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A COMPREHENSIVE REVIEW OF PAST AND PRESENT DRILLING METHODS WITH APPLICATION TO DEEP GEOTHERMAL ENVIRONMENT

C. Teodoriu, C. Cheuffa

TU Clausthal,
Agricolastr. 10
Clausthal-Zellerfeld, 38678, Germany
e-mail: catalin.teodoriu@tu-clausthal.de

ABSTRACT

Drilling and completing new wells are costly. Those costs account for 30 % to 70% of the initial capital expenses for oil and gas field developments.
The first step in this paper, which is primarily a literature overview, was to establish a list of advanced concepts and technologies, as well as their applications, advantages and disadvantages, etc.
The second step was to describe each of the concepts in terms of how they operate and perform based on following criteria: technical description, environmental impact, rate of penetration and applications and how that performance is, compared with what we call "conventional rotary drilling".
The paper will conclude with some possible future drilling systems.

INTRODUCTION

The challenge for the oil industry in the past years was to identify strategies for maximizing the upstream potential value of the discovered reserves and for optimizing future investments to reduce risk and costs in both exploration and exploitation activities, while minimizing the environmental impact (emissions, foot print etc.). The return of the renewable energy is creating more pressure on the drilling business to develop better, faster and cheaper drilling methods and well construction.
Since the turn of the twentieth century, rotary drilling has been the dominant technique for well production in the oil and gas industry. According to a study conducted by the Gas Technology Institute (GTI) in 1995, 50 % of the well production time is spent on making the hole, 25 % on tripping, and the rest of 25 % on casing/cementing.
The conventional "Rotary Drilling Technology" is defined by the Society of Petroleum Engineers in their "Advanced Drilling Engineering" Textbook as: "The hole is drilled by rotating a bit to which a downward force is applied. Usually, the bit is turned by rotating the entire drill string" (many joints of steel alloy), "using in general a rotary table at the surface, and the downward force is applied to the bit by using sections of heavy-cylinders, called drill collars, in the drill string above the bit. The cuttings are lifted to the surface by circulating a fluid down the drill string, through the bit, and up the annular space between the hole and the drill string." (Bourgoyne et al. 1986). This definition will be used in the following paper as reference to all other researched drilling concepts.
Firstly, a series of advanced concepts and technologies, their applications, equipments, advantages and disadvantages, etc. has been worked out.
In addition to drilling functions, the systems must also operate under following criteria: technical description, environmental impact, rate of penetration, and applications. Having secondly defined these criteria, each of the alternative systems was described in terms of how it performs with respect to the four functions and how that performance is, compared with what we call "conventional rotary drilling".
The paper will conclude with some possible future drilling systems.

DRILLING COSTS

The reduction of drilling costs is a task that has been challenged the drilling industry since centuries. However, the costs reduction must always be done while keeping up with the safety and HSE standards. One may say that the job of a drilling engineer is to safely reach the target at a minimum cost. To better understand the need of new drilling methods and technologies, it is necessary to understand first the cost drivers to drill a well.
If we use for deep geothermal systems the same technology as in the oil and gas industry, then the drilling and completion costs will inevitably be high. Figure 1 shows a comparison of actual drilling costs for both geothermal and oil and gas applications (Tester et al. 2008) and one can observe the classical exponential tendency of drilling costs with depth (linear if logarithmic scale is used). All reported geothermal well costs in Figure 1 are higher than the equivalent ones for oil and gas wells (same depth).

Some causes that will generate additional costs to a geothermal well are listed below:

- Drilling larger production casing
- Drilling deeper with respect to average oil and gas wells (especially in case of EGS)
- Drilling in hard formations which are unlikely to exist as oil and gas reservoir
- Drilling in tectonically “sensitive” areas and through faults
- High temperature environment
- Country regulations and specific subsurface conditions.

