GEOTHERMAL RESERVOIR ENGINEERING IN PERSPECTIVE

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ABSTRACT

Geothermal systems are dissipative hydrothermal systems in which most of the heat in the upper crust of the earth is transferred by circulating fluids rather than by conduction. The rising column of hot water sometimes leads to the existence of thermal areas at the surface and it is this mushroom of hot water which is explored for by geological, geochemical and geophysical methods. A knowledge of the physical processes operating within a geothermal system is required to make an assessment of the reservoir. In boiling hot water systems the upward migration and segregation of the steam water mixture is influenced by the relative permeabilities of the rock to the steam and the water phase and also depends on the volumes of each phase in the permeable volume of the rock. Since most high temperature geothermal reservoirs occur in highly fractured rock the double porosity storage theory has been put forward to model the rate at which heat and fluid can be transferred from the matrix to the fractures. The assessment of geothermal reservoirs involves techniques of estimating heat and fluid reserves, reservoir performance, well production capability and predicting the future trends of the behavior of the reservoir under exploitation. Well testing provides data to all sectors of geothermal reservoir engineering, including the in situ reservoir properties such as storativity and transmissivity, reservoir modeling and numerical simulation.

Due to the high compressibility of vapor dominated and two phase geothermal systems the pressure pulse induced due to exploitation travels slowly and wells act as isolated reservoirs making it difficult to use interference data. In liquid dominated geothermal systems the large mass withdrawal from the wells creates a pressure pulse which travels rapidly inducing large inflows into the system and the standard well tests can be used. In general with performance data available it is possible to first performance match with a lumped or a distributed model and then to forecast.

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1 INTRODUCTION

1.1 Scope of work

Kenya is one of the many countries in Africa lying on the Great African Rift Valley extending from the Red Sea to Mozambique and is thus endowed with enormous geothermal resources. The Olkaria geothermal field represents one of the fields which has been developed to date and at present active exploration is undergoing to delineate the other fields (Di Paola, 1985). The enhanced development at Olkaria and exploration of geothermal resources in the country requires trained manpower in this sector and the University of Nairobi is investigating the possibilities of introducing some basic courses in geothermal exploration and evaluation in the Faculty of Science and in geothermal engineering and utilization in the Faculty of Engineering in order to fullfill the increasing demand and to equip the graduates with a good background in these fields before they embark on postgraduate studies. Accordingly, my first aim was to study the structure and the organization of the training course, and learn the interrelationship between the various disciplines necessary in geothermal projects from the initial to the final stages to consider the adaptation of some of these courses in Kenya. The general lectures in geology, geophysics, geochemistry, drilling, utilization and reservoir engineering in the first six weeks were followed by lectures in the specialised field of borehole geophysics and reservoir engineering for eight weeks. A two week field trip during which seminars on the geology, exploration, development and the multipurpose utilization of geothermal energy in Iceland were held, was undertaken to view the actual projects discussed. A separate report covering the first half of the training course will be presented to the University of Nairobi.

The second half of the training course was spent in studying how data from multidisciplinary scientific and engineering subjects is used to formulate integrated and coherent models of geothermal systems to study the physical processes operating within the systems. The essay which follows is the outcome of a broad based literature survey in this field and deals with reservoir physics and some basic concepts of the science of reservoir engineering. Mathematical formulations of the concepts discussed are not included but can be found in the references cited.

The reports written by the former students at the training course which have been presented to me by the UNU will be deposited in the central library and the excellent lecture notes and working manuals will serve as teaching material in the University of Nairobi when courses in geothermics are introduced.

1.2 Brief historical background

There is a growing need throughout the world for increasing quantities of energy in all forms. Obviously the natural forms of energy that are readily available at low development costs are those in greatest demand. In countries having little or no petroleum resources and which have not yet attained a high level of technological and scientific development most interest is being shown in the newer forms of energy such as solar, biomass and wind energy. One of the least expensive energy sources is natural geothermal steam and although this form of energy has been recognised for centuries, it is only during the last twenty or thirty years that serious efforts have been made to harness it. Natural geothermal energy is now being produced in California, Iceland, Italy, Japan, Kenya, Mexico, New Zealand and many other countries not only for the generation of electric power but also for many direct industrial, agricultural and space heating purposes. Two of the largest industrial uses are the diatomaceous earth drying plant in Iceland and the wood processing plant in New Zealand. Geothermal energy provides nearly 40% of the total energy demand in Iceland and is extensively used for space heating.

Over most of the surface of the earth conductive heat flow from deep in the crust is normal and on the average this heat flux is 60 mW/msq and this maintains an average temperature gradient of 30°C/Km. Both this heat flux and the temperature attained at reasonable depths are too low to have any economic value at present. However, in anomalous regions the local heat flux and geothermal gradient may be much higher than these values and there may be surface discharges of hot water and steam. These zones thus provide a source of energy (hot rock) and the transport medium (fluid) through which we may exploit this energy. Surface studies are thus usually made in the "steam seep" zones and exploratory wells are drilled. The potential of any "hot" anomaly, however, has to be evaluated before any development can be initiated and recently there have been efforts to apply the most modern geological and reservoir engineering principles in order to quantify the reservoir parameters, particularly those related to estimates of reserves and future productivity.

Geothermal reservoir engineering draws heavily on the experience of underground petroleum and groundwater technology. Geothermal reservoirs are in general more complex and production of natural steam and hot water presents different problems to those encountered in the production of oil or groundwater. For example steam and hot water may be essentially single component systems, while hydrocarbon systems are mostly multicomponent fluid systems. Heat effects are much larger for geothermal than for hydrocarbon systems and the natural steam production may or may not be isothermal, while production of petroleum reservoirs is considered normally to be isothermal. However, the common thread among the reservoirs being fluid flow, petroleum and groundwater reservoir engineering principles may be applied to natural steam or hot water reservoirs if the inherent differences in the systems are considered. The technology that binds them together is well test analysis.

The developments in well test analysis in petroleum reservoirs since the drilling of the Drake well in 1859 have been reviewed by Ramey (1981) and those in groundwater reservoirs by Witherspoon (1978). A major landmark in the history of science of well testing was the general recognition during the early 1930s of the importance of the phenomenon of transient flow, which was recognised more or less contemporaneously in hydrology by Theis (1935) and petroleum engineering by Hurst (1934) and Muskat (1934). Miller, Dyes and Hutchinson (1950) and Horner

(1951) developed techniques for pressure buildup analysis and many workers have extended the buildup analysis to evaluate borehole damage, presence or absence of fractures and well bore storage effects. In 1967 Matthews and Russell (1967) published a monograph entitled Pressure Build Up and Flow Tests in Wells. Since the mid 60s to the present Henry Ramey and his associates at Stanford University have made important contributions in the development of well testing. The early 1970s witnessed a phenomenal breakthrough in the development of sensitive, automatic data gathering and recording devices and this provided a fresh impetus and challenge to develop new techniques of testing and analysis of data. This resulted in the development of pulse and interference testing and the modern log-log type analysis and the publication of a second monograph on well testing by Earlougher (1977).

Research effort relating to geothermal systems and their exploitation has followed a pattern similar to that for groundwater and petroleum systems. The earliest exploitation of geothermal steam for the production of electric power took place in Larderello, Italy in 1904 but did not generate much reservoir engineering technology. Grant (1982) has reviewed the developments since Einarsson (1942) developed the idea of deep circulation of groundwater as the mechanism supplying surface discharge of geothermal fluid in Iceland, and Bodvarsson (1951) began defining the heat transfer problems associated with geothermal exploitation. In the 1950s the development of geothermal fields in New Zealand, Iceland and USA led to improved understanding about how cold meteoric water may circulate to depth, be heated by magma and then flow up to build and sustain geothermal anomalies (Banwell et al. 1957; Bodvarsson, 1964; White, 1957). In the 1960s there was considerable development in many other parts of the world and data from vapor dominated and liquid dominated fields was being collected, and late in the decade the first attempts to apply petroleum techniques were made by Whiting and Ramey (1969). Since then coherent models of reservoirs in many parts of the world have been developed that are consistent with both the large scale concept of convecting systems and the small detail revealed by well testing. The increased exploration and exploitation of geothermal energy led to the first United Nations Symposium on the Development and Uses of Geothermal Resources in Pisa (1970) and a second one in San Francisco (1975). Simulation studies of many geothermal systems are also reported in the Transactions of Geothermal Resources Council and the Proceedings of Geothermal Reservoir Engineering Workshops, Stanford University.

2 RELATIONSHIP TO OTHER SCIENCES

2.1 Introduction

The sequence of activities undertaken during a geothermal exploration programme have been reviewed by McNitt (1977) and are summarised in Fig. 1 The initial phase consists of conducting multidisciplinary regional surveys to identify any promising prospects. In geological studies special emphasis is placed on tectonic and stratigraphic setting of the area, including a study of recent faulting and the age distribution of young volcanic rocks. Hydrologic studies include the mapping of aquifers, aquicludes and the static groundwater levels to determine the regional groundwater flow pattern, and the measurements of surface discharge from springs. Temperature and discharge measurements of natural hot water and fumaroles provide information on the heat flow from these sources which has to be added to the surface heat flux data in the determination of the total heat output from an area. Geochemical studies involve sampling water and gases from hot springs and fumaroles, and analysis of these samples provide information on the temperature to be expected at depth, the chemical nature of the fluids and the source of recharging water. Geophysical surveys are especially useful in delineating the boundaries of a prospect and for pinpointing targets for exploratory drilling. Electrical resistivity surveys are extremely useful as the conductivity of a porous medium containing brine or hot temperature fluid is extremely low. Seismic, gravimetric, magnetic and microearthquake surveys are also useful in defining reasonable conceptual models of a prospect. Shallow drill holes for the purpose of determining the geothermal gradient and the surface heat flux data are also useful to guide selection of a site for exploratory drilling. However, the acid test of any exploration programme is the drilling of an exploratory well.

When and if a successful borehole is encountered in a prospect the production engineer is responsible for the construction and maintenace of well head, steam collecting and seperating equipment and allocating plant load to individual wells. He also has the main task of determining the yield characteristics, the potential and efficiency of the well, and analysing the well test data to determine whether or not some remedial work is required to obtain optimum production from existing wells. The problems involve answering questions such as (a) is poor performance due to a low driving force moving the fluid into the well (low formation pressure), (b) due to low formation permeability, (c) due to a damaged well bore condition. The reservoir engineer is interested in the long term behaviour of the well and the reservoir. Important questions he must answer are (a) what is the optimum plan of development of the reservoir, (b) how many wells and what sort of pattern of wells will be required for the optimum development of the reservoir, (c) what sort of fluid will the reservoir produce throughout the producing life of the reservoir, and (d) what will be the future productivity of the wells.

This means that it is necessary for a reservoir engineer to estimate the areal extent, thickness, porosity and fluid content of the reservoir from early data obtained from geophysical measurements, geological information and quantitative analysis of core samples obtained from the reservoir. Core analysis involves the determination of storage of fluid within the pore space or the porosity of the rock sample. The fraction of pore space which is occupied by liquid involves the determination of the transmissivity of the reservoir rock to the reservoir fluid and well testing is the most common and reliable technique for providing data on the in situ reservoir parameters. The analysis of data provides the first estimates of formation permeability and other important producing mechanisms and involves the interpretation of pressure-time information obtained following a specific schedule of production of a well or wells in a reservoir, while reservoir modeling provides quantitative estimates of future fluid flow from the reservoir as a whole. Mathematical reservoir modeling involves developing a conceptual model of the field under investigation, quantifying the model with data obtained from well testing (permeability, the volumetric extent of the reservoir, etc.) and calibrating it with the history of the field under exploitation.

A conceptual model of a geothermal system is a qualitative or a descriptive model of the system or part of it that incorporates the essential physical features of the reservoir under development. It should describe the source of water, mechanisms for water transport to depth, the process of heating in the deeper sections of the system, the subsequent rise of buoyant hot liquid, its dispersion into chargeable aquifers, the cooling of aquifer liquids by near surface effects and all impervious boundaries that might effect future production. To construct and correctly interpret such a detailed conceptual model requires input data from a wide spectrum of geological, hydrological, geochemical and geophysical measurements as well as a profound understanding of the hydrodynamics of liquids convecting in rock formations. Vigorous convection will occur only in geological formations having adequate permeability derived from intergranular spaces and fracture distributions.

Before any field developments take place it is necessary that the conceptual model of the field be quantified because an estimate of the life and forecast of the performance of the reservoir under certain production constraints is required for planning, development, utilization, and the project economics. The different modeling approaches available to a reservoir engineer can be classified in different categories depending upon their complexity level and the methods used for the solution of the governing equations. There are basically two types of mathematical models, the lumped and the distributed parameter models and both are based on the laws of conservation of energy, momentum and mass, or concentration of chemical substances, which in fact is the mass conservation of the chemical species involved. Lumped models treat the system as an entity, consider the total flows of mass, energy, etc. in the system and the resulting equations may be solved analytically. On the other hand the distributed parameter models treat the system as an assemblage of elements, consider partial flows through finite or infinite elements and the resulting differential equations are highly nonlinear and have to be solved numerically. Whiting et al. (1969) and Bodvarsson et al. (1984) discuss in detail the lumped and distributed models respectively. The possible choice on how "lumped" or "distributed" a model should be depends upon the developmental stage of a field, the spatial and temporal extent and the accuracy of measurements of different parameters, and the purpose of modeling. As the data available before production is always incomplete, the initial lumped parameter modeling studies involve a variety of hypothesis concerning geology, temperature distribution and groundwater flow. Some parameters may be well defined from exploration data and well test analysis and some poorly or not at all. The unknown parameters are usually assumed or left to be filled later on by history matching.

The history of the field under exploitation should also be modeled. To find a reasonably unique problem which generated the answer (historical field data), it is important that the proposed model match geologic, geophysical, geochemical, and hydrological data at least. It is not necessary that a completely unique problem be discovered as long as the model closely resembles the historical data. This is usually a recurrsive procedure with trial and error adjustment of parameters. Sometimes major revisions of the basic conceptual model are required to obtain a satisfactory match to the actual field observations. When testing the validity of the model, it is possible to use both direct and indirect evidence. The direct evidence comes from the distribution of groundwater potential throughout the reservoir and its variation at observation wells and indirect evidence can be obtained from changes in groundwater salinity. After history matching some predictions of the future behaviour of the reservoir under exploitation can be made by which the model's predictive value can be judged and from which the development and management of the reservoir can be guided.

