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Report on Geothermal Drilling

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Authors: **P Dumas (EGEC), M Antics (GPC IP), P Ungemach (GPC IP)**

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Introduction

Drilling represents from 30% to 50% of the cost of a hydrothermal geothermal electricity project and more than half of the total cost of Enhanced Geothermal Systems (EGS). This Geoelec report aims at presenting proposals to overcome this substantial financial barrier.

Research and Development (R&D) can improve geothermal drilling technologies in order to reduce its costs, but the main challenge today is to improve market conditions for geothermal deep drilling.

However, the deep geothermal drilling market has still not been thoroughly assessed. For instance access to available geothermal drilling cost data is very limited. Moreover, the interaction between project developers and drilling contractors could be improved.

In order to stimulate both the market and the competition, this Geoelec report aims at:

- **providing information, when available, on drilling costs in some EU countries;**

- **creating an European database listing drilling companies in order to pave the way for a dynamic and regularly updated tool to be published online;**

- **producing a best practice geothermal drilling handbook for project developers**

Geothermal drilling in Germany. Copyright: H Kreuter

1. Analysis of deep geothermal drilling market in Europe

1.1 Insight into geothermal drilling technology

Although geothermal drilling often uses the same state of the art technology as the oil and gas industries, particularly in low enthalpy sedimentary settings, geothermal drilling displays several distinctive attributes. These, amongst others, concern volcano-tectonic hydrothermal and hard rock EGS environments, massive lost circulation, high to very high temperatures with related casing string expansion and measuring/monitoring limitations and, last but not least, the prerequisite of high, full bore, production flow rates.

In short, sustainable geothermal exploitation requires deep seated, large diameter boreholes and long lasting well integrities.

The established deep drilling technique is the rotary drilling, since 1909 by the tri-cone rotary bit, supplemented in the 1970's by the polycrystalline diamond bit and applied by diesel-electric drilling rigs to create boreholes protected by steel casings, one inside another until the final diameter is only a small fraction of the initial, by many viewed as the biggest drawback of conventional hole-making technology. There exists a wide variety of technologies amongst which rotary, preferably hydraulic, electrically driven drilling is best suited to deep seated targets.

Geothermal drilling benefits from on-going industry improvements. Top drive power swivels, air/foam balanced drilling, Polycrystalline diamond compact (PDC) bits (since the 70's), horizontal drilling(since the 90's) , casing while drilling(since the 50's) , reverse circulation cementing, logging while drilling(=MWD since the 90's) , environmentally safe fluid formulations(since the 90's) , microdrill, and coiled tubing (since the 80's) are all good examples of these improvements.

Rock destructive perforation concepts address:

- *High performance/mud jet bits*
- *Direct stream*
- *Millimetre wave*
- *High voltage electro impulses*
- *Spallation*
- *Molten ion penetration*
- *Plasma bit*

Given the impact of drilling costs on the economic viability of any geothermal project, particularly deep/ultra deep EGS projects, it is of utmost importance that new technologies be implemented in order to maximize drilling cost effectiveness. Consequently one should contemplate two strategic issues:

(i) ***<u>the transfer of the achievements of recently developed drilling technologies and equipment to EGS, and</u>***

(ii) ***<u>The potential application of novel technologies like spallation drilling, projectile</u> drilling, chemical drilling and others, presently in the early R&D stage,***

The support for any new drilling technology is recommended to be benchmarked by their demonstrated geothermal profitability-critical criteria:

Excavation productivity (m^3/hr), excavation energy efficiency (KWh/m^3) and specific borehole cost potential (€/$m_{borehole}$ & $cm_{final\ diameter}$).

Geothermal Drilling in Turkey, Copyright: Zorlu (Turkey)

1.2 Cost issues

Geothermal drilling costs follow the general oil and gas industry trend depicted in figure 1 which exemplifies a total dependence to (somewhat escalating) crude oil prices. This situation is likely to persist as long as the geothermal drilling sector does not build-up a strong market share of its own.

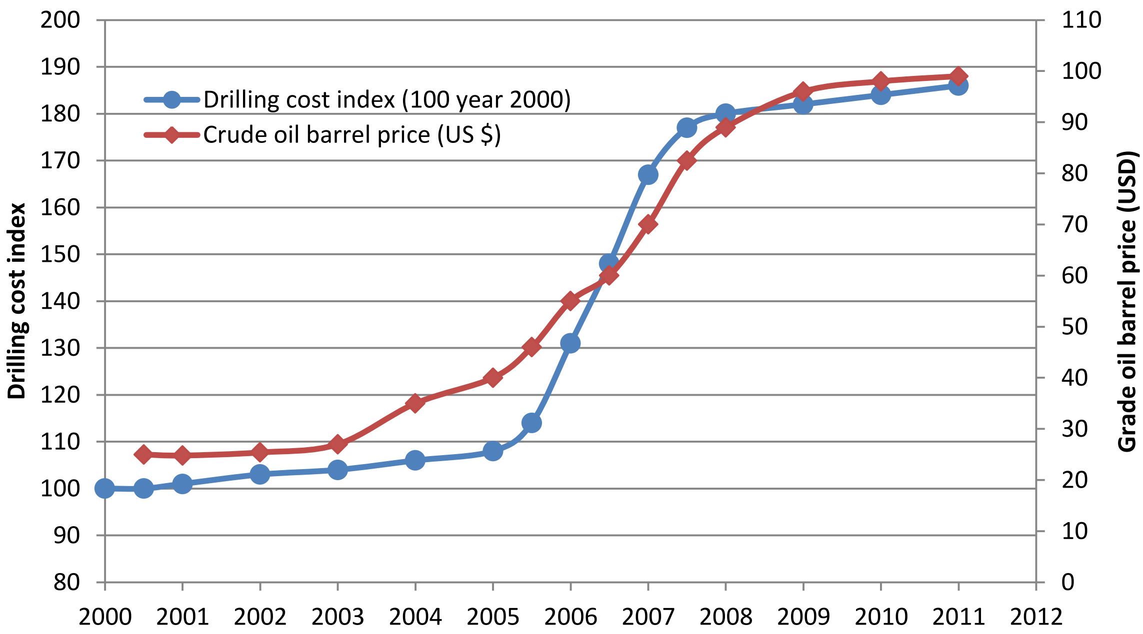
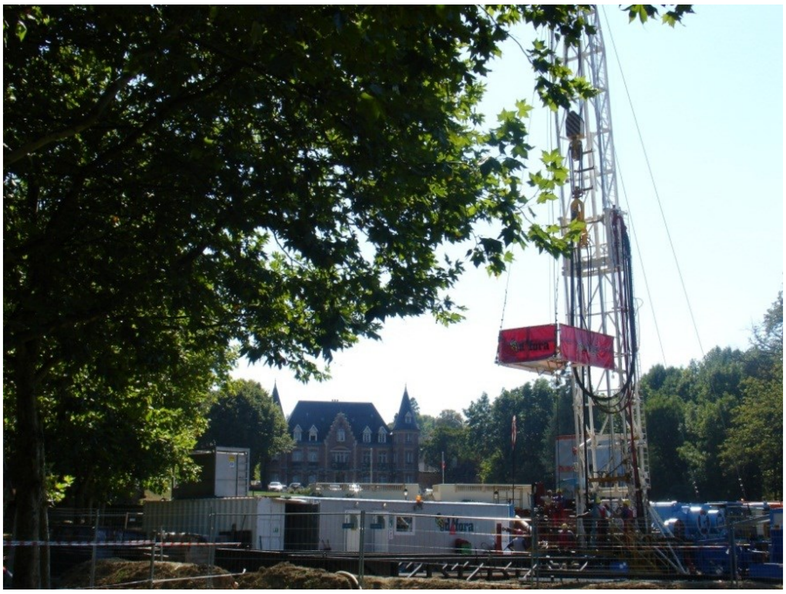


Figure 1 : Drilling cost vs. crude oil prices



Geothermal drilling in France. Copyright: GPC IP

Upfront drilling costs constitute between 30% and 70% of overall project development expenditure as displayed by the cost spectrum of a 20 MWe rated conventional geoelectric plant, from early surface exploration to final connection to the grid (or end use environment).

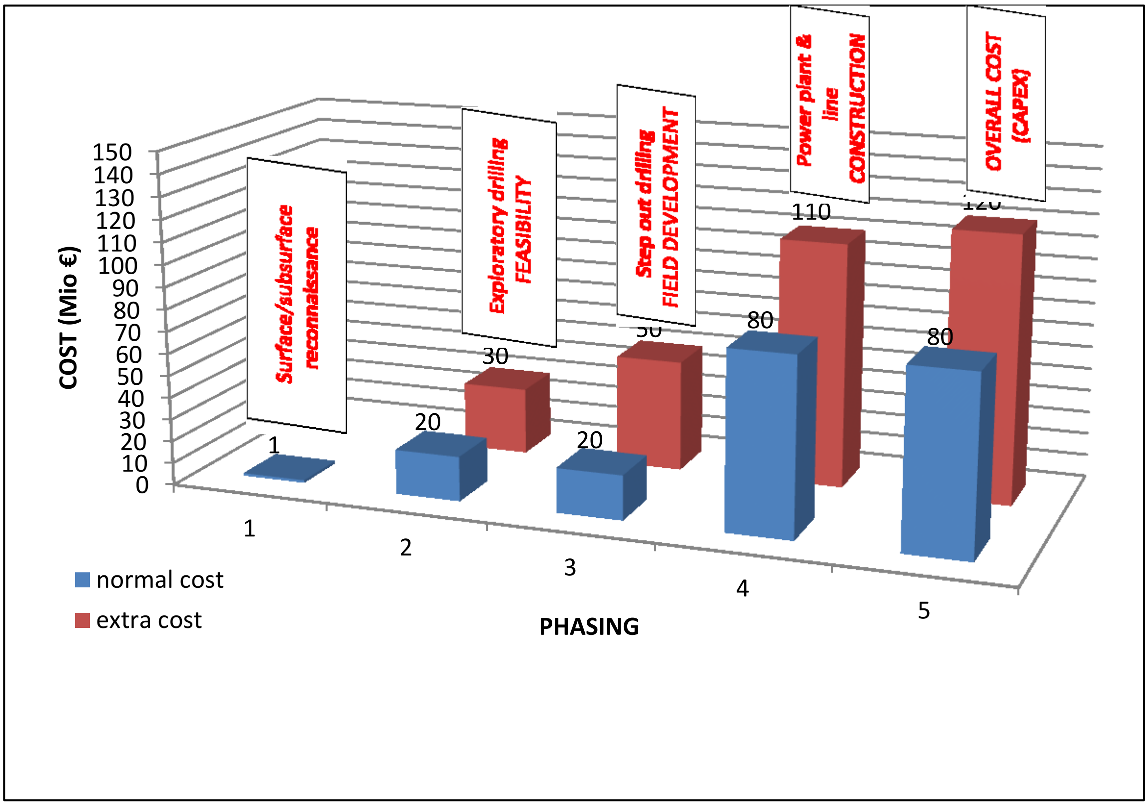


Figure 2 : Project phasing & cost breakdown. 20 MWe geoelectric plant

The only available information available to date regarding the types of drilling contracts and their features which are used in the EU are listed in table 1. Types of well designs are illustrated in figure 3 overleaf.

