Influences and limiting parameters of casing design on the success of hydrogeothermal projects - a new approach for the design of geothermal wells

C. Fichter*, K. M. Reinicke*, C. Teodoriu*, Y. Wang* and U Lotz**
TU Clausthal, **GeoEnergy GmbH

Keywords: pressure drop, well construction, casing design

Abstract

Wells drilled to produce geothermal energy from deep geologic formations have to be designed for conditions which are quite different from the standard settings encountered in oil and gas production. Because of the much lower energy content of the geothermal fluids compared to oil, high production rates are required to achieve economics. Using the rather narrow oilfield well designs, the required high rates will lead to high flow velocities in the flow conduit, associated with very high pressure losses to transport the fluids up the well to the surface. Excessive velocities in the flow conduit may cause pipe damage by erosion. At the sand face, excessive velocities may result in formation stability problems with an associated production of solids.

This paper discusses the optimization of the design of a geothermal well using the settings in the Upper Rhine Graben in Germany as an example.

1. Introduction

Wells to extract geothermal energy from deep geologic formations require high fluid rates to achieve economics. Geothermal projects worldwide are therefore prospecting and developing natural fracture systems typically associated with fault systems. For the low enthalpy geothermal projects to feed combined heat and power plants – as they can be developed in Germany – require production rates in the range of 60 to 120 l/s or up to ca. 10.000 m³/day at surface temperatures larger than 120°C in order to be economically feasible. On the other hand the production rates of profitable oil wells are typically in the range of “only” several hundred cubic meters per day and oil wells are generally drilled into tectonically undisturbed zones.

With respect to these basic preconditions, geothermal projects and the wells required herein are rather distinct from standard settings encountered in oil and gas production. High production rates through wells completed with the rather narrow oilfield designs will lead to high flow velocities in the flow conduit, associated with very high pressure losses to transport the fluids up the well to the surface. Excessive velocities in the flow conduit may cause pipe damage by erosion. Excessive velocities at the sand face may result in formation stability problems with an associated production of solids. Wells for geothermal projects have to be designed to meet these requirements, i.e.,

- velocities are required to stay below critical velocities causing erosion
- completions are required to prevent formation stability problems and solids production
- well dimensions should be selected to maximize project value in a tradeoff between well size and pumping requirements to achieve the desired rates.

This paper discusses the optimization of the design of a geothermal well using the settings in the Upper Rhine Graben in Germany as an example.

2. Geological Setting in the Upper Rhine Graben

The Upper Rhine Graben is a Tertiary graben structure in which the basement rocks and their Mesozoic cover have been displaced down by as much as 5.000 m in comparison to their recent position in the graben shoulders. These Mesozoic and basement rocks contain hydrothermal brine reservoirs, being the primary targets of geothermal exploration in the Upper Rhine Graben. Many of the fault zones are associated with fracture zones promising high fluid rates. The reservoir rocks like massive limestone in the Muschelkalk sequence or thick sandstone layers within the Bunter Sandstone are separated by clay- and mudstone sequences.

Tertiary – often marine – and Quaternary sediments have been deposited syntectonically into the graben structure to an extent that the reservoir rocks and the fault zones cutting through them are today occurring in depths ranging between 2.000 and 3.500 m below the recent “graben” floor or land surface. The Tertiary sedimentary rocks are mostly fine grained, impermeable often poorly consolidated rocks (mudstones and clay with thin sandstone layers). These rocks are sealing the hydrothermal reservoir rocks and also the fault zones towards the top causing the hydrothermal reservoirs to be artesic in many parts of the Upper Rhine Graben, even though the recently active fault zones often can be traced in seismic surveys up to the land surface and can be detected even in outcrops near surface. Within the Tertiary sequence several “trouble horizons” like the “Bunte Niederrödener Schichten” or the “Pechelbronner Schichten” are known from the extensive hydrocarbon exploration drilling phase in the period 1930 to 1990.