2.2 An example of reservoir modeling

Modeling studies of the Olkaria geothermal field illustrate very well the relationship of earth sciences, well test analysis and reservoir physics in building an initial working conceptual model and refining it as more and more data becomes available. Geothermal exploration in the Rift Valley of Kenya started in 1970, and at the three prospects shown in Fig. 2, geological, hydrological,geochemical and geophysical surveys were carried out to delineate the geothermal reservoirs responsible for the intense surface thermal manifestations in these areas in the form of hot water springs, fumaroles and geysers. In 1972 it was decided to concentrate drilling in the Olkaria prospect (Noble et al. 1976). An infra-red imagery of the area showed that the thermal activity in the form of fumaroles and hot ground is scattered over an area of 50 km^2 and is typically associated with N-S trending faults. Geological surveys indicated that the area is underlain by volcanic rock with basalt dominating below a depth of 500 m which would act as a caprock to the system and an underlying zone of rocks mainly consisting of tuffs. Hydrological surveys showed that the general groundwater movement is into the Rift Valley from the Mau and Abedares Range of mountains and southwards from Lake Naivasha, and the former areas were assumed to supply deep recharge to the system. Geochemical analysis of gas compositions in steam from fumaroles suggested that underground temperatures exceeded 300°C near the OLK2 well (Fig. 3a). Geophysical resistivity surveys showed four areas of less than 20 Ohm-m, and seismic surveys indicated that the basement rocks reside approximately 1600 mbsl (Bhogal, 1980).

The first conceptual model of the system (not shown) was largely based on the interpretation of electrical resistivity data on the premises that since the electrical resistivity of a porous medium containing dry steam can be very high, electrical resistivity surveys could discriminate between dry steam and the underlying hot water reservoir. The model conceived a dry steam reservoir occuring in patches in the area above a depressed water level. Well OLK1 was sited to exploit dry steam. The well gave negative results, with a temperature of 126°C at 1000m depth, but the water level was found to be very low. The steam zone was not discriminated and a new conceptual model of the field had to be built. Although another four cellars had been constructed in the vicinity of OLK1, it was decided to drill in the area which showed low 20 Ohm-m resistivity and favourable gas chemistry. Well OLK2 gave positive results penetrating a 100 m thick steam zone below 650 m depth. Aquifers were encountered at greater depths but the well was drilled to 1350m and the maximum downhole temperatures were about 280°C. Another five wells were drilled as offsets before a feasibility study to harness the steam was carried out by SWECO (1976).

Figure 4(a) shows the conceptual model and the processes operating in the reservoir around Well OLK2. It incorporates all the geological, lithological and downhole pressure and temperature information available in 1976. Circulating groundwater attains a high temperature of 320°C at 1600 mbsl under the area and due to the density difference between the hot fluid and colder water in surrounding regions the fluid rises under a buoyancy force. About sea level the water has reached the saturation pressure of 320°C and boiling initiates steam bubbles in the water. The rising fluid becomes a mixture of steam and water and the temperature of the mixture follows the boiling curve of water as pressure decreases upward. The upward migration of the steam water mixture is influenced by the relative permeabilities of the rock for each phase but these depend in turn on the relative volumes of each phase in the permeable volume of the rock. At low steam saturation the relative permeability for steam is so low that the steam is practically stagnant or carried with the water as small bubbles. As the steam saturation increases at lower pressures the relative permeability for steam increases and separate movement of the steam bubbles becomes possible. The steam then rises faster than the water and gradually dominates in the largest channels where resistance to flow is lowest. The water lags behind and the loss of steam with time builds up a concentration gradient of increasing salinity. At 1200-1250 masl, the impermeable caprock prevents further rising of the steam and the low piezometric head of the reservoir water allows the steam to accumulate under the caprock at a pressure of 35-38 bars absolute. Although steam is dominating in this zone, water is also present as condensed porewater and this flows downwards. With rapid developmentand exploitation (45 MWe in April 1985) and the increasing amount of data being gathered at Olkaria the reservoir model has been refined. Drilling and reinterpretation of resistivity data indicate that there is a lens of saline water overlying the steam reservoir and well test analysis indicates that the steam zone thickens eastwards. These observations have been incorporated in the new model shown in Figure 4(b).

New exploration wells OW101 to OW106, continued geological and geophysical exploration, and reinterpretation of previous data with the experience gained over the last ten years have also led to refinements of the original conceptual model of the Olkaria geothermal system. Lithological and well test data from the new wells has provided spatial information about the subsurface geology, the depth to the steam zone and the underlying boiling reservoir. The geological model incorporating all this information is shown in Fig. 5. The reinterpretation of geophysical data has redefined the upflow zone in a different area, has demarcated the areal extent of the saline aquifer and positive suggestions regarding the recharge and outflow areas from the system have been made (Fig. 3b). Well test data indicates anomalously high pressures in OW301 compared to the present production area around OLK2. At present, one of the important question about the Olkaria resource is whether the OLK2 east reservoir and the OW301 west reservoir are hydrologically connected or whether two separate resources are present (KPC, 1984). Chemistry of the fluids will provide an answer. If they are separate, a new conceptual model will have to be formulated. It will provide detail to the original model.

The development of the quantification processes of the Olkaria field follow a trend parallel to the conceptual models discussed above. The first study by Sweco (1976) used the models shown in Figs. 3(a) and 4(a) to estimate the resource energy of the reservoir. Using an areal extent of 12 km^2 for the low resistivity zone around well OLK2 and a thickness of 2.8 km for the reservoir, porosity of 10%, recovery factor of 10% a resource of 170 MWe for 25 years was estimated. In addition to this the potential of the 100 m thick zone was estimated to be 24 MWe for 25 years on the assumption that it had a constant thickness and similar areal extent as the underlying water reservoir. The probable resource for the whole area was estimated to be 218 MWe for 25 years assuming that the other low resistivity areas have a reservoir similar to the one discussed above. This lumped parameter model study based on data from six wells in a small area was used for planning and developing a 15 MWe power station. Simulation studies by Bodvarsson (1980), Bodvarsson and Pruess (1981) have used numerical modeling techniques to investigate the effects of vertical and horizontal permeabilities on the generatig capacity of the Olkaria field, and also have investigated the effects of exploiting aquifers at different depths. The results of these simulation studies indicated that the well field area (East Olkaria) was capable of providing steam for 45 MWe power production and the field has been developed to that capacity by April 1985. The conceptual model of the field shown in Fig. 4(b) with twenty two producing wells has been used to develop a well by well (distributed) three dimensional numerical model of the field that can be used to predict with confidence the future behaviour of the wells, the effects of reinjection, and the overall depletion of the reservoir (Bodvarsson et al., 1985). The surface locations of wells are used as nodal points to develop a grid and the outer elements without any wells are assumed to provide recharge to the well field. To determine the vertical dimension of the model the locations and relative strengths of feed zones for all of wells are considered. The model matches reasonably well the flow rate and enthalpy history of all the Olkaria wells. The main conclusions from the study are that 60% of the production fluid comes from the liquid zone and the rest from the steam zone, and the present East Olkaria area can apparently easily handle power production of 45 MWe for the next 30 years.

The above example clearly shows that the extent of available data and the accuracy of the measurements of different parameters play a dominant role in the choice of a particular model. It is for example an "overkill" to use a complex, finite difference, distributed parameter model to simulate a field where only the bulk parameters are known from two wells. But of more importance than this are the basic assumptions made in a particular conceptual model.

3 THE APPROACH TO RESERVOIR ENGINEERING

3.1 Introduction

To generate a physical appreciation of the mechanism of natural steam production it is helpful to consider the physical processes operating within the system before its response to exploitation can be modeled. Geothermal systems are generally of a complex nature and contain many zones representing different physical states. Fig. 6 is a vapor pressure curve for water and presents four regions of physical states in which geothermal activity can occur: A, the supercritical region; B, the single phase steam region; C, the liquid dominated region; D, the liquid saturated region. In three of these regions A, B and D the thermal fluids occur in a single phase and the vertical pressure gradient is proportional to the density of the fluid. The liquid saturated region D contains a class of geothermal systems where temperatures never reach boiling and are mostly found in the ocean crust along constructive plate boundaries where circulation is a single phase convection of sea water, (Red sea, the TAG field of the Mid Atlantic Ridge near 26 N, the Galapagos field). The geothermal systems in the south west of Iceland on the Reykjanes peninsula are located where the Mid- Atlantic divergent plate boundary enters the island and gives rise to boiling systems whose fluids have a salinity roughly two thirds that of sea water (Kjaran et al. 1979).

Case A is a geothermal reservoir at a pressure and temperature above the critical condition for water and such conditions are expected in systems that penetrate deep into the crust where young intrusions have generated supercritical temperatures. The fluid in such systems remains single phase to complete depletion as pressure declines. Although there is a slight decrease in formation temperature with a decline in pressure, single phase gas expansion in a porous medium is essentially isothermal. Case B is a single phase steam reservoir and such conditions are expected on active volcanoes where low pressure steam is common at shallow depths. Such a system remains steam filled with pressure decline, and again the pressure decline is nearly isothermal. Case C is a high temperature, liquid dominated reservoir initially, and the pressure decline is nearly isothermal until pressure reaches the vapor curve. To uniquely define the physical condition on the curve an additional parameter such as the water saturation is needed, and the density of the mixture of water and vapor can be defined as the weighted average of both phases. The vertical pressure gradient is intermediate between that for static steam and water. As in the case of petroleum reservoirs, expansion of the initial compressed liquid results in a rapid decline in pressure per unit mass produced. Boiling causes formation of two phase system which arrests rate of decline for a time. Pressure decline continues until the system boils dry, at which time rapid pressure decline takes place as dry steam expands from the system. For example, exploitation at Wairakei, New Zealand, has induced a vapor dominated zone in the upper part of a liquid dominated system.

Extraction of geothermal energy is a heat mining operation from a fixed reserve, which may be replenished to a certain degree by recharge of cooler water, and although there is some continuity in the response to fluid extraction from liquid to vapor dominated systems there are some major differences. Exploitation of liquid dominated fields induce changes in the properties of the fluid such as enthalpy, density, viscosity, compressibility and relative permeabilites of water and steam in the two phase system start playing a dominant role. The inherent differences in the natural geothermal systems, and the induced changes in the system components and their properties require different methods for the assessment of reserves and their response to exploitation.

3.2 Liquid dominated reservoirs

Many aspects of the behaviour of liquid dominated reservoirs can be studied with the model proposed by Donaldson (1970b). This model basically consists of a column of hot water fluid moving up through the formations surrounded by and in good hydrological contact with the cooler fluids (Fig. 7). By adjustment of the temperature of the hot column at depth, the vertical permeability of the formation, the rate of upward flow and (if necessary) the non-condensable gas content, the fluid may be made to flow up as water all the way to the surface or boil to various depths on the way up. For liquid dominated single phase reservoirs the model is visualized without the two phase and upper zones and with all wells tapping the hot water below. In the natural undisturbed state the heat in the reservoir has been built and maintained by a flow of hot water from below. If fluid is now withdrawn from wells in this reservoir the internal pressure drops and stimulates flow from the sides and may alter the base inflow and surface outflow. The base inflow still brings in hot water and the side flow brings in cold water which does not get into the central reservoir immediately and thus does not lower the overall enthalpy. Rather it removes heat from the hot rock at the side boundaries creating a slow moving cold front that reduces the reservoir size but not its internal characteristics.

The resource energy available from the hot fluid can be obtained by the volume method of Muffler and Cataldi (1978) which assumes no heat conduction from the hot rock into the fluid. Typically only 5 to 15% of the total energy is in the fluid and the large part is in the formation. A very small fraction of the total heat reserve is mined if the extraction process just consists of taking the hot fluid. The cold sweep model of Bodvarsson (1974) is the opposite extreme of the constant volume model. In this case the reservoir is subject to recharge by cooler water equal to the amount withdrawn. The withdrawal of fluid from a well creates a pressure transient which propagates to the boundaries of the system where it induces cold recharge into the reservoir. A cold pressure front thus sweeps through the reservoir and mines heat from the formation which contains the bulk of the heat content of the reservoir. This is a very desirable mode of exploitation because it means that the wells can have a long lifetime as their field of exploitation is the entire field, and all the heat in the rock is mined. The rate of inward movement of the thermal front is considerably slower than the actual fluid velocity. In permeable rocks, tens to hundreds of years may be required for cold water to reach production zones. However, in some fractured reservoirs more rapid quenching of wells along high permeability channels can occur (Horne, 1981).

One of the fundamental aspects of any reservoir evaluation is the determination of the aquifer properties such as permeability and storage. These parameters are important in determining the natural flow of hot water through the aquifers and its response to extraction. This information is normally obtained from test pumping wells. The aquifer parameters which can be obtained by the use various pumping tests are shown in Table 1. The performance test is one of the many tests that can be performed to provide guidance on the optimum rate of the supply source and consists of pumping the well at various discharges and is usually undertaken by incremental increases either in stepwise fashion without recovery or in what amounts to a series of short tests with full recovery after each stage as shown in Fig. 8. Knowledge of the initial performance of a new well will provide the well operator with valuable standard against which to compare any changes in yield performance during the history of the well. Yield-drawdown curves may be produced which visually present information on the performance of a well, and the efficiency of a pumping well can be determined by using the methods developed by Jacob (1946). The pressure drops within the wellbore can be written as

$$P = BW + CW^2$$

where P is the pressure drop, W is the discharge rate and B and C are constants. The first term on the right hand is due to the pressure drop in the reservoir as well as skin effect around the well. The second term is due to turbulent pressure drop. A plot of P/W versus W results in a straight line from which B and C can be determined. With known values of B and C the equation can be used to calculate pressure decline for various rates, and suitable pump arrangements can be designed. Constant rate pumping tests can also be used to determine the hydraulic properties and the nature and limits of the aquifers. In radial, homogeneous, and confined aquifers of uniform thickness the Theis log-log type curves can be used to obtain the aquifer parameters. When the aquifer is overlain by a confining bed of semipermeable nature, then the reduction of head within the aquifer as a result of extraction, may allow water to leak vertically through the confining bed as an increment to the aquifer. With continued pumping a quasi-equilibrium state will develop when the total leakage is equivalent to total extraction as in the heat sweep model above. Hantush and Jacob (1955) have presented the "leaky type curves" in which the divergence of the field data from the truely confined condition of Theis curves is indicated as being due to leakage. In unconfined (or water table) aquifers the response to well abstraction is effected by gravity drainage of the part of the aquifer. This produces complications arising from the reduction of both saturated aquifer thickness and the rate of drawdown. Boulton (1963) introduced the concept of delayed yield from storage and introduced a "drainage" function analogous to the "leaky" function. In the liquid state the pressure changes induced due to exploitation are transmitted over long distances in short times (days) and interference tests can be readily applied. The time-changing drawdown at an observation well provides information which can be used to define the properties of the reservoir over large distances, and the response to expoliation can be monitored. The Theis equation which relates the pressure decline at a distance (r) from a well pumping at a rate (W) for time (t) as

$$P_D(t_D,r_D) = \frac{1}{2}[\ln \frac{t_D}{r_D{}^2} + 0.8090]$$

where

$$P_D(t_D,r_D) = \frac{2\pi kh\rho}{W\mu}\,[P_i - P(r,t)]$$

$$t_D = \frac{Kt}{\phi\mu C_t r_W{}^2} \qquad r_D = r/r_W$$

can also be used to estimate the maximum expected drawdown in the whole field at a known distance (usually an observation well). In this case the total production from the field is assumed to be from a single well in a circular drainage area, and knowing the values of storativity and transmissivity from well test data analysis the pressure decline with time (t = 1, 2, -, N, years) can be calculated and compared to the actual drawndown. The actual depletion rate will, however, depend on the geometry of and recharge into the reservoir, and interference between the wells and modeling studies of the field which take into account these parameters can be carried out. Detailed discussion, including systematic development of working equations and applications of drawdown, buildup and deliverability tests as applied to liquid dominated geothermal reservoirs is given by Kjaran and Eliasson (1983). If the initial response to production in a high temperature liquid dominated reservoir is a decline in reservoir pressure, with time this decline spreads horizontally and vertically, and within the exploited reservoir the decline induces changes in fluid properties giving rise to a mixture of water and steam.