COUNTRY	TYPE OF CONTRACT	UNIT COST vs. depth (1,000 €/m)	REMARKS
France	Rig daily rate Lump sum	1000 m/ 1.5	2000 m deviated geothermal district heating doublets
Germany	Meter rate Rig daily rate Lump sum	2000 m/ 2	Deep ≥ 3000 m deviated wells. Several combined meter/daily rate contracts reported
Italy	Rig daily rate	3000 m/ 2.5	Mainly 2000-3000 m deep high enthalpy, dry/wet steam wells
The Netherlands	Lump sum Rig daily rate	≥ 4000 m/ 3 to 5	Most wells drilled on a lump sum base

Table 1 : Selected EU drilling contract features

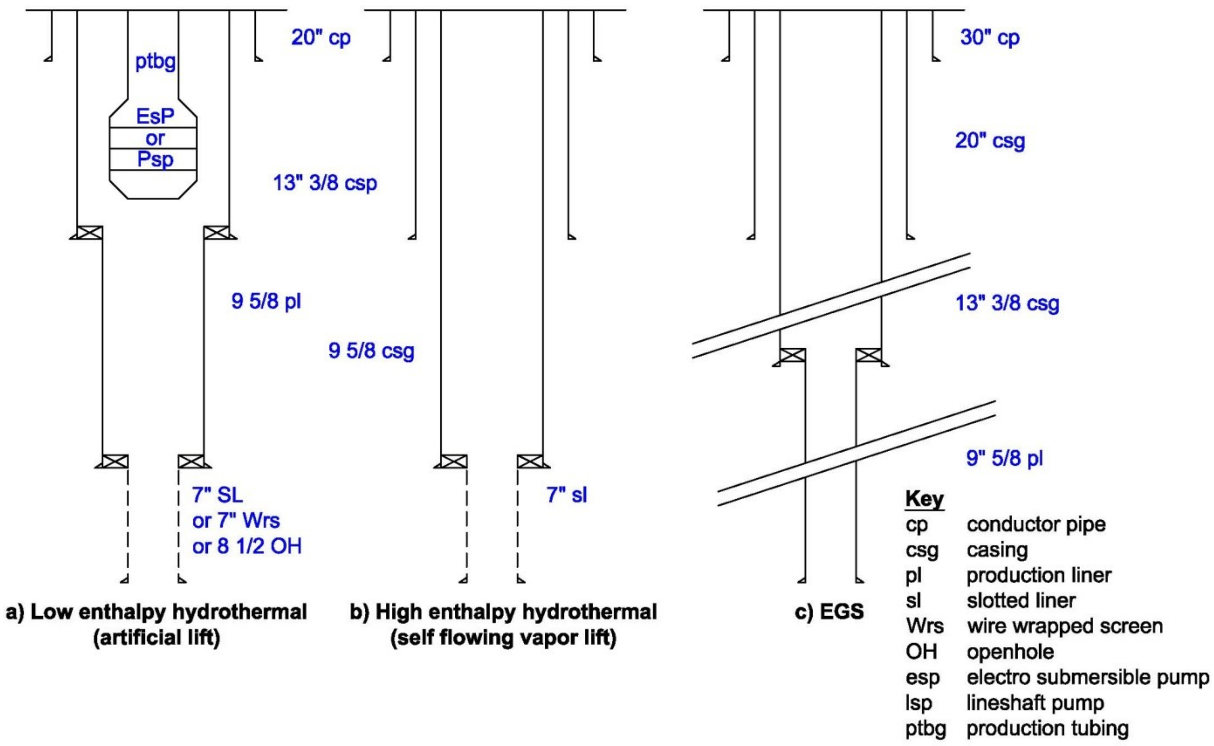


Figure 3 : Typical well profiles

Can and how might drilling costs be decreased?

There are two ways of cutting down, or at least reducing significantly, geothermal drilling costs:

1) R&D to improve current technology and develop novel technologies
2) Improvement of market conditions to develop market competition

The first method has already been addressed in the previous section and will not be commented any further in this report, the second part of which focuses on socio-economic aspects (more information available in the Strategic Research Agenda for Geothermal Electricity.

However it is worth noting the main segments of a drilling venture which are crucial in reducing costs and mitigating risks:
Firstly, drilling cost reduction concerns the costs decrease of equipments /methods:

- Drilling rigs
- Drilling services: drilling mud and directional drilling
- Drilling tools such as high performance drill bits, novel drilling technologies
- Directional drilling: side tracks, horizontal, multilaterals
- Drilling/completion concept: exploration wells, slim hole drilling, sustainable well completion

Secondly, risk mitigation is also an issue for rendering the geothermal drilling costs more competitive with both the technical drilling risk (Lost in Hole) and the Mining Risk (Seismic Prediction While Drilling (SPWD).

Methods for decreasing costs by improving procedures for reducing rig time

Rig time can be reduced by addressing procedures at several stages of the construction process.

- contract rig: bid preparation and tender evaluation, supervision of drilling contracts

- site preparation: well siting and pad preparation, well design

- rig move in/move out, rig up/rig down

- rig operation

- drilling management, supervision and services: well logging, drilling engineering, mud logging – on-site geology, stimulation, rig, equipment, consumables inspection/control, equipment, materials, well work-over programmes

- close: environmental reports

Enhance competition

Rig and contractor availability should not be a problem from a purely mathematical perspective. As a matter of fact there are over 30 drilling contractors operating in Europe, a figure deemed sufficient for meeting market demand. The problem is that there are often as many operators as wells (or doublets) to be drilled; this means that developers must pool their efforts in order to award attractive multiwell longer lasting contracts, as is routine practice in the oil and gas industry.

Another difficulty arises from different, often contrasting, mining laws and social regulations which add to the technical and non-technical barriers inherent when drilling in sensitive, densely populated areas.

It is therefore strongly recommended to review the current practices of National mining laws, licensing procedures on their incoherence with a joint and open market. The current praxis hinders drilling contractors to employ their equipment outside their domestic market, since regularly their operating license/permits are not recognized by mining authorities in other countries (on a national level as well as on a regional state level). This practice requires time consuming licensing procedures, which do form a market barrier and restrict competition.

1.3 How to improve market conditions

The geothermal sector will develop in the next 10 years and drill new wells in both:
- the electricity sector (1-5 Km depth)

- the district heating sector and other direct uses (500 m - 2 Km depth)

There are 62 geothermal power plants operating in Europe today. 210 projects (of which 44 are EGS plants) are either under development or under investigation (Figure 2). They will become operational by approximately 2019. In terms of total installed capacity (Figure 3) in the EU, it amounts to 1.7 GWe in 2012 (0.9 GWe in the EU-27) and it will reach nearly 4GWe by the end of the decade (1.4 GWe in the EU-27)

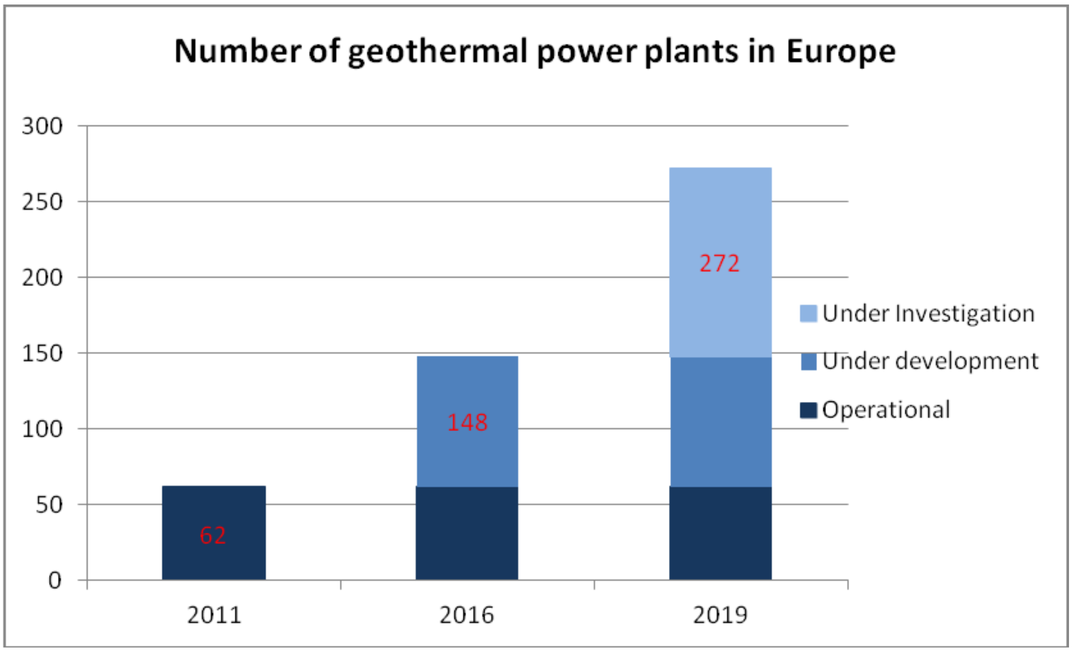


Figure 4 Actual number of geothermal power plants installed in Europe (2012-2019)

