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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 was spudded in January 2016; the drilling for 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 in two separate incidences due to differential sticking. Two sidetracks were drilled and after a total drilling period of about 8 months, the final depth of 6.084m 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 whilst not increasing the risk of differential sticking in formations with normal pore pressure. Therefore, this paper will discuss 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 stays the same.

1. Introduction

The Holzkirchen doublet comprised 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 half an hour drive by car 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 and 5,200 m depth, is known to have appropriate natural permeability and the geothermal fluid to be low in salinity. This, together with its expected naturally sufficient yield, makes the Malm 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 in about 4,200 m (Rupelian *Bändermergel* subformation), 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. From there on, the well was tested and stimulated successfully by mid-June. Following the Holzkirchen Th1, drilling of the second well (Th2) commenced in June, from the same drilling pad. The drilling program (e.g., mud weight) and the well path had to be adapted based on the experiences from the first well, to bypass the potential high-pressure area, and increase the kick tolerance. 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 in the third section. While running the 9-7/8" – 9-5/8" liner in the third section, drag forces became suddenly significantly higher, causing the liner to get stuck half way along the section length. Extensive fishing and milling operations followed. The fishing, milling and drilling operations for the Th2 took about three months. Finally, 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, while conducting a check trip before running the casing, the drill string got stuck again. The drill string couldn't be freed completely and a sidetrack (Th2b) was planned and drilled within another 5 weeks. Finally, the liner of the third section was put in place and cemented on the beginning of January 2017. 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 month-long 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 in a very fast manner thanks 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 south the drilling spot is located in the Molasse Basin. This is due to the increasing depth of the asymmetric Molasse Basin and closeness 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 Upper Cretaceous, despite data from near hydrocarbon offset wells being taken into consideration. These circumstances were largely to blame for the extraordinary events and therefore the delay of the drilling project.

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 in 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.

1.1 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 40-50 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 depth, the pore pressure could reach maximum values close to 2 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 depth.

1.2 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 major points:

Within the **Rupelian formation** the high pore pressures and tectonic stress cause the biggest problems. The technical hazards are either borehole instabilities or an inflow of fluids (kick). Borehole instabilities will be 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 well trajectory. Kicks will be faced 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* subformation) with insufficient mud weight can cause an intense kick with very high pore pressures. The measures to be taken are increasing the mud weight and setting the last casing shoe deep enough to obtain a high kick tolerance which should also account for any uncertainties in the pore pressure and fracture pressure prediction.

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, therefore borehole instability is not expected to be the primary issue. Pore pressures are expected to be over pressured 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 will be 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 whilst not 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.

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. However, some formations (especially sandstone and limestone in the Lower Cretaceous) are also 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 whilst maintaining acceptable kick tolerance. To obtain this, the Cretaceous must be drilled in one separate section as well.

The **Miocene** formations overlying the Chattian are not prone to hazards and are mostly drilled fast and without major troubles. The **Jurassic** (reservoir) is prone to total losses, which will 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 will assist hole cleaning. 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 chapter 1.1 and 1.2. Additionally, potential overpressure zones are highlighted using various shades of red to visualize the variable pore pressures in the geological zones.

2. Development and Evaluation of Alternative Well Designs

Taking into consideration the problems from the geothermal wells HZK Th1 and Th2, and the adapted maximum potential pore pressures as well as the risk matrix, it becomes obvious 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. For the purpose of developing this methodology, two alternative casing designs along a fictitious well path in the region around Holzkirchen were planned and their pros and cons evaluated.

2.1 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
  - Squeezing formation along the Rupelian — 2.0 SG

- The min. borehole diameter in the reservoir section must stay the same as in the original design (6-1/8”) in order 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.