3.3 Vapor dominated systems

The essential components of a vapor dominated system are its reservoir of steam and immobile water, an overlying condensate layer and a deep zone of boiling brine. A supply of liquid is needed as the amount of steam produced by these systems far exceeds what could be stored in them as vapor alone. The immobile water or the condensate from convective circulation may be the supply for the reservoir steam but in some steam reservoirs like Geysers and Larderello no water has been found. The term vapor dominated applies to the uppermost portion of the model shown in Fig.4(a), and the convective processes have been described before.

The discharge of steam comes from a region where pressure is nearly constant (steam static) with depth and may initially be wet, dry saturated or superheated. There is, however, a trend for vapor dominated systems to dry up with exploitation and become "dry steam systems" as the Big Geyser and Larderello where pressure gradients are almost zero. If the steam is superheated there is a dry zone around the well through which the steam flows isothermally, beyond which is a zone containing immobile water. The water boils to form steam and this flows to the well taking the mass and the heat with it supplied by the rock mass. Outside the vapor dominated section of the reservoir we may have a liquid dominated region of rocks saturated with cooler groundwater. As the cold water recharge enters the hot reservoir it mines heat from the boundary and boils. The supply of steam to the well comes from the cold groundwater and the energy from the boundaries where the fluid gains enthalpy. In general, as the pressures in vapor dominated reservoirs are largely well below hydrostatic to prevent flooding by cold exterior water there must be low permeability boundaries on all sides reducing external recharge to negligible amounts. In this case a small amount of heat is mined from the rock, and as most of the reservoir heat content is in the rock, such a system may become a "hot dry rock system" and reinjection of water may be necessary to exploit it.

In vapor dominated reservoirs pressure changes move out slowly and each well acts as an isolated reservoir making it almost impossible to measure permeability on any field or zonal scale. Even when some pressure change information is available, the fractured nature of the system limits its usefulness and there may be no clear indications of the thickness of any aquifer in transmissivity evaluation. A sustained well discharge is the only test that may indicate any long term changes with in the entire exploited field and may take years of production. However, the most useful test and frequently used is the pressure build up test. Basically the test is conducted by producing a well at constant rate for some time, shutting the well in, allowing the pressure to build up in the wellbore and recording the pressure in the wellbore as a function of time. The analysis of pressure build up data has been dealt with by Matthews and Russell (1967) and Lee (1981). A vapor dominated reservoir can be treated as an ordinary gas reservoir and all steady well testing equations used for liquid dominated reservoirs may be used if the pressure terms are squared (Russell et al., 1966) or using the Al-Hussiany et al.,(1966) formulation of real gas pseudopressure. In the saturated, immobile water case in geothermal systems the approximation of constant enthalpy linearises the well testing equations and Grant (1978) has suggested a pseudopressure proportional to P (13/7).

The assessment of resource energy available in superheated steam reservoirs can be made using the equation of state

$$P = \rho_S R'TZ/M, \quad R = R'/M$$

where R' is the universal gas constant equal to 8314 J/mole K, M is the molecular weight of water equal to 18 g/mole, Z is the gas deviation factor, P is the pressure and ρ_S is the density of steam. The mass of steam (m) derived from storage per unit decline in pressure per unit area is given by

$$\frac{dm}{dP} = (\rho_S \beta_S \phi h)P = \rho_S (\frac{1}{P}) \phi h = \frac{\phi h}{ZRT}; \qquad \beta \approx \frac{1}{P}$$

where β = compressibility of steam, ϕ = porosity, and the compressibility of rock has been neglected.

A two- phase mixture of water is far more compressible than either water or steam and it may be 100-10,000 times that of liquid water or 10-100 times that of super heated steam (Grant 1982). It takes long (years) for a pressure pulse to diffuse out to the boundaries of the reservoir and induce a recharge. The heat flow out of a well is sustained by the heat supplied to the incoming fluid by rock cooled on the field boundary, so again the well mines heat from the field boundaries. Along with the sideways propagation of the pressure wave and of mass and heat withdrawal front, there will also be some vertical propogation effects. In time the pressure wave will also reach the base of the steam zone and propagate relatively quickly through the saturated section. Water will thus boil at the interface and energy will be extracted from the rock in the immediate vicinity of the well.

The resource energy available from a boiling reservoir may be determined by the intergranular vaporization model of Bodvarsson (1974) which assumes that heat from rock is extracted by a stationary intergranular fluid undergoing vaporization provided the steam phase can be removed continuously. The intergranular fluid remains in fluid phase at any ambient pressure above the vapor pressure of the fluid. On the other hand any decrease in pressure brings about vaporization of the fluid. Because of close contact between solid and fluid phases the heat of vaporization is supplied by the enthalpies of both the fluid and the rock. The vaporization procedes as the pressure declines until at the "dryout" temperature the entire pore fluid has been vaporised, and the liquid content drops to zero. Dry out marks the depletion of the fluid reserves, unless there is recharge into the reservoir. In the case of saturated steam it can be shown (Kjaran and Eliasson 1983) that the mass derived from storage per unit decline in pressure per unit area is approximately given by

$$\frac{dm}{dP} = \rho_S \beta_S \phi h = \frac{T}{\rho_S L^2} \{(1-\phi)\rho_r C_r + \phi S_W \rho_W C_W\} h$$

Inserting typical numerical values for $T = 240°C$, $\phi = 10\%$, $\rho_r = 2500$ Kg/m3, $c_r = 1000$ J/Kg°C, $S_W = 0.5$, $C_W = 4700$ J/Kg°C, $\beta_W = 1.3 \cdot 10^{-4}$ bar^{-1}, $\rho_W = 814$ Kg/m3, $\rho_S = 16.8$ Kg/m3, $L = 1765$ KJ/kg and $h = 1000$m, in the previous and this equation gives 50.1 kg/bar m^2 of super heated steam, and 2393 kg/bar m^2 of saturated steam as the mass released for a unit decline in pressure. In two phase reservoirs the vaporization effect dominates the storage behaviour of the reservoir, and the results show the large difference in the magnitude of mass liberated.

The following treatment is related to the performance of a well in a super heated steam reservoir. The total pressure drop from the reservoir to the well is given by

$$p_e^2 - p_W^2 = BW + CW^2,$$

where p_e is the reservoir pressure and p_W is feed point pressure in the well and the other quantities have the same meaning as mentioned before. The first term is due to the laminar pressure drop and the second due to turbulent pressure drop just outside the well and is a skin effect, and real reservoir pressure exists only out of the skin zone. If we assume BW >> CW2 we get W = constant $*(p_e2-p_e2)$ which is an equation of a parabola and if CW >> BW , we get W = constant $*(p_e^2-p_W^2)^{1/2}$ which is an equation of a circle. In the above equation the reference point is the well pressure at the feeding point in the well. If we ignore frictional pressure drop in the well and assume the well to have zero length, the feeding point pressure becomes equal to the well head pressure (po) and (pw) can then be replaced by (po). We then get what are commonly called theoretical pressure curves and are parabolic according to the equation. The wellbore is not of zero length and when we take into account the frictional pressure drop and assume that acceleration is negligible and neglect the pressure drop due to the weight of steam in the wellbore the equation degenerates into an elliptical form and is

$$\left(\frac{p_o}{p_W}\right)^2 + \left(\frac{W}{bp_W}\right)^2 = 1 \qquad \text{for } M < 1 \text{ and}$$

$$b = \sqrt{\pi^2 C_1 D^5/16fl} \text{ and } C_1 = 1/ZRT \text{ and } M = V/C$$

where M = Mach number; V = Fluid velocity; C = Sonic speed; D = Diameter of the borehole; L = Length of the borehole; f = Friction factor; Z = Gas deviation factor; R = Gas constant for steam; T = Temperature °C.

Fig. 9 shows a parabolic theoretical perfomance curve with no well bore effects and a plot of the discharge rate W versus WHP for two values of (pw), the reservoir pressure. The upper curve is for the initial reservoir pressure when production started and the lower one for the reservoir pressure after some exploitation. Deliverability curves provide important information on which the long term planning of systems utilizing geothermal energy is based on and will be discussed in the section dealing with two phase flow. The well bore effect is greater for smaller diameter and longer boreholes and are related by the expression shown above. When the Mach number becomes large, the assumption of neglecting the acceleration term is no longer valid, and for increasing velocity we might end up with choked or critical flow, that is the steam flow in the well or in the formation becomes sonic. When this happens we can lower the WHP without increasing the mass flow rate.

3.4 Conclusions

The parameter most sensitive to any alteration in flow and to exploitation in general is pressure. In an unexploited reservoir the vertical pressure is normally close to that of a static column of water or steam at the reservoir pressure. Once the field is exploited this pressure pattern may change markedly and it is this change that we look for in our interference and long term tests. In liquid dominated systems the large mass output from the wells induces a pressure pulse which travels rapidly inducing large inflows into the production area from an extensive area, and it is important to determine the drawdown and the location of the boundaries of the field. As the pressure pulse travels rapidly all the standard well test methods can be readily applied. Fluid chemistry and temperatures in liquid regions respond much more slowly to flow change than pressure. Chemical changes, being fluid tagged only show up when the different fluids reach the well, and temperature changes may be even slower since the conduction of heat between rock and fluid buffers the effect. Vapor dominated reservoirs produce high enthalpy fluids, and as the pressure pulse takes a long time to travel each well acts as an isolated reservoir. In these cases long term tests and the use of ultra sensitive pressure measuring instruments may be helpful. Wells dry up with loss of high pressure steam and new wells have to be drilled for make up steam, e.g. in Geysers it requires drilling an average of one new well per year for each 100 MWe (Lipman, 1978). Moreover, it is important to know the initial water saturation and gas content in vapor dominated fields.

The "quality" of energy, as defined by the enthalpy of the fluid discharged depends directly on the temperature of the reservoir and on the type of reservoir system involved. The quality increases as the temperature goes up and also as we move along the sequence of field types from the warm water to the vapor dominated systems. Under exploitaion geothermal reservoirs are self-supporting to a limited extent and it is the cold water inflow that defines "how much" heat we can extract from any reservoir. If the reservoir is homogenous this inflow is uniform and much of the heat that is stored in the rock outside the production zone will be swept into the production zone and extracted. The "how long" primarily depends on the rate of extraction. This rate, however, is controlled in the reservoir itself by the drawdown that can be tolerated, a good measure of the health of a reservoir being the rapidity and smoothness of the return to normal during any shut down periods.

A reservoir engineer plays a very important role in the initiation of any development of a geothermal field. Data obtained from well tests, drawdown, production history, and from the various other sectors of the overall management of a field form the basis on which important decisions regarding the development of a field are based. The data has to be analysed to assess the general condition of the reservoir, performance match the production history to some mathematical model, and then forecast the behavior some time ahead. In case the reservoir is being depleted, early decisions regarding the number and siting of new wells have to be made to give ample time for drilling makeup wells to keep the utilization system in operation. In cases of excessive drawdown or environmental hazards from the effluent being disposed off on the surface, reinjection may have to be considered.

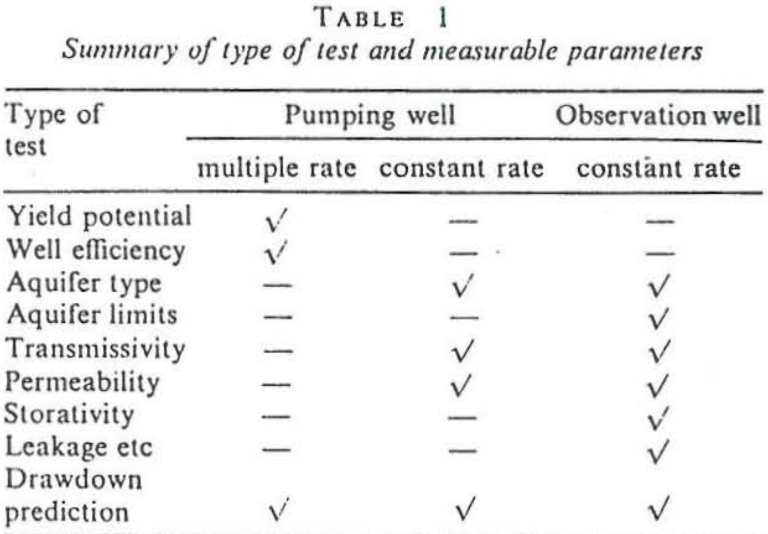

TABLE 1
Summary of type of test and measurable parameters

Type of test	Pumping well		Observation well
	multiple rate	constant rate	constant rate
Yield potential	✓	—	—
Well efficiency	✓	—	—
Aquifer type	—	✓	✓
Aquifer limits	—	—	✓
Transmissivity	—	✓	✓
Permeability	—	✓	✓
Storativity	—	—	✓
Leakage etc	—	—	✓
Drawdown prediction	✓	✓	✓

(Jones et al., 1981)

4 SPECIAL TOPICS

4.1 Introduction

A hydrothermal system is a heat transfer mechanism in the earth's upper crust relying for its operation on the transport of water but not necessarily the discharge of water at the earths surface and producing at the surface an area in which the heat flow is different from normal. The essential components of such a system are therefore the recharge, the reservoir itself and the heat source which supplies the energy to the geothermal convective system.

4.2 The recharge

The recharge fluid may be meteoric, originate at depth as juvenile water or be a mixture of both. Meteoric and juvenile trapped groundwaters can be identified from their chatacteristic hydrogen and oxygen "shifts" (White, 1957). However, in most of the models of geothermal systems, unless there is contrary evidence, it is usually assumed that cold meteoric water percolates through fault and fissure systems (the African Rift Valley, Imperial Valley Caldera, and the Icelandic Neovolcanic Belt) down to considerable depths where it is heated. Geothermal systems in Iceland where ocean water is the main source of fluid have been described by Kjaran et al. (1979). The recharge flow is maintained by a pressure gradient produced either by the physical differences in the levels of recharge and the discharge areas or by the convective pressure difference between the cold recharge and the column of hot discharge water. In some fields where there is pressure decline due to production, recharge water may be "sucked" into the system from the boundaries of the system.

