3. GEOTHERMAL RESERVOIR ENGINEERING

Reservoir engineering covers the methodology needed to obtain information on the hydrological characteristics of geothermal reservoirs and to forecast the long term response of the reservoirs to exploitation.

3.1. EXPLORATION OF GEOTHERMAL RESOURCES

Exploration is a significant step in the process of utilization of the geothermal resources. It is aiming at locating geothermal reservoirs for possible exploitation and at selecting the best sites for drilling production wells with the greatest possibly confidence. Geothermal exploration involves the application of a plethora of methods and techniques from various fields of Earth Sciences (geology, geophysics, geochemistry, drilling technology etc.) to locate reservoirs, to characterize their conditions and to optimize the locations of wells.

Exploration for geothermal resources typically uses geologic mapping, geochemical analysis of water from hot springs and geophysical techniques commonly used by the mining industry. With advances in seismic techniques, reflection seismic surveys are increasingly being used.

The exploration programme is usually developed on a step-by-step basis: *reconnaissance*, *pre-feasibility* and *feasibility*. During each of these phases we gradually eliminate the less interesting areas and concentrate on the most promising ones. The methods used also become progressively more sophisticated and more detailed as the programme develops. The size and budget of the entire programme should be proportional to its objectives, to the importance of the resources we expect to find, and to the planned forms of utilization.

Objectives of exploration

The objectives of *geothermal exploration* are (Lumb, 1981):

1. Identify geothermal phenomena.
2. Ascertain that a useful geothermal production field exists.
3. Estimate the size of the resource.
4. Determine the type (classification) of geothermal field.
5. Locate productive zones.
6. Determination the heat content of the fluids that will be discharged by the wells in the geothermal field.
7. Compilation a body of basic data against which the results of future monitoring can be viewed.
8. Determination the pre-exploitation values of environmentally sensitive parameters.
9. To acquire knowledge of any characteristics that might cause problems during field development.

The relative importance of each objective depends on a number of factors, most of which are tied to the resource itself. These include anticipated utilization, technology available, economics, as well as situation, location and time, all of which affect the exploration program.

A large number of methods and technologies are available in order to reach these objectives. Many of these methods are in current use and have already been widely experimented in other sectors of research. The techniques and methodologies that have proved successful in mineral and oil or gas exploration will however not necessarily be the best solution in geothermal exploration. Conversely, techniques of little use in oil exploration could turn out to be ideal tools in the search for natural heat (Combs and Muffler, 1973).

3.1.1. Geochemical Methods in Geothermal Exploration

The major goals of geochemical exploration are to obtain the subsurface composition of the fluids in a geothermal system and use this to obtain information on temperature, origin, and flow direction, which help locating the subsurface reservoir. Equilibrium speciation is obtained using speciation programs and simulation of processes such as boiling and cooling to get more information to predict potential deposition and corrosion. Environmental effects can be predicted and the general information is used as a contribution to the model of the geothermal system. Geochemical methods are extensively used and play a major role in geothermal exploration and exploitation. Geochemistry and geochemical methods are extensively applied in all phases of geothermal exploration and development.

The basic philosophy behind using geochemical methods in geothermal exploration is that fluids on the surface (aqueous solutions or gas mixtures) reflect physicochemical and thermal conditions in the geothermal reservoir at depth

Subsurface waters: It has proved difficult to obtain a genetic classification of subsurface waters. Water flow away from its point of origin and also undergo water-rock interaction during its travels making it increasingly difficult to decipher its origins. White (1986) attempted a classification which is summarized below:

- Meteoric water circulates in the atmosphere, co-existing with near-surface, un-cemented sediments, can circulate in subsurface rocks and dissolve constituents, e.g. evaporates.
- Ocean water is partly evaporated products of meteoric water
- Evolved connate water forms in young marine sediments. Variable salinity is observed and may be due to filtration, evaporation or dissolution of evaporates.
- Metamorphic water is contained in or driven from rocks undergoing metamorphic dehydration reactions. Being over pressured at depth, it may escape in response to litho-static load.
- Magmatic water is derived from oceanic and evolved connate waters sub-ducted along with oceanic crust into the mantle. At deep crustal level it is mostly due to rocks undergoing metamorphism.
- Juvenile water is classified as water that has never circulated in the atmosphere. If it exists it must be extremely rare. Juvenile 3He and CO_2 of mantle origin exist and thus suggest that juvenile H_2O may exist too but it has not yet been identified conclusively.

Geothermal waters: Ellis and Mahon (1978) classified geothermal water into four categories based on major ions:

- Alkali-chloride water: pH 4-11, least common in young rocks, e.g. Iceland. These are mostly sodium and potassium chloride waters although in brines Ca concentration is often significant.
- Acid sulfate water: These waters arise from the oxidation $H_2S \rightarrow SO_4$ near the surface and most of its constituents are dissolved from surface rock. Thus such water is generally not useful for prediction of subsurface properties.
- Acid sulfate-chloride water: such water may be a mixture of alkali chloride water and acid sulfate water, or it can arise from the oxidation $H_2S \rightarrow SO4$ in alkali-chloride water or dissolution of S from rock followed by oxidation. Sulfate-chloride waters need not be very acid and may then reflects subsurface equilibrium and be used for prediction of subsurface properties.

- Bicarbonate water: Bicarbonate water may derive from CO_2 rich steam condensing or mixing with water, it is quite common in old geothermal waters or on the peripheries of geothermal areas in outflows. They are commonly at equilibrium and may be used to predict subsurface properties.

The dissolved constituents of geothermal water do to some degree originate in the original meteoric or oceanic water. However, water-rock interactions and sometimes additions of magmatic gases will further modify geothermal solutions. The dissolved components are divided into rock forming constituents, e.g. Si, Al, Na, K, Ca, Mg, Fe, Mn and incompatible constituents, e.g. Cl, B, Br.

