technology was needed to discover or capture the resource. During those 75 years the need for energy resources has grown so fast that the new alternate energy sources - such as geothermal - must be developed on a much more compressed time scale. The only way to do this is to ensure that the major problems are solved quickly. To solve the major problems that still confront the HTG industry an emphasis on basic research and development is needed. In the remaining sections the requirements and availability of HTG measurements and calculations are reviewed.

THE HTG ENVIRONMENT

The first and most important concept associated with HTG resources is stated in the list of reservoir engineering fundamentals above, i.e., each HTG reservoir is unique. Although this is true, it is the task of earth scientists to categorize and generalize to the greatest extent possible. Through this process the "tools" will be developed that will make possible routine evaluation and development of HTG resources. The HTG environment is variable, but we can describe the bounds of our experience and we can define certain categories of mutually agreed upon resource properties.

The first thing to define is "high temperature." For most reservoir engineering and related disciplines, a resource that has temperatures below 150°C can be considered to be moderate or low temperature. Below 150°C very accurate and reliable measurement equipment is currently available, and when making calculations and analyses the thermal considerations are much less important. Therefore, we define HTG systems to be those resources with temperatures exceeding 150°C. The highest temperatures known in hydrothermal systems do not exceed the critical point of the brine. The critical temperature of water is ≈366 °C, and brines having large amounts of dissolved solids have critical points that are a few degrees higher. Dry rock and magma, of course, have been found with higher temperatures.

The pressures in hydrothermal systems are approximately hydrostatic, but the pressures in certain geopressured zones increase with almost a lithostatic gradient below the depths at which the geopressure zones are found. The hydrostatic pressures are usually related to the density of the brine, but the subsurface pressures in steam zones are also related to the boiling conditions at depth.

In all HTG systems the fluids interact with the rock, and the resulting brine is an equilibrated solution of hot water and minerals. The total dissolved solids are determined by the temperature, pressure, and rock types that the fluid has been exposed to during its existence. The temperature at which the maximum solubility of amorphous silica occurs is a few degrees below the critical point of water, but in HTG systems there are always alkali earths and metals present in various dissolved forms. These compounds have interesting effects in the development and evaluation of HTG resources. The major chemical effects associated with the mineralogy are the solution of certain low-temperature stable minerals and subsequent precipitation of different stable minerals at other characteristic temperatures. These chemical and mineralogical reactions can have a profound influence on both the subsurface reservoir behavior and the phenomena that occur in the wellbores and pipelines.

Required HTG Measurements

In the previous section the fluid and rock properties were summarized. Those fluid properties depend on pressure, temperature, flow-rate, and chemical concentrations of dissolved minerals. Hence these properties must be measured in order to understand and evaluate the size and performance of an HTG reservoir. In Table 1 the second fundamental concept of HTG reservoir engineering was: the well system must be considered to be part of the reservoir.

In order to determine true reservoir properties from wellhead measurements, appropriate corrections must be made for the fluid dependence on temperature, pressure, flow rate, and chemical composition. If the appropriate models were available the wellhead data could be used to estimate downhole conditions. Even so, downhole measurements would still be needed, especially during the exploratory phase of development. One reason is that the wellhead measurements cannot indicate where the fluid is being produced from within the well. In addition, complications such as fractures, and multiple production zones cannot be analyzed without transient downhole data.

Before making downhole transient measurements, data on the condition of the well and the static reservoir conditions are needed for subsequent transient analyses. The measurements that provide this information are:

Wellbore conditions
1. Caliper (for open hole or damaged casing)
2. Cement bond logs

Initial Conditions
1. Static reservoir pressure, temperature, and fluid samples
2. Static wellhead conditions

Static wellbore profiles
1. Pressure
2. Temperature

The wellbore profiles are required to provide information on the subsurface heat distribution, and to aid in the application of the wellbore models. Clearly, these static conditions should be as nearly equilibrated as possible.

After the static wellbore properties are known, transient (flowing) data must be obtained to provide estimates for the formation parameters (porosity, and permeability), the location of production zones, fluid state (single-phase, two-phase, etc.), and flow characteristics. These data are subsequently used in conjunction with all other available data in calculations aimed at satisfying the three goals that were stated above.

Instrumentation Availability

The static well condition is often measured while a rig is in place and drilling mud is still in the hole. The types of reservoir engineering measurements that can be made at that time are:

Caliper
Cement bond log
Casing collar locator

Currently caliper and cement bond logs cannot be made at temperatures over about 175°C. Temperature measurements can be made to any temperature using commercial downhole recording equipment. But accurate temperature logs require logging cable with surface readout. The latter is currently limited to no more than a few hours exposure to temperatures of about 260°C. In general, all accurate downhole measurements are limited currently by this cable requirement. The temperature transducers used for these electrical measurements include:

RTD transducer
Thermister
Thermocouple

The first is the most reliable and can survive temperatures to the cable limits. The second is very accurate but is limited to less than ≈250°C. Thermocouples have poor accuracy, but are cheap, and are usually restricted to wellhead measurements where short electrical connections can be used. Currently, the equipment with the highest temperature capability uses a manometer and scribe to record the temperature on a metallic plate wrapped around a clock-driven cylinder.