4.3 The heat source

The supply of heat in the earths crust, both on the local and regional scale, is maintained by several processes. In the time domain the long duration (the natural radioactive elements in the crustal rock with half lives of 10•E9 years) and the transient (the relatively short lived sources like magmatic intrusions) can be treated separately. The steady radiogenic heat supplies about 20-80% of the surface heat flow in the earths crust and varies over orders of magnitude with rock type, and in igneous rocks decreases from silicic through basic to ultrabasic rocks (Rybach,1981). Magmatic heat sources can give rise to and sustain hydrothermal convective systems provided the crustal rock is fractured to allow fluid circulation and in general an upward transfer of heat by moving masses (magma) has to be invoked. Basaltic magmas rise directly to the surface forming dykes and thin sheets and they dissipate their heat content rapidly and thus no large shallow intrusive bodies are formed. On the other hand silicic magmas usually get trapped at several kilometers depth in the crust due to their high viscosity and thus act as a heat source for substantial duration. On contients geothermal resources are more likely to be associated with silicic volcanism than with basaltic volcanism. In some cases, however, shallow basaltic magma chambers can have considerable geothermal potential in developing a hydrothermal system (Stefansson, 1981). Igneous intrusions have typical temperatures in the range of 700-1200°C and they drastically heat their neighbourhood upon emplacement, and due to conductive and convective cooling their thermal influence can prevail for only a limited time. As a general rule, only Quaternary intrusions (with ages in the range of 0.01 to 1 m.y.) in the upper crust are still thermally active today (Healy 1976). Magmatic activity on the global scale can be located and delineated within in the framework of plate tectonics (Muffler, 1976).

4.4 Geothermal convection

Thermal convection is a fundamental process of heat transport in hydrothermal systems and a thorough review of the basic characteristics of free convection of a single phase fluid in porous medium is included in Witherspoon et al. (1975). A linear stability analysis shows that thermal convection in a liquid saturated porous layer is initiated when the critical value of the Rayleigh number, Ra $=4\pi^2$is exceded. In a horizontal layer of thickness H and a temperature difference T across, the Rayleigh number can be expressed as

$$Ra = \frac{g\beta \rho_W C_W k \Delta T}{\rho_W \lambda_e}$$

where g = acceleration due to gravity; β = volume coefficient of thermal expansion; ρ_W = fluid density; C_W = specific heat of the fluid at constant pressure; k = permeability of the rock; υ = kinematic viscosity of the fluid; λ_e = thermal conductivity of saturated rock.

The upward heat flux caused by the convective process is measured by the Nusselts number, Nu and can be expressed as

$$Nu = \frac{\text{Heat flow with convection}}{\text{Heat flow without convection}}$$

Figure 10 shows the experimental relationship between these two numbers obtained by some workers, and some features stand out on the curve. When Ra is small convection is very weak and the heat transfer is dominated by conduction until when Ra reaches the value of about forty (when Nu = 1) there is onset of single phase convection as a result of the unstable vertical density gradient. Although the onset of convection in porous media results in hexagonal flow patterns, such as Bernard cells, the flow pattern later develops into convective rolls as the Rayleigh number increases. Let us consider the conceptual model of the Olkaria reservoir shown in Fig. 4a to clarify the concepts discussed above. Fig. 11 is a schematic picture of the geothermal system bounded by dashed lines. The reservoir consists of a highly permeable zone where the heat transfer is mainly by convection and is assumed to be underlain by a hot magma body at some depth "D" below the basement rock. Above and below the 3000 m thick reservoir we have low permeability zones where the Rayleigh number is less than the critical and heat transfer is only by conduction as shown by the linear temperature profile. To the left in the figure is shown the temperature as it would appear if there were no convection. Assuming the reservoir to contain single phase fluid, and 1100°C as the temperature of the magma body, the thickness of the conductive layer below the reservoir can be estimated as

$$320 + 215\ D / 600 = 1100$$

which gives D = 2176 m. and the depth of the magmatic body as 5.7 Km below the surface. The temperature gradient considering conduction only is given as 1075/5776 = 0.186°C/m and the temperature gradient in the caprock considering convection within in the reservoir is given as 215/600 =0.358°C/m and the Nusselt's mumber as

$$Nu = 0.358/0.186 = 1.92 \quad \text{and using } Nu = (1/4\pi^2)Ra$$

as the empirical correlation for the onset of convection in a porous bed heated from below (Lapwood, 1948) gives Ra = 76.8 indicating that convection takes place with in the geothermal systems.

The phenomenon of convection has been treated by many authors (Eliasson, 1973; Hardee et al.1977; Garg et al. 1981) with various boundary conditions and with respect to geothermal reservoirs. The most common approximation in the extensive literature reviewed by Witherspoon on the subject of thermal convection is to consider the viscosity, the permeability, the thermal conductivity and the specific heat as constant values in the free convection process. Variation in density are included in the buoyancy term of the vertical balances of forces but otherwise density is assumed constant.

Strauss and Schubert (1977) determined the critical Rayleigh number for the onset of convection for various thicknesses of the porous layer as well as for various thermal gradients in the layer. In contrast to the results obtained when the properties of water are assumed constant it was found that the critical value depends on the thermal gradients as well as on the thickness of the layer. For very thick layers the critical Rayleigh number was found to be reduced by as much as a factor of 30 below 4. The criteria for convection Ra > Ra can be interpreted as providing a minimum temperature difference for convection to occur in a layer of given thickness and permeability or as providing a minimum permeability for convection in a layer with a given thickness and temperature difference. Assuming H = 3000 m for the Olkaria reservoir, T = 558°C as shown in Fig. 11 and other quantities as

$$\beta = 1.7\mathrm{x}10^{-3}\,{}^{\circ}\mathrm{C}^{-1}; \quad \rho_W = 812\ \mathrm{kg/m}^3; \quad C_W = 4200\ \mathrm{J/kg};$$
$$\rho_W = 1.4\mathrm{x}10^{-7}\ \mathrm{m}^2/\mathrm{s}; \quad \lambda_e = 1.7\ \mathrm{Watt/m}{}^{\circ}\mathrm{C}$$

and using the necessary condition for convection $Ra > 4$ gives k(min) = 0.1 md. This is a very low permeability under the assumptions made indicating that convection is prominant in most high temperature geothermal reservoirs. The permeability necessary for convection is seriously over estimated when the thermal properties of water are assumed to be constant values. Due to the effects of variable water properties, convection can occur for smaller permeability at a given temperature. The primary reasons for the increased tendency to initiate convection are the substantial increase of thermal expansivity and the decrease of viscosity with temperature.

4.5 Relative permeabilities

In many geothermal systems the flowing water reaches the saturation pressue due to release of pressure and boiling is initiated. The fluid becomes a two phase mixture of steam and water with thermodynamic properties different from those of liquid water. The two phase flow is generally assumed to be laminar, and Darcy's law is applied separately to the steam and water phases introducing relative permeability factors to account for the restricted flow of each phase in the presence of the other. Fig. 12 shows relative permeability curves as a function of vapor saturation. When $S_s/1-S_s > O(1)$ steam is mobile and the water phase is immobile and when $S_s/1-S_s = 1$ we have two phase flow and when $S_s/1-S_s < O(1)$ steam is immobile and the water phase is mobile. These changes in mobility explain why two phase wells yield fluids of higher specific enthalpy. Experimental as well as theoretical studies of relative permeability and its influence on the characteristics of geothermal systems have yielded conflicting results as shown by the two curves on the figure, (Grant 1977; Sorey et al. 1980). The steam/water relative permeability is of major importance in reservoir simulation but it has been difficult to measure relative permeabilities in laboratory tests and experimental results show wide scatter. Moreover it has not been possible to show why relative permeabilities should depend on water saturation only. In view of the difficulties met in measuring and defining relative permeability many authors simply assume that the relative permeability factor for each phase is equal to the saturation value of the respective phase as shown in Fig. 12. Donaldson (1968) considered boiling processes with in a one dimensional steady upflow of hot water and found that a two phase zone of steam and water formed from vertical mass flow rates above a threshold value. The steam ascended more rapidly than the water and condensed at the upper two phase zone. Sheu et al. (1979) indicated that the critical mass flow rate U for the onset of a two phase zone in water ascending from base reference condition of 270°C and 90 bars was U = 383·E-5 kg/m2. Strauss and Schubert (1977) investigated the nature of convection in a porous medium containing a steam water mixture at saturation temperature and pressure and found that the tendency of these to convect is quite different from the Rayleigh criterion in single phase fluids. The two phase convection procedes by way of a phase change mechanism associated with the requirement that fluid temperature and pressure lie on the curve shown in Fig. 6 and the phase change instability mechanism induces convection prior to the onset of ordinary buoyancy driven thermal convection. The most striking aspects of convection in two phase systems are (a) the small lateral dimensions and the concentration of flow in the mushroom stem, (b) the phase change and temperature variations towards the roots of the mushroom. The saturated liquid convection cells are only about half as wide as those of buoyancy driven convection in water, and two phase cells are still narrower and the flow concentrated towards the bottom.

4.6 Double porosity storage

Most high temperature geothermal reservoirs are highly fractured systems. The fractures have high permeability and are the primary conducts through which fluid and energy flows at sufficiently large rates, and the porous medium blocks delineated by these fractures act as the long term energy suppliers feeding the fracture system. The rock matrix has low permeability but stores most of the heat and the fluid reserves. The fractures represent a very small fraction of the void volume and probably contain less than 1% of the total fluid and heat reserves in realistic cases and sustained production from a fractured reservoir is only possible if the depletion of the fractures can be replenished by leakage from the matrix. Different models than those for porous media have to be used to model the rate at which heat and fluid can be transferred from the matrix to the fractures, and is of crucial importance for an assessment of reservoir longevity and energy recovery. Double porosity also effects the transient pressure build up data.

Figure 13 shows an idealised model of a fractured reservoir. The reservoir is modeled with three perpendicular sets of infinite, plane, parallel fractures of equal aperature and spacing. Darcy's law is applied to the fluid in the matrix being discharged into the fracture to calculate the pressure decline. In the matrix heat is stored in rocks and fluids, and in the fracture solely in the fluid filling the void space. Upon entering the fracture system the fluid heat content is enhanced by the absorption of the conductive heat flux. The fluid in the double medium can be single phase water or a two phase mixture of water and vapor.

Numerical modeling studies of enthalpy transients in boiling fractured reservoirs by Pruess (1981) indicate that the discharge enthalpy depends much more strongly upon matrix permeability than fracture spacing and that enthalpy increases with decreasing matrix permeability. The pressure decline is more rapid in case of higher enthalpy due to the fact that the mobility of two phase fluids generally decreases with enthalpy. Using Corey type relative permeability functions the numerical studies indicate that porous medium type reservoirs have greater longevity than equivalent fractured reservoirs. However, if Grant's relative permeabilities are used substantially greater reservoir longevity should be expected. The effects of reinjection in fractured geothermal reservoirs have been treated by Bodvarsson and Tsang (1981).

Double porosity theory has been used to simulate the transient pressure behaviour in well test analysis. Figure 14(a) shows the rate of decline of a constant pressure well producing in an infinite double porosity reservoir, without wellbore skin, and is adapted from Sageev et al.(1985). The curve A represents the rate of decline based on single porosity homogeneous system and the curve B representing the double porosity system has three segments. The early decline represents the flow only in fractures and starts with a slope of -1/2 and at a certain time becomes asymptotic to a constant. The asymptotic flow period represents an increasing amount of interporosity flow from the matrix into the fractures. The second decline occurs when the pressure in the matrix and in the fractures are practically identical and represents the flow in the entire reservoir. Due to the large permeability and the small storage associated with fractures, and the small permeability and the large storage within the matrix, the fracture system experiences quicker drawdown than the matrix as shown in Fig. 14(b). There are two parallel lines, the slope of which correspond to the product of reservoir permeability and thickness. The first reflects the storativity of the fracture alone, and the second of the entire reservoir. The double porosity phenomenon in fractured geothermal reservoirs is similar to the delayed yield from storage in water well technology and type curves for double porosity systems can be used to analyse pressure drawdown and buildup data to obtain storativity and transmissivity of the reservoir.

4.7 Two phase flow

This section briefly describes the flow of fluid from the reservoir to the well head and the rate at which the fluid can be produced from the reservoir. The pressure drops the fluid goes through, assuming no boiling takes place, are due to laminar flow, turbulent flow and the skin at the wellface within the reservoir and due to friction, acceleration and potential drop within the bore. If the pressure in the formation reaches the saturation pressure of the fluid, the fluid will flash in the formation itself and produce a two phase column through the entire length of the wellbore. However, if during the flowing process the fluid state is still single phase at entry the pressure drops within the liquid phase in the bore are due to potential loss and friction, and acceleration is neglected in the liquid phase when the flow is steady. The pressure drops until such time that the fluid eventually flashes, developing into a water-steam mixture and undergoes through flow regimes changes such as bubble, slug, churn and annular. In any of these regimes the two phases flow separately and travel at different velocities resulting in slippage between the phases. The slip, and factors such as the void fraction occupied by each phase and the two phase friction have to be taken into account to determine the total pressure loss in the wellbore. The geofluid also usually contains significant amounts of salts and non-condensable gases raising their boiling temperature relative to pure water and corrections have to be introduced to account for this. For a full treatment of the subject of two phase flow in pipes see Chisholm (1972) and for applications to geothermal wells see Catigtig (1983).

Deliverability determines the number of wells required to produce a target fluid objective, year by year. In geothermal fluid production deliverability can be measured directly in the field, the procedure is to measure the flow rate at a variety of well head producing pressures and relate this information graphically as shown in Fig. 15. The objective is to obtain information which can be used to forecast flow rates under all conceivable future producing conditions related to pressure drawdown. This means that the producing rate must be related to time by some material balance of the reservoir. These aspects can be illustrated by considering the following data applicable to a hypothetical geothermal reservoir.

Depth range (m)	Description	Properties
0 - 600	Caprock	-
600 - 700	Aquifer	k = 30 md
700 - 1000	Main feeder zone	s = 2x10E-5

A well is drilled into this reservoir. It is cased with 9-5/8" casing down to 380 m depth and 7-5/8" liner from there to bottom. The following measurements were made in the well while it was bleeding (no flow):

Depth m	Temperature °C	Pressure Bars Abs.	Remarks
0	-	15.0	-
220	-	15.2	Boiling level
300	200		
400	210		
500	240		
600	250		
1700	250		

A flow test performed by the Russel James critical lip pressure method gives the following results:

Pipe Dia. Inches	Lip pressure, Pc, Bar	Well head pres. Po, Bar	Discharge W, Kg/s
6	2.3	23.0	35.1
8	2.4	16.5	64.27

The above information can be used to evaluate (a) the reservoir pressure in the main feeder zone at 850 m as being 66.1 bars and (b) the constantsb_1 and b_2 in an empirically derived equation given below relating the reservoir pressure (Pr), well head pressure, WHP, (Po) and the well flow rate (W),

$$\left[\frac{W}{b_1(P_r - 10\cdot 4)}\right]^2 + \left[\frac{P_o}{b_2(P_r - 10\cdot 4)}\right]^2 = 1$$

giving

$$b_1 = 1.517, \quad b_2 = 0.457$$

The decline of reservoir pressure with time can be determined by pressure logs. eg. if a pressure log is taken and it is found that the reservoir pressure has declined by 1.0 bar after 2 hours at a flow rate of 60 Kg/s, then using the given values of k and s, and assuming an infinite aquifer and using Theis equation we get

$$\Delta P = 0.2(\ln t + 4.307)$$

as the equation relating pressure decline with time (t) in hours. After 25 years the pressure decline is 3.3 bars and the reservoir pressure is 62.8 bars with a corresponding flow of 76.0 Kg/s at a WHP of 7 bars. If, however, it is assumed that the drawdown cone hits several boundaries within one year of operation so as to make the drawdown slope 8 times that of the infinite case above, we get 26.6 bars as the pressure decline in one year and a reservoir pressure of 39.5 bars and a flow rate of 37.5 Kg/s at 7 bars WHP. All this information is shown by deliverability curves in Fig.15.