For example, the geothermal well costs in Germany are higher than the worldwide average. Here we must mention that local geological conditions may generate additional costs for geothermal wells drilled in Germany. Some encountered problems are mentioned as follows:

- drilling problems (stuck pipe issues and mud losses, casing running problems, wellbore instability associated with stuck pipe and casing running, cementation problems, drilling through hard formation)
- risk associated with geothermal reservoir (temperature other than predicted, depth other than predicted)
- stimulation issues (fracture propagation other than predicted)

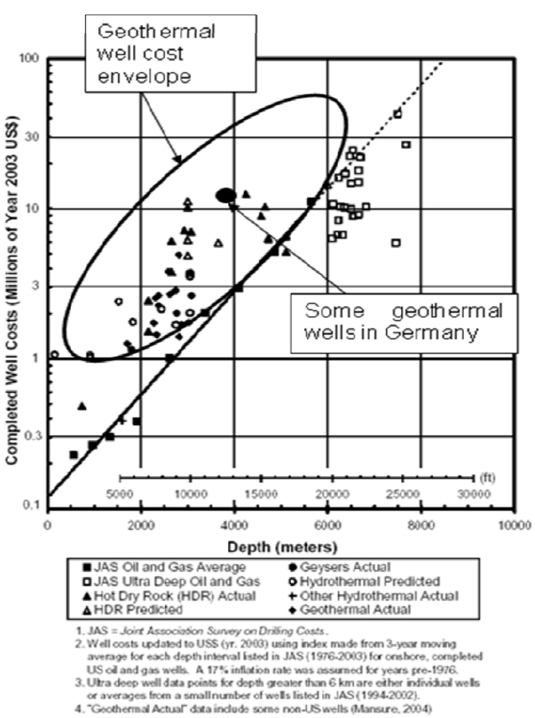


Figure 1. Drilling costs of oil, gas and geothermal wells, after Tester et al. (2008)

Since its existence, the oil and gas business has been working hard to reduce the drilling costs, without putting safety or environment in jeopardy. Therefore, in order to significantly minimize drilling and completion costs for future geothermal wells, new concepts and new technologies must be developed. A brief look at Fig. 1 clearly shows that geothermal drilling activities must be optimized as to reach the same current state of the art of the oil and gas drilling business.

In a study focused on German drilling activities, Paulus and Reinicke (2008) have showed that in order to cut drilled well costs with 18% one must reduce drilling rig costs, drilling and trip time with 50% respectively. Further costs reduction can be achieved only if well construction, rig concept and drilling method are newly defined.

Cutting drilling costs can be done by improving the actual drilling methods and technologies in order to adjust the costs to the oil and gas average or by developing new drilling methods (especially on rock destruction), new well construction solutions, new drilling equipment (especially drilling rigs) or a combination of them all.

BRIEF OVERVIEW OF DRILLING METHODS

We define drilling methods as the process used to destroy and transport the cuttings at the surface. Drilling methods can be combined with various drilling processes like underbalanced or managed pressure drilling and technologies like casing drilling or coiled tubing drilling.

The classical drilling method used today with “Rotary drilling” is crushing or scratching the rock by the means of a drilling bit which rotates. Two main designs are to be mentioned: roller cone bits and drag bits. The roller cone bits crush the rock (especially hard formations), while the drag bits permanently scratch and shear the formation. Some alternatives to these two concepts are combined bits that use both PDC to shear the formation and rollers to crush it. Pessier and Damschen (2010) pointed out that a hybrid bit can drill shale and other plastically behaving formations two to four times faster than a roller cone bit by being more aggressive and efficient. A special improvement was shown by low vibrations and torque due to roller effect.