Source: EGEC Geothermal Market Report 2012

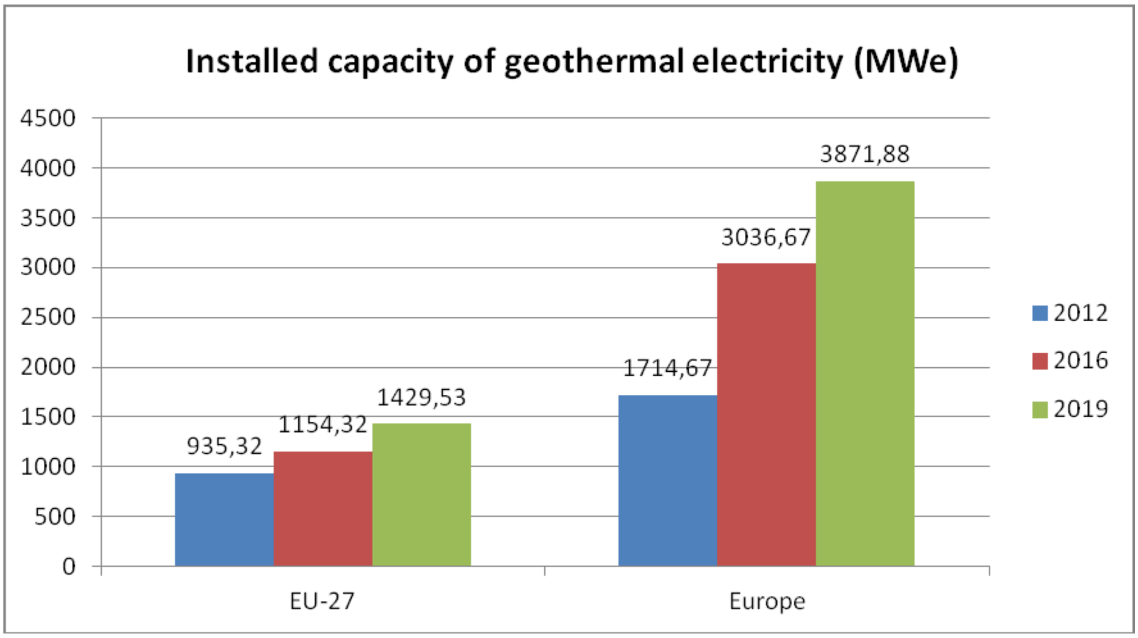


Figure 5 Actual installed capacity of geothermal electricity production; MWe (2012-2019)

Source: EGEC Geothermal Market Report 2012

Regarding Geothermal District Heating, there are 216 GeoDH systems operating in Europe (of which 157 in the EU-27), whereas 171 new projects are being developed (of which 3 are EGS) (Figure 3). This will bring in the installed capacity in Europe from 4.9 GWth to nearly 9 GWth.

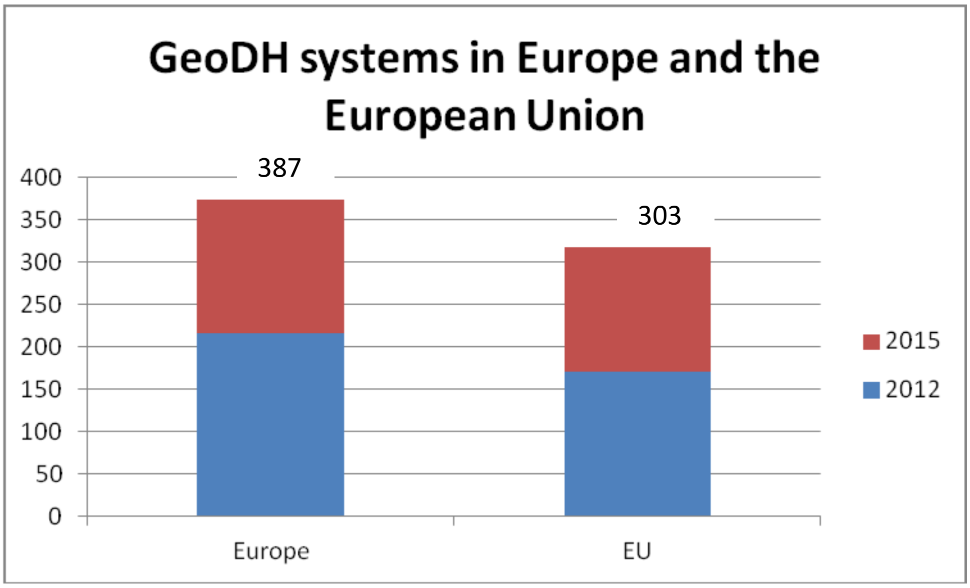


Figure 6 GeoDH systems in the EU (2012-2015)

Source: EGEC Geothermal Market Report 2012

Hence, assuming an average number of:

- 2 wells per plant per heating application;
- 5 MW per production well for electricity; and
- an equivalent number of reinjection;

the total geothermal wells in Europe in the next decade is estimated to amount to ca. **1300 new wells.**

Against this background, one of the main problems encountered by geothermal developers today is related to drilling financing and regulatory barriers.

The shortage of drilling companies and drilling rigs seem today a significant problem in Turkey; and for some extents in Central Europe and for countries like The Netherlands. Still, rig availability remains a problem for the reasons previously explained.

In the Netherlands, the situation of drilling companies/rigs is considered fairly serious. There are not Dutch owners of large drilling rigs. The Drilling companies operate smaller rigs which are inadequate for the required depths in deep geothermal. Therefore the Dutch market[1] relies on suppliers and rigs for deeper drillings from other countries - mainly Germany.

[1] The situation might be a bit different in the Netherlands as in most geothermal wells some small fractions of natural gas (typically 0,1 % in weight) are co-produced, which requires a totally different set of safety

The main problems of the drilling market in Europe can be summarised as follows:

- Manufacturing of a rig requires 1 year and costs circa €20 million.
- There is a lack of experienced and skilled drillers: it takes 3-4 years to train a specialist.
- There is an insufficient number of supervisors for geothermal projects.
- There are no continuous business streams in the geothermal markets.
- Stop-and-go legislations to support geothermal are a barrier for long-term investment in new rigs and crew.

Several measures could be introduced in order to improve the situation. For example:

- Create a database of deep drilling contractors (circa. 30 rig owners)
- Update rig occupation count and rig/equipment specifications
- Estimate future rig demand according to target depths
- Produce guidelines as an aid to geothermal developers: promoting daily rate more than turnkey project, developers endorse the risk as the drillers will not do it etc.
- Stimulate European pools of developers for contracting rigs on long term bases

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precautions. The safety standards are here basically identical to the oil & gas industry standards. So it could be that the 'normal' geothermal European drilling rigs and drilling contractors are aiming for water wells rather than gas co-producing wells. In any case a drilling company or drilling rig (drilling crew) which wants to operate in the Netherlands must be able to demonstrate the capabilities to deal with the local conditions (including gas co-production) and will be audited by the State Supervision of Mines before they are allowed to start operations.

2. Database of deep drilling companies

As mentioned in the foregoing chapter, information regarding drilling market operators in Europe and rig equipment specifications is spread and often not easily available to project developers.

In this context, the creation of an initial directory of the main deep drilling contractors operating in Europe is identified as a need for making the drilling market more transparent and thereby improving its current conditions. The list below includes drillers, drilling equipment manufacturers and providers and drilling services companies.

	Name of the company	Website	Geographical coverage	Availability Rig equipment specifications
1.	Aker Solutions	www.akersolutions.com/	worldwide	yes
2.	Amec	http://www.amec.com/	worldwide	no
3.	Apache	http://www.apachecorp.com/	Europe	no
4.	Bentec	http://bentec.de/	Europe	yes
5.	Boldon drilling	http://www.bdf.co.uk	Europe	yes
6.	BAUER	http://www.bauer.de/en/index.html	Europe	yes
7.	Baker Hugues	http://www.bakerhughes.com/	Europe	No, but rig counts available
8.	Cape Industrial Services	http://www.capeplc.com/	Worldwide	no
9.	COFOR	http://cofor.com/	Europe	yes
10.	CROSCO	http://www.crosco.com/	Europe	yes
11.	DAFORA	http://dafora.ro/indexplin.php?care=&lang=	Europe	no

12.	Drillmec	http://drillmec.com/viewdoc.asp?co_id=54	Europe	yes,
13.	Deep drill equipment	http://www.deepdrill.nl	The Netherlands - Europe**,** Egypt, Algeria, Libya, Spain **and** UAE	no
14.	Dalrup	http://www.daldrup.eu	Europe	no
15.	ENEL GP	www.enelgreenpower.com	Europe, Southern America, US	no
16.	Fugro	http://www.fugro.com	Worldwide	no
17.	Halliburton	http://www.halliburton.com	Worldwide	Yes, not complete
18.	Hekla	http://heklaenergy.com/index.htm	Europe	yes
19.	Huisman equipment	http://www.huismanequipment.com/en	Europe	yes
20.	Herrenknecht	http://www.herrenknecht.de/herrenknecht-ag.html	Europe	yes
21.	Iceland drilling	http://www.iceland-drilling.com/	Europe	yes
22.	ITAG	http://www.itag-celle.de	Europe	yes
23.	KCA Deutag	http://www.kcadeutag.com/	Europe	yes
24.	Maersk	http://maerskoil.com	Worldwide	yes
25.	Marathon	http://www.marathonoil.com	Worldwide	no
26.	Noble Drilling	http://www.noblecorp.com/	Europe	yes
27.	Odfjell Drilling	http://www.odfjelldrilling.com	Worldwide	yes
28.	SAIPEM	http://www.saipem.com/site/it/Home.html	Europe	yes
29.	Seadrill	http://www.seadrill.com/drilling_units	Europe	yes
30.	Schlumberger	http://www.slb.com/services/drilling.aspx	Worldwide	yes

31.	Stena Drilling	http://www.stena-drilling.com/	Europe	yes
32.	Transmark eds	http://www.edsnl.com/	Europe	no
33.	Weatherford	http://weatherford.com/#	Europe	yes
34.	Welltec	http://www.welltec.com/	Europe	Yes, but not about rigs

Table 2: Database of deep drilling companies

Such a list represents a first step towards a dynamic and regularly updated database available online on *www.geoelec.eu*. The database will also contain information about the general features of the rigs available, e.g. operating climate conditions, draw works capacities, hook load capacities, drilling depth capacities.

