Germany`s Deepest Hydro-Geothermal Doublet, Drilling Challenges and Conclusions for the Design of Future Wells

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Abstract

From 2016 to 2017 two hydro-geothermal wells were successfully drilled in Holzkirchen, a market town south of Munich, Germany. The carbonate reservoir in this region (the Jurassic “Malm”) is found between 4,600 m and 5,200 m depth and is known to have suitable transmissivity and a geothermal fluid with low salinity.

The first well spudded in January 2016; the drilling of the first two sections went according to plan. Following an intense gas kick, the third section had to be abandoned, and a sidetrack was drilled following a new well path to avoid the potential gas-bearing zone. The final depth of 5.600 m MD was reached in May. After successfully testing the first well, the second well commenced in June. In the third section, part of a liner, as well as a drilling BHA, were lost due to differential sticking. Two sidetracks were drilled, and after a total drilling period of about 8 months, the final depth of 6.084 m MD was reached and followed by a well test which verified the required productivity and temperature.

The most significant drilling challenge was the high variance in pore pressures and the difficulty in foreseeing these pressures within the lower part of the basin sediments (Oligocene and Upper Cretaceous) (approx. 3000 - 4500 m TVD), despite data from hydrocarbon offset wells. The primary conclusion for future wells to be drilled further south of Munich is to incorporate an additional sixth casing string, which would allow the use of higher mud weights in potential overpressure zones to achieve a sufficient kick tolerance without increasing the risk of differential sticking in formations with normal pore pressure. This paper discusses two different design options for future wells. Option 1: Standard clearances are used resulting in an increased surface casing diameter and Option 2: No change in surface casing diameter but the incorporation of a low clearance section. The final borehole diameter in both design options remains the same.

1. Introduction

The Holzkirchen doublet represents the first deep geothermal wells to be drilled in the southern extents of the German Molasse Basin after a fall off in project activity between 2008 and 2013 and a dry well in 2013. The operator Geothermie Holzkirchen GmbH (GHG) pushed the project to assure that renewable geothermal energy can be provided to its customers in the form of direct use for district heating and power generation.

The Bavarian market town of Holzkirchen, which is about 30 km to the south of Munich (South Germany), benefits from a strong local economy and the ideal geological conditions for direct use and power generation from a deep geothermal aquifer in its subsurface. The Upper Jurassic carbonate *Malm* reservoir, which in this region is found between 4,600 m TVD and 5,200 m TVD depth, has appropriate natural permeability, a geothermal fluid with low salinity and a temperature of approximately 160°C. Therefore, the Malm at this depth is the ideal source for a combined direct use for district heating and power generation with a binary ORC power plant.

The drilling of the first well (Holzkirchen (HZK) Th1) began in January 2016. Following an intense gas kick at about 4,200 m MD (Rupelian *Bändermergel* sub formation), the third section had to be abandoned and cemented back up to about 2,400 m MD to the liner shoe of the previous section. The subsequent sidetrack Th1a was drilled along a redesigned well path to avoid the previously encountered potential high-pressure gas-bearing zone. The final depth of 5,600 m MD / 5,079 m TVD was reached in mid-May, the testing and stimulation of the well was completed one month later. The drilling of the second well (Th2) commenced in June, from the same drilling pad. The mud weight in the third section was increased based on the experiences from the first well. For the first three sections, the drilling went according to plan. After seven weeks of drilling the casing was ready to be set at a depth of approx. 4,600 m MD in the third section. While running the 9-7/8” – 9-5/8” liner in the third section, drag forces increased suddenly and significantly, causing the liner to get stuck halfway along the section length. Extensive fishing and milling operations followed before drilling was resumed. After three months of unsuccessful efforts, the third section of the Th2 had to be abandoned, and the well was cemented back up to about 2,600 m MD to the liner shoe of the second section. A sidetrack Th2a was drilled parallel to the abandoned third section of Th2. However, during a check trip before running the casing, the drill string got stuck again. Only a partial recovery of the string was possible, and a sidetrack (Th2b) was planned and drilled. Finally, the liner of the third section was run and cemented at the beginning of January 2017. Differential sticking is likely to be the reason for getting stuck with liner and drill string, since high mud weights were used in this section. After a total drilling period of about 8 months, the final depth of Th2b 6.084 m MD / 5.050 m TVD was reached in March 2017 followed by a successful short-term testing phase that also included a circulation test of the geothermal doublet.