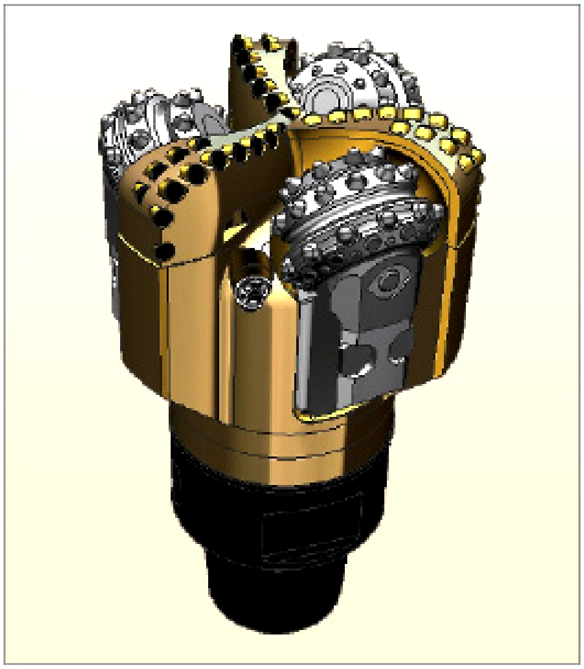


Fig. 2. A hybrid bit that combines roller cone bit for crushing the rock and a PDC bit to shear the rock (Pessier and Damschen 2010)

Another drilling method that still uses mechanical rock destruction is the hammer drilling. This method is very common in mining activities, but it is still uncommon for deep drilling activities. Hard rock drilling requires high energy for rock destruction. The use of rotation and hammering simultaneously allows a significant increase of the rate of penetration (ROP) through the increase of the force between bit and formation. Hammer drilling works well in hard formations, having low or no efficiency when soft formations are encountered.
The main advantage of the mechanical drilling methods is that they are compatible with the existing hardware (surface and downhole) and therefore they can be easily tested under field conditions. However, in spite of all these improvements, the resulting ROP is lower, compared with other drilling methods that will be presented below.
Jetting has been used for decades for various industrial applications. The major use of this technology has been to clean various surfaces, as well as to demolish or cut different materials. In drilling activities, jet drilling uses the drilling mud energy to destroy the rock. The drilling process is done mostly by erosion or/and abrasion. Several types of jet drilling exist in the oil and gas industry: High Pressure Water Jet Drill (UHPD), Mechanically-Assisted Jet Drilling (MAWJ), Abrasive Jet Drilling (AJD), Cavitating Jet Drilling (CJD). Kolle (1999) pointed out that the ROP for various jet drilling methods can be as high as 100 times when compared to diamond bits in hard formations. However, his investigations were performed on shallow drilling using the horizontal directional drilling technology. When deep drilling is required, the total pressure losses in the system may limit the applicability of the jet drilling systems. The literature has shown an increasing interest in using this technology (Buttler et al 1990, Aslam and Alsalat 2000, Busset and Riiber, 2001, Akers, 2006), especially in drilling shallow sedimentary rocks.
The jet drilling technologies require special surface equipment (high pressure/high flow rate pumps) and subsurface (special drill string and downhole pressure enhancer). It might become an alternative technology when drilling surface casings in sedimentary rocks, but not yet the adequate technology for deep geothermal drilling.
Thermal drilling is a drilling method that uses heat to destroy or melt the rock. In what follows, thermal drilling methods will be shortly presented.
Laser (Light Amplification by Stimulated Emission of Radiation) drilling seems to be the first fundamental change to the rotary drilling concept since more than 100 years ago. The laser drilling is based on the three common energy transfer processes between the laser and the rock: reflection, scattering and absorption. According to Graves and O'Brien (1998) "It is the absorbed energy that gives rise to rock heating and destruction". Some rock properties help the laser drilling process. The main properties are: low thermal conductivity that keeps the heat around the hole, low reflectivity that allows a good laser to rock energy transfer and deep penetration of the laser that allows good volumetric absorption. Although laboratory tests have shown good results, there are still many technical challenges to solve, especially how a laser beam is to be transported down hole.
Lasers can be used in various ways for destroying rock, but two of them have become attractive for deep drilling: rock weakening with further application of mechanical tools and direct rock destruction via ablation. According to Graves and O'Brien (1998) several methods of ablating rock are available with application for drilling and completion (spalling, fusing or vaporizing). Spalling or spallation process is that process that will fragment the rock in smaller parts (through temperature gradients induced into rocks) which can be then hydraulically transported to surface. The spallation process requires less energy than fusing or vaporizing and therefore it is more likely to be used for deep drilling applications.
Another thermal drilling method is the thermal spallation process which consists of the rock fragmentation into small disk-like flakes by rapidly heating a confined volume of the rock. Several variations of the thermal spallation have been tried on dry rocks, but as reported by Augustine (2009), the hydrothermal spallation seems to be a revolutionary method that can work in deep hard rock environment.