Pressures can be measured very accurately to the limiting temperature of the downhole electronics, ≈200°C. Moderate accuracy is possible using strain gauge pressure transducers to the temperature limitations of the cable. The

clock-driven equipment using a low-resolution manometer also allows pressure measurements to essentially any required hydrothermal temperature.

The flow-rate is needed to analyze transient data, but in addition, the relative downhole flow velocity is often very valuable for providing indications of casing damage, and evaluating the production intervals (zones) in a well. Without question these flow related measurements are the most difficult and have the least accuracy and resolution of all HTG measurements for any hydrothermal condition.

Transient Flow Analysis

The measurements and analyses for the isothermal hydrocarbon and groundwater data are well-developed, and the methods used in HTG reservoir engineering are based on these techniques. The information that can be obtained from the classical isothermal methods includes:

1. The well condition (quantitative appraisal of how the drilling, has damaged the near wellbore formation)
2. Productivity or injectivity (steady-state production/injection characteristics)
3. Average formation parameters
4. Leakage (or recharge) from adjacent formations
5. The extent and flow characteristics of fractures

Recent studies (Miller, 1979a,b) have shown that some of the traditional methods that were derived for isothermal systems are not applicable, or are usable only in special HTG circumstances. In the case of two-phase flow in the wellbore or in the reservoir no satisfactory analysis methods are currently available to the well test analyst. Since all HTG reservoirs eventually flash to steam in the formation after prolonged production, and since almost all deep HTG production is from fractured rock, it is safe to say that the two major unsolved problems in HTG reservoir engineering are the analysis of transient hydrothermal data from natural fractures, and two-phase flow phenomena. These complications cannot be easily analyzed using analytical approximations because both fractures and two-phase phenomena introduce additional degrees of freedom (non-linearities) that cannot be removed by any satisfactory approximation. In the case of fractures the new degrees of freedom arise from the anisotropy, and in the case of two-phase phenomena, the new degrees of freedom are associated with the propagation of separate phases (i.e., a saturation front). The latter phenomenon is subtly influenced by gravity, which again results in a directionality that requires two- or three-dimensional models for satisfactory analysis. This leads us to review the final set of "tools" that are used by reservoir engineers to make the estimates needed for reserves, depletion, and optimization of recovery.

Numerical Modeling

Every HTG resource is evaluated in a series of increasingly accurate estimates for reserves and depletion. The simplest approach is to use zero-order lumped models for estimation. This can only provide estimates that are obtained by using broad averages for the formation properties and hydrothermal characteristics. The quality of such a result is very dependent upon both the resource being analyzed and the skill and experience of the analyst. Models have been developed for single and two-phase reservoirs, and for dual permeability and dual porosity reservoirs. The results from these models are primarily heuristic, since quantitative results, in general, are only available for cases which satisfy the restrictive assumptions that are inherent in zero-dimensional models.

During the past few years several distributed models have been developed for use with large computers. These models are based on the conservation laws with detailed initial and boundary conditions required as input. Computer programs are now available for use in the following types of calculations:

Single-phase reservoir flow
Two-phase reservoir flow
Two-phase multicomponent reservoir flow
Wellbore transients for two phase and two components.

Currently, research is under way at LBL to link the two-phase transient wellbore and reservoir models to allow detailed study of complications associated with heterogenieties, two-phase flow, and noncondensable gases.

The distributed models (reservoir and wellbore simulators) allow the multidimensional phenomena to be computed. The lumped models cannot provide these capabilities due to their zero dimensional nature.

Reserves and Depletion

In hydrocarbon reservoirs the reserves are related to the amounts of mass of fluid in place. Since the resources are produced using the energy stored in the compressed fluid and rock, the depletion is dependent only on the fluid density. (The matrix is usually assumed to be approximately rigid, but the pore volumes are assumed to be compressible.)

The HTG reservoir reserves are determined by the amounts of both mass and energy in place. Whereas single-phase depletion is dependent upon average reservoir pressure decline, the two-phase depletion is dependent upon average reservoir temperature decline. In general, the pressure decline is dependent upon both the average density and average temperature. But the two-phase depletion (average temperature) is almost solely dependent upon the rate of boiling in the reservoir. At large mass extraction rates, the depletion (pressure vs. time) occurs at the same rate as at low extraction rates. When the reservoir liquid is approximately exhausted, the rate of boiling declines rapidly and the depletion becomes primarily dependent upon the average reservoir density.

In all cases the initial depletion is strongly dependent upon the presence of dissolved gas, and

is less dependent upon reservoir gas content as the average reservoir pressure declines.