In the exploratory phase the task of geochemistry is mainly to:

- Estimate subsurface temperatures by using chemical and isotope geothermometers as well as mixing models
- Identify the origin of the geothermal fluid, mainly with isotopic techniques
- Define chemical properties of the fluid with respect to environmental issues, scaling ...
- Provide data to a conceptual model of the geothermal system

In the phase of exploration drilling the main task of geochemistry is to:

- Provide information on water to steam ration in the reservoir
- Assess the quality of the geothermal fluid with respect to the intended use
- Assess the quality of the geothermal fluid with respect to the environment
- Provide information on scaling tendencies of the fluid in production as well as injection wells and surface equipment
- Provide additional information to a conceptual model of the geothermal reservoir

In the phase of production drilling and operation of a power plant the main task of geochemistry is to:

- Identify recharge into the reservoir of shallow groundwater or deeper hot water
- Assess boiling processes in production aquifers
- Identify changes in the chemistry of the geothermal fluid
- Quantify changes in scaling and corrosion tendencies
- Monitor the quality of the geothermal fluid with respect to the environment

3.1.2. Geophysical Methods in Geothermal Exploration

Geophysical methods used in geothermal exploration can be divided into four main groups, depending on the physical parameters measured:

- potential methods, based on density and magnetic properties of rocks and two of the Earth potential fields: magnetic and gravity;
- electrical and electromagnetic (EM) methods, based on the electromagnetic properties of rocks (conductivity, permittivity) and the Maxwell equations;
- seismic methods, based on the elastic properties of rocks and the equations of wave propagation in continuous media;
- radiometric methods, based on radioactive emission of rocks and atomic physics equations. These methods are most commonly used in well-logging.

Each method has a specific application, depending on the physical properties of the target and how precisely these properties can be detected by the technology available.

Gravimetric methods are comparatively easy to use and fairly economical; they provide a good estimate of the extent of bodies with certain density. The resolution and quality of data, however, decrease considerably with depth. Gravimetric studies therefore provide a useful tool to be used for shallow reservoirs *in combination* with other geophysical methods.

Similarly, *magnetic* methods have been very popular during the last 30 years for the rapidity with which the measurements can be made and the low cost of operation. Restrictions are the resolution with depth, the complexity of the interpretation which makes it most reliable only for structures with simple geometric shapes, and the insensitivity to the actual presence of water.

Methods to measure the *electrical* resistivity of the subsurface can basically are divided into two general groups:

- Those that measure the difference in electrical potential
- Those that measure an electromagnetic field, natural or artificially created

Electrical potential has been used mainly for shallow depths, for example for ground water aquifers or very shallow geothermal reservoirs.

The most commonly used methods today are electromagnetic. They are either induced actively, as in the *TEM (Transient Electro Magnetic*) method, which is now routinely applied to depths of down to 2000m. For greater depths, the *magneto telluric (MT)* method, which measures the earth's impedance to naturally occurring electromagnetic waves, has become the standard choice in most geothermal areas.

Seismic methods use the propagation of elastic waves, which are either generated artificially by an explosive source or occur naturally due to earthquake activity. Active seismic methods are the standard tool for hydrocarbon prospecting, as they can be used to supply a detailed image of the subsurface structure in the sedimentary environment of most oil and gas reservoirs. Passive seismology, if recorded appropriately, can be used to help understand the structural context or to give an outline of the actual fluid/geothermal reservoir.

Last not least, electrical and seismic methods are also used for down-hole tools. Some specific tools are specially developed for well-logging, for example for radiometric measurements of the rock units accessed by the well (neutron and gamma-ray measurements).

Examples of how these methods have been applied at some European sites in metamorphic, volcanic and sedimentary environments were gathered in a specific work package of the EU-project IGET.

Electromagnetic methods. Electromagnetic induction (EM), as the name implies, uses the principle of induction to measure the electrical conductivity of the subsurface. Unlike conventional resistivity techniques, no ground contact is required. This eliminates direct electrical coupling problems and allows much more rapid data acquisition. Because EM instruments provide rapid and easy data collection, they are often employed as the reconnaissance tools, used to identify anomalies for greater detailing. There are two categories for which electromagnetic field, and time domain measures decay time of an electromagnetic pulse induced by a transmitter.

Electrical methods. Various methods for measuring electrical resistivity are used in geothermal exploration, based on the premises that temperature affects the electrical properties of rocks. At the lower end of the temperature scale, up to the critical temperature for water, the effect of temperature is to enhance the conductivity of the water in the pores of the rock. In such rocks, electrical conduction takes place solely by passage of current through the fluid in the pores, since almost all rock-forming minerals are virtual insulators at these temperatures. The maximum enhancement in conductivity is approximately sevenfold between 350°C and 20°C for most electrolytes.

Magnetic methods. This is an efficient and effective method to survey large areas for underground iron and steel objects such as tanks and barrels. Magnetic measurement of the Earth's total magnetic field and local magnetic gradients are usually made with proton precession magnetometers at points along a line which should be oriented at a high angle to the suspected trend of structures. For local surveys, the Earth's ambient field may be considered uniform. Local geological and cultural magnetic materials will then express their distribution by local perturbations in the Earth's field. In general, sedimentary rocks are non-magnetic while igneous and metamorphic rocks are magnetic.

The magnetic method has come into use for identifying and locating masses of igneous rocks that have relatively high concentrations of magnetite. Strongly magnetic rocks include basalt and gabbro, while rocks such as granite, granodiorite and rhyolite have only moderately high magnetic susceptibilities. Magnetite is the most common ferromagnetic mineral and so, in most cases, the magnetic permeability is controlled by the presence of varying amounts of magnetite and related minerals in the rock.

The magnetic method is useful in mapping near-surface volcanic rocks that are often of interest in geothermal exploration, but the greatest potential for the method lies in its ability to detect the depth at which the Curie temperature is reached. Ferromagnetic materials exhibit a phenomenon characterized by a loss of nearly all magnetic susceptibility at a critical temperature called the Curie temperature. Various ferromagnetic minerals have differing Curie temperatures, but the Curie temperature of titan-magnetite, the most common magnetic minera1 in igneous rocks, is in the range of a few hundred to 570°C. The ability to determine the depth to the Curie point would be an ability to determine the depth to the Curie point isotherm as well.

Seismic methods. Seismic techniques are commonly used to determine site geology, stratigraphy, and rock quality. These techniques provide detailed information about subsurface layering and rock geomechanical properties using seismic acoustical waves. Reflection and Refraction are the most commonly used seismic techniques. These methods determine geological structure and rock velocities by either refracting or reflecting waves off boundaries between rock units with different seismic velocities or impedance.

These methods can be divided into two main subclasses: passive seismic methods, dealing with the effects of natural earthquakes or those induced by fracturing related to geothermal fluid extraction and injection; and active seismic methods, which cover all seismic prospecting's having an artificial wave source.