It will be in line with, for instance, the general features published online for the benTEC's EURO RIG:

EURO RIG™ GENERAL FEATURES

- Climate: Temperate -20°C to +40°C
- Drawworks capacities: 1,000 hp–2,000 hp
- Hook load capacities: 440,000 lbs–1,000,000 lbs/ 200 t–450 t
- Drilling depth capacities: Up to 19,700 ft/ up to 6,000 m

- API, DIN EN, ATEX, certified
- HAZOP risk assessment
- CE equipment
- Testing & commissioning

Source: bentec.de

The Geoelec database will also provide information on future geothermal drilling projects, giving information about:

- Location of the project
- Depth of the wells
- Number of wells
- Diameter of the wells

It can be presented in a map based on the EGS map of the EGEC market report 2012:

Map of EGS in Europe

3. Best practice handbook

The formation and reservoir conditions that characterise geothermal systems require the adoption of drilling practices that differ from those utilised in conventional oil, gas, and water well drilling operations. Temperature, Geology, and Geochemistry are the principal areas of difference.

This chapter 3 outlines typical geothermal drilling conditions, and the drilling practices that have been developed to optimise the drilling processes in these conditions.

Introduction

Although heat from geothermal sources has been used by mankind from the earliest days – for cooking and bathing, for instance - its major development has taken place during the past 30 years. This has occurred in parallel with the significant advances made in deep drilling practices, and it's importance has risen dramatically during the last few years as the price of petroleum has soared, and awareness of the importance of 'renewable energy' has developed.

The equipment and techniques used in the drilling of geothermal wells have many similarities with those used in exploring and exploiting petroleum reservoirs. However, the elevated temperatures encountered; the often highly fractured, faulted, and permeable volcanic and sedimentary rocks which must be drilled; and the geothermal fluids which may contain varying concentrations of dissolved solids and gases have required the introduction of specialised drilling practices and techniques.

Temperature

The temperature of the earth's crust increases gradually with depth with a thermal gradient that usually ranges from 5° to 70° per kilometre. In anomalous regions, the local heat flux and geothermal gradients may be significantly higher than these average figures. Such anomalous zones are typically associated with edges of the continental plates where weakness in the earth's crust allow magma to approach the surface, and are associated with geologically recent volcanism and earthquakes. It is in such settings that the majority of geothermal resources are found and that the majority of geothermal wells have been drilled. While a few wells have been drilled into temperature conditions that approach the critical point of water (374°C) and a number of fields produce dry and superheated steam, the majority of higher enthalpy resources are two phase – either vapour or water dominated, with temperature and pressure conditions controlled by the saturated steam / water relationship – 'boiling point for depth'. For design purposes, where downhole pressures and temperatures are not known, 'boiling point for depth' (BPD) conditions are assumed from ground level as indicated in Figure 1.

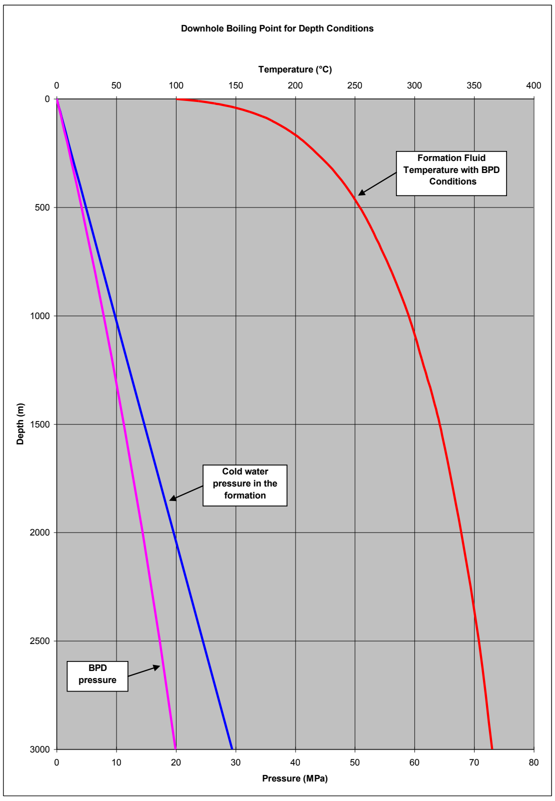


Figure 1. Downhole fluid conditions - BPD.

Saturated steam has a maximum enthalpy at 235°C and consequently many geothermal fields are found to exist at temperatures approximating this value (dissolved solids and gases change this value somewhat).

Such elevated formation temperatures reduce drill bit and drilling jar performance and often precludes the use of mud motors and directional MWD instrumentation equipment; it adversely effects drilling fluid and cementing slurry properties; and reduces the performance of blow out prevention equipment. In addition it significantly increases the potential for reservoir fluid flashing to steam resulting in flowback or blowout from shallow depths.

The well, the downhole well components and the near well formations are subject to large temperature changes both during the drilling process and at the completion of drilling. The circulation or injection of large volumes of drilling fluid cools the well and the near well formation, but as soon as fluid circulation is ceased, rapid re-heating occurs. These large temperature differentials require special precautions to be taken:-

- to avoid entrapment of liquids between casing strings – which can exert extreme pressure when heated resulting in collapsed casing.
- to ensure casing grade and weight, and connection type is adequate for the extreme compressive forces caused by thermal expansion.

- to ensure the casings are completely cemented such that thermal stress are uniformly distributed.
- to ensure casing cement slurry is designed to allow for adequate setting times and to prevent thermal degradation.

Geology

Geothermal fields occur in a wide variety of geological environments and rock types. The hot water geothermal fields about the Pacific basin are predominantly rhyolitic or andesitic volcanism, whereas the widespread hydrothermal activity in Iceland occurs in extensively fractured and predominantly basaltic rocks. In contrast the Larderello steam fields in Italy are in a region of metamorphic rocks, and the Geysers steamfield in California is largely in fractured greywacke.

The one common denominator of all of these fields is the highly permeable, fractured and faulted nature of the formations in which the reservoirs reside. This high permeability is one of the fundamental and requisite components for any geothermal system to exist.

Typically, the permeable nature of the formations is not limited to the geothermal reservoir structure alone, but occurs in much of the shallower and overlying material as well.

In addition, a characteristic of most of these geothermal systems is that the static reservoir fluid pressures are less than those exerted by a column of cold water from the surface – the systems are "under-pressured". The high temperatures of the systems result in reservoir fluid densities which are less than that of cold water, and the majority of geothermal systems are located in mountainous and elevated situations – resulting in static water levels often hundreds of metres below the surface.

Drilling into and through these permeable and "under-pressured" zones is characterised by frequent and most often total loss of drilling fluid circulation.

Particularly in the volcanic geothermal systems, many of the shallow formations comprise low bulk density materials such as ashes, tuffs and breccias, which as well as being permeable, are often unconsolidated and friable, and exhibit a low fracture gradient, and thus provide low resistance to blowouts.

Geochemistry

Geothermal fluids contain varying concentrations of dissolved solids and gases. The dissolved solids and gases often provide highly acidic and corrosive fluids and may induce scaling during well operations. Dissolved gases are normally dominated by CO_2 but can also contain significant quantities of H_2S, both of which can provide a high risk to personnel and induce failure in drilling tools, casings and wellhead equipment.

The presence of these dissolved solids and gases in the formation and reservoir fluids imposes specific design constraints on casing materials, wellhead equipment and casing cement slurry designs.

Drilling practices

In general, the drilling processes and equipment utilised to drill deep geothermal wells are substantially similar to those developed for petroleum and water well rotary drilling. However, the downhole conditions experienced in geothermal systems, as described above, require some significantly different practices to be adopted. Some of these differences are outlined below.

Well design

The thermal efficiency of converting geothermal steam/water to electricity is not particularly high (±20%), therefore large mass flows and therefore volume flowrates are required, particularly in vapour dominated systems. These large volume flowrate requirements necessitate large diameter production casings and liners.

Typically a ‘standard’ sized well will utilize standard API 9 5/8” diameter casing as production casing and either 7” or 7 5/8” diameter slotted liner in an 8½” diameter open hole section.

A “Large” diameter well will typically utilise standard API $13^{3}/_{8}$” diameter casing as the production casing, with either $9^{5}/_{8}$” or 10¾” diameter slotted liner in a 12¼” diameter open hole.

Casing sizes utilised for the Anchor, Intermediate, Surface and Conductor casings will be determined by geological and thermal conditions.

Figure 2 illustrates schematically the casing strings and liner of a typical geothermal well.

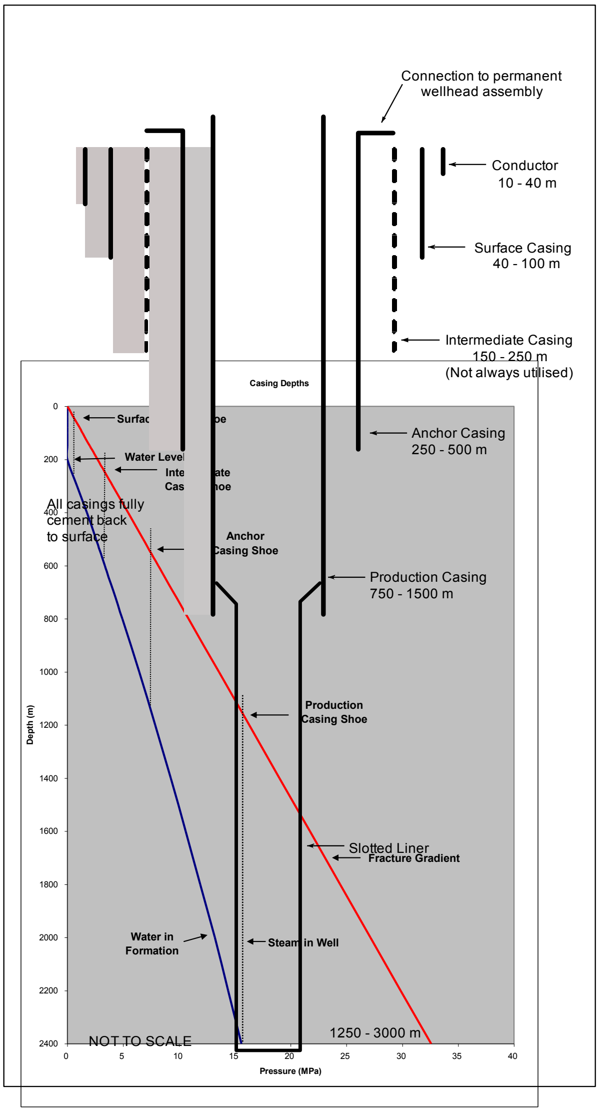


Figure 2. Casing strings and liner for a typical well.