The geological and the tectonical setting for planning deep geothermal wells in the Upper Rhine Graben is generally quite demanding and many parameters have to be taken into account in the planning process. The basic parameters to be regarded are:

- The wellbores have to pass through a partially unconsolidated Tertiary sequence with several known “trouble horizons” like swelling clays etc. before reaching the underlying reservoir rocks and fault-hosted reservoirs.

- Within the Quaternary sequence often aquifers of up to 450 m total thickness have to be penetrated and must be secured against any potential influences from the geothermal wells.

- The wellbores are aimed at the fracture zones associated with geologic fault systems, i.e. the most intensively tectonically overprinted zones, within the Mesozoic and basement rocks. Also on the path through the Tertiary sequence fault zones have to be penetrated. Rock instability within the fault / reservoir trans-sections of the wellbores has thus to be taken into account, meaning that leaving reservoir sections of the well as open hole sections might not be possible.

- The reservoir rocks are stratified by intercalated impermeable rock sequences like clay- or mudstones. So several reservoir zones of different lithology and rock stability might have to be made accessible by the well.

With respect to the geological setting and the parameters described above, deep geothermal wells within the Upper Rhine Graben have generally to be designed with a minimum of four sections. Three sections are generally required to reach the top of the reservoir rocks, the fourth section will penetrate into the reservoir rocks and the main exploration targets, i.e. the fault zones. Respecting the rules of good well design practice at least one contingency section should be taken into calculation and so a total of five sections will be the base for the well design. This contingency

section allows for example to put in one or even two slotted liner sections in case the tectonically overprinted reservoir rocks within the fault zones should prove not to be sufficiently stable during testing and production or two separate reservoir horizons have to be brought behind a slotted liner in different depth levels.

Figure 1 shows a schematic of the proposed well and the corresponding geology specifically to the Rhine Graben Zone. Note the contingency casing at the so second reservoir in the “Mittlerer Buntsandstein” denoted as Ziel 2.

The design for deep geothermal wells in the Upper Rhine Graben has to start with the two basic constraints being the possibility to insert as much as five casing / liner sections and also to provide casing / liner diameters in the deep sections of the well, which are capable to produce the required high flow rates of up to 60 or even 120 l/s at economically feasible energy consumption of the production pumps.