The process uses a fuel and an oxidant which must be separately transported downhole, where they ignite, and the resulted flame is capable to burn under water (or other wellbore fluids), generating the necessary heat to destroy the rock. Although some laboratory tests have been promising, the entire drilling process is far from a thoroughly understanding. However, it is to mention one of the latest attempts to apply this technology under field conditions (Potter, 2010).

The hydrothermal spallation process requires a certain minimum bottom hole pressure in order to be initiated and controlled.

The electro-impulse drilling is a high energy input drilling method that is using the destructive force of high voltage electro-impulses to break (destroy) the rock due to local pressure pulses induced at rock interface. This method is also known as spark drilling when the control of the process can be done by spark intensity. The electro-impulse method is under development at the TU Dresden and seems to be a good alternative to the spallation drilling presented above. The method is using a rotating electrode head which generates impulses capable to destroy hard formations. According to Anders (2010), the concept has been partially tested in laboratory with good results. A schematic of a possible bottom hole assembly (BHA) is shown in figure 4. The electro-impulse drilling and spark drilling can be also used as enhancement for conventional drilling, by accommodating special electrodes in a drilling bit.

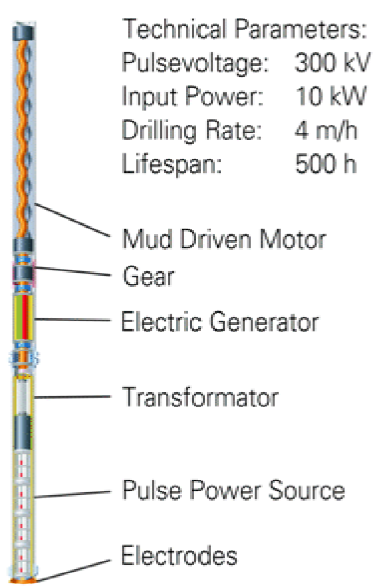


Fig. 4. Schematic of the BHA for electro-impulse drilling, Anders (2010)

The main challenge which is also its main disadvantage is the high current and power transmission from the surface to the bottom. Special insulators are necessary that may not be easy to accommodate into a small diameter. Most of the authors mentioned high ROP for this method, however, it is mentioned that the ROP may decrease with well depth.

BRIEF OVERVIEW OF DRILLING TECHNOLOGIES

We will define drilling technologies as the sum of all processes and equipment designed to support a drilling method. For example, the “rotary drilling process” uses classical rock crushing by the means of a drilling bit, which is supported by a BHA and a drill string through which drilling mud is pumped in order to transport the cuttings. The drilling mud generates pressure in the hole, which supports the wellbore until a protection (casing) is inserted. The entire “rotary drilling process” is performed in two major sequential steps: drill the hole and case the hole. In what follows, the actual technologies will be discussed: underbalanced drilling, managed pressure drilling, casing drilling, coiled tubing drilling.