Casing depths

The depths of all cemented casing strings and liners is determined such that the casings can safely contain all well conditions resulting from surface operations and from the characteristics of the formations and fluids encountered as drilling proceeds.

Casing shoe depths are determined by analysis of data from adjacent wells which will include rock characteristics, temperatures, fluid types and compositions and pressures. In particular fracture gradient data gathered from nearby wells. At any time the depth of open hole below a particular casing shoe should be limited to avoid exposure of the formations immediately below the casing to pressures which could exceed the fracture gradient at that depth and hence lead to a blowout. It is usual to assume worst case scenario's such as exposing the previous casing shoe to the saturation steam pressure at the total drilled depth of that section. Figure 3 illustrates how the shoe depths may be chosen using a somewhat simplistic and theoretical model with boiling point for depth fluid pressure condition from a nominal water level at 200 m depth; and a uniform formation fracture gradient from the surface to the total depth of 2400 m.

Figure 3. Casing Shoe Depths

This simplistic model suggests that the production casing shoe would need to be set no shallower than 1100m; the anchor casing shoe at approximately 550 m; an intermediate casing set at 250 m depth; and a surface casing set at around 40 m depth.
It is likely that with real data that this casing programme would be somewhat simplified, the production and other casings shoes somewhat shallower, and the intermediate casing eliminated.

Casing diameters
Casing diameters will be dictated by the desired open hole production diameter – typically either 8½" or 12¼". Slotted or perforated liners run into these open hole sections should be the largest diameter that will allow clear running – there is an obvious advantage to utilise 'extreme line' casing connections from a diameter point of view, however this is often offset by reduced connection strength of this type of casing connection.
Casing internal diameters should not be less than 50 mm larger than the outside diameter of connection collars and accessories, to allow satisfactory cementing.

A typical well design would include:-

- Conductor:– 30" set at a depth of 24 metres, either driven or drilled and set with a piling augur.
- Surface Casing:- 20" casing set in 26" diameter hole drilled to 80 metres depth.
- Anchor Casing:- 13 3/8"casing set in a 17½" hole drilled to 270 metres depth.
- Production Casing:- 9 5/8" casing set in a 12¼" hole drilled to 800 metres depth.
- Open Hole – 7" perforated liner set in 8½" hole drilled to 2400 m –Total Depth.

Casing materials
Steel casing selected from the petroleum industry standard API Spec. 5CT or 5L.
In general the lowest tensile strength steel grades are utilised to minimise the possibilities of failure by hydrogen embrittlement or by sulphide stress corrosion. The preferred API steels are: Spec 5CT Grades H-40, J-55 and K-55, C-75 and L-80; Spec 5L grades A, B and X42.
In cases where special conditions are encountered, such as severely corrosive fluids, use of other specialised materials may be warranted.

Casing connections

The compressive stress imposed on a casing strings undergoing heating after well completion is extreme. As an example, an 800 metre length of casing undergoing heating from the cement setup temperature of around 60°C to the final formation temperature of 210°C (a change of 150°C), would freely expand 1.44 m. If uniformly constrained over the full length, the compressive strength induced would be 360 MPa; the minimum yield strength of Grade K-55 casing steel is 379 MPa. As this illustrates, axial strength is critical and it is therefore important that the casing connection exhibits a compressive (and tensile) strength at least equivalent to that of the casing body.

It is usual that a square section thread form is chosen, and this is typically the API Buttress threaded connection.

Cementation of casings

Unlike oil and gas wells, all of the casings down to the reservoir are usually run back to the surface, and are fully cemented back to the surface. The high thermal stresses imposed on the casings demand uniform cementation over the full casing length, such that the stress is distributed over the length of the casing as uniformly as is possible and such that stress concentration is avoided.

The objective of any casing cementing programme is to ensure that the total length of annulus (both casing to open hole annulus, and casing to casing annulus) is completely filled with sound cement that can withstand long term exposure to geothermal fluids and temperatures.

Of course, as suggested above, the permeable and under-pressured nature of the formations into which these casings are being cemented means that circulating a high density cement slurry with S.G.'s ranging from 1.7 to 1.9, inevitably result in loss of circulation during the cementing procedure.

The traditional method of mitigating this problem was to attempt to seal all permeability with cement plugs as drilling proceeded, however, this is usually an extremely time consuming process, and more often than not, circulation is still lost during the casing cementing process.

Many approaches to overcome this problem have been tried, and include:-

- Low density cement slurry additives – pozzalan, perlite, spherical hollow silicate balls
- Sodium silicate based sealing preflush
- Foamed cement
- Stage cementing
- Tie back casing strings – the casing is run and cemented in two separate operations.

Many of these options were tried but generally none have proven totally successful nor economic.

To date, in the experience of the author, the most successful procedure has been to utilise the most simple high density cement slurry blend, and to concentrate on the techniques of placing the cement such that a full return to the surface without fluid inclusions can be achieved. This nearly always involves a primary cement job carried out through the casing, and in the event of a poor or no return and immediate annulus flushing procedure, which is then followed by an initial backfill cement job through the casing to casing annulus, with sometimes repeated top-up cement jobs. Particular care must be taken to avoid entrapment of any water within the casing to casing annulus.

Perforated and slotted liner

Unlike the cemented casings discussed above, it is usual to run a liner within the production section of the well. This liner is usually perforated or slotted, typically, with the perforation or slots making up around 6% of the pipe surface area. As it is extremely difficult to determine exactly where the permeable zones within the production section lie, it is usual that the entire liner is made up of perforated pipe.

The liner is not cemented, but either hung from within the previous cemented production casing, or simply sat upon the bottom of the hole with the top of the liner some 20 to 40 metres inside the cemented production casing shoe, leaving the top of the liner free to move with expansion and contraction.

Drilling rig and associated equipment

The drilling rig and associated equipment are typically the same as is utilised for oil and gas well drilling, however a few special provision are required.

- Because of the large diameter holes and casings utilised in the surface and intermediate (if used) casing strings, it is important that the rotary table is as large as practicable – typically a 27½" diameter rotary table is utilised, and even 37½" is sometimes seen.
- Again, due to the large hole diameters drilled in the upper sections, large diameter Blow Out Preventers (BOP's) are required, however only moderate pressure rated units are necessary – a typical set of BOP stacks would include:-

  - 30" (or 29½") 500/1000 psi annular diverter and associated large diameter hydraulically controlled diversion valve.

  - 21¼" 2000 psi BOP stack including blind and pipe ram BOP's and an annular BOP.

  - $13^{5}/_{8}$" 3000 psi BOP stack including blind and pipe ram BOP's and an annular BOP.

  (comparatively – oil and gas rigs would usually have 5000 psi and 10000 psi rated BOP's)

  For aerated drilling 21¼" and $13^{5}/_{8}$" rotating heads and a $13^{5}/_{8}$" 'Banjo box' is required.
- The use of a 'choke manifold' is not mandatory in geothermal operations; usually an inner and outer choke valve is sufficient.
- As the BOP stacks are relatively large and occupy a significant height above the ground level (in particular if aerated drilling is to be used) it is necessary that rigs are equipped with an 'extra' height sub structure – a clear height of at least 6 metres is necessary.

- All of the elastomeric parts of the BOP's must be high temperature rated.
- It is preferable, although not mandatory, that rigs are fitted with top drive units – allowing for drilling with a double or triple stand of drill pipe; for easy connection and circulation while tripping the drill string in or out of the hole; and for back reaming.
- Rig mud pumps – (usually tri-plex) must be capable of pumping 2000 to 3000 lpm on a continuous basis. Pressure rating is not as important as pumped volume; pumps must be fitted with large diameter liners (usually 7" diameter).
- Rig mud pumps must be piped to the rig such that fluid can be pumped to both the rig standpipe and to the kill line (annulus) at the same time. It is important that the pump sizes or quantity of pumps is such that sufficient fluid can be pumped for drilling purposes, while a secondary volume – say 1000 lpm can be simultaneously pumped to the kill line.
- The drilling fluid circulating system requires a fluid cooling unit – often a forced draft direct contact cooling tower, or chilling unit.
- Drilling water supply must be capable of providing a continuous supply of at least 2000 lpm and preferable 3000 lpm - backup pumps and often dual pipelines are utilised.
- Drillpipe should be lower tensile strength material to avoid hydrogen embrittlement and sulphide stress corrosion – usually API Grade E or G105. Drillpipe is now usually supplied with a plastic internal lining, it is important that this lining has a high temperature rating.
- A high temperature rated float valve, (non return valve), is always fitted immediately above the drill bit in the drill string to prevent backflow into the drill string which often results in blocking of the drill bit jets.
- Drill bits – usually tri-cone drill bits are utilised however the elastomeric parts of the bearing seals and the lubrication chamber pressure compensation diaphragm are particularly heat sensitive. It is important that while tripping the drill string into the hole, that the bit is periodically cooled by circulating through the drill string.
- PDC – polycrystalline diamond compact drill bits are now being used more often - initially they were found to be totally unsuitable for hard fractured rock drilling – improvements in materials are now making this type of bit a real option. With no moving parts, bearings and seals they are essentially impervious to temperature.
- Drilling tools – the high downhole temperatures limit use of mud motors and MWD instrumentation tools to the upper cooler sections of the hole.

Drilling fluids

The upper sections of a well are usually drilled with simple water based bentonite mud treated with caustic soda to maintain pH. As drilling proceeds and temperatures increase, the viscosity of the mud is controlled with the addition of simple dispersants. If permeability is encountered above the production casing shoe depth, attempts will be made to seal these losses with 'Loss of Circulation Materials' (LCM), and cement plugs. If the losses cannot be controlled easily, then the drilling fluid is switched to either water 'blind' – that is drilling with water with no circulation back to the surface, or to aerated water.

Once the production casing shoe has been run and cemented, and drilling into the production part of the well commences, mud is no longer use as drilling fluid as it has the potential to irreparably damage the permeability and thus the production potential of the well.