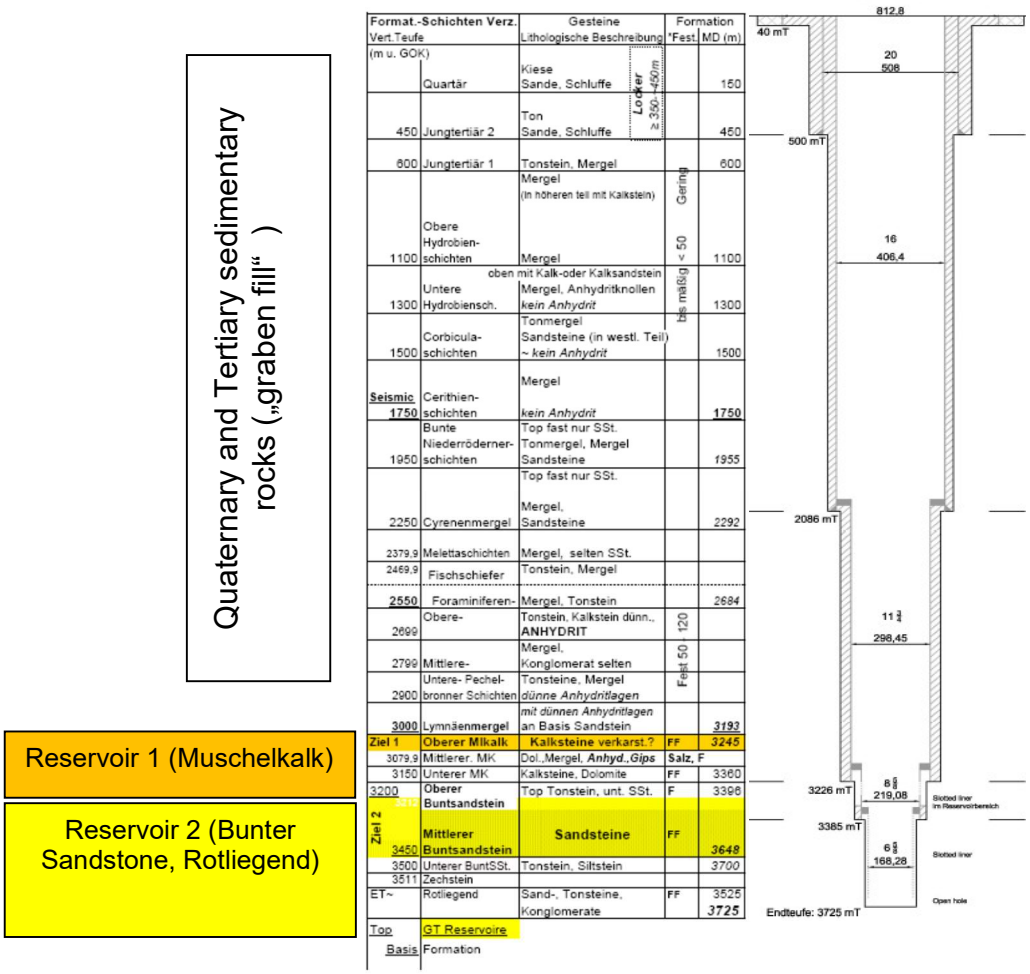

Figure 1. Geological profil and well schematic for a hydro-thermal well to be drilled in the Rhine Graben Area

3. Well diameter selection based on hydraulic performance

The figure 2 depicts the hydraulic schematic of a geothermal well. The pump lifts the fluid from the liquid level to the surface. The dynamic water level lower than the static water level implies a bottom hole flowing pressure lower than the reservoir pressure. This pressure difference between bottom hole and reservoir pressure, the draw down pressure, causes fluid to flow from the reservoir into the wellbore. The draw down pressure and hence the liquid level, necessary to achieve the desired rate, are dependent on factors like flow resistance or permeability within the reservoir, the pressure loss across the completion, and the pressure losses within the flow conduit up the well.

The pressure losses in the flow conduit result in particular from the weight of the fluid column and frictional pressure losses. The latter are velocity dependent, implying that increasing flow rates result in increasing frictional pressure losses, increasing the bottom hole flowing pressure. To achieve the same rate, the dynamic liquid level has to be lowered which will require a deeper location for the centrifugal pump. In order to minimize the pressure drop within the casing, an economic optimization of well diameter versus pump requirements has been performed with the target to minimize/optimize the pressure drop below pump and thus the pump size and energy requirements of the pump in the longterm production phase.