The importance of matching the measured discharge characteristics for a known reservoir pressure to an empirical equation which takes into account the two phase flow parameters discussed above lies in the fact that a family of curves can be drawn for decreasing reservoir pressures due to exploitation, and well output can be predicted. For example, as shown in Fig. 15 if the well is operated at a constant flow rate equal to the designed well output of 60 Kg/s, the WHP drops as the reservoir pressure drops, finally when the minimum WHP is reached the well must be operated at that constant WHP, and the mass flow declines as indicated by the arrow in the figure. Deliverability curves thus provide information on which the long term planing of a system can be based on, and on the short term provide information on how many and when new wells will be needed to produce the required quantity of geofluid to keep the system in operation. The most important parameter in the above analysis is the rate decline of the reservoir pressure and it should be noted that in the above hypothetical example the pressure drawdown was calculated using the Theis equation which assumes an infinite aquifer. The actual measured pressure drawdown, however, among many other factors, basically depends on the boundaries of and the recharge into the system and Theis equation may not be valid. Hence the pressure drawdown in the system has to be matched to the available historical data using different models before any predictive value can be assigned to deliverability curves. For example, the pressure drawdown at the Svartsengi geothermal field in Iceland is greater than what can be explained by the infinite aquifer assumption of Theis solution, and Kjaran et al. (1979) based on geological evidence modeled the system as a rectangular trench bounded by impervious walls on three sides to calculate the long term drawdown. Using this model the calculated and the measured drawdown agreed very well, and a 16 bars reservoir pressure drawdown was predicted over the next 25 years for an average withdrawal rate of 150 Kg/s for a 100 MWe power plant. Gudmundsson et al. (1985) modeled the same field as a large volume of hot water filled rock surrounded by warm and cold aquifers, and using three different models for the aquifers providing recharge to the system showed that there is a correlation between the cumulative production rate and the reservoir drawdown and explained this by water influx into the reservoir.

Another method of predicting future mass flow is simply to treat the past history as a time series. It may be fitted to a convenient formula which in turn is used for extrapolation. No geological or geophysical structure enters such a model and methods such as decline and trend analysis and unit response function can be readily applied. Fetkovich (1973), showed that exponential rate decline is a natural consequence of a compressed fluid system expanding to a constant pressure producing system and has presented log-log type curves to match declining pressures. Regalado (1981) determined the empirical unit response by curve fitting the production for the Svartsengi geothermal field and used it to forecast drawdowns for the next 25 years. This and the model proposed by Kjaran et al. (1979) match the production history of the Svartsengi equally well. However, although mathematical techniques can be very effective, they are limited by the lack of any physical background and can only follow the path defined by history. This approach cannot predict how the reservoir will respond if the exploitation or the operating mode of the power system is changed from that in force during the history match.

It is good engineering practise to monitor the response of a system to any external perturbations. The discharge associated with the exploitation of geothermal fields disturbs the reservoir and permits the determination of some basic reservoir parameters. However, to predict the future behaviour of the system and trends of mass flow, modeling studies based on concrete data have to be undertaken and it is therefore essential that drawdown, enthalpy and the quantity of discharge be monitored on a regular basis to provide the necessary background data for any meaningfull predictive studies. If there is excessive drawdown, reinjection may have to be considered to provide pressure support to the system.

5 LITERATURE REVIEW

5.1 Introduction

Barbier et al. (1985) give a comprehensive reference guide of geothermal publications in symposia proceedings and in journals covering all sectors of research and utilization of geothermal energy. Although there is a vast amount of published literature available relating to the various facets of geothermal energy in scientific journals there are very few textbooks which deal with the reservoir engineering aspects of geothermal energy. The first two books reviewed here provide a general background to geothermal resources and introduce the reader to the physics of geothermal systems, while the two other books and the lecture notes deal specifically with the science of reservoir engineering. Secondly the pioneering paper of Whiting and Ramey (1969) and a series of four papers which represent the present state-of-art of geothermal reservoir engineering by Bodvarsson et al. (1984) are reviewed.

5.2 Books

Geothermal Systems: Elder, J. (1981).

This book is based on studies of global convection, hydrothermal ore deposits and measurements made in connection with current geothermal power projects, and discusses geothermal systems in relation to their origin, mechanism and behaviour in both the natural and the exploited state. The book concentrates on how the heat gets out, with heat and mass transfer in hydrothermal systems deriving their energy from a vigorously convective mantle, with emphasis on the mechanisms by which energy is delivered to the surface. Case studies of wet (Taupo), gassy (Ohaki) and vapor dominated (Larderello) systems are included, and the effect of long term exploitation are also included.

Geothermal Systems, Principles and Case Histories: Ed. by Rybach, L and L.J.P. Muffler (1981).

This book focuses on the earth aspects of geothermal energy, including geology, geophysics, geochemistry, hydrology and mathematical modeling. The principles dealt with in this book are: conductive heat flow, convective heat and mass transfer in hydrothermal systems, the heat extraction processes from the systems, the resource assessment terminology and several case histories are also described. The book provides the necessary general background required for a serious study of reservoir engineering.

Fundamentals of Reservoir Engineering: Dake, L.P. (1978).

Although this book is primarily written for the assessment of hydrocarbon reservoirs, it gives an excellent introduction to the basic physics of reservoir engineering, the practice of well testing and pressure analysis techniques and the methods and mathematical techniques used for reservoir performance. There is a chapter devoted to relative permeabilities, which though dealing with immiscible oil and water displacement, should prove valuable for a good understanding of steam/water permeabilities, a knowledge of which is of major importance in depletion and simulation studies of geothermal systems. This is an excellent textbook for a student as it assumes no prior knowledge of the subject.

Geothermal Reservoir Engineering: Grant, M.A, et al. (1982).

This book brings together all the currently available information on and provides a comprehensive guide to the present state of art of geothermal reservoir engineering technology, and roughly follows in sequential order the general activities undertaken to develop a field and the part played by reservoir engineering studies at each stage of the total development: conceptual models, measurements in wells, flow measurements, determination of reservoir parameters using transient pressure analysis. The observed response to exploitation of eight fields are discussed.

This is the first textbook to appear on this subject and provides an excellent indepth study of the principles involved, and their application to liquid, vapor, and two phase fields from all over the world.

Geothermal reservoirs engineering, Lecture notes,: Kjaran and Eliasson (1983).

These excellent lecture notes prepared for the UNU training course in reservoir engineering initiate the reader to the basic concepts and the mathematical background of analysis of well testing theory, reservoir mechanics and well performance data. The rock and fluid properties of porous media, convection in hydrothermal systems, conceptual models of and the methods to analyse the response of liquid, vapor, and two phase systems are described in detail. A thorough study and understanding of these notes provide a good background and foundation of the elements of the subject. These notes and the books mentioned above together with the monographs on well testing by Matthews et al.(1967), Earlougher (1977) and Lee (1982) provide adequate background material for advanced study in one of the specialised fields of reservoir engineering.

5.3 Articles

Application of material and energy balances to geothermal steam production. Whiting and Ramey (1969).

This classic, pioneer paper on geothermal reservoir engineering begins by a description of the response to exploitation of the liquid, vapor and two phase systems by the use of temperatutre enthalpy diagrams and goes on to derive the material and energy equations for forecasting. The equations present a relationship between the energy and mass produced, and the reservoir size. Using a large number of field data available, the system constants are determined by least- square fitting techniques and matching past performance data. The Wairakei geothermal field in New Zealand is modeled and future performance predicted to the year 2000, assuming various annual production rates. However, the predictions of future behaviour did not agree with later observations (Grant, 1982).

The Krafla Geothermal Field, Iceland. Bodvarsson et al. (1984):

This series of four papers dealing with the reservoir assessment of the Krafla geothermal system probably represent the most comprehensive and an integrated publication related to a geothermal system. The analyses of injection well test data dealt with in the first paper indicates that the average transmissivity of the Krafla reservoir is 2.0 Dm. which is approximately an order of magnitude lower than those reported for most commercially successful geothermal fields; and also high storativity values which clearly indicate the two phase nature of the reservoir. The second paper deals with the development of a two dimensional model of the natural state of the system based on the conceptual model of the field described in detail by Stefansson (1981). The major objective of the work was to obtain a better understanding of the dynamic nature of the reservoir as a basis for modeling studies of the system under exploitation. The main finding of the study is that although convection dominates the heat transfer in the system, conductive heat loss through the caprock is substantial. The third paper models the generating capacity of the field using the lumped model. The model indicates a maximum capacity of 60 MWe for 30 years and the field would will apparently become depleted of fluid due to limited recharge rather than heat. The fourth paper describes the quasi-three-dimensional model of the field in which all the wells are represented individually. The model achieves a good match to production and flowing enthalpies from ten wells during the period 1976-1982, and provides a basis for extrapolating future field performance and for evaluating impacts of reinjection sechemes. This paper concludes that future exploitation will give rise to extended vapor zones in the reservoir after ten years and then reinjection may improve well deliverabilities.

ACKNOWLEDGEMENTS

"The complexity of a system is in the eye of a beholder. It is measured by how well we understand causes, expect behaviours and in praxis achieve purpose. Hence large number of variables, non-linear relations among them, and the open nature of a system are important only to the degree that they present barriers to understanding."

Holling, C.S. (UNU Newsletter, Vol.8 No.3 May, 1985).

The above summarises my general impressions about the reservoir engineering aspects of geothermal systems before I came to Iceland to participate in the UNU geothermal training programme . However, after having gone through the course at Orkustofnun (National Energy Authority) my opinions have changed. I have been introduced to well testing theory and data analysis and the mathematical techniques available to a reservoir engineer to study the physics of geothermal systems and have now a much better understanding of the concepts of reservoir engineering. For this I thank firstly all the members of staff at Orkustofnun who taught me during the programme. Secondly, I thank Prof. Jonas Eliasson under whose able supervision and guidance this essay was written, Dr. Ingvar Birgir Fridleifsson for the excellent management of, and providing dynamic and outstanding leadership to the training programme and Mr. Sigurjon Asbjornsson for the fine administrative support. I also thank the Government of Iceland and the United Nations University for providing me financial assistance to attend this centre of excellence in geothermal sciences and the University of Nairobi for granting me sabbatical leave.

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REFERENCES

Al-Hussainy, R., H.J. Ramey and P.B. Crawford (1966): The flow of real gases through porous media. J. P. Tech., May: 637-642, Trans. AIME.

Barbier, E., M.F. Fanelli and I.B. Fridleifsson (1985): Selected titles for a basic geothermal library. Trans. GRC, International Vol. p 241-246.

Banwell, C.J., E.R. Cooper, G.E.K. Thompson and K.J. McCree (1957): Physics of the New Zealand thermal area, N.Z. Dept. Sci and Ind. Research Bull. 123, 109 p.

Bhogal, P.S. (1980): Electrical resistivity investigations at the Olkaria geothermal field, Kenya. Trans. GRC, Vol.4, p 9-12.

Bodvarsson, G. (1951): Report on the Hengill Thermal area. J. Eng. Assoc., Iceland, 36,1.

Bodvarsson, G. (1964): Physical characteristics of natural heat resources in Iceland. Proc. U.N. Conf. New Sources, Energy Sol.Energy, Wind Power, Geothermal 1967 (1964) Vol.2, Paper G/6, p 82-90.

Bodvarsson, G. and D.E. Eggers (1972): The exergy of thermal water. Geothermics, Vol.1, No.3, p 93-95.

Bodvarsson, G.S. and C.F. Tang (1981): Injection and thermal breakthrough in fractured geothermal reservoirs, submitted to Jour. of Geophy. Res. L.B.L.-12698, Univ. of California.

Bodvarsson, G.S. (1980): Olkaria geothermal field - Preliminary studies of the reservoir behavoir under exploitation. Report presented to KPC by Virkir.

Bodvarsson, G.S. and K. Pruess (1981): Olkaria geothermal field - numerical studies of the generating capacity of the reservoir. Report prepared for the Virkir Consulting Company, Iceland and Kenya Power Company, Kenya, 80 p.

Bodvarsson, G.S., K. Pruess, V. Stefansson, S. Bjornsson and S.B. Ojiambo (1985): A summary of modeling studies of the East Olkaria geothermal field, Kenya. Trans. GRC. International Vol. p 295-301.

Bodvarsson, G.S., S.M. Benson, O. Sigurdsson, V. Stefansson, E.T. Elliasson and K. Pruess (1984): The Krafla geothermal field, Iceland. (1) Analysis of well test data, (2) The natural state of the system, (3) The generating capacity of the field, (4) History match and prediction of individual well performance. Water Resources Research Vol.20, No.11, p 1515-1584.

Boulton, N.S. (1963): Analysis of data from non-equilibrium pumping tests allowing for delayed yield from storage. Proc. Instn Civil. Engrs 26, 469-82.

Catigtig, D.C. (1983): Boreflow simulation and its application to geothermal well analysis and reservoir assessment. UNU Geothermal Training Prog. Iceland, Report No.8.

Chisholm, D. (1983): Two phase flow in pipelines and heat exchangers. George Godwin, London.

Dake, L.P. (1978): Fundamentals of reservoir engineering. Developments in Petroleum Science 8, Elsevier.

Di Paola, G.M. (1985): The role of the UN in the field of Geothermal Resources Exploration in Developing Countries. GRC International Vol. p 247-250.

Donaldson, I.G. (1968): The flow of steam and water mixtures through permeable beds, A simple simulation of a natural undisturbed hydrothermal region. N.Z. J. Sci.,11, p 3-23.

Donaldson, I.G. (1970b): A possible model for hydrothermal system and methods of studying such a model. Proc. Third Aust. Conf.in hydraulics and fluid mechanics, Sydney, Australia, p 25-29.

Earlougher, R.C.Jr. (1977): Advances in well test analysis. Soc. Pet. Eng. Monograph Series.

Einarsson, T. (1942): Ueber das wesan der heissen Quellen Islands. Soc. Sci. Int. Reykjavik.

Elder, J. (1981): Geothermal Systems. Academic Press.

Eliasson, J. (1973): Convective groundwater flow. Inst. of Hydrodynamics and Hydraulic Eng. Tec. Univ. of Denmark, Series Paper 3.

Fetkovich, J.J. (1973): The isochronal testing of oil wells. Paper SPE 4529, 48th Annual meeting of SPE of AIME, Las Vegas, Nevada.