Once permeability is encountered in the production section of a geothermal well, drilling was traditionally continued with water, 'blind' – with no return of the drilling fluid to the surface. The drill cuttings are washed into the formation, and periodic 'sweeps' with either mud or polymer assists in keeping the hole cleared of cuttings.

While this method alleviates the impractical and uneconomic loss of large volumes of mud, and the associated mud damage to the formation, the build up of cuttings within the hole often results in stuck drill strings, and the washing of cuttings into the formation causes damage to the permeability, although not on the same scale as bentonite mud.

Aerated water is now more commonly utilised for drilling this section of the well. To enable circulation of drilling fluids to be continued despite the presence of permeability and 'under pressured' reservoir conditions, the density of the drilling fluid must be reduced. The addition air to the circulating water allows a 'balanced' downhole pressure condition to be established, and the return and circulation of the drilling water and cuttings back to the surface.

Well control

Perhaps one of the most crucial differences between geothermal and oil and gas drilling operations is the nature of the formation fluids and how they can be controlled.

A geothermal well has the potential of being filled with a column of water at boiling point – even the slightest reduction in pressure on that column can cause part of, or the entire column to boil and flash to steam. This process can occur almost instantaneously. The potential for 'steam kick' is always there and requires special drilling crew training and attention.

Whilst the likelihood of a well kicking at any time is real, the method of controlling such a kick is simple and effective. Steam is condensable, so by simply shutting in the BOP's and pumping cold water into the well – both down the drilling and down the annulus, the well can be quickly controlled. The pressures involved are not high, as they are controlled by the steam / water saturation conditions.

During such a 'steam kick' it is normal that some volume of non-condensable gas (predominantly CO_2) will be evolved. After the steam fraction has been quenched and cooled, it is usual that this usually small volume of non-condensable gas be bled from the well through the choke line. Some H_2S gas may be present, usually in small quantities, so precautions are required.

Running the open-hole liner

One of the final tasks in completing the drilling of a geothermal well is the running and landing of the perforated or slotted liner. At this stage the drilling operations have been completed and hopefully permeability and a productive resource has been encountered. This operation is potentially critical as while a string of perforated or slotted liner (casing) is through the BOP stack, the functionality of the BOP stack is disabled. It is critical that a significant volume of quenching water is pumped to the well prior to and throughout the entire process.

In the event that a kick occurs in this condition, there are only two options available. A capped blank joint of pipe must be readily available so that it may be screwed in and run into the BOP stack so the well may be closed and then quenched. The alternative is that the liner is released and dropped through the BOP stack allowing it to then be closed and the well then quenched. Neither option a very satisfactory situation – it is crucial that a full understanding of the behaviour of the reservoir and the necessary quench volumes that are required to maintain the well in a fully controlled state.

The reliability of the water supply system for this process is of paramount importance.

Geothermal district heating and cooling: typical well designs and drilling/completion programs

Contrary to current oil and gas practice, drilling and completion of high enthalpy, dry and flashed steam, wells address non sedimentary volcano-tectonic settings and hard and abrasive rock environments, often exhibiting massive circulation losses. Such is not the case of low to medium enthalpy geothermal wells which, in most instances, are completed in sedimentary reservoirs, therefore applying straightforwardly standard petroleum drilling technology. However, completion designs should differ; as a matter of fact geothermal completions aim at maximizing fullbore well delivery, whereas hydrocarbon production, at least one order of magnitude lower than its geothermal counterpart , is in general completed inside the wellbore via a tubing-packer-safety valve- perforated casing/cement suite.

Current low to medium enthalpy geothermal drilling/completion technology will be illustrated through selected examples focused on (i) deep district heating and cooling wells drilled in carbonate and sandstone reservoirs, (ii) design of injection wells in fine grained clastics alternating sand, clay, sandstone depositional sequences, (iii) medium depth dual completion wells exploiting tepid aquifers in conjunction with water/water heat pumps, and, last but not least, (iv) an anti-corrosion well concept combining steel casings and fiberglass liners.

Geothermal district heating and cooling wells

Deep wells

The standard design of a geothermal district heating and cooling (GDHC) system is described in Fig. 1 (geothermal loop features).

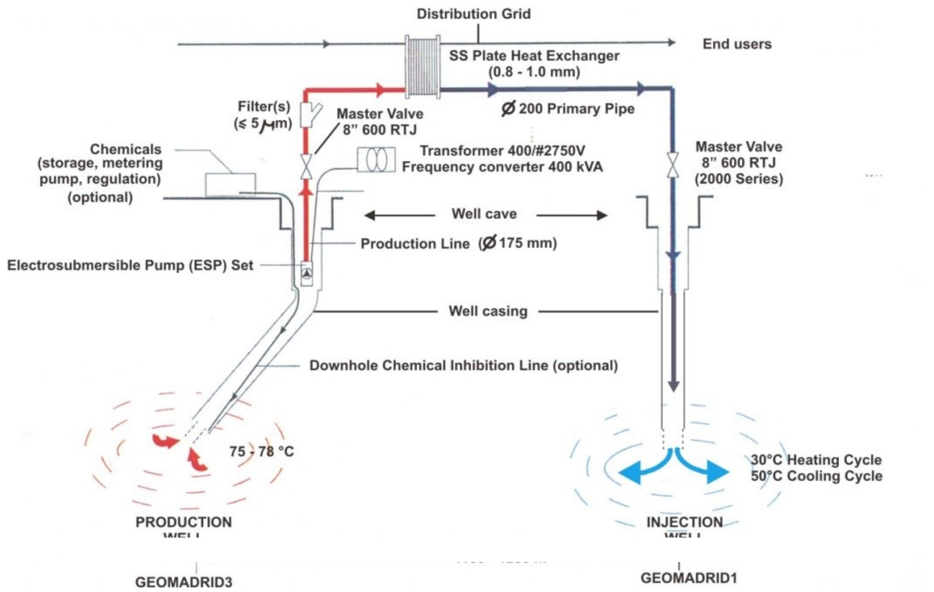


Figure 4. Geothermal District Heating & Cooling – Primary Loop Schematic

The system for waste disposal, pressure maintenance and heat recovery considerations is based on the geothermal doublet concept of heat extraction depicted in Fig.2 and 3 with respect to carbonate reservoir environment and either a casual steel cased or combined steel cased/fiber glass lined well completion.

The impact of two standard GDHC production casing programs [pumping chamber x production casing] on well losses can be visualised in Fig. 4.

Fig. 5 addresses the design of a well producing from a thick sandstone hot water aquifer, complying with the programme summarised in Table 1 and in Fig. 6 time-depth chart.