Gravity methods. State-of-the-art gravity meters can sense differences in the acceleration (pull) of gravity to one part in one billion. Measurements taken at the Earth's surface express the acceleration of gravity of the total mass of the Earth but because of their high sensitivity the instruments can detect mass variations in the crustal geology. For example a high angle, basin and range type fault will have older consolidated rocks on one side and relatively unconsolidated valley fill sediments on the other side of the fault. Mass is volume x density, and there is a density contrast in the order of 0.5 gm/cc across the basin and range fault, therefore the gravity field will express the position of the fault, in the high gradient zone, between the mountain and the valley. The amplitude of the variation from the high to the low of the gravity gradient zone is a function of the displacement on the fault. In addition to providing insights to fault problems, gravity methodology applies to any geologic problem involving mass variations.

Gravity surveys are used during geothermal exploration to define lateral density variation related to deep magmatic body, which may represent the heat source. These anomalies can be created also by different degrees of differentiation of magma or variation in depth of crust-mantle interface which creates also depth variation of isotherms.

Gravity monitoring surveys are mainly performed in geothermal areas to define the change in groundwater level and for subsidence monitoring. Fluid extraction from the ground which is not rapidly replaced causes an increase of pore pressure and hence of density. This effect may arrive at surface and produce a subsidence, whose rate depends on the recharge rate of fluid in the extraction area and the rocks interested by compaction.

Repeated gravity monitoring associated to weather monitoring may define the relationship between gravity and precipitation which produces the shallow ground water level change. When gravity is corrected by this effect, gravity changes show how much of the water mass discharged to the atmosphere is replaced by natural inflow. The underground hydrological monitoring done by gravity survey is an important indication of the fluid recharge in geothermal systems and the need of reinjection.

3.2. DRILLING AND COMPLETION

Geothermal drilling relies on technology used in the oil and gas industry modified for high temperature applications and larger well diameters. Well testing and reservoir engineering rely on techniques developed in the oil and gas industry for highly fractured reservoirs because the high flow rates needed for economic production usually require fractures.

Drilling of *exploratory wells* represents the final phase of any geothermal exploration program and is the only means of determining the real characteristics of the geothermal reservoir and thus of assessing its potential (Combs and Muffler, 1973). The data provided by exploratory wells should be capable of verifying all the hypotheses and models elaborated from the results of surface exploration and of confirming that the reservoir is productive and that it contains enough fluids of adequate characteristics for the utilization for which it is intended. Sitting of the exploratory wells is therefore a very delicate operation.

3.2.1. Nature of Geothermal Formations

Common rock types in geothermal reservoirs include granite, granodiorite, quartzite, greywacke, basalt, rhyolite and volcanic tuff. Compared to the sedimentary formations of most oil and gas reservoirs, geothermal formations are, by definition, hot (production intervals from 160°C to above 300°C) and are often hard (240+ MPa compressive strength), abrasive (quartz content above 50%), highly fractured (fracture apertures of centimeters), and under-pressured. They often contain corrosive fluids, and some formation fluids have very high solids content (TDS in some Imperial Valley brines is above 250,000 ppm). These conditions mean that drilling is usually difficult—rate of penetration and bit life are typically low, corrosion is often a problem, lost circulation is frequent and severe, and most of these problems are aggravated by high temperature.

Common geothermal systems almost always contain dissolved or free carbon dioxide (CO_2) and hydrogen sulfide (H_2S) gases. While these gases contribute to the corrosion problem, H_2S in particular limits the materials that can be used for drilling equipment and for casing to the lower strength steels, because higher strength steels will fail by sulfide stress cracking. H_2S also presents a substantial safety hazard during the drilling process. These material limitations, and the associated safety hazards, increase the cost of drilling geothermal wells.

Depth and temperature of geothermal resources vary considerably. Several power plants, (e.g., Steamboat Hills, Nevada and Mammoth Lakes, California) operate on lower-temperature fluid (below 200°C) produced from depths of approximately 330 m, but wells in The Geysers produce dry steam (above 240°C) and are typically 2500 to 3000 m deep. In an extreme case, an exploratory well with a bottom hole temperature of 500°C at approximately 3350 m has been completed in Japan, and experimental holes into molten rock (above 980°C) have been drilled both in Hawaii and in Iceland.

Well Cost Drivers. Geothermal drilling is more expensive (in cost/depth) than on-shore oil and gas drilling for three principal reasons:

1. Technical challenge: the conditions described above mean that special tools and techniques are required for the harsh down-hole conditions.
2. Large diameters: because the produced fluid (hot water or steam) is of intrinsically low value, large flow rates and thus, large holes and casing, are required. In many cases, it will also require more casing strings to achieve a given depth in a geothermal well than in an oil well to the same depth.
3. Uniqueness: geothermal wells, even in the same field, are more different than oil and gas wells in the same field, so the learning curve from experience is less useful.

An indirect cost effect comes from the fact that almost all produced fluids must be re-injected, thus requiring additional wells. Taken together, these factors can drive the cost of drilling the production and injection well field toward 50% of the total project cost for a geothermal power plant. It is clearly important, then, to drill the well as effectively and inexpensively as possible. Some specific aspects of drilling with a major impact on well cost are described below.

Well design: Design of a geothermal well is a “bottom-up” process. Location of the production zone determines the well’s overall length, and the required flow rate determines diameter at the bottom of the hole – the well’s profile above the production zone is then set by iteration of the successively larger casing strings required by drilling or geological considerations. Because of the large diameters in geothermal wells, however, casing and cementing costs form a relatively large share of the cost, and the ability to eliminate one string of casing would have a major impact.

Directional Drilling: The need for directional drilling is usually dictated by geological targets (intersect as many fractures as possible) or lease boundaries, which must be included in the well design. These are important factors in cost. While there is usually little choice about these requirements, there is usually a lot of choice in the method used to meet those requirements. These can be as simple as understanding the formation tendencies and using an engineered bit and bottom hole assembly selection, to as complicated as using sophisticated MWD systems and motors to follow a planned and specified well trajectory. The method chosen can have a large effect on the cost of the well and the success in meeting the directional objectives.

Drilling Hazards: “Trouble” is a generic name for many sorts of unplanned events during drilling, ranging from minor (small amounts of lost circulation) to catastrophic (BHA stuck in the hole and the drill string twisted-off). In some cases, experience in the same or similar reservoirs will give a hint that certain types of trouble are likely, but at other times events are completely unexpected. It is difficult, therefore, to estimate a precise budget for trouble, but all well expenditure planning must contain some contingency funds, and this number is often taken to be around 10% of the total budget.