To use an HTG resource optimally a compromise is required between the number of wells that are drilled and the maximum allowable reservoir drawdowns. To determine what the drawdowns will be, well testing is necessary. Production tests provide estimates for long-term productivity. Interference tests provide estimates for the average reservoir properties, and for hydrologic barrier locations. These estimates obtained from well tests provide the basis for drawdown calculations. For optimal HTG resource utilization, injection of fluids is required. However, a second compromise is necessary between the amount of heat swept out of the hot reservoir rock by the injected fluid and the breakthrough time of the cool fluid at the production well. The most efficient and economical production and injection strategy is much more difficult to estimate for the HTG reservoirs than it is for isothermal hydrocarbon resources. Figure 3 illustrates the interrelated picture of the reservoir management considerations. The strategy chosen for field management is also dependent upon the available reservoir data. If the latter data are relatively incomplete, a more conservative field management strategy is necessary. That is, lower reservoir power output will be chosen to prevent premature resource depletion. A change in the production fluid characteristics that would adversely impact the power generating equipment could result in a change from an economically produceable resource to one that is submarginal, or uneconomical. For example, if the field changes from predominantly liquid in the reservoir to predominantly steam, the wellhead pressures may fall below the existing turbine inlet requirements.

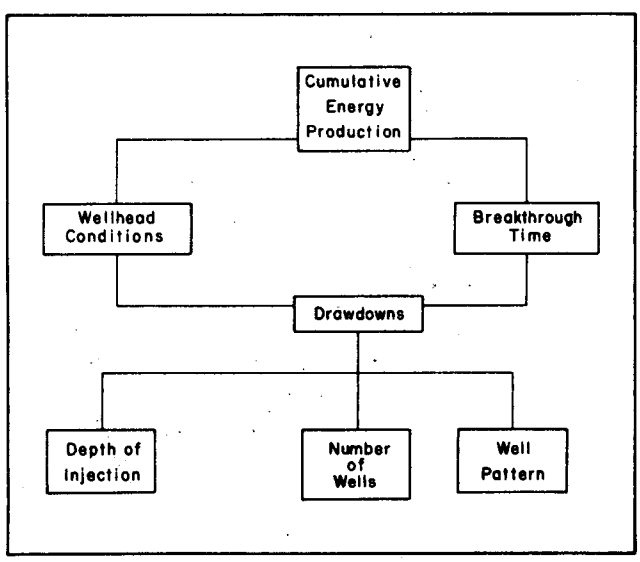

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Figure 3. Interrelationships among important field management variables.

SUMMARY AND CONCLUSIONS

During the first two years of the cooperative research at Cerro Prieto, we have been primarily involved with gathering data and developing the methodology needed to interpret the data. In order to focus on the purpose for these activities, we have reviewed the general approach that is taken by HTG reservoir engineers during the exploration and development phases of geothermal field development. More importantly, the role of reservoir engineers in HTG resource development has been delineated.

The three major aims of the reservoir engineering activities were defined to be:

1. Estimation of reservoir reserves
2. Estimation of reservoir depletion
3. Optimization of resources (i.e., field management optimization).

These activities, we have pointed out, begin during the exploratory phase of HTG resource development, and continue through the final production phases.

We have reviewed the comparison between petroleum engineering (reservoir engineering) and HTG reservoir engineering, and noted that with the exception of the Stanford Educational Program in petroleum engineering there is no formal geothermal curriculum at major universities that culminates in a degree in geothermal reservoir engineering. The result of this lack of a formal degree program in HTG reservoir engineering is that the required expertise is obtained from petroleum engineers who have developed a sufficient background in the additional disciplines of thermodynamics and hydrology that are prerequisite in HTG engineering.

A review of reservoir fundamentals was presented, and was summarized in Table 1, and the general methodology used in HTG reservoir engineering was outlined. The importance of synthesizing all of the geological, geophysical, geochemical, reservoir engineering and mineralogical data to construct a consensus model of the geology and hydrology of an HTG reservoir was emphasized. The improvement of such models begins with zero-order estimates for reserves, lifetime, and optimal field management strategy. These initial estimates are improved by continuously collecting, and evaluating resource data during the exploration, development, and mature production phases of the HTG project.

The importance of making certain types of measurements during the development of the HTG system was reviewed and the relationship of those measurements to the chemistry of the brine, and subsequent phenomena that occur in the reservoir, boreholes, and surface equipment was discussed. A summary of the available instrumentation to make HTG measurements was presented and remaining requirements for HTG reservoir engineering needs were reviewed. The primary limitation in making these measurements was identified as logging cable survival above 260°C. Although higher temperatures can be endured for a few hours, the HTG reservoir engineering measurements often

require days, weeks, and even months of continuous measurement. These are currently not possible at high temperatures (>250°C).

The primary analysis and interpretation problem is associated with two-phase wellbore measurements. Recent studies have shown that we have no satisfactory analysis techniques for two-phase well tests--including drawdown tests, step-rate tests, or buildup tests. The current research at LBL is emphasizing the development of a linked wellbore-reservoir simulator. The latter will have both practical and heuristic value, and may point the way toward acceptable engineering approximations for interpretation of test data from flashed wells and two-phase reservoirs.

Finally, the important aspects of determining HTG reserves and estimating reservoir depletion were covered briefly. The compromise between economically feasible well patterns and satisfactory reservoir production characteristics was discussed, and the importance of making the field management decisions using adequate data from well tests was noted.

ACKNOWLEDGMENT

Work performed for the U. S. Department of Energy, Division of Geothermal Energy, under contract W-7405-ENG-48.

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This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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