Casing drilling. Casing drilling technology uses down-hole and surface components allowing application of standard oil field casing as the drill-string; hence, the well is drilled and cased simultaneously. The casing can be rotated from the surface with a top-drive while drilling fluid is circulated down the casing and up the annulus just as the process used for conventional drilling with drill-pipe (Warren et al. 2001). One of the main differences between drilling with a conventional drill-string and drilling with casing is that drill collars are not used to provide weight-on-bit for casing drilling. The casing used during the casing drilling process is generally the same (size, weight, and grade) that would normally be used for setting casings in a conventionally drilled well. However, the connections for the casing strings may be different. Generally, eight-round connections are replaced with buttress connections that include a torque ring for additional torque capacity but other connections such as premium integral or coupled connections may be used as well. Newly developed connections help reducing the risk of failure, but additional costs are induced. The drilling rigs used for the casing drilling process can be either specially designed to apply this technology or be modified from conventional rigs (Warren et al. 2001). As a variation of casing drilling we must mention the liner drilling technology and rotating casing while running.

The technology has gained in the past years industry acceptance worldwide, which is proved by the large number of casing drilling applications reported. However, casing drilling has been proved a good technology in shallow wells (typical for oil and gas business), so further research might be necessary for deep hard rock casing drilling applications.

Coiled tubing drilling. Coiled tubing drilling (CTD) has been used for several years because it provides a new way to significantly improve economics when used in the proper application. The technology uses a conventional drilling assembly with a down-hole motor. One difference is that coiled tubing drilling uses higher bit speeds at lower weight on bit due to the structural differences in coiled tubing compared to jointed pipe (ICOTA 2005).

The latest developments include dedicated drilling rigs (hybrid drilling rigs) to accommodate the coiled tubing unit. It is here worth to mention the revolutionary revolver coiled tubing drilling rig that has been recently developed (Reel, 2010).

Coiled tubing drilling and hybrid coiled tubing drilling technologies have many advantages. Among the advantages one should mention the faster mobilization and demobilization of the drilling components. In addition, tripping times are faster than those achieved with conventional technology. Moreover, the use of coiled tubing drilling improves safety, lowers the footprint impact and enables underbalanced conditions. The main disadvantages are the depth limitation, the coiled tubing size restriction and the mechanical issues associated, buckling and fatigue notably.

Coiled tubing drilling or hybrid coiled tubing drilling have shown the best results when drilling small diameter wells and reducing rig footprint are essential; and has also proven to be an optimal choice for re-entering or sidetracking wells and drilling reservoirs under underbalanced conditions. This will definitively limit the ability of a coiled tubing drilling rig to drill deep wells from the surface to the target depth. However, drilling lateral wells may be useful for development of novel Enhanced Geothermal Systems (EGS).

Underbalanced Drilling. Underbalanced drilling can be defined as a drilling process that intentionally keeps the wellbore fluid gradient less than the natural pore pressure gradient (BP 2008). Thus, the well starts flowing while the drilling operation is still ongoing, that requires dedicated wellhead and surface equipment. The lower well pressure will improve the drilling process and, as a result, the ROP is increasing. Many of the reported advantages of the underbalanced drilling technology are related to reservoir protection and the ability to drill through problem zones, but in geothermal drilling the main advantage of UBD is the increased ROP, especially in hard formations.

Managed Pressure Drilling. Managed pressure drilling (MPD) is defined by the International Association of Drilling Contractors as "an adaptive drilling process to precisely control the annular pressure profile throughout the well". The goal is to control the pressure profile in the well staying within the wellbore operating envelope (Malloy et al. 2009).

Managed pressure drilling can be then divided into reactive or pro-active techniques. Reactive managed pressure drilling uses a basic configuration (a rotating control device and a choke) to deal with drilling problems that could occur in the wellbore. However, proactive managed pressure drilling includes the entire well design (casing, tubing, fluids) to precisely manage the wellbore pressure profile since the beginning of the drilling operations (Malloy et al. 2009).