Both wells and the drilled sidetracks highlight that the wells could be drilled quickly due to a high ROP and low drilling flat time experienced throughout all drilling phases. Nevertheless, it also became clear that the geological conditions become more challenging the further to the South the drilling spot is located in the Molasse Basin. This circumstance is due to the increasing depth of the asymmetric Molasse Basin and the proximity to the northern fringe of the Alps. The greatest drilling challenges were the high variance in pore- and formation-pressure as well as the difficulty in foreseeing these pressures within a confined space from the Oligocene (Lower Tertiary) down to the Upper Cretaceous, despite data from near hydrocarbon offset wells being taken into consideration. These circumstances were the main reasons for the extraordinary events and therefore the delay of the drilling project.

2. Well Design Review

As a first step, after having experienced the Gas Kick in the HZK Th1 and the stuck casing as well as the stuck drill string due to differential sticking in the third section of the Th2 and Th2a (differential sticking occurred in sandstones of the lower part of the *Baustein* beds within the Chatt formation) the expected pore- and frac- pressures along the original well path of the Th1 as well as the “Risk Matrix” were reviewed.

2.1 Pore Pressures

Overpressure in this part of the North Alpine Foreland Basin is strongly related to fast subsidence and therefore high sedimentation rates during the Oligocene and Lower Miocene. According to literature (Müller et al. 1988) and data from adjacent oil wells (drilled 40 to50 years ago), pore pressure for the deeper basin sediments was assumed not to exceed 1.4-1.5 specific gravity (SG) in this area. In accordance with the observations from the newly drilled geothermal wells in Holzkirchen from 2016 and a new publication (Drews et al. 2018), pressure gradients for this region must be adapted to higher values. In the Chattian formation (Late Oligocene) pore pressure probably reaches maximum values of 1.2-1.4 SG, however in the lowest part of the underlying Rupelian formation (Early Oligocene), at approx. 4.200 m TVD depth, the pore pressure could reach maximum values close to 2.0 SG. Below this high-pressure zone, the pressure gradients in the underlying Mesozoic sediments decrease significantly down to 1.2-1.4 SG in Upper Cretaceous shales followed by hydrostatic conditions in the Lower Cretaceous to underbalanced hydrostatic conditions in the Jurassic Malm reservoir at approx. 4.600 m TVD depth.

2.2 Risk Assessment

Based on the hazards faced in Holzkirchen and the experience from nearby wells, the risk assessment for future wells in this area should consider the following significant points:

The **Miocene** formations overlying the Chattian are not prone to hazards and are mostly drilled fast and without significant troubles.

The highest risks in the **Chattian formation** (above the Rupelian) are kicks due to elevated pore pressures but also differential sticking due to increased mud weight. The Chatt is dominated by sandstone, and therefore borehole instability is not expected to be the primary issue. Pore pressures are expected to be overpressured but much lower than in the underlying Rupelian formation. The mud weight in the Chattian should be as close as possible to the real pore pressure to minimize both risks: differential sticking and fluid inflow. However, this is difficult as the real pore pressure can vary highly from well to well. Therefore, it is not possible to drill the Chattian and Rupelian formation in one section without facing higher risks. To minimize the risks, the Chattian should be drilled in one section with moderate mud weight which leads to an acceptable kick tolerance without increasing the risk of differential sticking to an unacceptable degree. The Rupelian can then be drilled in one section with very high mud weight to avoid intense gas kicks or borehole instabilities.