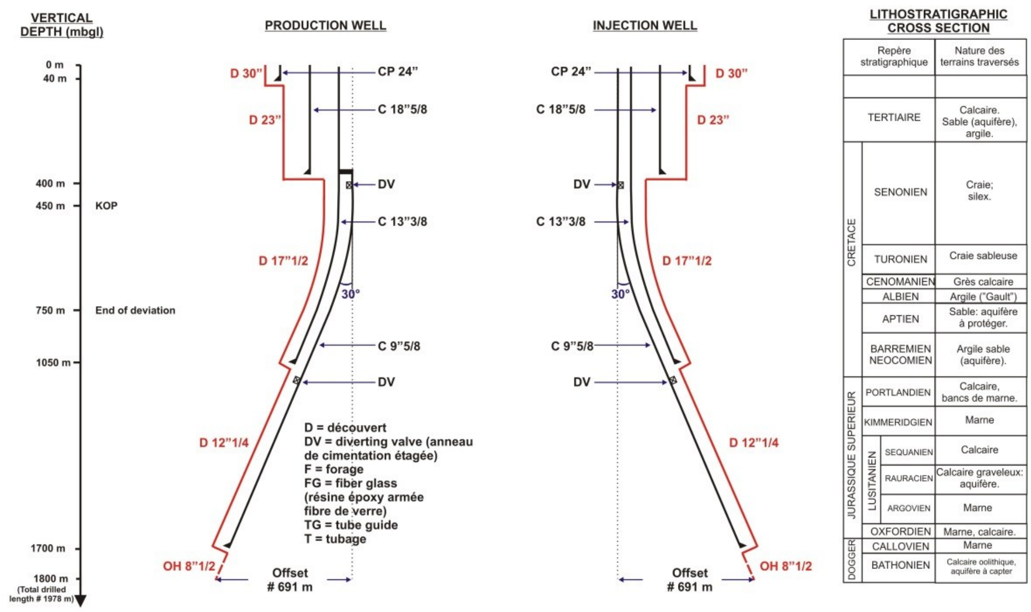


Figure 2. Conventional (steel cased) GDH doublet design

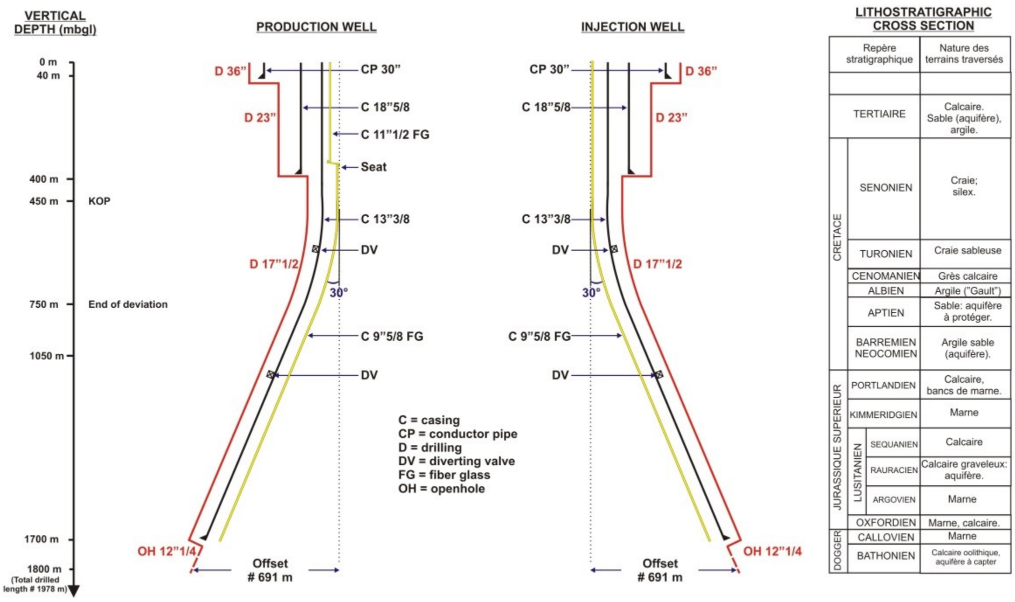


Figure 5. GDH doublet completion combining steel casing and fiber glass liners

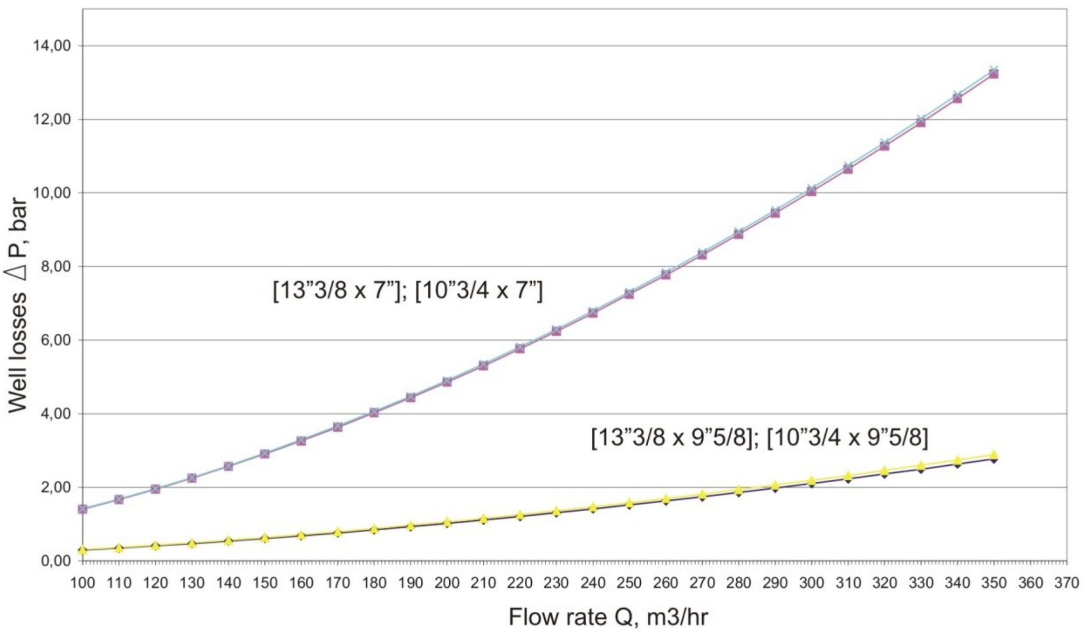


Figure 6. Friction losses as a function of production casing programmes

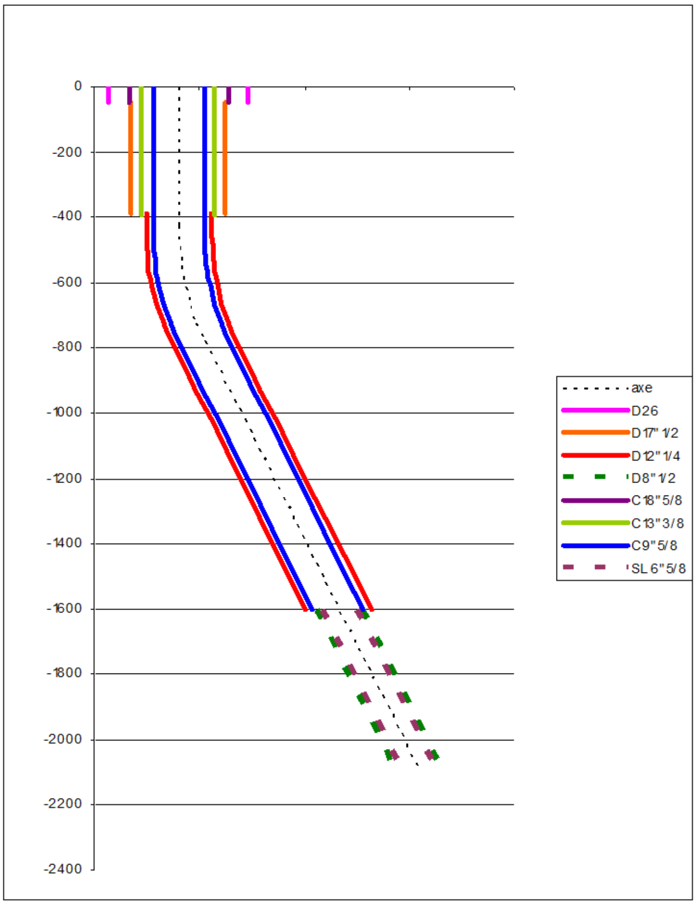


Figure 7. Production well profile. Consolidated sandstone reservoir

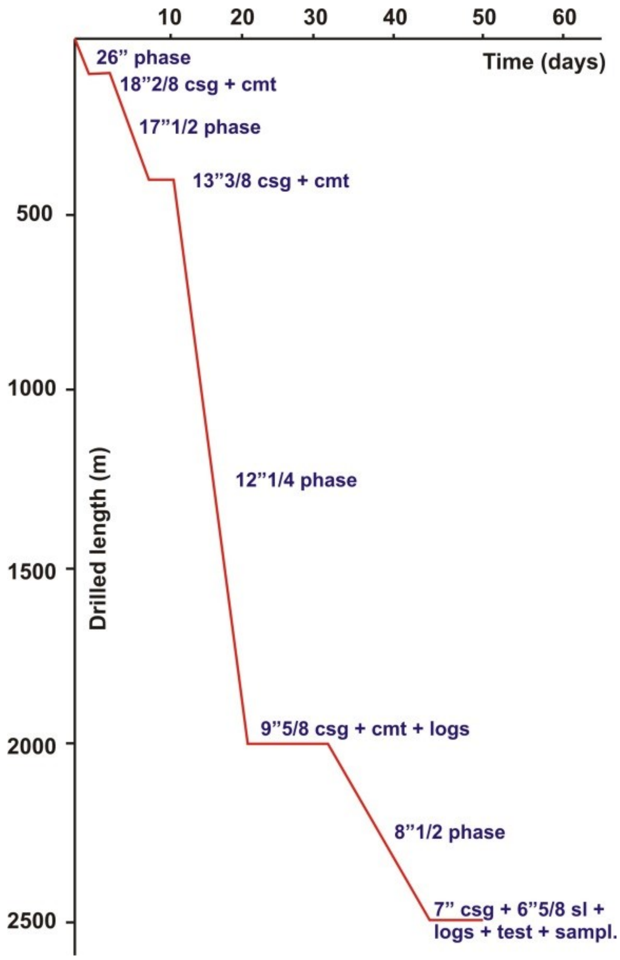


Figure 8. Projected drilling/completion/testing time vs depth diagram

Medium depth wells

Fig.9 is an illustration of a water/water heat pump assisted GDHC doublet based on a dual aquifer completion scheme in a sandy formation context, casual in petroleum production but unusual in geothermal and groundwater projects.

Note incidentally that Fig. 7 design may accommodate the operation of two submersible pump sets.

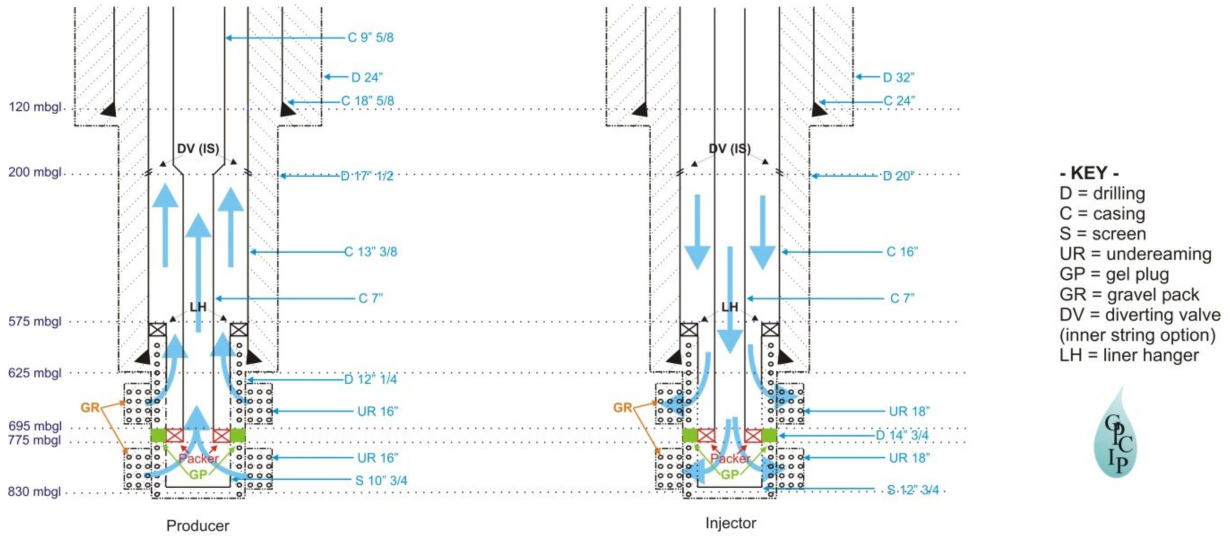


Figure 9. Dual, heat pump oriented, water well completions. Note that the producer well can be equipped with two submersible pump sets.

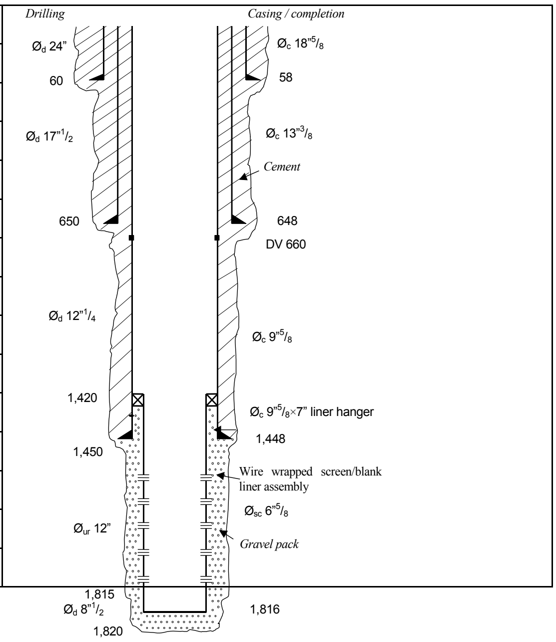
Water injection in fine grained reservoir clastics

Injection wells are known to undergo severe injectivity losses further to near wellbore permeability impairment and subsequent formation damage, a topic further discussed in section 6.5.