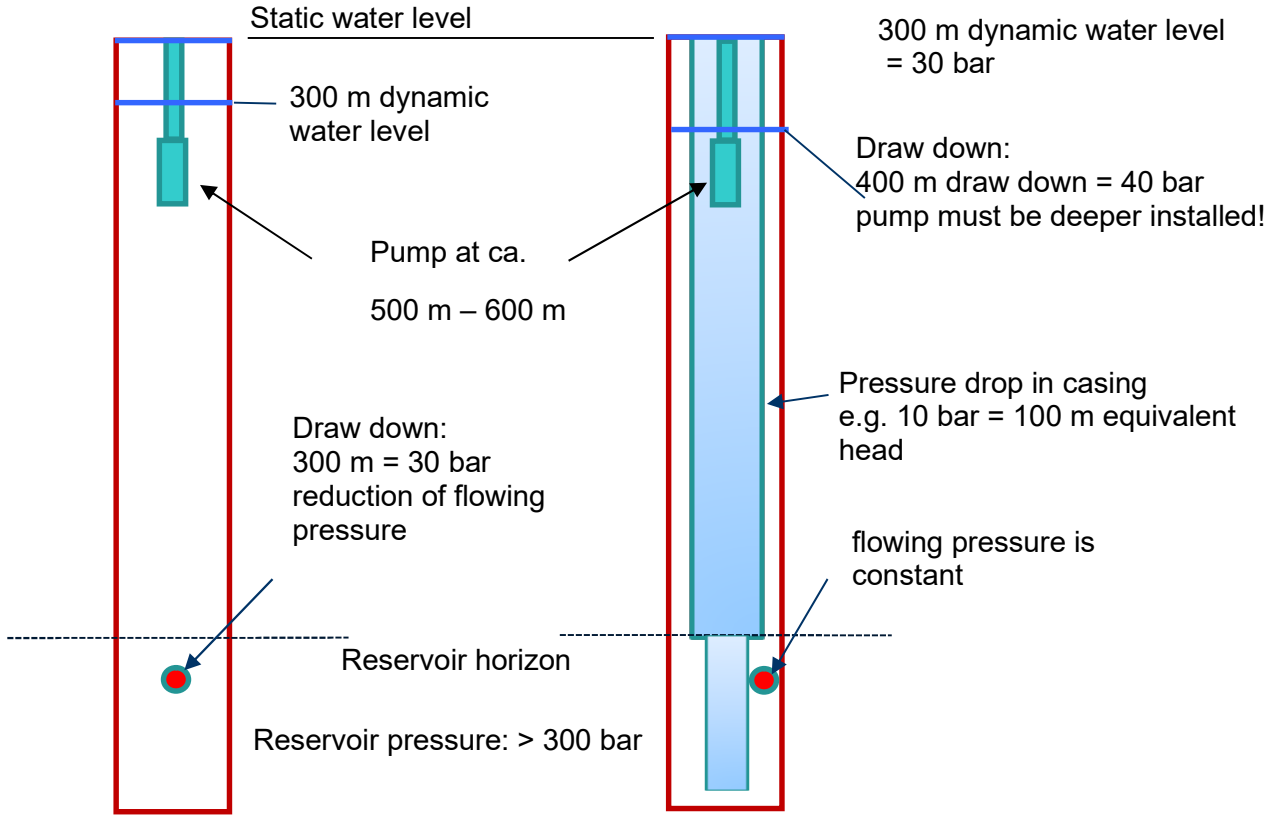

Figure 2. Effect of hydraulic pressure drop on pump installation depth (Left: virtually open hole well; right: cased hole casing pressure losses)

A excel based calculation sheet has been developed in order to analyze the pressure drop within wellbore. The flow was split in three major zones: flow through tubing, flowing through cased section and flow through open hole section.

To determine the pressure drop the following equation has been used:

$$\Delta p = f \cdot L \cdot v^2 \cdot \rho_{SW} / (2 \cdot d)$$

where:
f – Darcy Weißbach friction factor
L – length of tubing or casing
v – fluid velocity
d – inside diameter of casing or tubing
ρ_{SW} - fluid density (salt water)