Garg, S.K. and D.R. Kassoy (1981): Convective heat and mass transfer in hydrothermal systems. Geothermal Systems, Principles and Case Histories; Ed. by L.Rybach and L.J.P.Muffler p 37-76, John Wiley and Sons Ltd.

Grant, M.A. (1977): Permeability reduction factors at Wairakei. AICHE-AIME Heat Transfer Conf. Paper 77-HT-52.

Grant, M.A. (1978): The Pseudopressure of saturated steam. Proc. 4th Workshop, Geothermal Reservoir Engineering, Stanford.

Grant, M.A., I.G. Donaldson and P.F. Bixley (1982): Geothermal Reservoir Engineering. Academic Press.

Gudmundsson, J.S., G. Olsen and S. Thorhallsson (1985): Svartsengi field production data and depletion analysis. Proc. 10th Workshop, Geothermal Reservoir Engineering, Stanford, p 45-51.

Hardee, H.C. and R.H. Nilson (1977): Natural convection in porous media with heat generation. Nuclear science and engineering, 63, p 119-132.

Hantush, M.S. and C.E. Jacob (1955): Non steady radial flow in an infinite leaky aquifer. Trans. Am. Geophys. Un. 36(1), p 95-100.

Healy, J. (1976): Geothermal fields in zones of recent volcanism. Proc. 2nd UN Symp. on Dev. and Use of Geo. Res. San Francisco.

Horne, R. (1982): Geothermal reinjection experience in Japan. J.Pet.Tech 34(3), p 495-503.

Horner, D.R. (1951): Pressure buildup in wells. Proc. Third World Pet. Cong. E.J. Brill., Leiden, 11, 503-521.

Hurst, W. (1934): Establishment of the skin effect and its impediment to fluid flow in a well bore. Pet. Eng. (Oct, 1953), 25, B-6.

Jacob, C.E. (1946): Radial flow in a leaky artesian aquifer. Trans. Amer. Geophy. Un. Vol.27, 198-205.

Jonas, G.P. and K.R. Rushton (1981): Pumping test analysis. Case studies in groundwater resources evaluation, Ed. J.W. Lloyd. Oxford.

KPC. (1984): Background report for Scientific Review meeting of Olkaria geothermal project; Kenya Power Company,(not published).

Kazemi, H. (1969): Pressure transient analysis of naturally fractured reservoirs with uniform fracture distribution. Soc. Pet. Eng. J 9 (12), 451.

Kjaran, S.P., G.K. Halldorsson, S. Thorallsson and J. Eliasson (1979): Reservoir engineering aspects of Svartsengi geothermal area. Trans. GRC, Vol.3, p 337-339.

Kjaran, S.P. and J. Eliasson (1983): Geothermal reservoir engineering lecture notes. The UNU University, UNU Training Prog., Iceland Report No.2.

Lapwood, E.R. (1948): Convection of a fluid in a porous medium. Proceedings Cambridge Philosophical Society, 44, 508-521.

Lee, J. (1982): Well Testing. Soc. Pet. Eng.of AIME, Monograph series, Dallas.

Lipman, S.C., C.J. Strobel and M.S. Gulati (1978): Reservoir performance of The Geyser Field. Geothermics, Vol.7, No.2-4, p 209-219.

Martin, J.C. (1975): Analysis of internal drive in geothermal reservoirs. J. Pet. Tech.

Matthews, C.S. and D.G. Russel (1967): Pressure buildup and flow tests in wells. Soc. Pet.Eng.of AIME, Monograph series, Dallas.

McNabb, A. (1975): A model of the Wairakei geothermal field. Unpublished report, Applied Maths Div. Dept. of Sci. and Ind. Res. New Zealand.

McNitt, J.R. (1977): The UN approach to geothermal resource assessment. Proc. of the ENEL, ERDA Workskop, Larderello, Italy, p.351.

Miller, C.C., A.B. Dyes and C.A. Hutchinson (1950): Estimation of permeability and reservoir pressure from bottom-hole pressure buildup characteristics. Trans. AIME, 189, 81-104.

Muffler, L.J.P. and R. Cataldi (1978): Methods for regional assessment of geothermal resources. Geothermics, Vol.7, p 53-89, Pergamon Press.

Muffler, L.J.P. (1976): Tectonic and hydrologic control of the nature and distribution of geothermal resources. Proc. 2nd UN Symp. on Dev. and use of Geo. Res. San Francisco, 499-507.

Muskat, M. (1934): The flow of compressible fluids through porous media and some problems in heat conduction. Physics, Vol.5, p 71-94.

Noble, J.W. and S.B. Ojiambo (1976): Geothermal exploration in Kenya. Proc. 2nd UN Symp. on Dev. and use of Geo. Res. San Francisco, 189-204.

Pruess, K. (1981): Heat transfer in fractured geothermal reservoirs with boiling. Proc. 7th Workshop, Geothermal Reservoir Engineering, Stanford, p 151-156.

Regalado, J.R. (1981): A study of the response to exploitation of the Svartsengi geothermal field, SW-Iceland. UNU Geothermal Training Prog., Iceland, Report No.7.

Ramey, H.J.Jr. (1981): Reservoir engineering assessment of geothermal systems. Dept. Pet. Eng. Stanford University.

Ramey, H.J.Jr., M.J. Economides, C. Ehlig-Economides, F.G. Miller and D.O. Ogbe (1981): Pressure Transient Testing and Analysis. Reservoir engineering assessment of geothermal systems, Dept. Pet. Eng. Stanford University; Ed, H.J. Ramey,Jr.

Russell, D.G., J.H. Goodrich., G.E. Perry and J.F. Bruskotter (1966): Methods of predicting gas well performance. J. Pet. Tech., Jan: 99-108. Trans. AIME.

Rybach, L. and L.J.P. Muffler (1985): Geothermal systems: Principles and case histories. John Wiley & Sons, New York.

Rybach, L. (1981): Geothermal systems, conductive heat flow, geothermal anomolies. Geothermal systems, principles and case histories; Ed. L. Rybach and L.J.P. Muffler; p 3-31.

Sageev, A., G. DaPrat and H.J. Ramey Jr. (1985): Decline curve analysis for infinite double-porosity systems without wellbore skin. Proc. 10th Workshop, Geothermal Reservoir Engineering, Stanford, p 163-168.

Sorey, M.L., M.A. Grant and E. Bradford (1980): Nonlinear effects in two phase flow to wells in geothermal reservoirs. Water Resources Research, Vol.16, No.4 Aug., 767-777.

Strauss, J.M. and G. Schubert (1977): Two phase convection in a porous medium. Jour. Geophy. Res. 82, p 3411-3421.

Sheu, J.P., K.P. Torrance and D.L.Turcottee (1979): On the structure of two phase hydrothermal flows in porous media. Jour. Geophys. Res. 84 p 7524-7532.

Stefansson, V. (1981): The Krafla geothermal field, northeast Iceland. Geothermal systems, principles and case histories, Ed. L. Rybach and L.J.P. Muffler; p 273-293.

SWECO (1976): Feasibility report for the Olkaria geothermal project. Submitted to the Kenya Power Company (not published).

Theis, C.V. (1935): The relationship between the lowering of the piezometric surface and the rate and duration of discharge using groundwater storage. Trans. AGU, 519.

White, D.E. (1957): Thermal waters of volcanic origin. Geol. Soc. Am. Bull. 68, p 1637-1658.

Whiting, R.L. and H.J. Ramey,Jr. (1969): Application of material and energy balances to geothermal steam production. J. Pet. Tech. Vol.21, p 893-900.

Witherspoon, P.A., S.P. Newman, M.L. Sorey and M.J. Lipman (1975): Modelling geothermal systems. Paper presented at the Inter. Meeting on Geo. Pheno. and its app.,Academic Nazionale del Linci, Rome, Italy.

Witherspoon, P.A. (1978): Well testing, a recapitulation of its development. Proc. Well Test Symp. Berkeley, Ca.

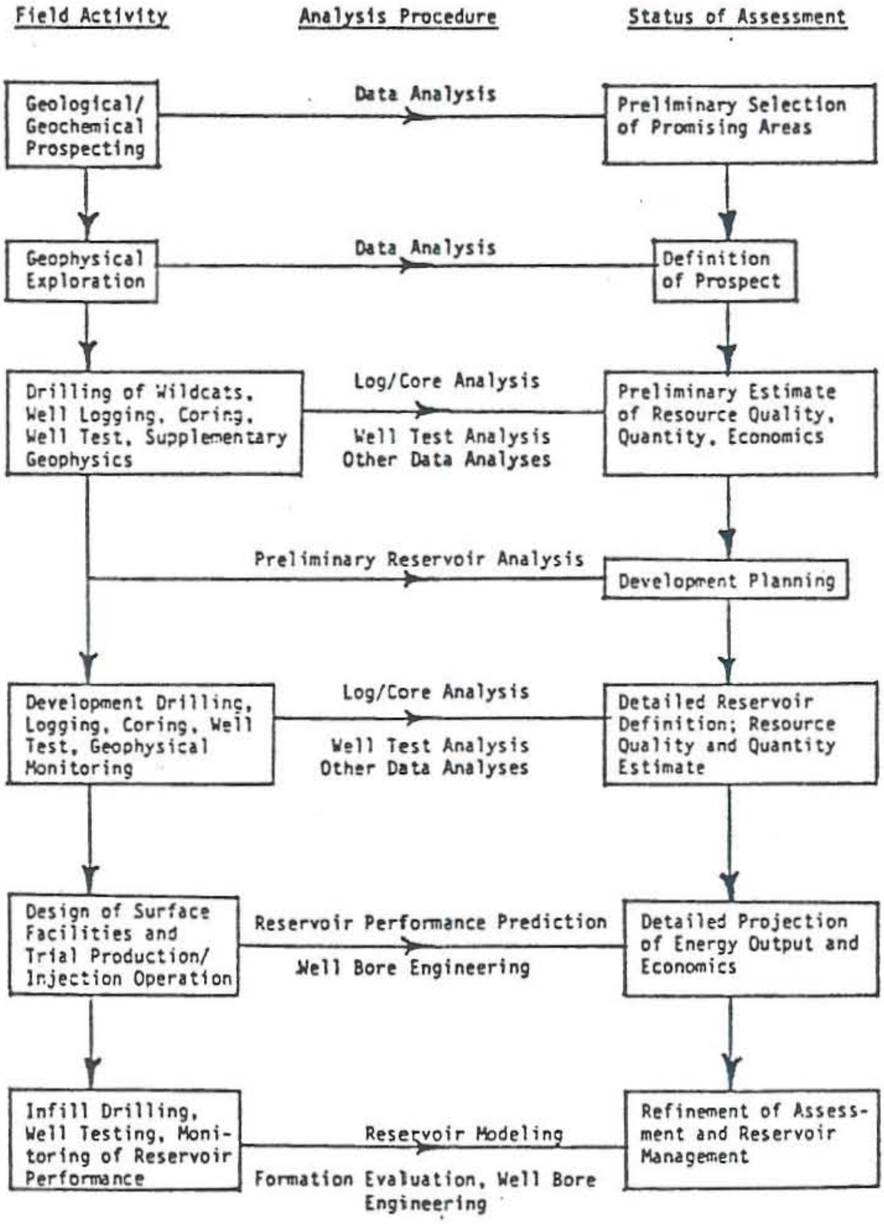

Fig. 1 Flow chart of geothermal reservoir assessment (Ramey, 1981).

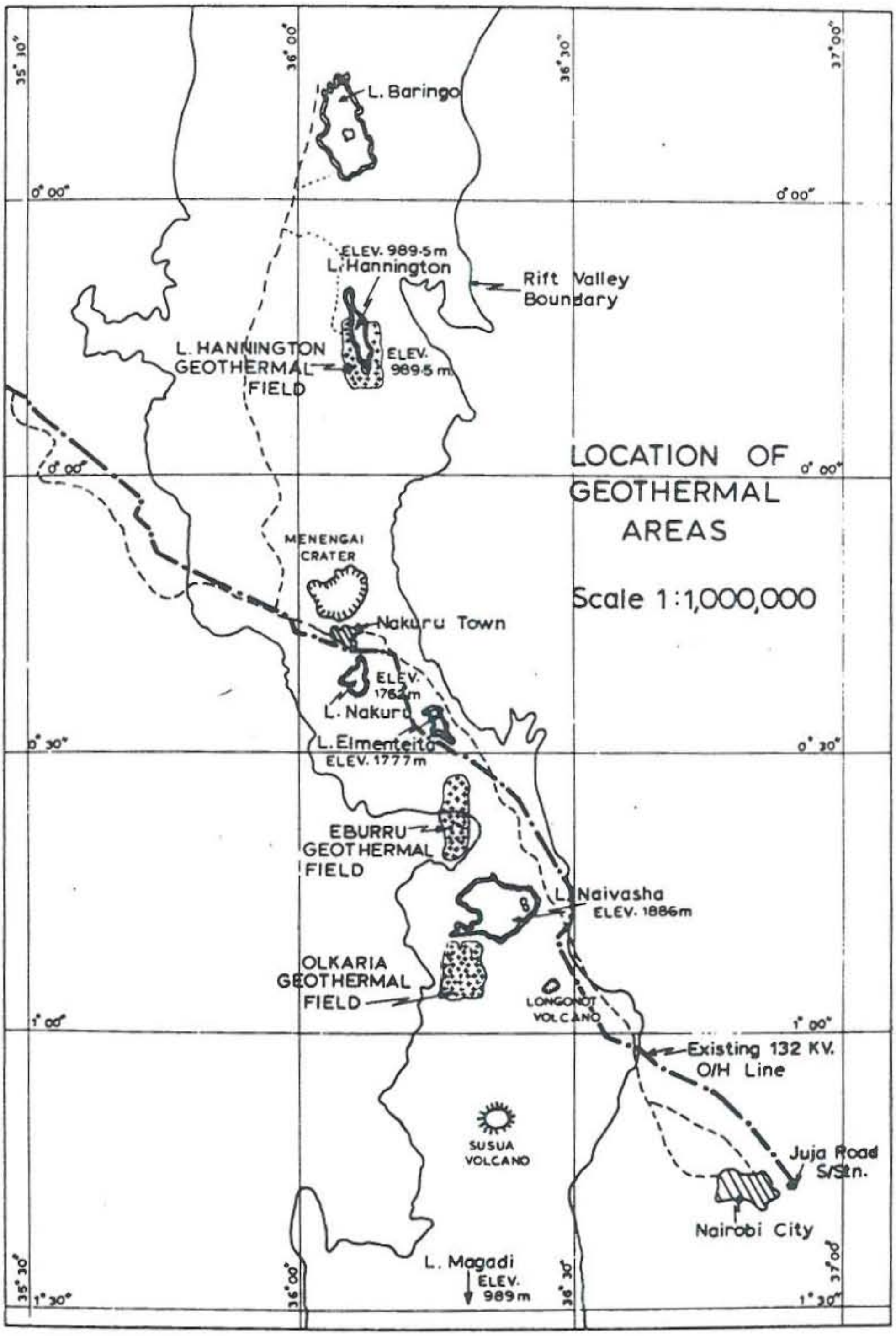

Fig. 2 Location of geothermal areas in the Rift Valley of Kenya (Noble et al., 1976).