Within the **Rupelian formation,** the high pore pressures and tectonic stress cause the most significant problems. The technical hazards are either borehole instabilities or an inflow of fluids (kick). Borehole instabilities are faced mostly in impermeable formations where the pore pressure manifests as borehole breakouts (cavings) or in formations where tectonic stress is present, depending on the orientation of the well trajectory. Kicks can be encountered in permeable formations where fluids can enter the borehole easily. The Rupelian formation is mostly shale with some interbedded permeable sandstones of limited lateral and vertical extent. Therefore, the probability of a kick in the Rupelian is moderate. However, drilling through an interbedded permeable sandstone in the Rupelian (especially in the *Bändermergel* sub formation) with insufficient mud weight can cause an intense kick with very high pore pressures. Necessary measures are a higher mud weight and a sufficient setting depth for the last casing to obtain a high kick tolerance. These precautions should also account for any uncertainties in the pore pressure and fracture pressure prediction.

In the **Cretaceous** (below the Rupelian), pore pressures decrease. Some hydrocarbon-bearing, shale or marl rich formations in the Upper Cretaceous might indicate moderate overpressure, while some formations (especially sandstone and limestone in the Lower Cretaceous) are prone to losses. Therefore, the most prominent risks are gas/oil kicks, losses and differential sticking. To minimize these risks, the mud weight should be decreased to the lowest acceptable value while maintaining acceptable kick tolerance. To obtain this, the Cretaceous must be drilled in one separate section as well.

The **Jurassic** (reservoir) is prone to total losses, which happen in almost every (productive) well. However, in most cases, it is not a hazard for drilling. Where the reservoir is reached, all oil and gas bearing formations above are already cased and cemented. Differential sticking is not an issue as the pressure equalizes in the borehole quite rapidly. Cuttings are transported into the loss zone. Pumping of high-viscosity pills and frequent backreaming assists the cleaning of the hole. Furthermore, it is good practice to minimize the risk by changing the BHA to “dumb iron” before drilling ahead with total losses.

Figure 1 and Figure 2 below provide an overview of the geological sections discussed in this chapter. Additionally, potential overpressure zones are highlighted using various shades of red to visualize the variable pore pressures in the geological zones.

3. DEVELOPMENT AND EVALUATION OF ALTERNATIVE WELL DESIGNS

Taking into consideration the lessons learned from the geothermal wells HZK Th1 and Th2, it becomes evident that an additional well section should be installed to reduce the risk and isolate the potential high-pressure zones in the Rupelian formation from the underlying permeable zones in the Cretaceous. Therefore, two alternative casing designs along a fictitious well path in the region around Holzkirchen were planned and their pros and cons evaluated.

3.1 Design Parameters

The following design parameters were defined for the new alternative casing designs:

- Design parameters:
  - Production rate: 65 l/s
  - Anticipated maximum production temperature: 160°C
  - Injection temperature: 10°C
  - Dynamic fluid level: 900 m
  - Pore pressures: See section 2.1
- The min. borehole diameter in the reservoir section must stay the same as in the original design (6-1/8”) to achieve the necessary production rate with acceptable pressure losses along the production casing and liners.
- The first section must fit an “Electric Submersible Pump” (ESP) that is designed for the maximum anticipated production rate and dynamic fluid level.
- Additional production tubing is not accounted for as the geothermal water is produced through the production casing and liners.

3.2 Standard Clearance Design with 26” Surface Casing

The first conceptional design adheres to standard clearances for the casing and bit selection. Therefore, it is planned that the first section is drilled with a 30” bit and 26” casing is run. The second section is drilled with a 23” bit and 18-5/8” casing is run. The third, fourth, fifth and sixth sections are drilled with 16”, 12-1/4”, 8-1/2” and 6-1/8” bits and 13-3/8”, 9-5/8”, 7” and 5” liners are run respectively. Additionally, a 13-3/8” tieback is planned to be set after successfully running and cementing the third section. Figure 1 below provides an overview of the stratigraphy, the well schematic as well as an overview of the planned well path.