Rate of penetration (ROP): Many of the costs attributed to drilling are time-dependent (primarily related to the rental rate on the rig and service company expenses) so it is clear that anything that speeds up the hole advance without compromising safety, hole stability, or directional path is beneficial. (Keep in mind, however, that increased ROP at the expense of more trips, or lower tool life, is usually not effective) A tremendous amount of research has been done to improve bit performance, both in terms of drilling speed and life, and there is no doubt that today's bits are far better than those of an earlier generation. Still, even with improved bits it is not always easy to optimize the performance with a new bit design drilling an unfamiliar formation. The three parameters that can be easily changed for any bit/formation combination are rotary speed, weight on bit (WOB), and hydraulics (combination of jet size and flow rate) and it often takes some experimentation to determine the best combination of these values. Bit performance data from offset wells in the same formations, and with the same hole size and bottom-hole assemblies can often be very useful.

Bit and tool life: Much of the commentary above about ROP applies to bit and tool life. Improved tool life means, of course, that the expense of replacing a bit or other piece of equipment can be avoided or delayed, but there is also a time saving if trips can be eliminated. This becomes more important as the hole gets deeper and the trips take more time.

The abrasive nature of many geothermal reservoir formations accelerates the wear on down-hole tools. This can require additional trips to replace under-gauge bits and stabilizers, earlier replacement of drilling tubular and severe damage to thinner-walled tools such as drilling jars.

The three factors that most affect bit and tool life are lithology, drilling parameters (including well path), and bottom-hole assembly design. The drilling engineer has little or no control over lithology, but significant improvements can sometimes be made by changes in the latter two factors.

3.2.2. Planning a Geothermal Well

There are two separate but closely related parts of preparing for a drilling project—*planning* the well and *designing* the well. "Planning" means to list, define, schedule, and budget for all the multitude of individual activities required to drill the well, and "designing" means to specify all the physical parameters (depth, diameter, etc.) that define the well itself.

Careful planning is critical for any drilling operation. It will not only minimize cost, but will reduce the risk of injury or property damage from unexpected events. A drilling plan should list and define all the activities required to complete the well, with their related costs and times, and should give sufficient descriptions of individual tasks to make clear the sequence in which they must be performed.

Descriptions in the plan must be relatively detailed. For example, to specify drilling an interval between two given depths and running casing in it would typically require, at minimum, the following information:

- Hole size and suggested bit type (include weight on bit and rotary speed, if available from similar wells)
- Definition of all components of the bottom-hole assembly, and whether downhole motors are to be used
  - Expected rate of penetration and bit life (thus, expected time to drill the interval)
  - Any directional drilling instructions
  - Drilling fluid type and flow rate

- Any required logging during drilling or before casing is run
- Any required testing after cementing an interval of casing or at completion of the well
- Size, weight, connection, and grade of casing, and whether it is a liner
- Proposed cementing program
- Any problems expected in that interval, or special precautions to be taken.

To begin designing the well, a great variety of information is desirable, but it is not always possible to get the complete package. It is worth considerable effort to get as much of it as possible, but sometimes the designer must just go with the best available data. The desirable information includes, but is not limited to, the following parameters.

- Purpose of the well:
- Surface or shallow borehole conditions:
- Reservoir conditions:
- Logistical requirements:
- Likely problems in drilling:
- Casing requirements:

Drill Rig Selection. Most of the criteria used to select a drill rig will be derived from well parameters; specifically diameter, depth, and casing design. The process of planning and designing the well will have established the diameter, which is the primary criterion for whether the well is considered a “slimhole” or a conventional well and, thus, what kind of rig will be used.

Several factors define the minimum borehole diameter, and also bear upon whether a core rig can be used for the hole.

- Logging tools - Typical temperature-pressure-spinner logging tools will fit into almost any reasonable hole size, but if more complex tools, especially imaging tools such as a formation micro-scanner or a borehole televiewer are to be used, the heat-shielding they require at high temperature sometimes defines a minimum hole size.
- Core size – If core is required to validate a geologic model of the reservoir or to assess the fracture dip, density, and aperture, then a coring rig is advantageous, compared with taking core samples with a rotary rig, but the core size must be considered. Diameter is not too important for fracture data, but sometimes a rock mechanics evaluation will need a minimum core diameter. Larger diameter core also gives better recovery in highly fractured or unconsolidated formation.
- Packers - Inflatable packers are sometimes used to isolate a specific section of the wellbore for injection tests, fluid sampling, or other diagnostics. In general, this means that some kind of logging or sampling tool must be run through the packer into the zone below it, and the size of this tool will determine the minimum size of the packer and thus the hole. Based just on the diameter of the cable head for most logging cables, it would be very difficult to run a pass-through packer in a hole smaller than approximately 10 cm diameter.
- Flow test - If a flow test is expected after drilling, there are two advantages to keeping the hole diameter as large as possible: scaling up for predicted flow in a large-diameter well will be more accurate; and if the combination of depth, pressure, and temperature means that the well's ability to produce a self-sustaining flow is marginal, a larger diameter hole is more likely to flow. The larger-diameter wellbore is particularly important if the flow turns two-phase.

If a large-diameter hole is required, then a conventional rotary rig will probably be used and the basic choice to be made is whether it should be a top-drive. For many years, in “traditional” drill rigs, the drill string was turned by a “rotary table” in the rig floor.

3.2.3. Classification of drilling methods

Drilling is a process where certain tools are used to create a slim hole in the ground, often to a considerable depth. The drilling equipment is fed by energy, often obtained by diesel or electrical driven motors and hydraulic loops. The efficiency of the process vary greatly and depends on how much of input energy is actually used to create the hole and how much is energy losses in the process. The energy is not only used for the drill bit to penetrate the soil or rock, but also for creating the forces needed on the drill bit (thrust) and the resistance against rotation (tongue). Furthermore, some is also used for flushing the cuttings to the surface. By regarding the process of destruction, the cleaning of the borehole and the forces applied on the drilling equipment, the most common drilling methods can be described as shown in figure 1.

- Cable tool drilling
- Hammer drilling with air
- Conventional Rotary Drilling
- Auger drilling
- Sonic drilling

3.2.3.1 Cable tool drilling

The cable tool drilling originates from China where it was used for more than 2 600 years ago. It became a common method in Europe when drilled wells became common for water supply and it stayed as the dominating well drilling method up till the 1950-ties: It was then gradually replaced with the more efficient and much faster rotary drilling methods.

In shallow geothermal drilling it is still occasionally used for large dimension screened wells in course formations such as river beds and eskers.