Slim Hole Drilling. Although slim hole drilling has been associated with geothermal activities, it will be later shown that this technology may not directly revolutionize the drilling technology because of the production casing restrictions. However, it is worth to be mentioned, since the slim hole drilling is one of the main approaches that looks directly into cutting costs through well construction. According to the Society of Petroleum Engineers and the National Energy Technology Laboratory, slim-hole drilling is usually defined as a well with more than 90% of the overall measured depth with casing size less than 7 in (Long 2005). The main benefit of slim-hole drilling is that a smaller hole size will result directly in a higher rate of penetration and a decrease in well cost. It is very important to mention here some related concepts like "Lean Well Concept" which are making the transition to a "monobore well concept".

DISCUSSIONS

When comparing drilling methods or technologies, it is important to have a good reference. It is known from the drilling experience that even when two wells are drilled nearby, using identical technology, the results may differ due to the underground non-uniformities and other factors. Therefore, it is always difficult to compare drilling methods outside laboratory. For example, it has been shown that laser drilling may offer ROP 8 to 100 times more than conventional drilling (Graves and O'Brien, 1998) which is comparable with high pressure jet drilling (Kolle, 1999). However, since no field scale trials are known, it makes it difficult to be assessed if can be applied to drill wells in depth larger than 6000 m. Similar is the hydrothermal spallation drilling, that have shown good laboratory results, but no field trial exists.

Casing drilling does not have a much better ROP compared to conventional drilling, but it is a good alternative when drilling problems are encountered, therefore it is not the first choice of technology when drilling deep wells, unless drilling problems are known.

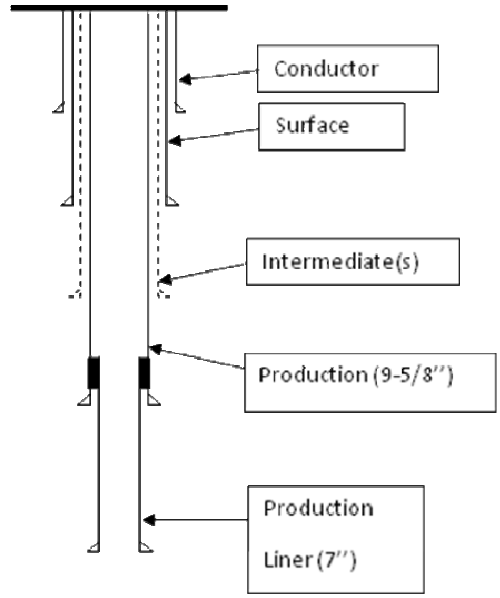
ROP is a very important parameter when comparing drilling methods and technologies, but some other criteria must be considered. For example it is important to assess the environmental friendly aspect of such methods through the amount of energy consumed to drill a well.

According to Fame et al. (1994), the size of the drilling rig as well as the technology used to drill the well will strongly affect the emissions. At this time there are not enough information about laser drilling, hydrothermal spallation and electro-impulse drilling to assess the amount of energy consumed to drill a well. According to NAS (2009), the specific energy requirements for jet drilling and thermal spallation are 10 to 15 times higher than conventional rotary bits. This implies the need of large power supply for rigs that use such drilling methods to excavate the hole, with consequences in gas emissions, if conventional diesel-generators are used.

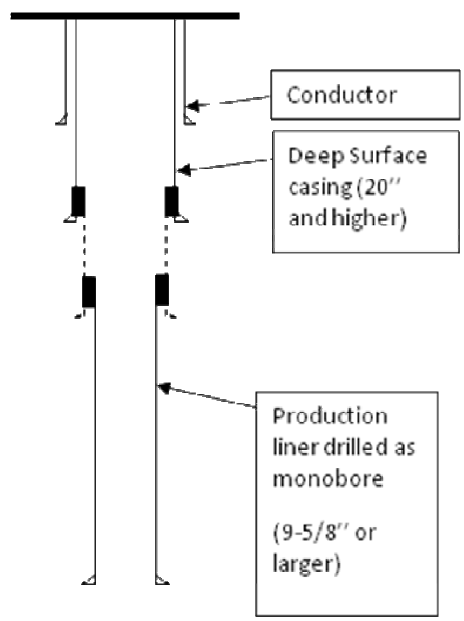
Table 1. Fuel Consumption and Gas Emissions of a CTD Unit, Slimhole Rig and Conventional Rig (Fame et al. 1994)