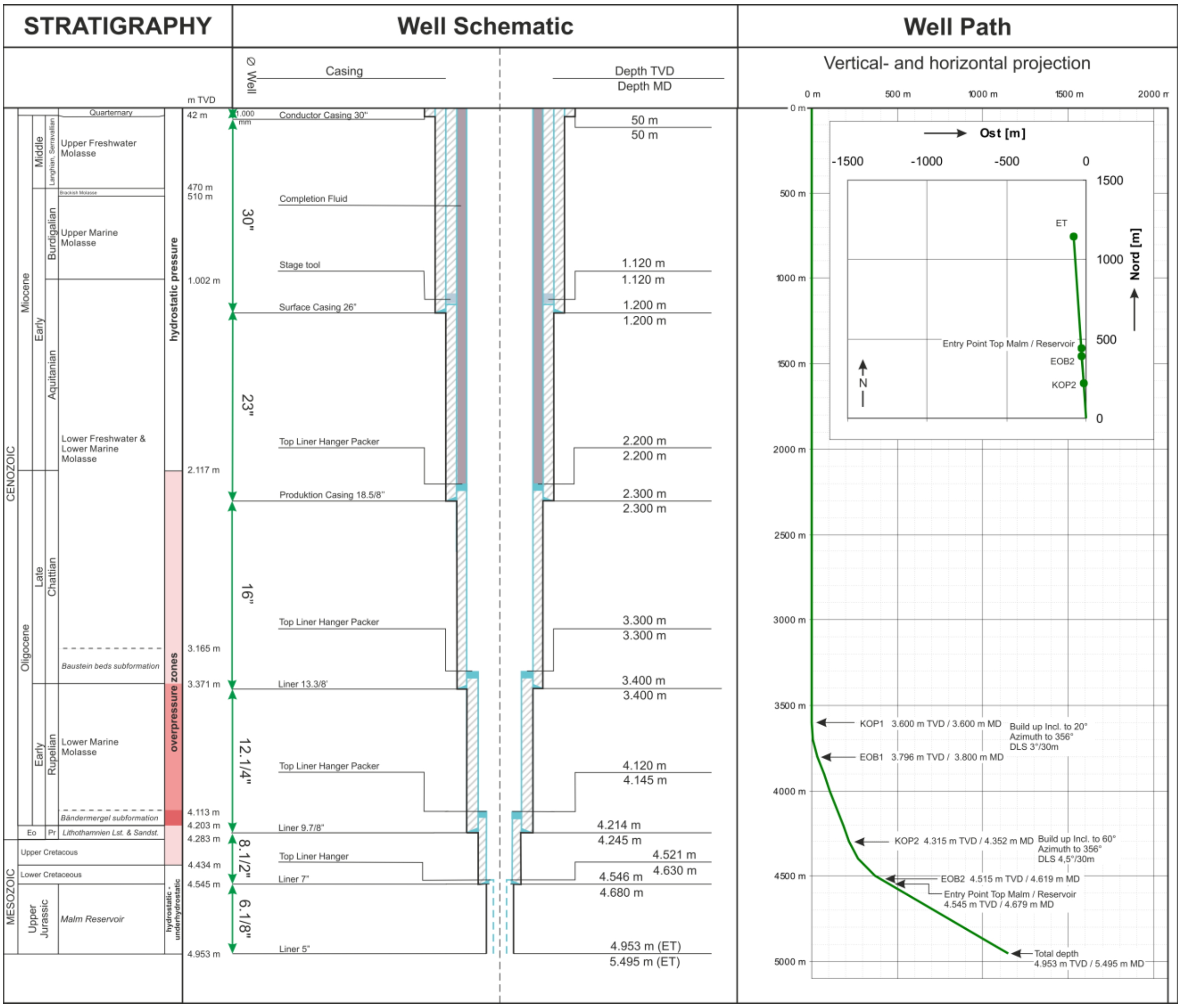

Figure 1: Well Schematic and Well Path of the Standard Clearance Design

3.2.1 Design Limitations

Although the selected bit and casing sizes for this design are all standard sizes, the availability of 30” bits and 26” casing is limited. Additionally, due to the high weight of the selected 26” casing string, the number of potential rig contractors is restricted. While these problems can be overcome, the main problem could be insufficient cutting transport as the pump limits are reached, and a low annular velocity cannot be avoided in the upper two sections. Following the installation of a long 13-3/8” tieback to the surface, no significant technical challenges are expected in the subsequent sections.