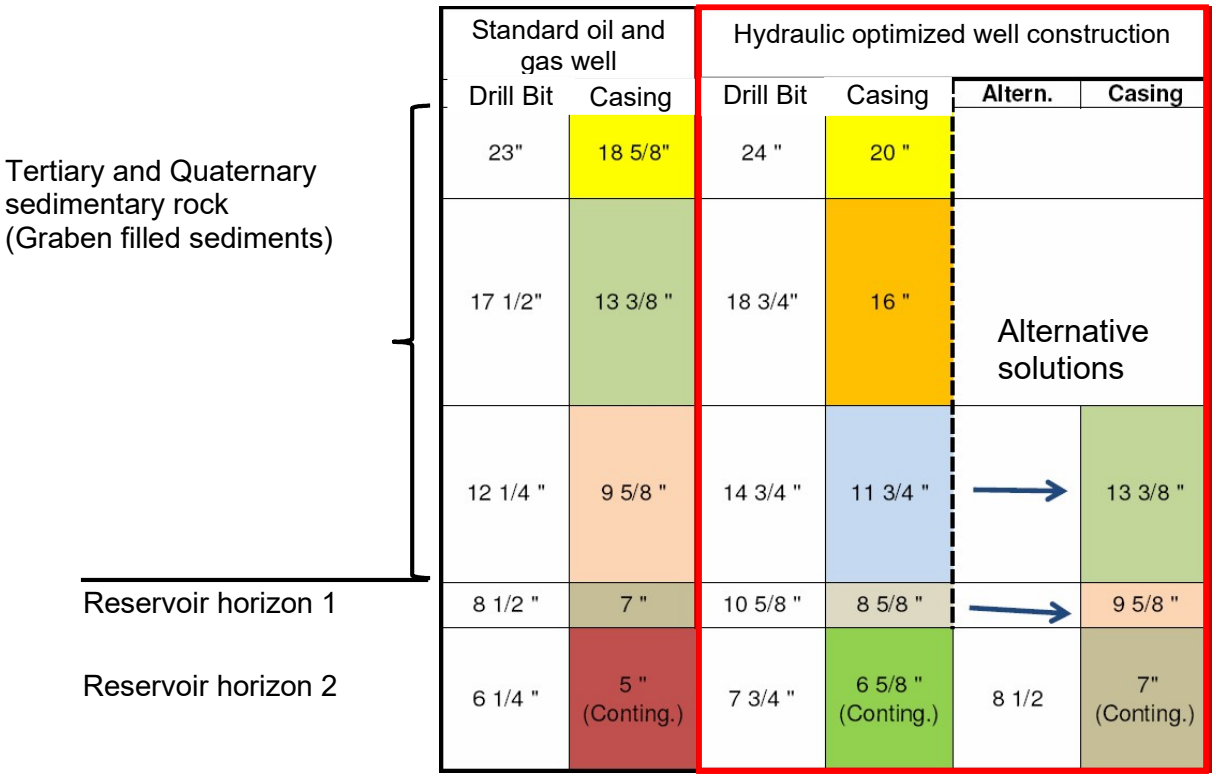

Figure 3. Comparative view of a standard oil and gas well and the hydraulically optimized concept (Example shows a typical well design for Upper Rhine Graben projects including on contingency section)

The main input parameters for this calculation are: casing, tubing and open hole inner diameter, relative roughness for each section, fluid density and viscosity, local pressure loss coefficients for diameter changes and well head. The flow rate was varied between 60 l/s and 100 l/s. The calculations where performed starting from a conventional well schematic (oil and gas well) as recommended in current regulations. Figure 3 shows the reference wellbore construction showing open hole and casing diameters. On the right side the hydraulic optimized model is shown. The alternative solution presented herein is considered for those cases where no drilling problems exist and low clearance solution can be used with minimized risk. It must be noted that the well

construction is today limited due to the possible combinations between bit size and casing diameters including their couplings. When special clearance couplings are used some additional bit size/casing combinations are possible but with some associated risks like getting stuck during casing running job. Figure 4 shows the required bit size / casing combinations for oil and gas wells after Economides (2005).

In table 1 the calculated pressure losses are shown. For this example – depending on the dimensions of the flow conduit in lower portion of the well- between 24 and 48 bar at 100 l/s can be "saved" using the hydraulically optimized well. The "hydraulically optimized" well is the design according to column 4 in Fig. 3.

For the calculations shown in table 1 the following assumptions were made:

- For the cased holes an absolute roughness of 0.2 mm was used
- For the open hole section a conduit with an absolute roughness of 10 mm was considered