	Diesel m3/month	Conventional Drilling 160	Slimhole Rig 35	CTD 25
Gas emissions Kg/Day	CO2	15.055	3.293	2.122
	CO	16,8	3,7	2,5
	NOX	21	4,6	2,1
	HC	17,8	3,9	2.8
	HC (gas)	8,4	1,83	1,1
	SO2	19,4	4,2	2,2

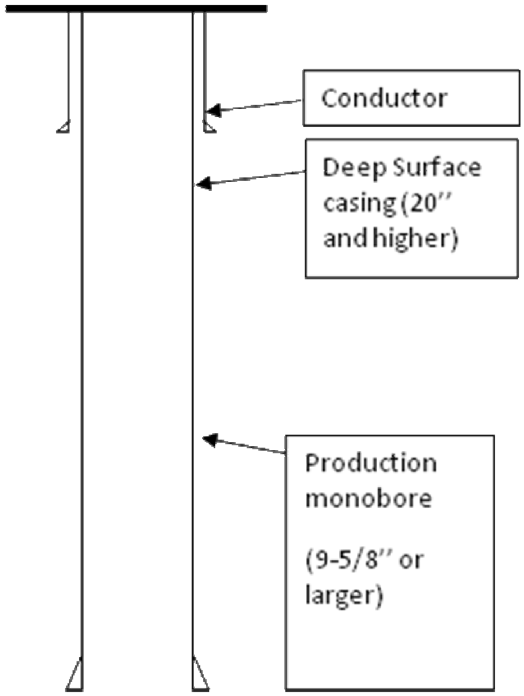
Several authors pointed out that the improvement in ROP only will not cut the total well costs significantly (Paulus and Reinicke, 2008, Pierce et al. 1996). Well construction, especially casing selection and design will affect the well costs more than 50% when deep drilling is required. Geothermal drilling requires large diameters in order to produce heat economically. The references studied within this paper showed the need to increase wellbore diameter while keeping the costs at an acceptable level by new well design: monobore (Reinicke et al., 2009), linear casing design and use of expendables, (Polsky et al., 2009), single well instead of doubles, (BGR, 2009) and/or reducing drilling costs (Reinicke et al, 2009). Historically, the geothermal industry has moved from classical well construction to the use of liners and expandables and probably will end with a full monobore construction as reported by Reinicke et al. (2009). Figure 5 a) b) and c) shows such an evolution based on existing current research projects.



a) typical geothermal well (Teodoriu and Falcone, 2009)



b) use of liners and expandables (Teodoriu et al. 2009)



c) a monobore construction (after Reinicke et al 2009)

Figure 5. A possible evolution of well construction for geothermal deep wells

Reducing the number of drilled casings and their size will drastically reduce the drilling costs of a deep well but will also increase the associated risks and investments in new technologies.
Most of the reviewed new technologies seem to work better with large diameter downhole tools, which is beneficial for geothermal wells.
As future drilling method and technology we should consider a self drilling monobore well construction that does not require any other trips in order to reach the target.

CONCLUSIONS

Cutting drilling costs is not only important for oil and gas business, but becomes a challenge for economical exploitation of geothermal resources.
This paper presents several drilling methods that are currently under testing and evaluation. They seem to have a good ROP compared to conventional systems but require however new and specialized equipment for field applications.
Several drilling technologies have been selected and presented herein. A study of these current technologies showed that some of them may be applicable for deep drilling while most of them have been optimized for drilling oil and gas wells.
A significant costs reduction for geothermal well drilling can be achieved through new well construction concepts, but new technologies are required to achieve such goals.

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