3.3 Low Clearance Design

For the second conceptional design, a rather unconventional low-clearance casing design was developed. The first section consists of a smaller 20” casing in a 26” borehole. In the second section 16” casing is run in an 18-1/2” hole. For the third section, a 13-5/8” liner is used in a borehole that is drilled with a 14-3/4” bit and underreamed to 16” to provide sufficient clearance for running and cementing the casing. In the following three sections the design follows a standard clearance design. Figure 2 below provides an overview of the stratigraphy, the well schematic for the low-clearance design and the associated well path.

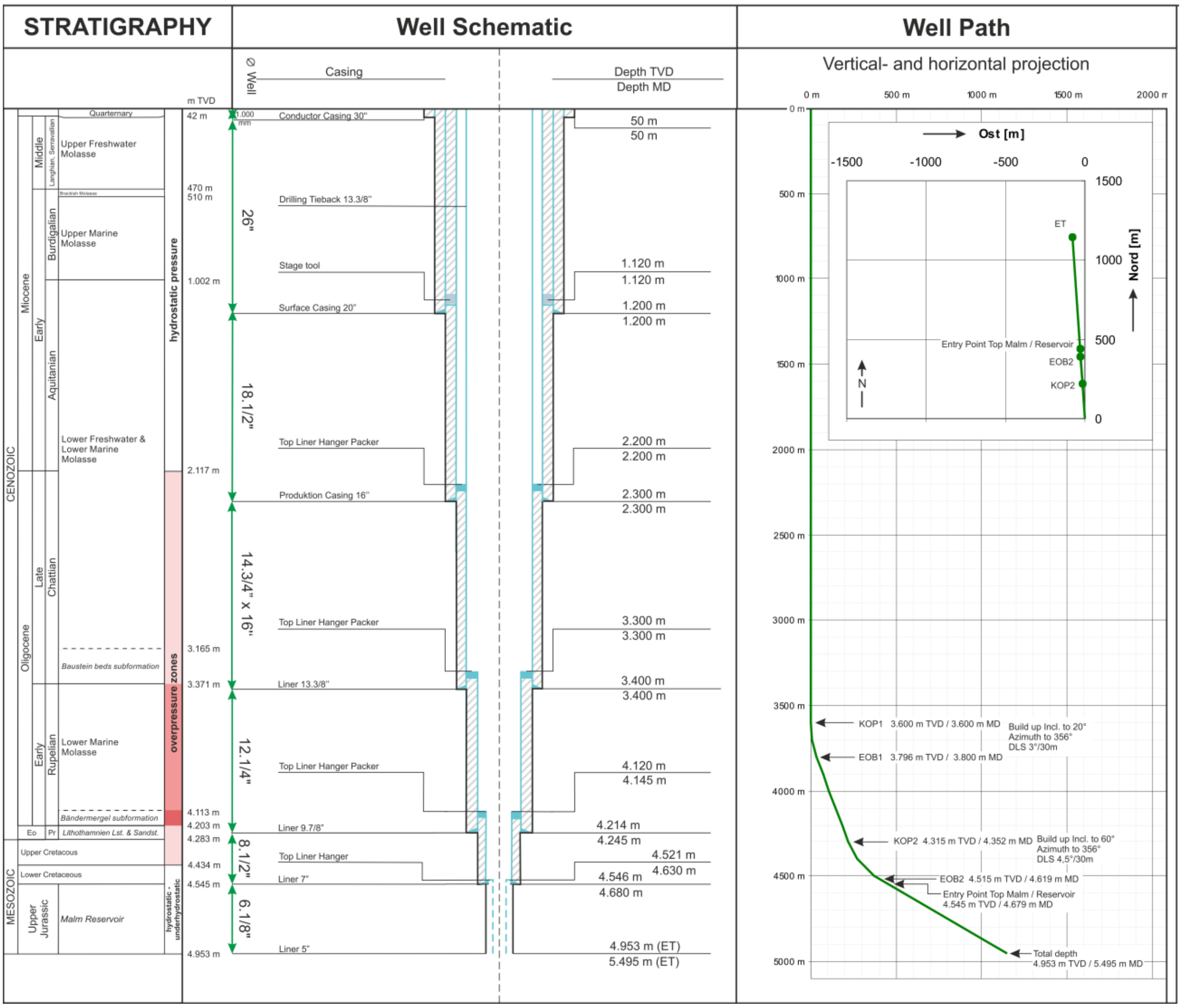

Figure 2: Well Schematic and Well Path of the Low Clearance Design

3.3.1 Design Limitations

In the second section, an 18.1/2" bit must be deployed. The availability of this unconventional bit size is limited. The 14.3/4"-16" underreaming BHA, used in the third section bears additional technical risks.

3.4 Low Clearance- vs. Standard Clearance Design

Table 1 provides a comparison of the low clearance design with the standard clearance design, considering the advantages and limitations detailed above.

Table 1: Low Clearance vs. Standard Clearance Design

Advantages	Disadvantages
+ Reduced hook loads while running casing + Good wellbore cleaning conditions in the first and second sections + Reduced costs due to smaller casing sizes for the first and second section	- Undreaming in the third section - Unconventional bit (18.1/2") in the second section

The low clearance design provides good wellbore cleaning conditions in all sections, it is more cost effective and the overall risks are lower compared to the standard clearance design.

In the following section the low clearance design is evaluate in further detail.

3.5 Design Evaluation

3.5.1 Casing Design