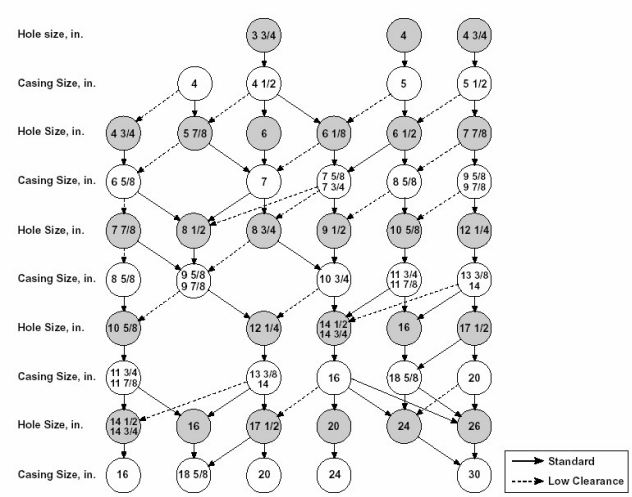

Figure 4. Required clearance between casing and wellbore, after Economides, 2005

Table 1. Hydraulic pressure loss calculations

	Hydraulically optimized			Conventional		
Option / Pressure loss in casing and open hole (bar) / Flow rate	Open Hole section in all reservoirs	Wellbore Section in Reservoir 1	Total pressure drop (Casing in Res. 1 and 2)	Open Hole section	Wellbore Section in Reservoir 1	Total pressure drop
0,06	3,446	3,506	3,819	12,117	12,282	20,96
0,07	4,691	4,772	5,199	16,493	16,718	28,529
0,08	6,127	6,233	6,79	21,541	21,835	37,262
0,09	7,754	7,889	8,594	27,263	27,388	47,16
0,10	9,573	9,74	10,61	33,658	34,117	58,222
			Δ1bar=10m			Δ25bar=250m

➔ these figures show the additional pressure losses for completely cased wells (columns 4 and 7) compared to open hole wells (columns 2 and 5)

In order to estimate the additional costs, required to complete a larger diameter hole ("hydraulically optimized"), a similar calculation procedure has been used as presented in the paper by King et al. 1995. Getting real prices from past projects is rather difficult due to the lack of communication between different project operators. Therefore our hypothetical well will be analyzed using the following assumptions:

- Drilling larger diameters requires additional drilling time
- Drilling larger diameters requires additional drilling equipment and the corresponding costs (i.e. heavier well head, BOPs, drillstring and Bottom Hole Assembly – BHA)
- The increase of casing diameter does not require a different rig type (this assumption can be done for hydrothermal wells with depths not deeper than 3000 m)
- Additional costs (water supply, drilling, well testing, etc) are increasing the total costs with ~ 10%
- The casing connections are considered to have less impact on total casing costs. (assumption is available for API connections only)

The casing costs will be analyzed in order to identify the additional impact of a larger casing. The calculated casing costs are normalized and compared with the equivalent cost per meter of a 7 in casing. The actual costs of casing may differ from project to project therefore the numbers in table 2 must be carefully used for real projects. However, in this paper the emphasis is put on a comparison of the relative and not the absolute cost figures.

Table 2. Casing costs in $/m (values not to be considered as today's reference), after King 1995

Casing Size	Casing costs in $/m
20" Line pipe	185
18 5/8 casing J55 Buttress	179
16" casing J55 Buttress	150
13 3/8" casing J55 Buttress	142
11 3/4" casing N80 Buttress	101
9 5/8 " casing N80 Buttress	99
8 5/8 " casing N80 Buttress	76
7" casing N80 Buttress	70

For this example the casing strings will have same casing setting depth, therefore the costs difference will be determined by the larger casing size only. Table 3 shows the comparison calculation for the casing of the wider diameter well.

The estimated casing costs increase represents ~14% of the initial casing costs (base case). Paulus and Reinicke (2009) pointed out that for average oil and gas wells the tubular total costs represent about 11% of the total well costs. Extrapolating from here, the additional casing costs will increase the total material costs from 11% to 13 %.

Additionally to material costs (casing), drilling time will respectively increase since a larger bit must be used. As reported by King, 1995 the additional rig time for equivalent well construction will vary from 3 to 4 additional days. At a daily rate of over 70.000 $/day (estimated costs for Europe in 2009), 3 to 4 days represent a significant increase of the well costs. All together it is estimated that the incremental costs of the hydraulic optimized well will be in the range of 500.000 to 600.000 $. The additional rig time is the component that will definitively increase the overall well costs. Compared with some reported values (Paulus and Reinicke, 2009) these additional increases can

be up to 11% increase of total well costs. To conclude, it is estimated that a “hydraulically optimized well” will generate a total cost increase ranging from 12% to 20% if associated drilling problems are similar for both wells. It is worthy of note that the “hydraulically optimized well” has the advantage of a bigger contingency liner size compared to the conventional well (6 5/8” or 7” compared to 5”). As reported by King (1995) the hydraulically optimized wells used for the dry steam geothermal project in New Zeeland had a payback after a time frame between 50 days and 670 days, depending on the steam flow rate and steam quality.