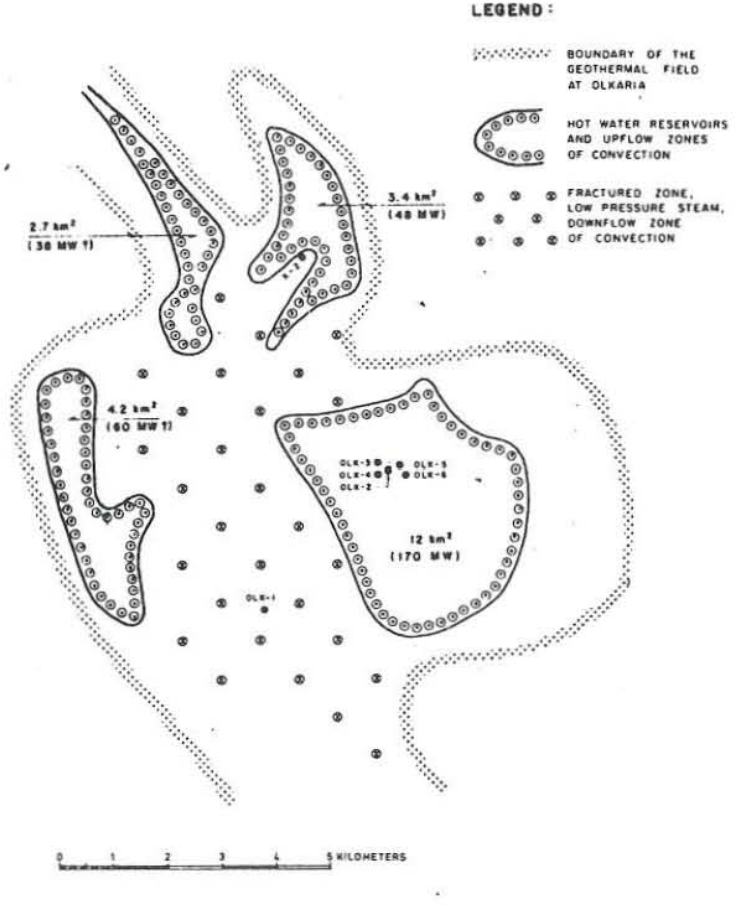

Fig. 3a Potential hot water reservoirs at Olkaria (Modified after Hochstein et al., 1981).

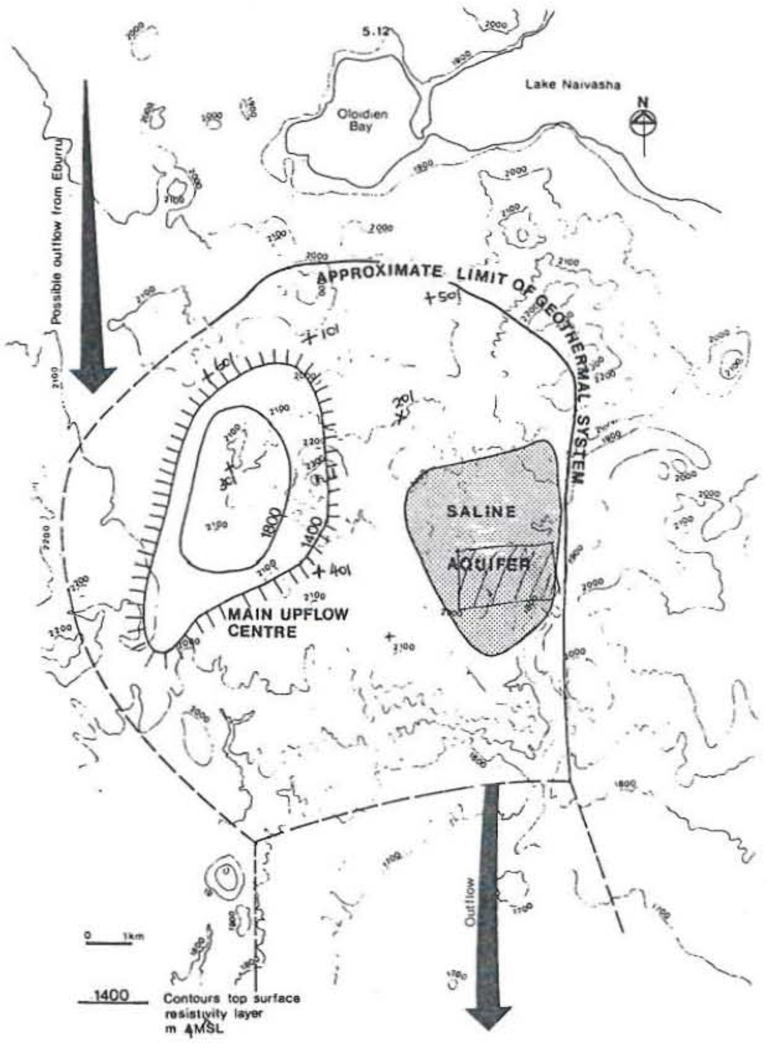

Fig. 3b Location of upflow inferred from geophysics (Modified after Hochstein et al., 1981).

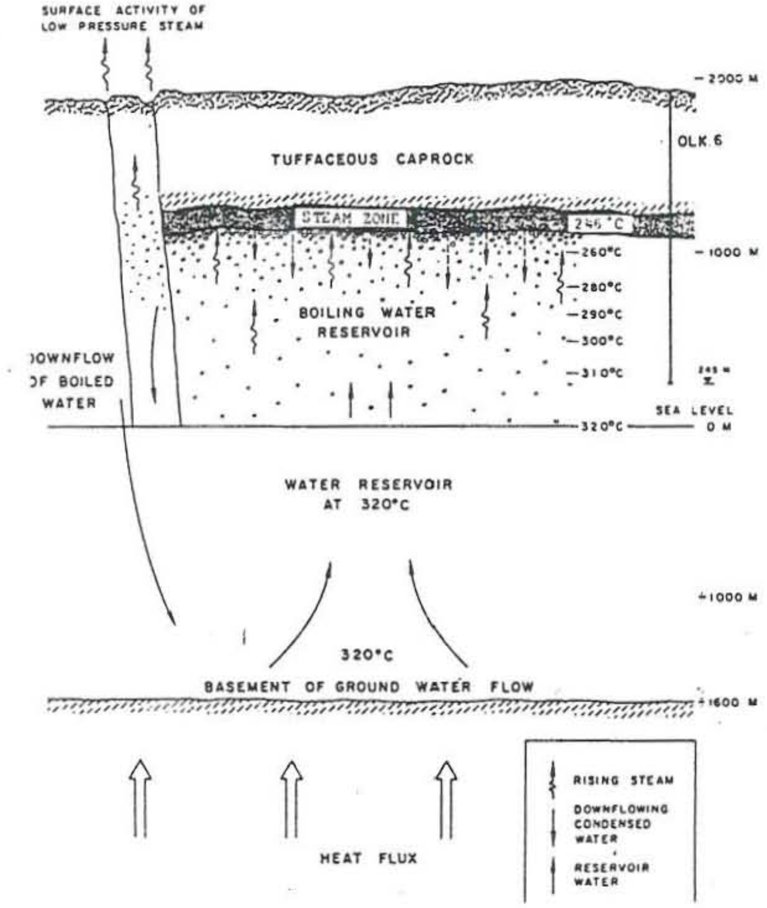

Fig. 4a Schematic section through the Olkaria geothermal reservoir (SWECO, 1976).

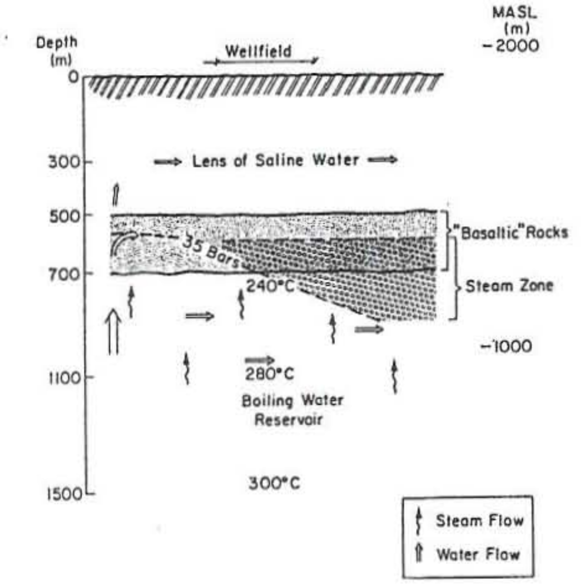

Fig. 4b Schematic cross-section through Olkaria reservoir (from Kenya Power Company Ltd., 1984).

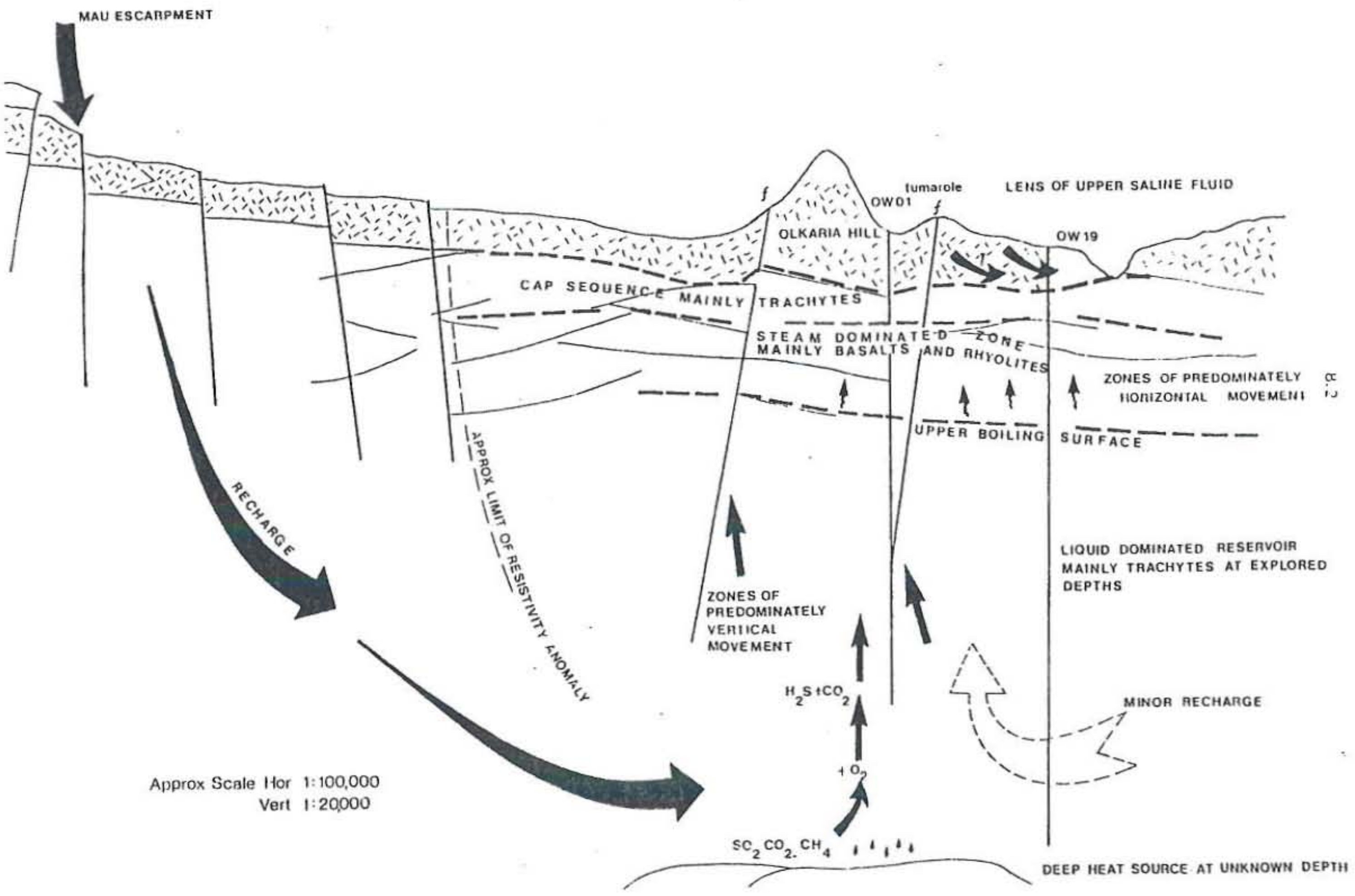

Fig. 5 Schematic geological cross section through Olkaria reservoir (from Kenya Power CompanyLtd., 1984).

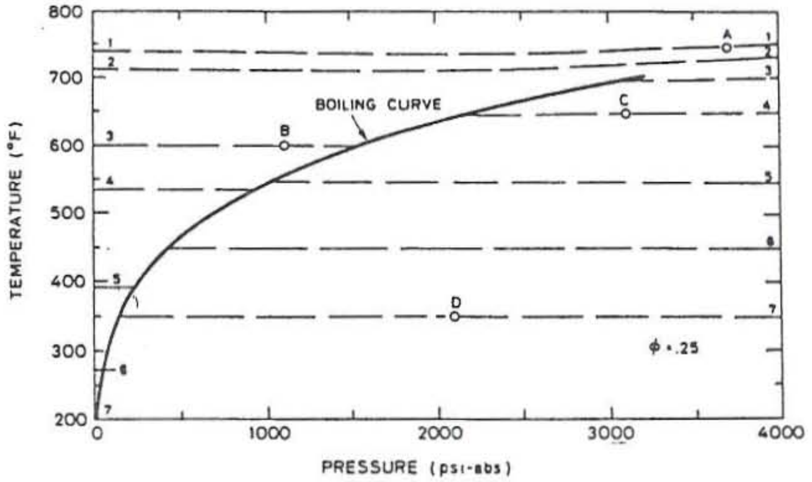

Fig. 6 Temperature Vs pressure for geothermal reservoirs containing fresh water (Martin, 1975).