To verify the feasibility of the low clearance design, further calculations were applied to simulate different stress situations during the drilling and production phase. These calculations follow the guidelines of the BVEG (Bundesverband Erdgas, Erdöl und Geoenergie e.V.) and the NZS 2403:2015 "Code of practice for deep geothermal wells" and were performed using the software StressCheck^{TM}. For the well design in Germany, the use of the BVEG standard is the minimum requirement. Additionally, the NZS guidelines are applied for relevant load cases as they have been developed explicitly for geothermal well design.

3.5.2 Considerations for the Low-Clearance Design

20" Surface Casing

The 20" casing is not designed to withstand the loads during the production phase. After drilling the second section and running the 16" casing, the 20" surface casing lies behind the cemented 16" casing. Therefore, the dominant stress scenario for this section is the external load during the cementation of the 20" surface casing.

With available grades and wall thicknesses, the essential design factors according to BVEG can be achieved.

16" Production Casing

Decisive for the design of the 16" production casing is the lowered dynamic fluid level during the production phase in connection with high axial compressional loads due to the temperature increase as well as the external loads throughout the cementation.

The 16", 97 pounds per foot (ppf) casing is the last casing with a drift of 14-3/4", which allows passage for the anticipated bit of the third section. It must also be kept in mind that the highest hook load (290-ton neutral weight of the casing in mud) is experienced while running the 16" casing. Not all NZS design limits can be adhered to even with high-end grades (e.g., VM 95 HCS). Nevertheless, the planned design meets the BVEG requirements. The limit of the 16" casing complies the design factor of about 1.25 for the compressional load and lies in between the minimum design factor of 1.10 for BVEG and 1.40 for NZS standard.