Given the produced, heat depleted, brine is injected into the source reservoir, no water incompatibilities are to be feared. Therefore, matrix plugging by fine, preferably external, particles is the prevailing damaging mechanism. To be defeated or at least mitigated it requires, in addition to surface filtration facilities, careful completion design regarding casing diameters, undereaming and gravel pack grain size and placement, screen selection among others. Based on field experience the foregoing should lead to sandface velocities lower than the 1cm/s critical threshold.

A typical well completion designed to secure 150m3/h injection flowrates in the Great Hungarian Plain (Pannonian basin), fulfilling the aforementioned requirements, is attached in Fig. 8.

Projected well/reservoir performance	
Top reservoir depth	1,500 m
Static WHP	-5 bars
Total pay	400 m
Net pay (h)	110 m
Effective porosity (ϕ_e)	0.2
Permeability (k)	100 mD
Skin factor (S)	-2
Formation temperature	90 °C
Mean injection temperature	35 °C
Fluid (eq. NaCl) salinity	2.5 g/l
Fluid dynamic viscosity (production) (μp)	0.32 cp
Fluid dynamic viscosity (injection) (μi)	0.73 cp
Total compressibility factor (c_c)	10^{-4} bars^{-1}
Fluid density (ρp) at 90 °C	965.34 kg/m^3



Fluid density (ρi) at 35 °C	994.06 kg/m^3	
Target injection rate (Q)	150 m^3/hr	
WHP (150 m^3/hr, 35 °C)	20.5 bars	
Sandface velocity (v_{sf})	0.23 cm/s	
Velocity at completion outlet (v_c)	0.61 cm/s	

Figure 10. Water injection in a clastic sedimentary environment. Typical well completion design [Ungemach, 2003]

Anti-corrosion well concept

The design, depicted in Fig. 9, is a material response to corrosion damage. It has been successfully implemented on a Paris Basin self flowing well in early 1995 and since then the well has been operating, at a constant 200 m^3/h discharge, without any workover nor even light well head servicing recorded whatsoever, contrary to his steel cased GDHC companions which undergo at least one heavy duty workover every ten years or so.

The well combines steel propping casings, providing the required mechanical strength, with a fiberglass production/injection column, chemically inert vis-à-vis any geothermal corrosive fluid environment. The annulus is kept free in order (i) to circulate (or simply fill) corrosion inhibitors, preserving steel casing integrities, and (ii) to remove the fiberglass string whenever damaged (wheap destructuring) and replace it by a new one thus achieving long well life. Fiberglass integrity is assumed to last 25 to 30 years.

Operating temperatures are limited by the glass vitreous transition temperature, the practical limit being set at ca 90°C. Well inclination should not exceed 35°C. The production well architecture, displayed in Fig.9, requires (i) a larger diameter fiberglass column, to accommodate an ESP placed in compression on a fiber glass coated seat at the (18"5/8 x 13"3/8) casing transition, and (ii) a slimmer liner, freely suspended under its own weight below the seat. Both liners are centralised via fiberglass coated centralisers so that there is no contact other than with fiberglass materials. Thermomechanical effects are compensated at well head by an *ad hoc* expansion spool.

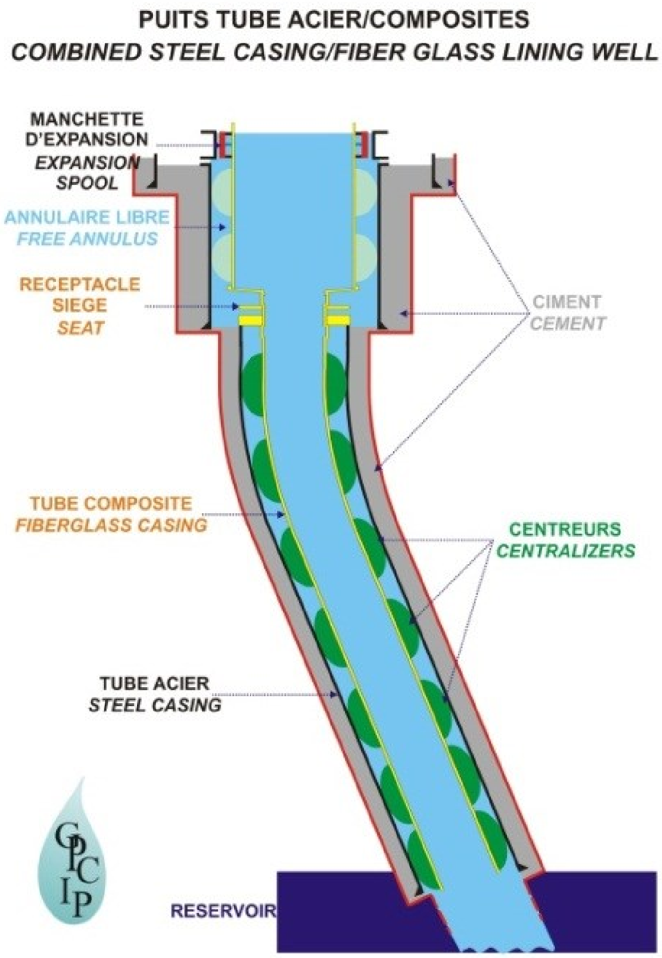


Figure 11. Combined steel casing/fiber glass lining well (GPC)

Table 1. Drilling/completion/testing programme

DRILLED DEPTH INTERVAL (mbgl)	PHASE DESCRIPTION	REMARKS
0 – 50	Drill ϕ 26", tricone roller bit, WOB # 12-25 t ; 800-200 rpm ; >3500 l/min ; penetration rate 5 m/hr. Bentonite base mud: d = 1.10 – 1.15; V # 30 – 50 M. Run 18"5/8 casing. Inner string cementing = CP55 Cement slurry, d = 1.80	Possible meterage change owing to completion of a large diameter, 0 – 20 m, foreshaft
50 – 400	Drill " 17"1/2, tricone roller bit, WOB # 15-20 t ; 80-200 rpm ; >3500 l/min; penetration rate 7-8 m/hr. Bentonite base mud: d = 1.10 – 1.15; V # 35 M. Run 13"3/8 casing. Inner string cementing = CP55 Cement slurry, d = 1.80	Designed as a future pumping chamber withstanding a 150 – 200 m water level drawdown
400 – 1850	Drill " 12"1/4, PDC bit, WOB # 12 t ; 120 rpm ; 2500-3000 l/min; penetration rate 4-5 m/hr. Bentonite/PAC, PAC+CMC/polymer base mud formulations: d = 1.10 – 1.15; V # 35 M. Start deviation @ KOP=450 m with downhole, steerable, motor, MWD, KMonel, hydraulic jar, assembly; build up gradient = 1°/10 m; slant angle # 380, azimut = __*. When reaching # mbgl drilling depth continue either with identical motorised, steerable, BHA or, with rotary assembly instead. Run 9"5/8 casing with either a liner hanger or DV + left hand connection (casing cut) to accommodate the required 13"3/8 pumping chamber space. Conventional stage cementing procedure with cementing head, shoe, float collar and DV placed @ # 1100, above the upper lost circulation horizon, POZZMIX (dry blended puzzolane/class G cement) slurry, d # 1.60. Wireline (OH/CH) logging programme = BGL/GR; SPGR; MRT; STI; CIC; CBL-VDL	The 9"5/8 casing cutting strategy should be selected instead of the liner hanger configuration in order to meet the 13"3/8 pumping chamber space requirements. The left hand connection would enable to recover the DV and ease an eventual further 13"3/8 x 9"5/8 casing lining issue.
1850 – 2485	Drill " 8"1/4, PDC bit (rotary assembly), WOB # 8t ; 120 rpm ; 1500-2000 l/min; penetration rate 5-7 m/hr. Polymer base mud: d = 1.05; V # 35 – 40 M, 50 m full size 5" sample coring. OH/production logging programme = CNL, SGR, SpeD, BGL, HMI (optional), PLT, T, pressure build-up, BHFS (PVT). Run completion string according to flowmeter identified producing layers: 7" casing x 6"5/8 slotted liner assembly. Liner hanger set @ __** mbgl. Mud acid (HF + HCl) well stimulation (10 -20 m^3 HF 4X + HCl 14X). Bottomhole fluid sampling. Surface suspended particle monitoring. Production/injection well loop circulation test.	Mixed (casing x slotted liner) column designed and run downhole according to flow meter logging survey. Bottomhole fluid sampling aimed at liquid and gas phase analyses at reservoir conditions.

* from reservoir modelling

** from geology

Conclusion

The processes of drilling geothermal wells is very similar to those developed by the oil and gas and water well drilling industries, however the nature of a geothermal reservoir system; the temperature; the geology and the geochemistry require that some quite different practices be followed if the drilling process and the resulting well are to be successful.

Conclusions/Recommendations

- More competition between drillers is needed

The number of deep drilling companies offering their services to project developers should increase in order to improve competition in pricing and to allow for more transnational activities. Today, in many countries, barriers exist to this competition.

- Improve rig availability

The start dates of geothermal projects are often rather uncertain, mainly due to licensing procedures. Consequently, developers often encounter problems when contracting drilling; better information on rig availability will allow for more accurate forecasting and activity planning.

- Increase financing

Drilling is capital intensive and, because of the geological risk can result in failure. In order to decrease risk and increase funding, both a risk insurance scheme and a support scheme (drilling funds with grants, or feed-in tariffs) should be established.
Moreover, innovative financial models should be developed, for instance the creation of a pool of developers for contracting loans with both banks and drilling companies, and for improving the conditions of these loans.

- Upgrade quality

Geothermal developers need to carefully supervise the drilling operation in collaboration with the drillers. Proper drilling is crucial for both the economy and the environmental impact of the operation.

- Simplify regulations

The negotiation between the project developer and the driller can be time consuming especially when the risk is not enough assessed. To simplify the process, some guidelines should be developed:

- Standard for drilling contract: technical description and price table
- Standard for pre-qualification procedures

Geothermal drilling in Germany. Copyright: Kreuter