3.2.3.2 Hammer drilling with air

Hammer drilling using pneumatic top hammers was introduced in the early last century. It was at that time used for construction drilling and blast-hole drilling in the mining industry. In the 1970- ties a Down-The Hole (DTH) hammer was introduced for water well drilling in hard rocks. From then it has been further developed to be one of the most efficient drilling methods and is commonly used for drilling boreholes in crystalline rocks, as well as in consolidated sedimentary rocks. The method is dominating in Baltic-Scandinavian shield area with granites and gneisses and Paleozoic sedimentary rocks at the shield border. However, the method is also spottily used in the rest of Europe, especially in regions with consolidated rocks. A typical drill site with a normal size rig and compressor is shown in figure 2.

The DTH hammer is by tradition driven by compressed air that is obtained from powerful compressors. In the 70-ties the size of compressors had about 10 bars working pressure, to be around 20 bars in the 90-ties. Currently, it is common to use compressors with 30 bars, which makes the penetration rate to be as fast as 0.5-1.0 m/min drilling in granites and gneisses.

The rigs designed for hammer drilling are normally capable of handling drill rods to a depth of 200-250 m that would be a practical depth limit for drilling closed loop systems. However, this limit could be restricted by unfavorable geological structures such as hitting tectonic unstable fractures zones. More often the target depth is restricted by entering high permeable fractures. In such cases the air force is used to carry the water up to the surface leaving less power for driving the hammer. Even with a 30 bars compressor further drilling is not possible at a water production of 15-20 l/s.

Drilling in sedimentary rocks will not be possible, unless the whole formation is consolidated. For example, a loose layer of unconsolidated silt or sand in a consolidated formation will continuously produce material due to the hydrostatic pressure towards the borehole. This will in worst case put an end to further drilling and will of cause be the depth limit for inserting a borehole heat exchanger.

An advantage with hammer drilling is that the holes can be drilled directional. This means that several holes can be made from almost the same spot forming a triangle shaped configuration. Angles up to 45^o are sometimes used, but more common is to direct the boreholes with an angle of 10-20^o. This has become common for shallow geothermal applications in cities with a limited surface for drilling.

Hammer drilled boreholes will in any case never be perfectly straight. Measurements made in "straight" boreholes show a deviation at 150 m that typically is in the order of 10-20 m. This is of cause a hazard, especially if a system consists of densely placed boreholes (BTES). Under such a situation one or several boreholes may cross each other causing damages. This problem could at least partly be avoided by having steering guides on the bit, hammer and drill string.

Another danger with closely placed boreholes is that fractures may connect the boreholes. In such cases the high air pressure used at drilling may cause damages to already complete nearby boreholes.

3.2.3.3 Hammer drilling with water

In later years a hydraulic water driven DTH hammer has been developed and introduced on the shallow geothermal drilling market (Wassara), preferably in Scandinavia.

Since the Wassara method combines the efficiency of percussion drilling with the benefits of having a hydraulic stabilizing overpressure in the borehole such as in the conventional rotary method, the method has gradually been more and more used for shallow geothermal in Scandinavia. Especially this is the case for deeper holes in crystalline rocks and in regions with younger sedimentary rocks.

A limiting factor with Wassara is that the flushing water has to be clean from particles, especially the lower fractions of silt and upper of clay. A system for cleaning the return water from cuttings is still to be developed to make the system fully compatible on the market. Hence, the consumption of water while drilling is therefore still a substantial obstacle.

3.2.3.4 Conventional rotary drilling

Governed by geological conditions, conventional rotary is the dominating drilling method in areas with sedimentary rocks. It was originally developed in oil and natural gas industry in late 1800-early 1900 and became the "oil drilling method", and still is. The method was scaled down to shallow water drilling in 1940-ties and has since then gradually replaced the cable tool method worldwide.

In consolidated sedimentary rocks a three cone "roller bit" is used to crush or break the rock into pieces (cuttings). For drilling in soft rocks another type of drill bit is used, a drag bit. This will carve pieces of the rock at the borehole bottom. By flushing a fluid through the drill rods and out through the drill bit the borehole bottom is cleaned from cuttings and transported to the surface in the annular between the rods and the borehole wall. The fluid is then cleaned by separating the cuttings from the fluid using a sieve (shale shaker) and by sedimentation in tanks or a sedimentation pit. The fluid is then and re-circulated back through the rods (straight circulation). For larger dimensions the fluid is circulated the other way around (reversed circulation). For shallow geothermal closed loop systems the straight circulation method is practically always used and if possible water as the fluid medium.

Depending on geological and hydro geological conditions, additives have to add to the water. This is commonly done in order to stabilize the borehole (prevent borehole collapse) and/ or to prevent loss of fluid if high permeable layers are entered. A common such additive is to mix the water with bentonite, a natural clay mineral. Drilling wells for open loop systems, bentonite should be avoided and replaced with a substance that is self breakable, such as organic polymers (CMC). A fluid with additives that changes its properties is called a drilling mud.

The rotary method has several advantages compared to hammer drilling with air. The most pronounced one is that the borehole can be kept stable by the hydrostatic overpressure that is created in the borehole compared to the hydrostatic pressure in the formation. This is of cause not the case if an artesian aquifer is reached. However, in such a case the fluid can be made heavier by adding for example fine grained chalk or something else that increases the density of the mud. On the other hand an obvious disadvantage is that the conventional rotary in hard rocks will be comparatively slow, and in practice not even suitable for magmatic rock types.

3.2.3.5 Auger drilling

The auger drilling method is based on a well known way of making holes into a soft material by a carving principle. It is commonly used for geotechnical site investigations, but is in a larger scale also used for water well drilling and shallow geothermal applications to a moderate depth.

In principal a screw is rotated down the soil and either drawn back at certain intervals for empty the flanges, or (more commonly) the material is automatically transported by the flanges to the surface.

For shallow geothermal applications the method may be used for moderate depths and systems placed closed loop systems penetrating fine grained sediments. For drilling in rocks, other methods should be considered.

3.2.3.6 Sonic drilling

The sonic drilling method is fairly new on market, even if it was developed during the 1990-ties. The driving force for penetration is a high frequency vibration that is transferred from the rotary head down to a drill bit. As such it reminds of the top hammer method, but with the distinction that the energy losses are much lower.

The method was originally developed for core sampling in unconsolidated formation, but has then been further developed also to drill open holes in almost any type of rocks. For making that possible it also contains a flushing possibility, ether by air or a fluid. This makes the method very flexible when it comes to drill in different geological situations. However, there are no experiences stated in literature yet to value the method for shallow geothermal applications.