The cementation of the 16" production casing is performed as a two-stage cementation to split weight and length of the cement column in the annulus. This will reduce the load on the formation and allows for the use of high weight cement slurries. Moreover, it will lead to a good cementation in the annulus between the surface casing and the production casing which is important to decrease the risk of annular pressure build up and axial movement or buckling of the casing. Therefore, sufficient excess volume of cement needs to be allowed for in the first and second stage. Additional measures to increase the collapse/burst ratio between the outer and inner casing string may also be considered. This includes increasing the collapse rating of the upper 16" casing. Finally, the side doors of the stage tool must be placed as close to the packer as possible, and a burst disc needs to be included directly below the packer, which may rupture at a specific external load to release pressure in the case of trapped fluid pockets directly beneath.

13-5/8" Production Liner

As for the 16" casing, the lowered dynamic fluid level during the production phase in connection with high axial compressional loads due to the temperature increase is decisive for the design of the 13-5/8" production liner. Additionally, the axial tension load scenario, due to the significant temperature decrease in the lower part of the well during injection, drives the design limitations in the deeper sections of the well.

With available grades and wall thicknesses, the essential design factors according to BVEG/NZS can be achieved.

9-7/8" Production Liner

As for the second and third sections, the driving factors for the design of the 9-7/8" production liner is the lowered dynamic fluid level during the production phase and the associated high axial compressional loads due to the temperature increase as well as the axial tension due to the low temperatures during the injection. Also, a highly elevated pore pressure is considered along the Rupelian formation to act with 2.0 SG mud weight equivalent (MWE) on the casing.

Even with high-end grades, the calculation shows that the design is not able to meet the design factor for the collapse load following the NZS (1.2). However, the design factor after BVEG (1.0) is fulfilled.

7" Production Liner

In this case, the most dominant design load for the 7" production liner is the reinjection of the cooled water and the accompanying axial tension, with the connections being the most probable point of failure. At these depths, the differential temperature between the injection fluid and the ambient temperature becomes much more of a challenge than in the previous well sections. Firstly, this problem is mitigated with the selection of higher-grade steel. Secondly, the assumption that the 7" liner experiences 10°C is very conservative. Therefore, the fulfillment of the design factor for the axial tension at the connection following BVEG (1.6) is considered sufficient.

4. CONCLUSIONS

Considering the drilling experiences in Holzkirchen Th1 and Th2 and the resulting revision of the risks and pore pressures, it became clear that an additional sixth casing string should be incorporated allowing the use of higher mud weights to achieve a sufficient kick tolerance without increasing the risk of differential sticking in other sections.

New casing setting depths have been defined to incorporate the sixth casing string, whereby the setting depth of the third section is set directly after the *Baustein* beds (deeper Chattian formation; Late Oligocene) to separate lower-pressure permeable zones from potential high-pressure gas-bearing zones in the underlying Rupelian formation (Early Oligocene). The fourth section is included to solely drill through the Rupelian formation with higher mud weights to mitigate the risk of a gas kick. The setting depth is defined shortly after the *Fischschiefer* (dark shale base layer of the Early Oligocene) to separate the less pressurized and more permeable formations in the Eocene and Cretaceous from the overlying high-pressure Rupelian formation. Due to an additional sixth section also, the length of the second and third sections are reduced.

Of the two alternative designs with an additional sixth section, the low-clearance design is preferable compared to the standard-clearance design with larger surface casing for several reasons. The hook loads while running the first and second casings can be reduced. Due to the smaller diameter in these sections, cleaning conditions can be improved. Finally, better availability and expected lower cost of the necessary equipment increase the economic efficiency.

The dominant design loads, especially in the upper sections, are caused by the lowered dynamic fluid level during the production phase and high axial compressional loads due to the temperature increase. In the lower sections, the predominant design load is the reinjection of the cooled produced water and the accompanying axial tension of the casing. By applying high-end steel grades and thicker-walled casing, the design meets the requirements of BVEG, yet it is not feasible to meet every aspect of NZS. However, the underlying assumptions are most conservative. Therefore, the fulfillment of the design factors according to BVEG is considered sufficient.

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