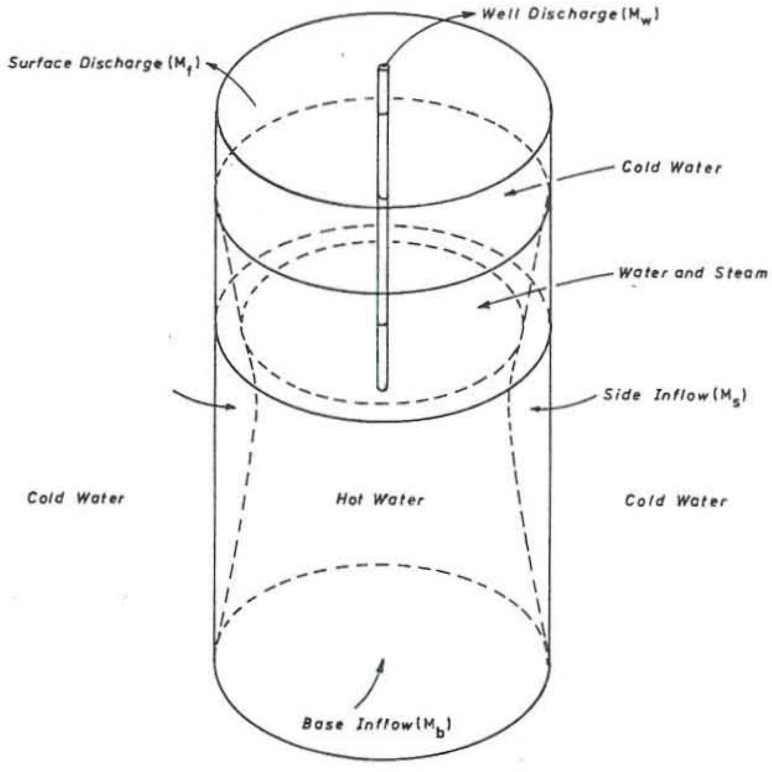

Fig. 7 The assumed basic model for a geothermal reservoir (adapted from McNabb, 1975).

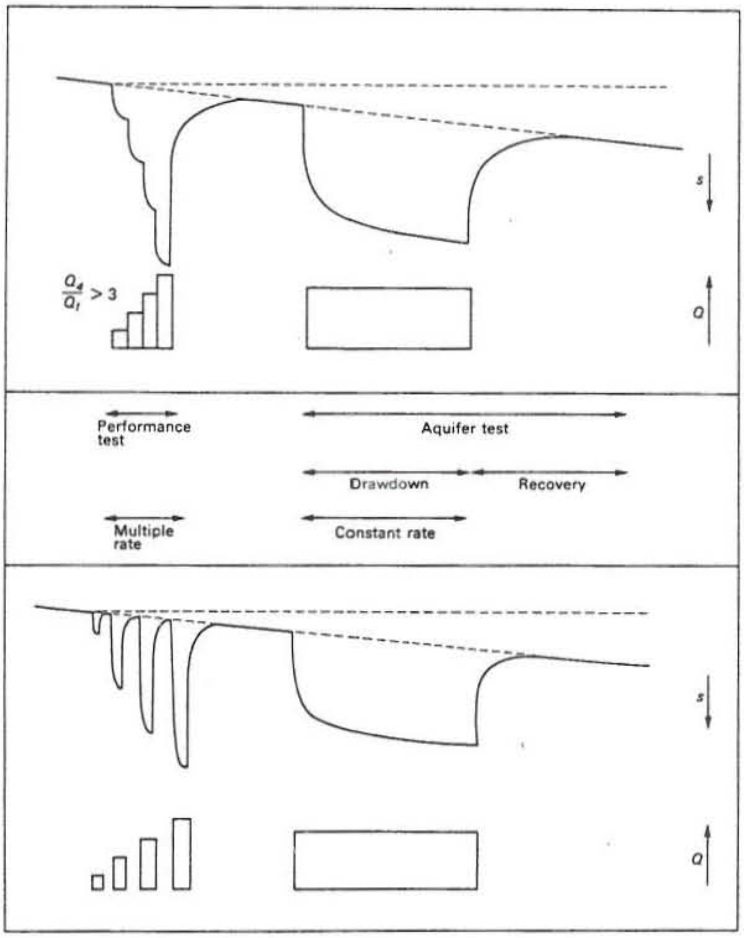

Fig. 8 Alternative well testing schedules (Jones et al., 1981).

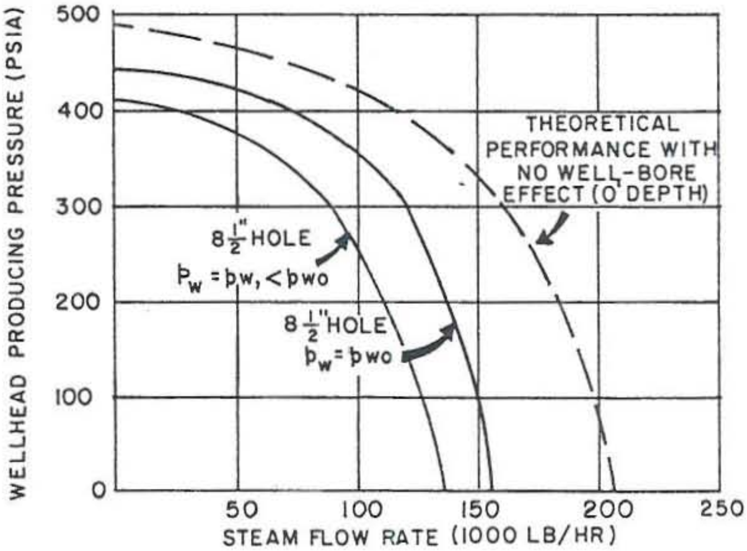

Fig. 9 Steam flow rate Vs well head pressure, theoretical curve and for two reservoir pressures.

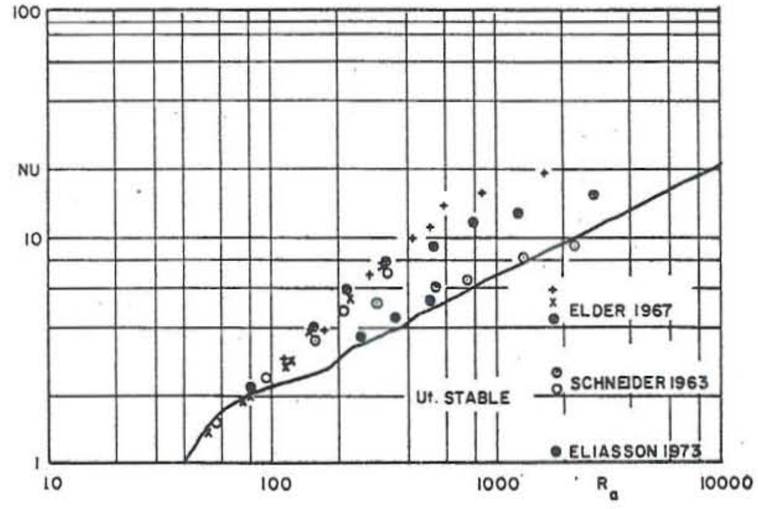

Fig. 10 Nusselt-Rayleigh experimental results (Eliasson, 1973).

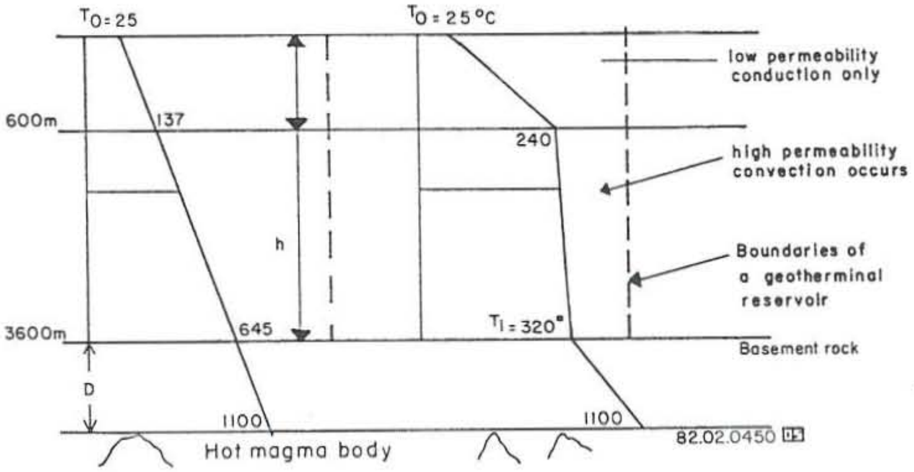

Fig. 11 Temperature profiles with and without convection (adapted from Kjaran et al., 1983).

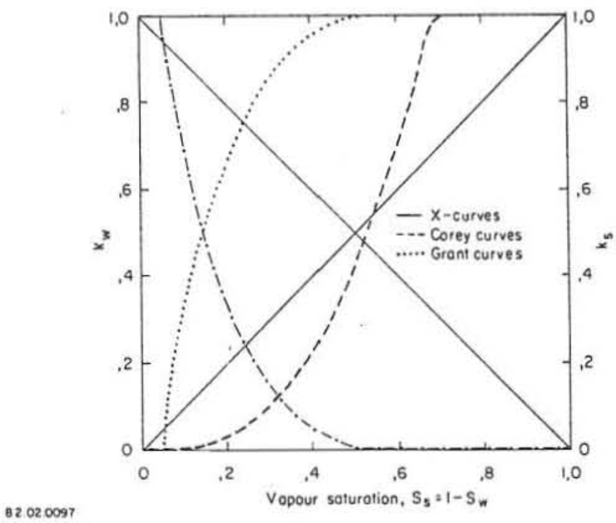

Fig. 12 Relative permeability curves.

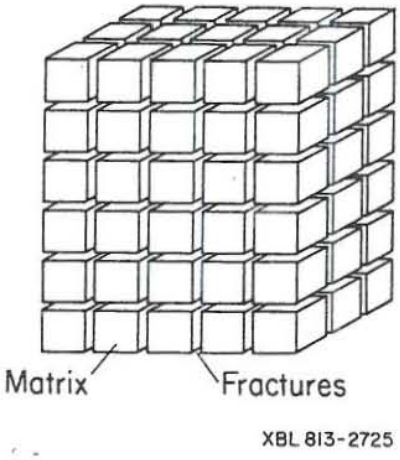

Fig. 13 Idealized model of fractured reservoir (Pruess, 1981).

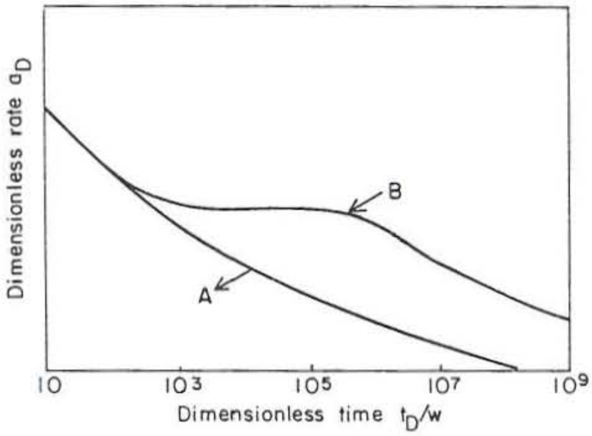

Fig. 14a A typical response of an infinite double porosity system (adapted from Sageev et al., 1985).

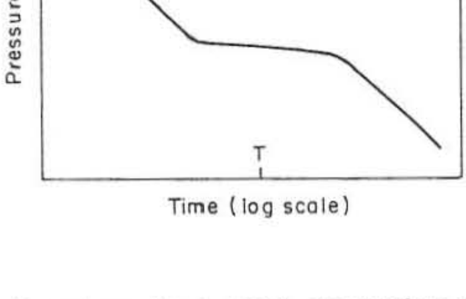

Fig. 14b Drawdown in a well producing from a fractured medium (after Kazemi, 1969).

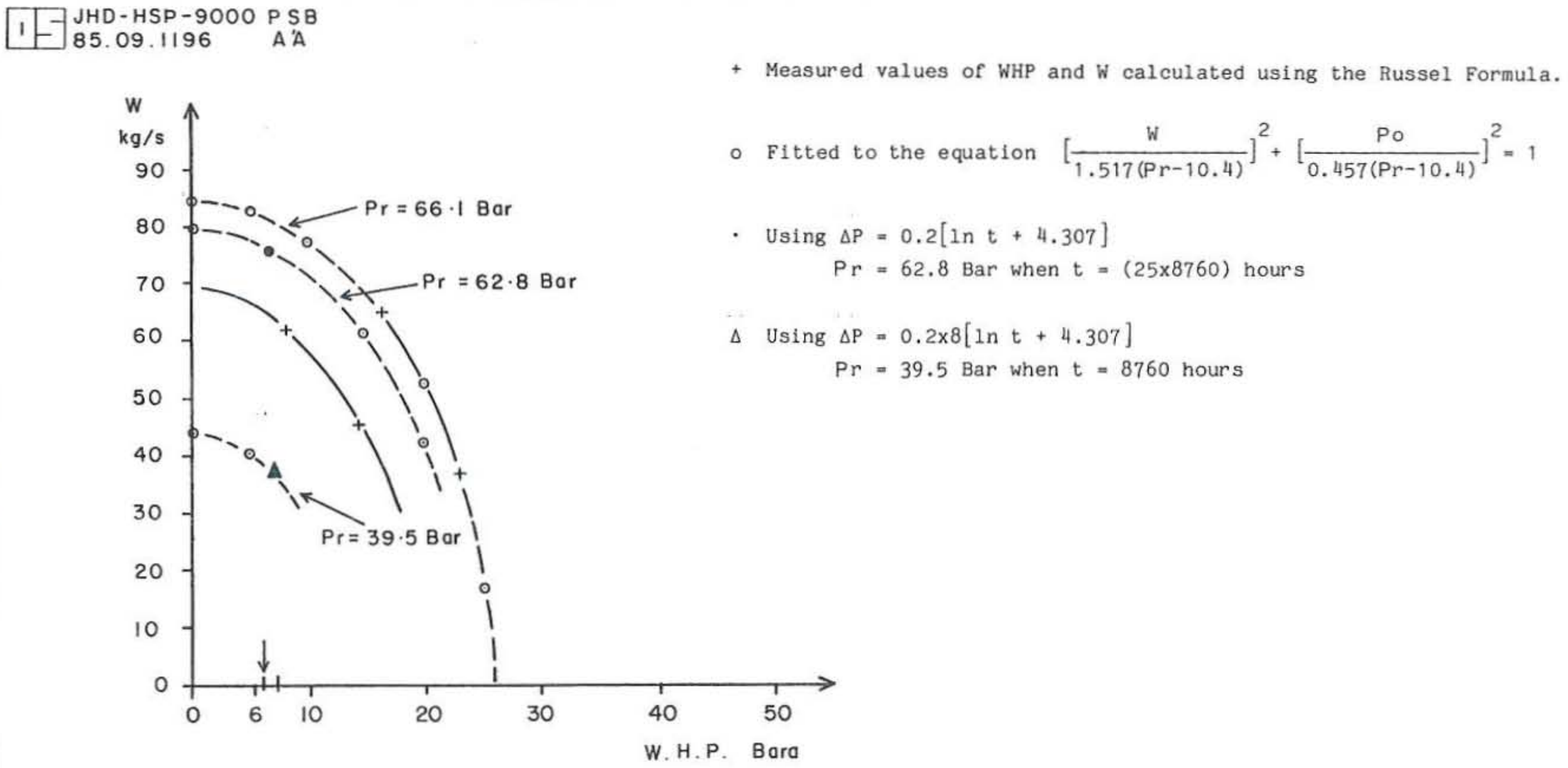

Fig. 15 Deliverability curves for two phase flow in borehole.