Figure 5 shows the schematic of the hydraulic optimized well. Alternatively, if the experience gained during drilling the first wells shows positive results, a lean well concept can be used as suggested in figure 3. It must be mentioned that a lean well concept has generally a higher risk when running the casing if the drilled area is not well known. Therefore the authors will recommend using the well design presented in the figure 5 for the first well, while the lean concept model will be used for future wells.

Table 3. Estimated casing costs (material costs) for the based case and hydraulically optimized well

Casing Size	casing costs for the base case	casing cost for the optimized well	Casing costs increase of a wider diameter well
Surface 20” @ 500 m	N/A	185 x 500 = 92500	3000
Surface 18 5/8” @ 500 m	179 x 500 = 89500	N/A	3%
Intermediate 16” @ 2086 m	N/A	150 x 2086 = 312900	16688
Intermediate 13 3/8” @ 2086 m	142 x 2086 = 296212	N/A	5%
Liner 11 ¾” @ 1140 m	N/A	142 x 1140 = 161 880	49020
Liner 9 5/8” @ 1140 m	99 x 1140 = 112860	N/A	2%
Liner 8 5/8” @ 150 m	N/A	76 x 150 = 11400	500
Liner 7” @ 150 m	70 x 150 = 10500	N/A	4%
Total	509072	578680	69608

4. Conclusions

The different requirements for geothermal wells, in particular the required high rates, require a well design different from those used for oil and gas production.

The design must address the questions of, erosion, formation stability, well dimension and pump requirements.

To achieve maximum project value, well dimensions should be chosen in a tradeoff between well size and pumping requirements to achieve the desired rates. There is ample room for optimization.

5. Acknowledgments

The authors would like to thank to GeoEnergy GmbH for permission to publish this paper.

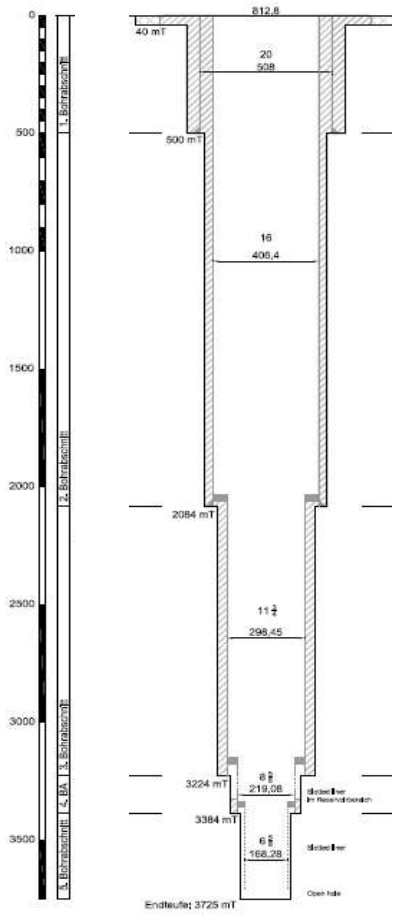

Figure 5. The “hydraulically optimized well concept” as proposed in this paper

References

Economides, M: Petroleum well Construction, John Wiley and Sons Inc., New York, May 2000

King, T.R., Freeston, D.H., Winmill, R.L. A case study of Wide Diameter Casing for Geothermal Systems, Proceedings 17th NZ Geothermal Workshop 1995.

Paulus, M., Reinicke, K.M.: Kostentreiber von 4000 bis 5000 m Bohrungen in Deutschland, DGMK/ÖGEW Früjahrstagung 2009

Postadresse, ITE, TU Clausthal, Agricolastr. 10, 38678 Clausthal-Zellerfeld
E-Mail-Adresse, carsten.fichter@tu-clausthal.de