Except for the flexibility when it comes to handling different geological conditions there are a couple of potential advantages with the method. These are less maintenance, less noise and easier drawback of casing, all compared to hammer drilling methods.

Advantages of sonic drilling for geothermal installations

- fastest drilling method on earth
- world's most advanced drilling technique
- holes are drilled to the desired depth by rotating and vibrating the casing at resonant sonic frequencies while keeping the bit face open with high-pressure fluid
- Ability to
    - simultaneously drill and case holes to full depth
    - drill in any geological formation
    - drill very straight holes
    - drill without using drilling mud, which provide a much cleaner and safer work environment
- economical drilling rates due to the efficient sonic drilling method, especially in gravel and boulder ground where other rigs experience great difficulty due to loss of drill mud through gravel zones and where other rigs must case the hole to prevent collapse of the borehole well
- Full length cased hole allows for:
    - easy installation of one or a multitude of geo loops in the same hole
    - quick and efficient installation of pre-coiled geo loops without the leading edge hanging up against the sidewall of a mud drilled borehole
    - installation of any size geo loop or cooper heat exchanger
    - ease of grouting by the tremie line method or pressure grout method and provide accurate monitoring of the grouting process
    - complete grout coverage around the geo loop
- Steal casing is vibrating out of the ground after geo loop installation and placement of thermally enhanced grout
- Cased hole provides the ability to deal with free-flowing hole or artesian conditions.

3.2.4. Shallow geothermal drilling methods

Shallow geothermal systems are commonly drilled to a depth of less than 200 m and consist of boreholes for closed loop systems or wells for open loop systems.

All the methods mentioned in the classification are in use for shallow boreholes; which one would be applied at specific location depends on the geological conditions and available equipment, methods and drilling procedures in the country.

3.2.5. Advanced Geothermal Drilling Technology

The objective of advanced drilling and logging technologies is to promote ways and means to reduce the cost of geothermal drilling through an integrated effort which involves developing an understanding of geothermal drilling and logging needs, elucidating best practices, and fostering an environment and mechanisms to share methods and means to advance the state of the art. Drilling is an essential and expensive part of geothermal exploration, development, and utilization. Drilling, logging, and completing geothermal wells are expensive because of high temperatures and hard, fractured formations. The consequences of reducing cost are often impressive, because drilling and well completion can account for more than half of the capital cost for a geothermal power project. Geothermal drilling cost reduction can take many forms, e.g., faster drilling rates, increased bit or tool life, less trouble (twist-offs, stuck pipe, etc.), higher per-well production through multi-laterals, and others. Activities in the Advanced Geothermal Drilling and Logging Technologies Task will address aspects of geothermal well construction, which include:

1) Developing a detailed understanding of worldwide geothermal drilling costs;
2) Compiling a directory of geothermal drilling practices and how they vary across the globe; and
3) Developing improved drilling and logging technologies.

The objectives of Advanced Geothermal Drilling and Logging Technologies are:

1. Quantitatively understand geothermal drilling costs from around the world and identify ways to reduce those costs, while maintaining or enhancing productivity.
2. Identify and develop new and improved technologies for significantly reducing the cost of geothermal well construction to lower the cost of electricity and/or heat produced with geothermal resources.
3. Inform the international geothermal community about these drilling technologies.
4. Provide a vehicle for international cooperation, field tests, etc. toward the development and demonstration of improved geothermal drilling and logging technologies.

3.3. GEOHEAT EXTRACTION AND PRODUCTION TECHNOLOGIES

Thermal energy is extracted from the reservoir by coupled transport processes (convective heat transfer in porous and/or fractured regions of rock and conduction through the rock itself). The heat extraction process must be designed with the constraints imposed by prevailing *in situ* hydrologic, lithologic, and geologic conditions. Typically, hot water or steam is produced and its energy is converted into a marketable product (electricity, process heat, or space heat). Any waste products must be properly treated and safely disposed of to complete the process. Many aspects of geothermal heat extraction are similar to those found in the oil, gas, coal, and mining industries.

Techniques for extracting heat from low-permeability, hot dry rock (HDR) began at the Los Alamos National Laboratory in 1974 (Armstead and Tester, 1987). For low-permeability formations, the initial concept is quite straightforward: drill a well to sufficient depth to reach a useful temperature, create a large heat-transfer surface area by hydraulically fracturing the rock, and intercept those fractures with a second well. By circulating water from one well to the other through the stimulated region, heat can be extracted from the rock. Fundamentally, this early approach – as well as all later refined methods – requires that good hydraulic conductivity be created between injection and production wells through a large enough volume of rock to sustain economically acceptable energy-extraction rates and reservoir lifetimes. Ultimately, field testing will need to produce a commercial-sized reservoir that can support electricity generation or cogeneration of electrical power and heat for a variety of applications such as heat for industrial processes and local district heating.

3.3.1. Steam production

Steam may be produced from compressed liquid, two phase liquid/vapor or superheated vapor reservoirs. Here, liquid and vapor are referred to water and steam although it should be borne in mind that they often coexist with gases (in particular non condensable) and solids (salts) dissolved in the liquid and vapor phases.

Fluid may also change state during production further to pressure depletion. Such is the case of an initially compressed liquid turning two phase as can be noticed from steam tables (Keenan *et.al,* 1969).

Energy densities of the rock and soaking fluid states and related volume requirements and energy outputs show the dominant energy contents of the rock and of the fluid respective to the single phase and two phase settings, a situation reflected example which addresses a 250°C reservoir and 40/34 bar initial/final pressures respectively. Here, the advantages of the two phase reservoir are obvious, from both the energy density and volume requirements stand points. It supplies ca 90% of the total energy content and requires a volume of $1.5x10^9$ m^3 to sustain a 30 year life of a 50 MWel rated plant, compared to the $9x10^9$ m^3 figure for the single phase (liquid, vapor) cases.

The foregoing have obvious implications on field development of superheated and flashed steam reservoirs when both water injection and make up well issues are implemented to sustain the production objective.

In hole flashing· Most commercially developed fields are of the liquid dominated type and are likely more to two phases during exploitation above a 230°C temperature cut. Wells are produced in self-flowing mode by vapor lift, as a consequence of in hole flashing, and may achieve productivities in excess of 500 t/h and power capacities nearing 30 MWel (assuming a 40% steam fraction and a dual flash condensing cycle). Note that well bore flashing may cause scaling shortcomings by precipitation, above the flash front, of Calcium carbonates for instance, whenever the well head pressure is depleted below CO_2 partial pressure. In such case the remedial would consist of either increasing well head pressure, at the expense of production losses, or to inject scale inhibitors, preferably stable at high temperatures, below the flash front.