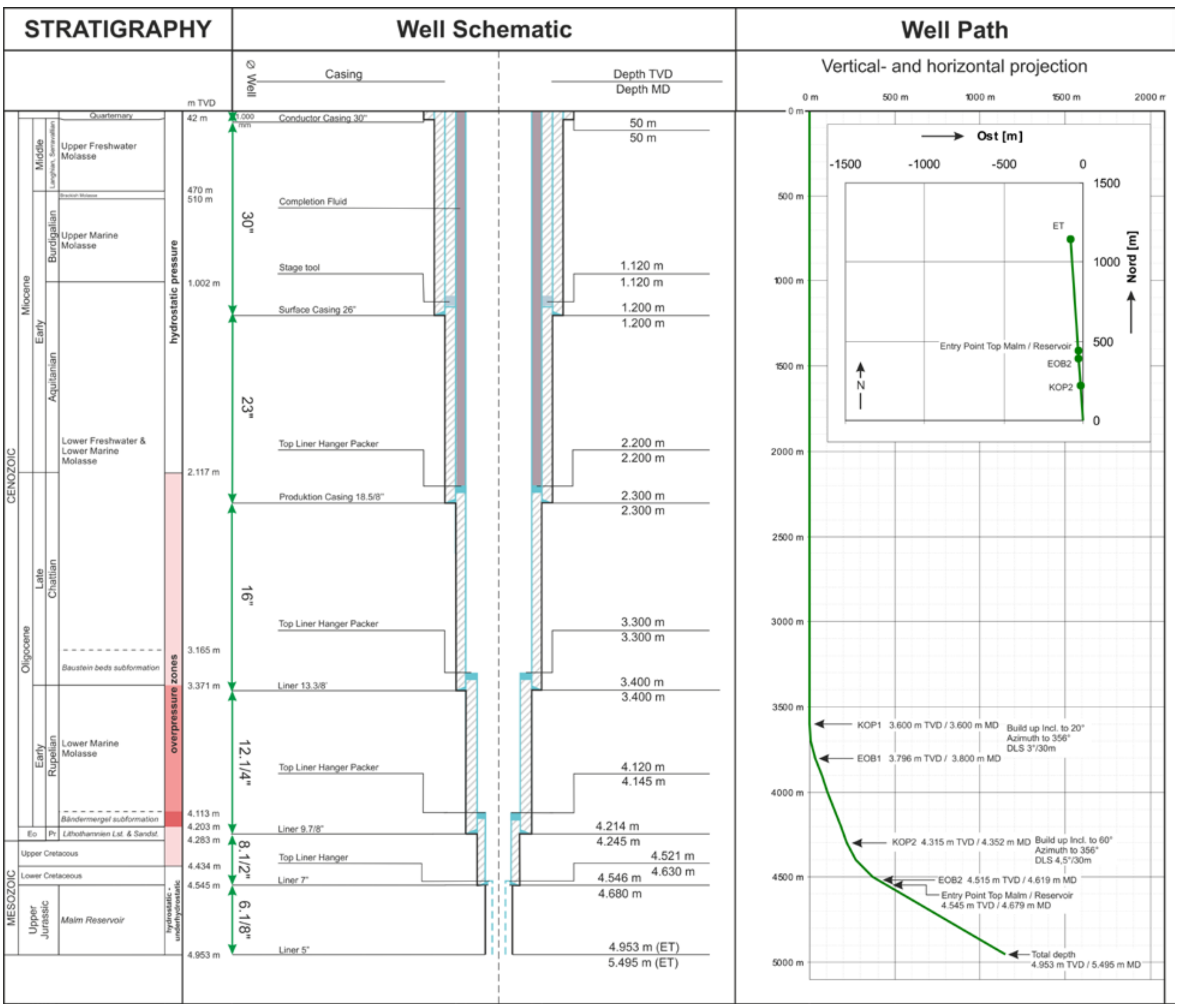

Figure 1: Scenario 1 Well Schematic and Well Path

2.2 Enlarged Standard Design with 26” Surface Casing

The first conceptional design adheres to API 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 for the enlarged standard design with 26” surface casing as well as an overview of the planned well path.

2.2.1 Design Limitations

Initially, the main benefit of the first alternative design was assumed to be that the selected sizes were all standard sizes and widely available. This is not quite the case for the first section where 26” casing is planned. Additionally, due to the high weight of the selected 26” casing string, the number of potential rig contractors is limited. Moreover, the general availability of 30” roller cones could be a problem. All these problems can be overcome, however cutting transport could be problematic, as the pump limits will be reached, and a relatively low annular velocity cannot be avoided. The planned second section encounters similar problems to the first, with the expected high weight of the 18-5/8” casing as well as the availability of a 23” PDC bit. Following the installation of a long 13-3/8” tieback to the surface, no significant technical challenges are expected in the following sections.

2.3 Low Clearance Design

For the second conceptional design a more unconventional low-clearance casing design was developed. Here the low clearance in the most outstanding section (third section) was bypassed by deploying an underreamer in the BHA while drilling. Therefore, the first section consists of a smaller 20” casing in a 26” borehole. In the second section 16” casing is run in a 18-1/2” hole. For the third section it is planned to run a 13-5/8” liner in a borehole that is drilled with a 14-3/4” bit. Therefore, the low clearances of the third section increase the risks of getting stuck while running the 13-5/8” liner and may result in a poor cementation. The liner will experience high temperatures and external pressures during production and a good cement job is essential. An additional underreamer should be employed, which will widen up the borehole to 16”. The following three sections the design follows the same approach to the first alternative design. Figure 2 below provides an overview of the stratigraphy, the well schematic for the low-clearance design and the associated well path.

2.3.1 Design Limitations

The maximum load will be reached while running the 16” casing. An underreamer must be deployed along the BHA to widen the borehole while drilling and provide sufficient clearance. The extra downhole equipment bears additional risks that cannot be eliminated, however they are minor compared to those associated with the low clearance.

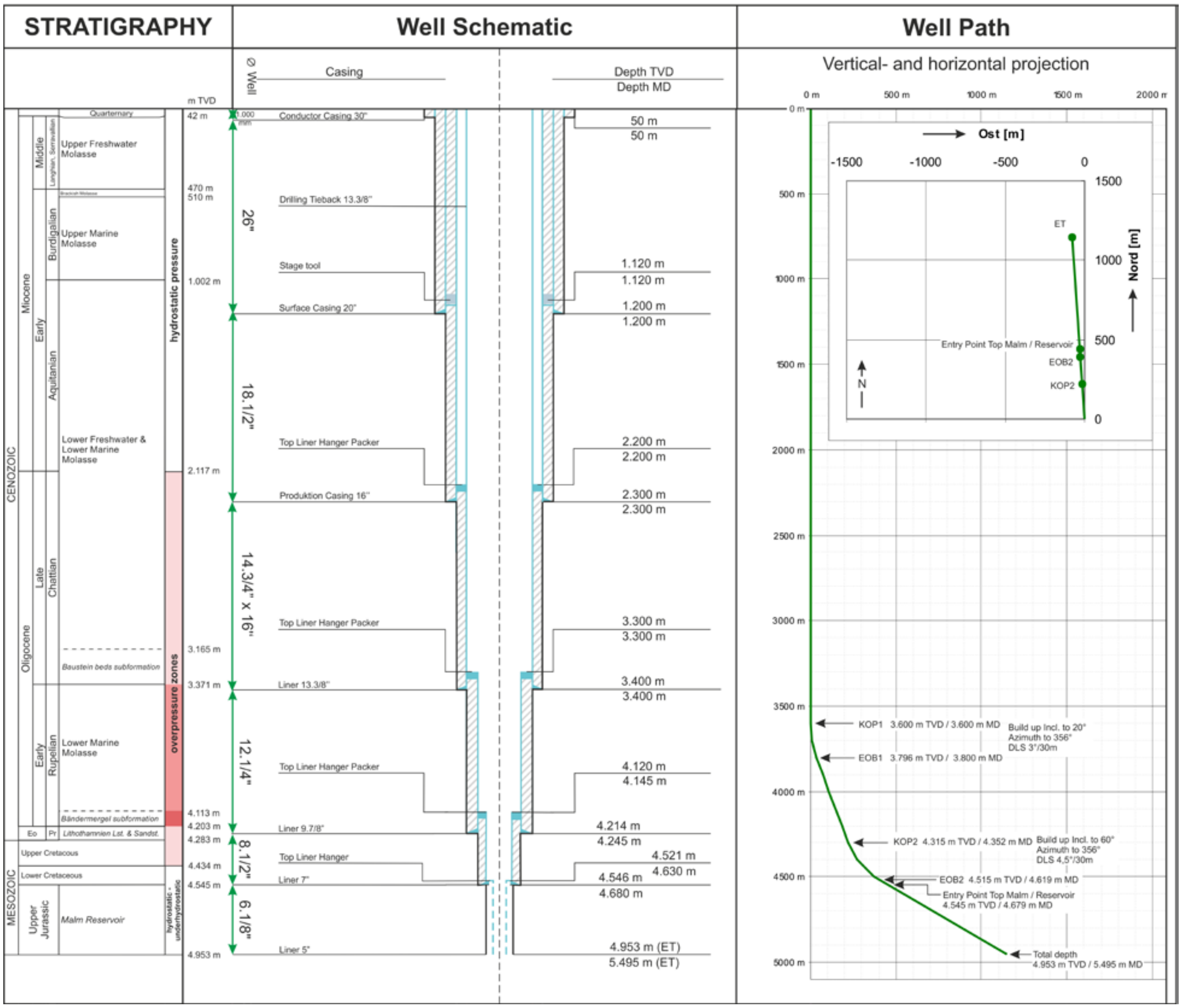

Figure 2: Scenario 2 Well Schematic and Well Path

2.4 Low Clearance- vs. Standard- Design

Table 1 below provides a comparison of the low-clearance design with the enlarged standard design, considering the limitations detailed above. This comparison allows the most favorable design to be identified for further planning.