Resources in the 180°C to 230°C range will not exhibit such high well performances due to weaker self flowing/vapor lift capacities and the upper 190°C temperature limit of commercial down-hole submersible pumps which readily discards sustained artificial lift production.

Below 180°C, resources, eligible to binary (ORG, Kalina) conversion and combined heat and power uses, are currently produced via down-hole line shaft pumps.

Vapor/liquid separation is completed by cylindrical vessels of either the vertical or horizontal type. Both apply a forced vortex principle. The vertical separator is based on streamlined inlet fluid admission and centrifugal steam separation whereas in the horizontal outfit the fluid enters tangentially and the steam is recovered by gravity. The pros and cons of both separation principles, discussed by Eliasson (2001), tend to favor the vertical separator option which can accommodate a wider pressure range and achieve higher, steam quality and sharper cut off. It further requires limited maintenance commitments. A reasonable compromise would consist of dedicating vertical units to, first stage, high pressure separation and horizontal vessels to, second stage, low pressure separation. The quality of the steam is controlled by the liquid level in the separator(s). Steam needs to be kept dry, almost 100%, to avoid carryover of water droplets and subsequent mechanical (impact) and chemical (scaling) damage to turbine blades and ancillary equipment.

Non-condensable gases. Carbon dioxide, a major constituent in geothermal vapor, affects brine thermo chemistry turbine efficiency and steam condensing. As a result of fluid flashing, degassing will occur below bubble point pressure, thus decreasing pH, reducing solubility and generating carbonate scale.

Depending on non condensable gas content two extraction systems may be contemplated, a part from pre-flashing, ejectors and compressors respectively. Ejectors display poor efficiencies (15%) and require 12% of the steam mass flow available at well head to extract 1% (vol) of non condensable gases, which clearly restricts their use to low non condensable gas contents.

Higher gas volumes require, because of low inlet pressure, large multistage compressors, with compression rates as high as 8 and high (80%) efficiencies and related costs. Consumption amounts to 3% (mass) of well head vapor flow per 1% (vol) of CO_2 (Ungemach. 1987).

Whenever non-condensable gas contents exceed 10% (wt) as recorded in the Monte Amiata field of southern Tuscany (Italy), condensing should be abandoned and back pressure cycles favored instead.

Waste water disposal. Assuming a 250°C, 40 bar fluid pressure, i.e. a single phase compressed liquid state at reservoir conditions, a 7 bar turbine inlet pressure, a 50 MWel rated geo-electric plant with a 20% conversion efficiency, the waste water discharge rate would amount to ca 4200 m^3/h. Therefore, waste disposal and environmental consequences become a major concern, to which, water injection, seems the most relevant remedial solution.

A superheated steam field would not face such constraints, the sole liquid waste consisting of steam condensates.

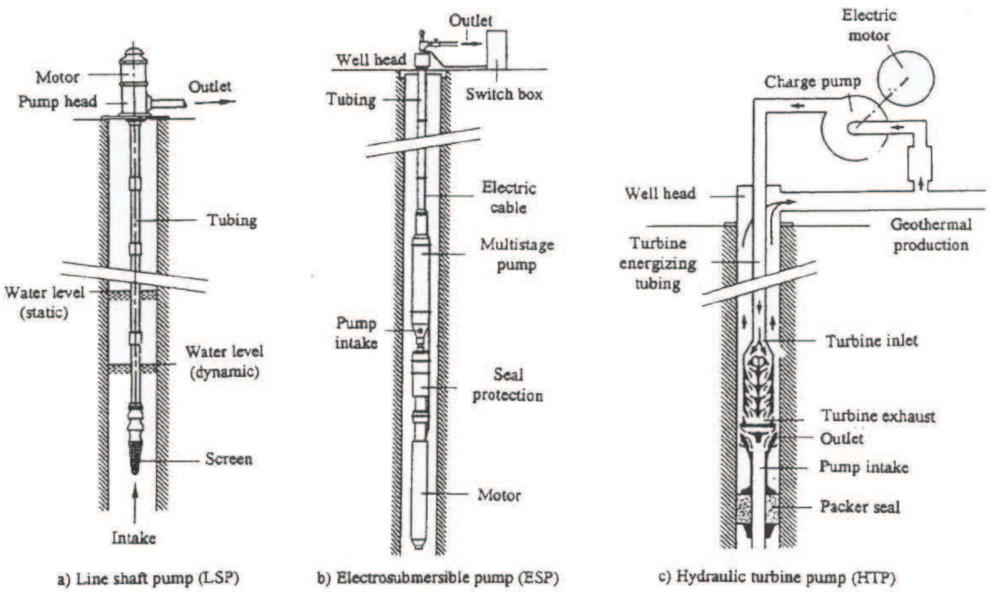
3.3.2 Hot water production

The circulation of hot water from the well can be either self-flowing or artificial lift (forcing circulation with pump). Self flowing is by far the most attractive production mode provided it can supply target flow rates without excessively depleting well head pressures (i.e. below bubble point), in which case adequate degassing/gas abatement facilities would be required.

Therefore artificial lift is most often the rule in geothermal, low grade heat, direct uses. It is best achieved thanks to the three submersible pumping alternatives, line shaft, electro submersible, turbine respectively, whose principles are illustrated in figure 3.3.1.

Line shaft pumps (a), widely used in ground water production, are quite popular in Iceland and in the Western United States. The, well head installed, motor drives an in hole multistage centrifugal pump via a shaft/bearing assembly enclosed in a slim diameter tubing housing in which a makeup lubricating fluid is circulated. Icelanders have solved the severe material abrasion problem, caused by silica originated waters, by substituting teflon to metal alloyed bearings. The nature of the lubricating fluid (either mineral oil or make up water), which is, unless recycled, lost in the formation, may be a problem in sensitive environments (mineral waters, thermal baths, medicinal uses).

Many operators rely on electro submersible pump sets (b). The technology, derived from the oil industry whenever formation temperatures are in excess of 50°C, consists of submersing in hole the complete multistage centrifugal pump, protector seal and motor (induction squirrel cage type), electric cable string. A degassing outfit may be added in case of high solution gas (GWR) contents. Material definition, seal protector efficiency and motor/cable insulation are the critical problem areas faced by this technology.



a) Line shaft pump (LSP) b) Electrosubmersible pump (ESP) c) Hydraulic turbine pump (HTP)

Fig.3.3.1 Down-hole production pump types

Turbine pumps apply a hydraulic motor concept (c). A surface, high pressure, charge pump actuates, via injection tubing, a down-hole turbine driving a single stage centrifugal pump whose intake and outlet are isolated by a packer seal. According to this design, both turbine exhaust and pump outlet fluids are mixed/produced through the energizing tubing/pumping chamber casing annulus and part of the geothermal fluid recycled through the charge pump. Only three district heating wells (two in the Paris basin, one in the Hampshire basin), apply this technology which could be regarded as a, fairly exotic, curiosity.

All three sustained production concepts exhibit reliable operation records with lifetimes close to if not higher than five years in hole continuous service. Pros and cons may be summarized as follows.

3.3.3 Deep borehole heat exchangers (*ground source heat exchangers*)

Deep borehole heat exchangers have been installed to depths of about 1500 m – 3000 m and maximum temperatures of about 60°C – 110°C. In contrast to shallow borehole heat exchangers, U-pipes cannot be used here anymore due to the much greater depth of the boreholes. Instead, these systems consist of a coaxial arrangement of an inner production pipe inserted into an outer borehole casing. Water flows down the annulus of this coaxial system and up again in a central production pipe. In order to minimize heat losses, the production pipe needs to be insulated where the production temperature exceeds the ambient rock temperature. The available operational data from the small number of currently operating deep borehole heat exchangers indicate a specific power of about 20 W/m – 54 W/m, similar to that of shallow systems.

3.4. ENHANCED GEOTHERMAL SYSTEMS

The term enhanced geothermal systems (EGS), also known as engineered geothermal systems (formerly hot dry rock geothermal), refers to a variety of engineering techniques used to artificially create hydrothermal resources (underground steam and hot water) that can be used to generate electricity. Traditional geothermal plants exploit naturally occurring hydrothermal reservoirs and are limited by the size and location of such natural reservoirs. EGS reduces these constraints by allowing for the creation of hydrothermal reservoirs in deep, hot geological formations, where energy production had not been economical due to a lack of fluid or permeability. EGS techniques can also extend the lifespan of naturally occurring hydrothermal resources.

Similar to traditional geothermal generation, EGS technologies use the heat of the earth's crust to generate electricity. Traditional geothermal plants draw on naturally occurring hydrothermal resources at relatively shallow depths. EGS, however, attempts to artificially reproduce the conditions of naturally occurring hydrothermal reservoirs by fracturing impervious hot rocks at 3 to 10 kilometers depth, pumping fluid into the newly porous system, and then extracting the heated fluid to drive an electricity-generating turbine.

An Enhanced Geothermal System (EGS) is a man-made reservoir, created where there is hot rock but insufficient or little natural permeability or fluid saturation. In an EGS, fluid is injected into the subsurface under carefully controlled conditions, which cause pre-existing fractures to re-open, creating permeability.

Increased permeability allows fluid to circulate throughout the now-fractured rock and to transport heat to the surface where electricity can be generated. While advanced EGS technologies are young and still under development, EGS has been successfully realized on a pilot scale in Europe and now at two DOE-funded demonstration projects in the United States.

Two or more boreholes are drilled to depths where the temperature of the rock is of commercial interest, and then fluid is circulated around the loop(s) formed by the holes. The fluid heats-up as it passes through the hot rock mass between the boreholes and the heat is extracted at the surface. The problem with this simple scheme lies in the fact that the permeability of deep crystalline rocks is generally too low to allow the requisite flow to pass between the wells and thus must be enhanced. The engineering of this enhanced-permeability linkage between the wells constitutes the primary challenge of EGS system development, and is the factor that distinguishes them from natural geothermal systems.

3.4.1. Current EGS drilling technology

Temperature effects on down-hole drilling tools and mud have been largely overcome by refinement of seals and thermal-expansion processes. Fluid temperatures in excess of 190°C may damage components such as seals and elastomeric insulators. Bit-bearing seals, cable insulations, surface well-control equipment, and sealing elements are some of the items that must be designed and manufactured with these temperatures in mind. Elastomeric seals are very common in the tools and fixtures that are exposed to the down-hole temperatures.

Logging. The use of well logs is an important diagnostic tool that is not yet fully developed in the geothermal industry.

Thermal expansion of casing. Thermal expansion can cause buckling of the casing and casing collapse, which can be costly.

Drilling fluids/"mud" coolers. Surface "mud coolers" are commonly used to reduce the temperature of the drilling fluid before it is pumped back down the hole. Regulations usually require that mud coolers be used whenever the return temperature exceeds 75°C, because the high temperature of the mud is a burn hazard to rig personnel. The drilling fluid temperature at the bottom of the well will always be higher than the temperature of the fluid returning to the surface through the annulus, because it is partly cooled on its way upward by the fluid in the drill pipe. High drilling fluid temperatures in the well can cause drilling delays after a bit change.

Drill bits and increased rate of penetration. While many oil and gas wells are in sedimentary column formations, geothermal operations tend to be in harder, more fractured crystalline or granitic formations, thus rendering drilling more difficult. In addition to being harder, geothermal formations are prone to being more fractured and abrasive due to the presence of fractured quartz crystals. Many EGS resources are in formations that are igneous, influenced by volcanic activity, or that have been altered by high temperatures and/or hot fluids. Drilling in these formations is generally more difficult. However, not all geothermal formations are slow to drill. Many are drilled relatively easily overall, with isolated pockets of hard, crystalline rock. In these conditions, drill bit selection is critical.

Lost circulation. Lost circulation is a drilling problem that arises when the circulation of the drilling fluid is interrupted and it does not return to the surface. The return flow in the annulus is laden with cuttings cleaned from the well. The sudden loss of fluid return causes the cuttings to be suspended in the annulus and/or to fall back down the well, clogging the drill pipe. With a total loss of fluid return, the drilling fluid must be mixed and pumped fast enough to sustain flow and keep the bit clean, which can be an expensive process. Lost circulation exists in oil and gas drilling, mining, and in water-well drilling as well, but is much more prevalent in geothermal well drilling.

Directional drilling. Directionally drilled wells reach out in different directions and permit production from multiple zones that cover a greater portion of the resource and intersect more fractures through a single casing. An EGS power plant typically requires more than one production well. In terms of the plant design, and to reduce the overall plant "footprint," it is preferable to have the wellheads close to each other. Directional drilling permits this while allowing production well bottom-spacing of 900 m or more.