Table 1: Low Clearance vs. Standard Design

Advantages	Disadvantages
+ Smaller casing sizes for the first and second section + Reduced hook loads while running the casing + Better wellbore cleaning conditions in the first and second sections + Reduced costs compared to the larger design	- Undreaming in the third section - Unconventional bit (18.1/2”) in the second section

After comparing both designs it was concluded that the low clearance design is the best approach. The following sections detail the further planning to evaluate if the design is applicable for further wellbores around Holzkirchen.

2.5 Design Evaluation

The main reasons why the low clearance design was selected over the enlarged standard design were the reduced hook loads while running the first and second sections, the smaller diameter of the first and second section and therefore the better wellbore cleaning conditions, the ability to handle the equipment on the surface more easily, and finally expected lower costs.

2.5.1 Casing Design

To verify if the selected design is feasible along the planned well path further calculations were undertaken to simulate different stress situations during the drilling and production phase. These calculations follow the guidelines of the WEG (Wirtschaftsverband Erdöl- und Erdgasgewinnung e. V.) and the NZS 2403:2015 “Code of practice for deep geothermal wells” and were undertaken with the software StressCheck™. For the purpose of well design in Germany the use of the WEG standard is the minimum requirement however, for relevant load cases the NZS guidelines are applied as they have been specifically developed for geothermal well design.

2.5.2 Considerations for Low-Clearance Design

The bottlenecks encountered that needed special attention are discussed in the following paragraphs.

20” Surface Casing

The 20” casing is not designed to withstand the loads during the production phase as it is purely designed to fulfill its role as surface casing. After drilling the second section and running the 16” casing, the 20” surface casing will lie 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. The additional simulated loads do not play a significant role for the design of the 20” surface casing.

With available grades and wall thicknesses, the required design factors according to WEG/NZS 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) will be experienced while running the 16” casing. Even with high end grades (e.g. VM 95 HCS), not all NZS design limits can be adhered to. Nevertheless, the planned design meets the WEG requirements.The high collapse limit of the 16” casing complies with the design factor of about 1.25 for the compressional load and lies in between the minimum design factor of 1.1 for the WEG and NZS standards.

The cementation approach shall adopt a two-stage cementation to split the weight and the length of the cement column in the annulus. Particular attention needs to be paid to the second stage of cementation between the 20” surface casing and 16” production casing. It is essential to avoid fluid pockets between the two casing strings as these fluid pockets will exert high external loads on the 16” casing during the production phase due to a marginal increase in volume (due to the temperature expansion) that may lead to a collapse 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 certain 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 required design factors according to WEG/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. In addition, a squeezing formation is considered along the Rupelian formation to act with 2 SG mud weight equivalent (MWE) on the casing.

Even with high end grades, the simulation undertaken shows that the design is not able to meet the design factors in accordance with the NZS. However, the design factors after WEG are fulfilled. Again, the dominant design load is experienced during production. The assumption of a squeezing formation with 2 SG MWE existing in the Rupelian is considered very conservative planning and also an additional safety measure on top of the design factors.

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, whereby the connections are the first part prone to fail. At such 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 a 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 in accordance with WEG (DF 1.6) is considered sufficient.

3. Conclusion

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 which would allow the use of higher mud weights to achieve a sufficient kick tolerance whilst not increasing the risk of differential sticking in other parts.

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* (base layer (dark shale) of the Early Oligocene) to separate the less pressurized and more permeable formations in the Eocene & 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.

From the two alternative designs with an additional sixth section, the low-clearance design is chosen over the expanded standard-clearance design, because the low clearance design has reduced hook loads while running the first and second casing, better wellbore cleaning conditions due to a smaller diameter in the first and second section, better availability of equipment and expected lower costs.

The low-clearance design is applicable despite some special design considerations which must be addressed. 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 comes from 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 WEG. But 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 WEG is considered sufficient.

REFERENCES

Drews, M.C., Bauer, W., Caracciolo, L., Stollhofen, H., 2018. Disequilibrium compaction overpressure in shales of the Bavarian Foreland Molasse Basin: Results and geographical distribution from velocity-based analyses. Marine and Petroleum Geology 92, 37–50. https://doi.org/10.1016/j.marpetgeo.2018.02.017

Müller, M., Nieberding, F., Wanninger, A., 1988. Tectonic style and pressure distribution at the northern margin of the Alps between Lake Constance and the River Inn. Geologische Rundschau 77, 787–796. https://doi.org/10.1007/BF01830185